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Demonstration and Evaluation of an Advanced Integrated Operations Concept for Hybrid Control Rooms

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Demonstration and Evaluation 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 Evaluation 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 describes the methods, results, and design recommendations for the concept based on an operator workshop to evaluate the concept.

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ACRONYMS

ADAPT	Analytics, Decision-Support, and Advanced Procedure Tool
AOP	Abnormal Operating Procedure
AP	Alarm Procedure
COTS	Commercial Off-the-Shelf
CVCS	Chemical Volume Control System
DOE	Department of Energy
EID	Ecological Interface Design
EOP	Emergency Operating Procedure
ERFDADS	Emergency Response Facility Data Acquisition and Display System
F	Fahrenheit
FW	Feedwater
GONUKE	Guideline for Operational Nuclear Usability and Knowledge Elicitation
HABA-MABA	Humans are Better At - Machines are Better At
HFE	Human Factors Engineering
HSI	Human-System Interface
HX	Heat Exchanger
I&C	Instrumentation and Control
IRD	Information Rich Display
LOA	Level of Automation
LWRS	Light Water Reactor Sustainability
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
P&ID	Piping and Instrumentation Diagram
PVGS	Palo Verde Generating Station
PZR	Pressurizer
R&D	Research and Development
RCS	Reactor Coolant System
RO	Reactor Operator
SA	Situation Awareness
SI	Safety Injection
SME	Subject Matter Expert
SRO	Senior Reactor Operator
TBD	Task-Based Display

U.S.	United States
VCT	Volume Control Tank
WDA	Work Domain Analysis

DEMONSTRATION AND EVALUATION OF AN ADVANCED INTEGRATED OPERATIONS CONCEPT FOR HYBRID CONTROL ROOMS

1 INTRODUCTION

The United States (U.S.) nuclear industry is facing a need to transform the way in which the nuclear power plants (NPPs) are being operated, maintained, and supported (Kovesdi, St Germain, Le Blanc, & Primer, 2019). These NPPs are largely composed of a legacy instrumentation and control (I&C) infrastructure, from a 1970s vintage, when these plants were initially licensed (Joe & Remer, 2019). While reliable and state-of-the-art at the time of initial licensing, this I&C is now a limiting factor for the continued operation of these plants due to obsolescence and availability of parts. A consequence of this has been a reactive approach to the maintenance and modifications of plant systems and equipment for many NPPs, characterized by like-for-like replacement without a strategic end-state vision. The industry at large has historically undergone modifications done in piecemeal or partial fashion, often leading to the blind application of technology without realizing the synergistic benefits that could be attained with a more strategic approach that leverages technologies across different functional areas (Joe, Boring, & Persensky 2012; Kovesdi et al., 2019).

Another major driver for the need of a pivotal transformation in the nuclear industry pertains to the evolving U.S. energy market. That is, the U.S. has seen an increased use of natural gas and renewables due to reduced cost for resources and capital expenditures (EIA, 2020). In regions where the U.S. energy market is competitive (a.k.a. merchant market), electricity prices have notably decreased in part due to increased use of natural gas and renewables, which has further created economic strain on these NPPs operating in the same market (EIA 2018). Collectively, the aging legacy infrastructure and shifts in market demands have created an emerging need for a total transformation of the way in which U.S. NPPs are operated, maintained, and supported.

The U.S. Department of Energy (DOE)-sponsored Light Water Reactor Sustainability (LWRS) Program Plant Modernization pathway is collaborating with industry to address these challenges by conducting targeted research and development (R&D). This R&D is focused on developing a vision and roadmap for industry that describes how enabling technology can be strategically implemented to promote business-driven innovation that reduces operating and maintenance cost and improves performance. This work fits within the LWRS Program Plant Modernization Pathway's mission through development of an advanced yet realistic end-state control room concept that demonstrates how strategic integration of advanced technology can greatly reduce cost.

This concept, named Analytics, Decision-Support, and Advanced Procedure Tool (ADAPT), utilizes commercial off-the-shelf (COTS) technology to gather data from the field, control systems, and additional sensors for use in advanced analytics, modeling, and decision support capabilities that streamline operations and maintenance functions by transforming the way in which work is done (Kovesdi et al., 2020). The selection of these technologies was guided by findings in previous research undergone by the LWRS Program that indicated high economic value with operating and maintaining the plant (e.g., Al Rashdan & Mortenson, 2018; Boring et al., 2017; Hunton & England, 2019; St. Germain et al., 2018; Oxstrand & Le Blanc, 2014). The ADAPT concept was introduced in INL/EXT-20-57862 (Kovesdi et al., 2020), which describes the overarching design philosophy, analyses used to inform the design, the implementation approach, as well as detailed descriptions of the primary functions and display systems of ADAPT. Further, the design bases used in ADAPT incorporate state-of-the-art human factors engineering (HFE) design principles described in recent LWRS work described in INL/EXT-18-44798 (Le Blanc et al., 2018), as well as regulatory guidance like U.S. Nuclear Regulatory Commission (NRC) *Human-System Interface Design*

Review Guidelines (NUREG-0700) and *Human Factors Engineering Program Review Model* (NUREG-0711).

Extending upon this line of the work, this report documents the findings from a design workshop with licensed operators at Palo Verde Generating Station (PVGS).

- Section 2 presents the key features and functions of ADAPT, describing their purpose and proposed value in reducing operating and maintenance cost.
- Section **Error! Reference source not found.** describes the HFE design process followed in t he development of ADAPT; this section presents the importance of following an iterative design process. Further, Section **Error! Reference source not found.** describes the key design t hemes, design assumptions, and design tradeoffs that motivated and ultimately structured the objectives of a design workshop that took place in March, in collaboration with an industry partner PVGS.
- Section 4 presents the objectives, methodology, findings, and specific design changes that came from the design workshop.
- Finally, Section 5 provides generalized design guidance and implications that can be used across industry, using the evidence-based insights collected from the workshop. Ultimately, this guidance can be used by industry to inform future design considerations in developing an end-state vision and roadmap of an integrated operations concept that reduces operating and maintenance costs.

2 BACKGROUND

2.1 Key Features of the Analytics, Decision-Support, Advanced Procedure Tool (ADAPT)

Analytics-Decision Support Advanced Procedure Tool (ADAPT) is an integrated control room operations technology that includes decision support, online monitoring, real time collaboration with field operations (and other necessary parties outside of the main control room) as well as plant analytics. One of the primary goals of ADAPT is to reduce operations and maintenance costs for nuclear power plants. In addition to streamlining operations to a single operator within the main control room, ADAPT also enables real time data analytics and communication which increases efficiency and safety.

Figure 1. ADAPT Concept Visualization

The ADAPT tool is controlled by an operator in the main control room and includes a hierarchal approach to operations (Figure 1). ADAPT is controlled from a seated workstation on four screens that display a plant overview, task overview, task-based display, and a secondary task-display. The plant overview provides dynamic at-a-glance status of important plant indications to generate the 'big picture' of the plant's current status. In addition to everyday monitoring, the operator is able to determine any normal, abnormal, or emergency statuses from the plant overview.

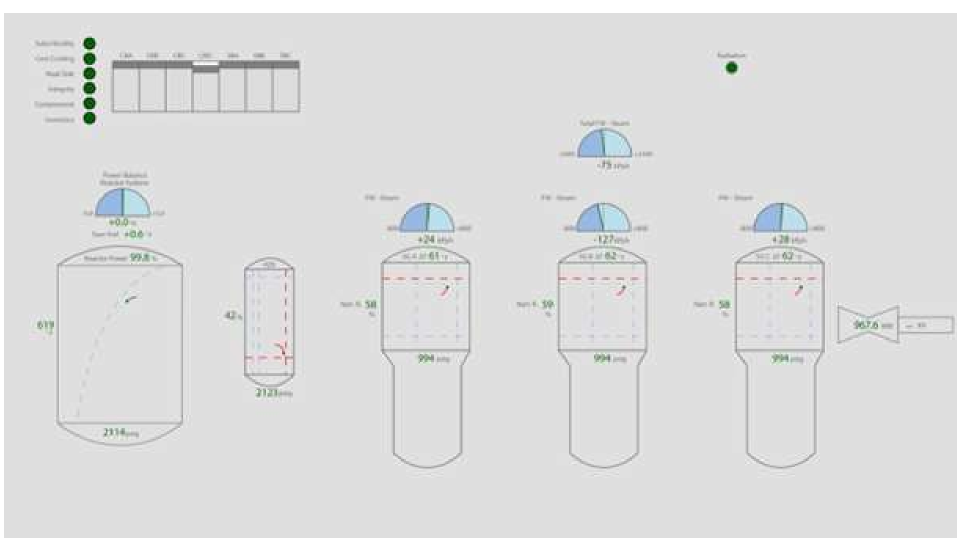

Figure 2. ADAPT Plant Overview Screen

When specific information is needed to perform a task, a task overview is provided to enhance situation awareness. Task overviews assist operators with critical plant information and parameters that are relevant to the task. Both the plant overview and task overview provide dynamic statuses but strictly serve as aids for monitoring.

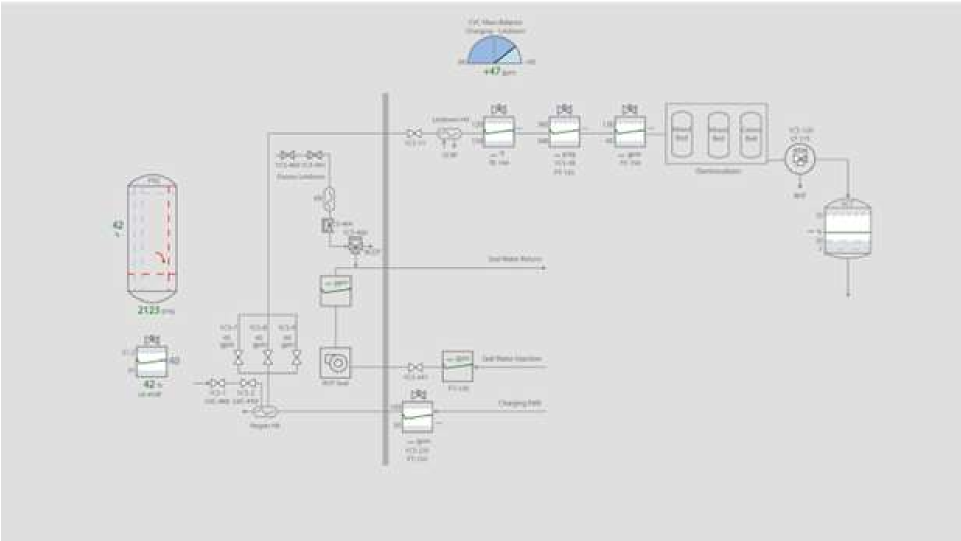

Figure 3. ADAPT Task Overview Screen

When an operator needs to complete a task (i.e. control or change one or more indications), task-based displays are provided. Task-based displays (TBDs) are a comprehensive arrangement of the most important information needed to complete any predefined task (e.g. startup). They include embedded control and serve as the control center for operator interaction. TBDs feature monitoring information, task-related instructions, and equipment controls. Each aspect of the TBDs assists operators in completing their responsibilities as efficiently and safely as possible.

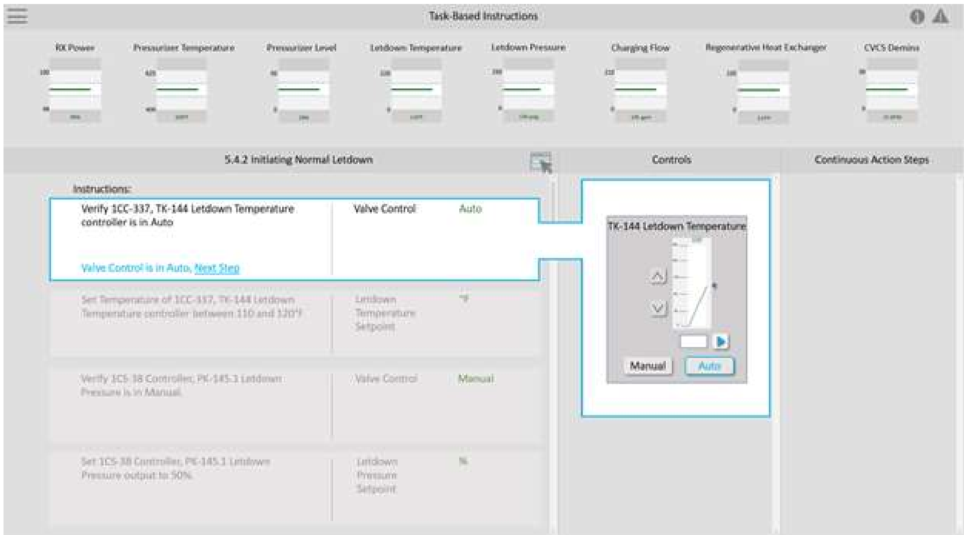

Figure 4. ADAPT Task-Based Display Screen

The indications pane within the TBD provides the monitoring information that an operator might need to have continuously available while executing task instructions. The important parameters relevant to the task are available in the form of mini trends. These designs display the present value of the equipment in relation to lower and upper limits as well as a brief history of how that value has developed over time. Although the plant overview and task overview are still available to the operator for monitoring purposes, the indications pane within the task-based display limits, if not eliminates, the need to navigate between multiple screens. This feature ensures task-monitoring relevancy while simultaneously reducing physical and mental workload for the operator.

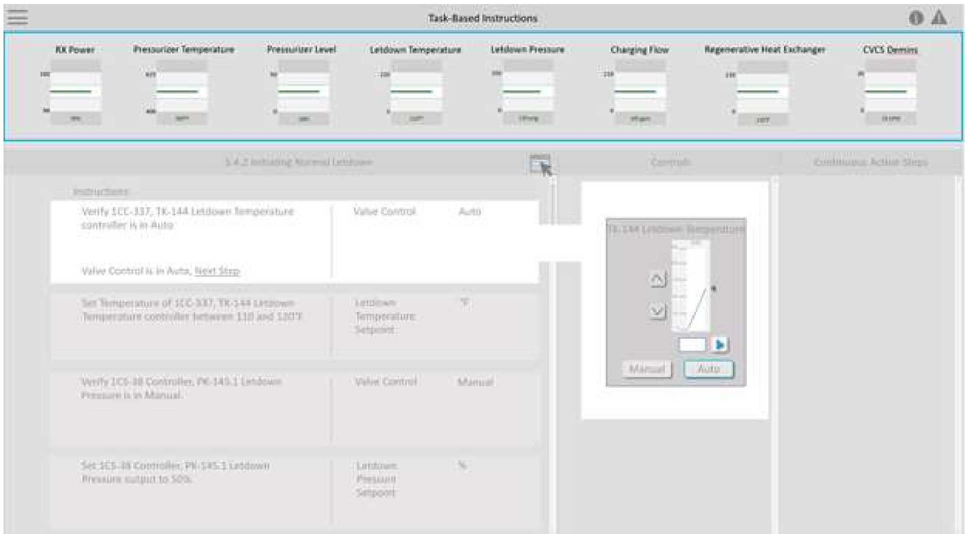

Figure 5. ADAPT Task-Based Display Indications Pane

The dynamic instructions feature incorporates step logic evaluation, lives process values, plant response validation as well as additional decision and task support for the operator. Any data that is related to the task instructions is pulled into the procedure in a dynamic fashion to provide the operator with real-time values and decision support. Soft controls relevant to the current 'active' step appear in a designated controls pane next to the task instructions. If additional controls that are not listed in the instructions are needed, secondary methods are available to interact with other equipment controls in an ancillary display. Contrary to current paper-based methods wherein the operator has to search for the majority of information needed to complete the task, ADAPT includes all necessary information in one singular location (i.e. task instructions). The main control room operator is also able to electronically communicate in real time with field operators when communication is required between them to execute a task (e.g. open a manual valve).

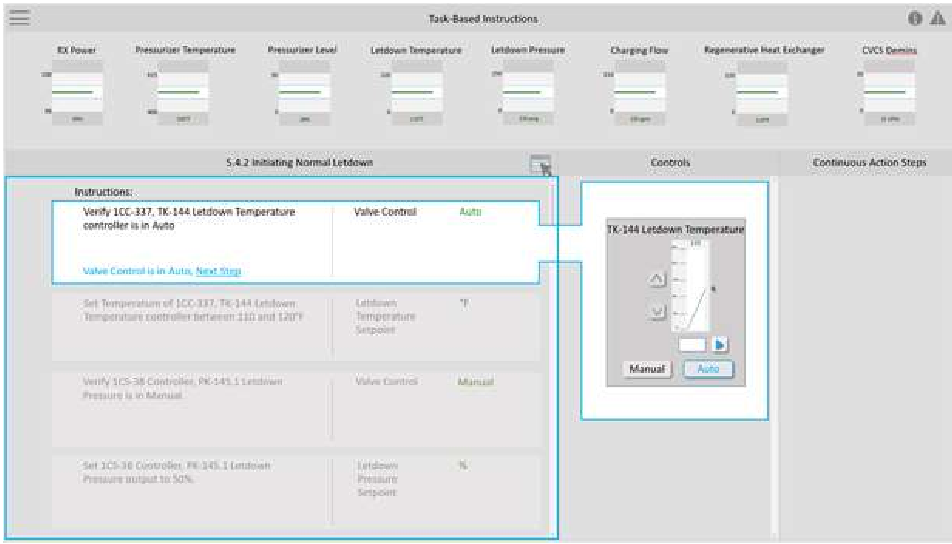

Figure 6. ADAPT Task-Based Display Dynamic Instructions

Additionally, notifications and alerts are included in task-based displays to notify the operator of unexpected conditions as well as expected conditions that are nearing 'out-of-range' bounds. These features provide decision support to the operator and decrease mental workload. For example, alerts are provided when an action is required by the operator and decision support is integrated with alerts to direct the operator to the relevant procedure and/or action to take.

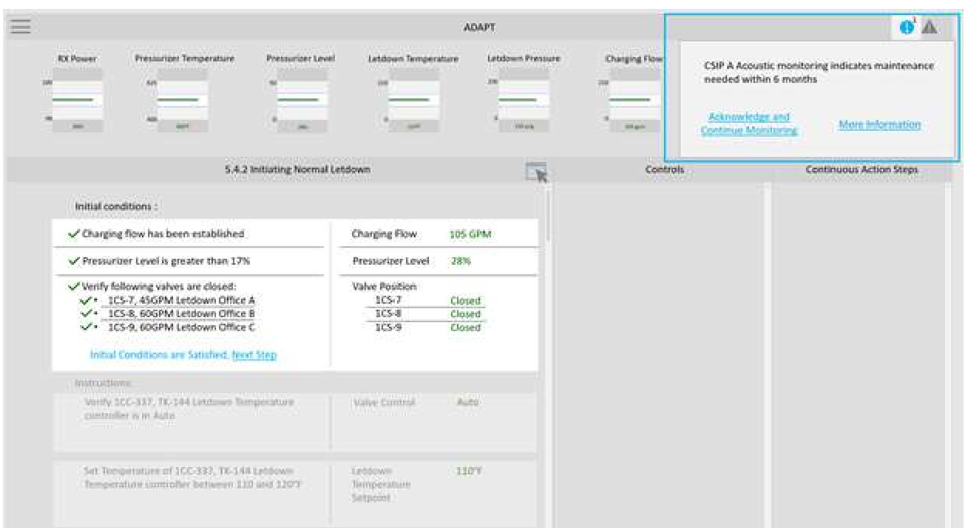

Figure 7. ADAPT Task-Based Display Notifications and Alerts Pane

2.2 Overview Displays

Overview displays can be used for a variety of purposes including facilitating shared situation awareness and providing overall assessment of status at-a-glance (NRC Library, NUREG-0700 Rev. 2). The overviews designed for the ADPAT system are designed to be at-a-glance monitoring displays that support specific tasks under specific conditions, therefore it is imperative that the information contained in the overview display is appropriate for that purpose and is presented in an intuitive manner. Several approaches have been used to collect information requirements, design layouts, and examine human-system interfaces (HSIs). Ecological interface design (EID) is a theoretical framework that attempts to support knowledge-based tasks, minimize the potential for control interference, and support error recovery in complex work domains (Rasmussen & Vicente, 1989). It was invented to resolve unanticipated and abnormal events when the data available to operators could not always specify the state of the system due to the uncertainty (Vicente & Rasmussen, 1990). Recent advancements in simulation, machine learning, and artificial intelligence, can now identify the system state and provide recommendations or suggestions to the operators. However, in the EID framework, the HSIs would contain all the constraints, invariants, and parameters that are crucial to operators regardless of system state. Operators need to choose critical information from many given parameters to make decisions.

Burns et al. (2008) have found that EID could improve situation awareness (SA) under unanticipated situations, whereas operators have better SA with the display design based on operating experience than EID during within-design basis events. The fail-safe concept has been widely implemented in the nuclear industry; and developing HSIs for anticipatable events is more important because theoretically, engineers and researchers can simulate all possible circumstances. The current concept was developed under this assumption. Therefore, instead of applying the entire EID framework with work domain analysis (WDA), the design of the overview displays has integrated the conceptual understanding of system dynamics and the invariant described in Vicente and Rasmussen (1990) to show the relationship of valves and parameters.

Information Rich Display (IRD) is another approach used in HSIs. In IRD, the information is condensed such that each display contains more relevant information for the users (Braseth, et al. 2004). IRDs features graphical elements for process data with additional information (e.g., temporal data, setpoints) (Braseth & Oritsland, 2013). Analog plants typically only show the current value for process data on the control board displays. Under dynamic situations (e.g., start-up, abnormal, shutdown), the plant state evolves in time, and displaying temporal information can allow operators to recognize the changes easier. Displaying setpoints also give operators a sense of whether the parameter is approaching the setpoints. In the overview displays, all the process data have been presented in a time-series trend with alarm and plant trip setpoints when applicable.

Researchers claim that adaptive user interface designs can reduce mental workload by adapting to the needs of the task, the machine, and the human (Hancock & Chignell, 1988; Langley, 1999). This concept is integrated into the design such that the overview displays adapt based on the system state. If the plant transitions to emergency operating conditions, the plant overview will provide additional information relevant to safety injection. The task overview display changes to match the current task.

Analog plants have alarms and parameters for monitoring at the top and middle parts of the control boards, while most of the controls are at the bottom. Similarly, the overview displays are for monitoring only to maintain consistency and prevent confusion.

Overall, the ADAPT concept integrates some characteristics in EID, IRD, and the current analog system with user-centered design. The representations of pipes, valves, and parameters in the overview displays are from P&ID graphs, commonly used in EID, which show operators' conceptual knowledge of the (sub) system. This kind of representation reveals the interrelationships of the components and measurements. The overview displays also implement IRD concept, in which the process data has been shown in trend plots with temporal information and setpoints. Like current analog plants, the ADAPT concept separates the overview monitoring and controls.

2.2.1 Plant Overview Display System

The design philosophy of the plant overview display for normal operations is to provide operators only the necessary information to monitor the overall plant health out at a glance and to present information that serves as leading indicators from normal to abnormal operations (e.g., pressurizer level). It is a goal-driven approach that is consistent with the ecological approach for supporting direct perception and the detection of affordances. EID is work domain goal-driven, while the current concept is operator goal-driven approach for different system states. The critical indications presented in the plant overview display can be determined by conducting interviews, the common technique in user-centered design (Wilson, 2013), to understand what operators need to monitor under different system states.

The plant overview display is adaptive, and it changes over time based on the system's state. For instance, under normal operations, the plant overview display is as shown in Figure 8. Once the plant enters abnormal operation, the screen would transition to the layout in Figure 9, with more information available to operators for diagnosis. The design of the plant overview display does not limit to these two types of operations.

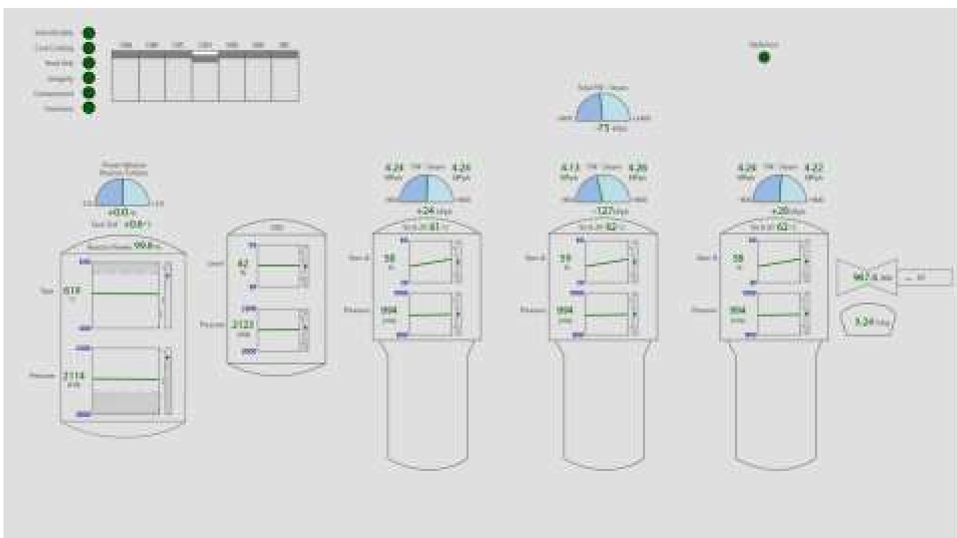

Figure 8. The second iteration of ADAPT plant overview display system for normal operations

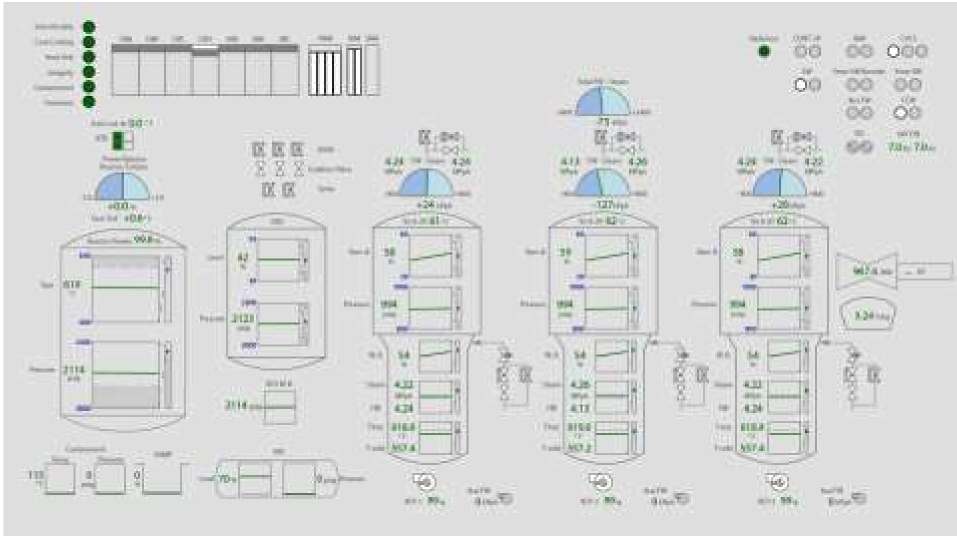

Figure 9. The second iteration of ADAPT plant overview display system for abnormal operations

The displays represented in figures 8 and 9 were modified based on operator feedback, the original design can be found in Kovesdi et al., (2020). We choose the second iteration of overview displays to explain the IRD concept because it contains more information (i.e., zoom-in scale) than the first prototype. For example, the T-average graph also contains temporal information, saturation curve, and zoom-in scale. Operators may zoom-in to monitor the minor fluctuations of the system dynamics under normal operations, whereas operators may zoom-out when the system is in the transition from one state to another. The representations of process data in the second iteration (Figure 8) are more information-rich than in the first iteration (refer back to Figure 2). The IRD concept does not limit to this format for process data.

2.2.2 Task Overview Display System

The task overview display is goal-driven, and it provides task-specific information to enhance operators' SA of the system state relevant to the task being performed. A task is defined in the Oxford dictionary as "a piece of work to be done or undertaken". Every task has a goal that some task analysis approaches (e.g., hierarchical task analysis) defined tasks by goals that the person is seeking to achieve (Annett, 2003; Annett & Stanton, 2000). The parameters presented in the task overview display can be obtained by understanding what procedures operators need to perform to achieve their goals and by gathering parameters from the procedures. It may also contain relevant parameters that would change during the task. The task overview display intends to show the progress of task completion with task relevant indications. The layout (Figure 10) is based on the conceptual representation of the sub-system. The graphic element for process data is the same as the plant overview display, following the IRD concept.

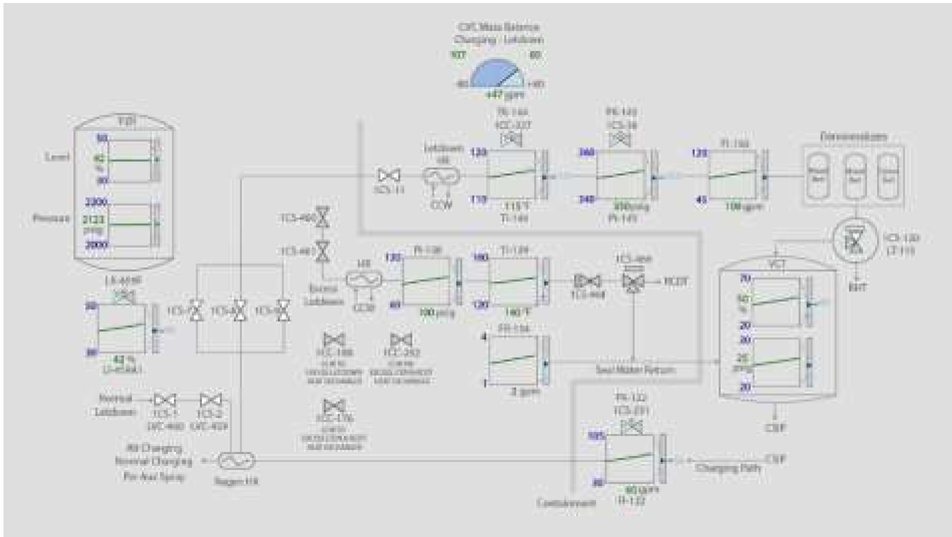

Figure 10. The second iteration of ADAPT task overview display for restoring normal letdown after maintenance

2.3 Task-Based Display System

The task-based display system presents task-relevant indications, procedure instructions, and decision support. The task-based display system is a comprehensive presentation of information and indications required for the completion of predefined operator tasks and is the launchpad for all tasks and actions that are required in the control room. The system is designed to guide the operator through the instructions to complete operational tasks. Alerts and warnings are provided to operators when conditions that require operator's attention and provide the additional detail he will need to diagnose and resolve adverse operating conditions. This section describes the philosophy of the task-based display system.

Figure 11 illustrates the layout of the procedure instructions. Each of the display elements is consistently defined and is populated by procedure data that is extracted from the existing paper procedures.

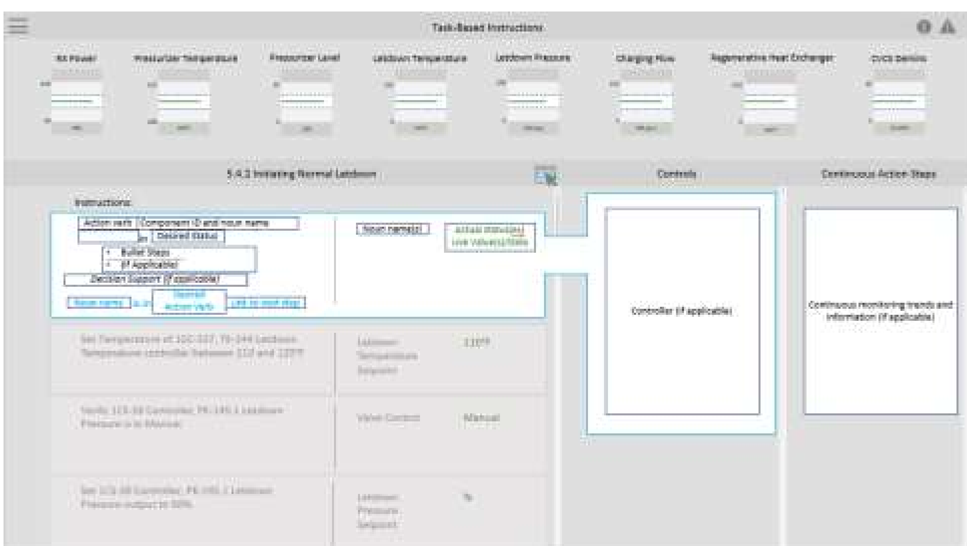

Figure 11. Layout of instructions

Design principles for the task-based displays were extracted from Kovesdi et al., (2020) and Oxstrand et. Al. (2016). Specifically, the design requirements developed by Oxstrand et al., were adapted to work with the adapt concept, and additional design requirements were added to capture the increased use of automation and decision support for the operator in the ADAPT concept. Table 1. summarizes the design requirements with examples to illustrate the implementation of the requirements in the ADAPT concept. The following sections describe in more detail how automatic monitoring and decision support are provided in the ADAPT concept.

Table 1. Design requirement for the task-based instructions

Design Requirement	Example(s)
Only show display elements that are relevant to the context	Hide options that are not relevant to the current status of the workflow. For example, the link to navigate to the next step is hidden until the conditions defined in the step are met.
	Only show relevant controls when the step instructions call for modifying the state of equipment. Steps that require the operator verify the state should simply show the current state or process parameter reference in the procedure step.
Provide automatic support everywhere possible	When available from the control system, the process parameters referenced in the procedure should be presented to the operator and should be used to evaluate the step logic to determine if required conditions are met and what action should be taken.
	Calculations using process parameters that the control system has access should be done automatically, and the result and recommended action should be presented to the operator.
	Conditions that are relevant to the procedure should be monitored continuously by the control system and should alert the operator when actions are necessary.
	When plant conditions require that the operator to switch to a new task due to a higher priority event, the system should alert the operator and provide recommended actions and the rationale for those actions.
	Where possible, the system should verify expected plant response and alert the operator if the expected response did not occur.
Provide embedded controls and indications alongside the procedure instructions	When procedure steps require opening, closing, placing, ensuring, or adjusting, the relevant control should be presented in the controls section. When multiple soft controls are required for the procedure step hyperlinks are created withing the procedure step to select which soft control will appear in the controls section. See Figure 12 for an example.
	When available from the control system, the process parameters referenced in the procedure should be presented to the operator within the procedure step.
Provide information needed for operator to verify step evaluation	When an automatic evaluation is made or decision support is offered, the basis for that evaluation should be presented to the operator. The information should be easily understandable to the operator and should provide links to more detail so the operator can validate the decision.
Provide flexibility for operator to perform task as required.	The operator should be able to override a step evaluation, calculation, or recommendation. The system should provide a way to document the justification for the override and should alert the operator to potential undesirable actions.

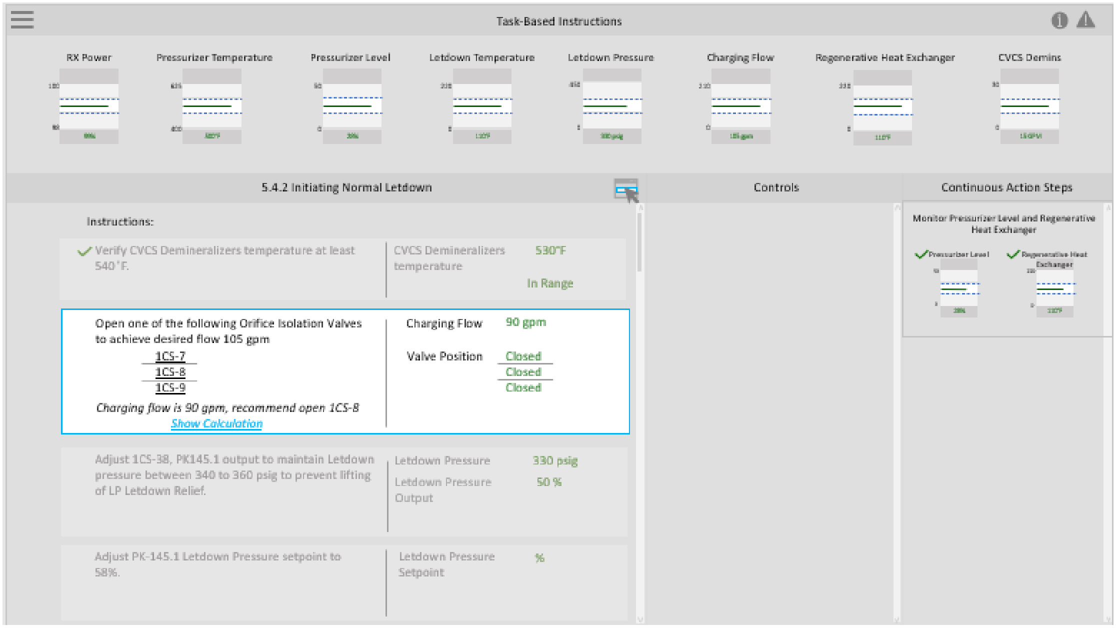

Figure 12. Illustrates the design implementation for the selection of three soft controls

2.3.1 Online Monitoring

Online monitoring of plant systems in the ADAPT concept leverages advanced technology such as sensors to monitor plant conditions through continuous data collection (e.g., Al Rashdan & St. Germain 2018; Yadav et al. 2018). This concept will help to increase efficiency through communications between operations and maintenance, coordinated resource management, and scheduling updates. The ADAPT system offers predictive data driven maintenance from advanced technology including sensors to optimize maintenance needs and reduce costs (Al Rashdan & St. Germain 2018). Operators are alerted to potential maintenance issues and recommended actions based on the status of equipment. The operator can choose to continue with their task by acknowledging the maintenance notification and logging the report in the system or can notify maintenance of the recommended equipment concerns to coordinate maintenance. For instance, in Figure 13 two maintenance concerns have alerted the operator to potential maintenance needs.

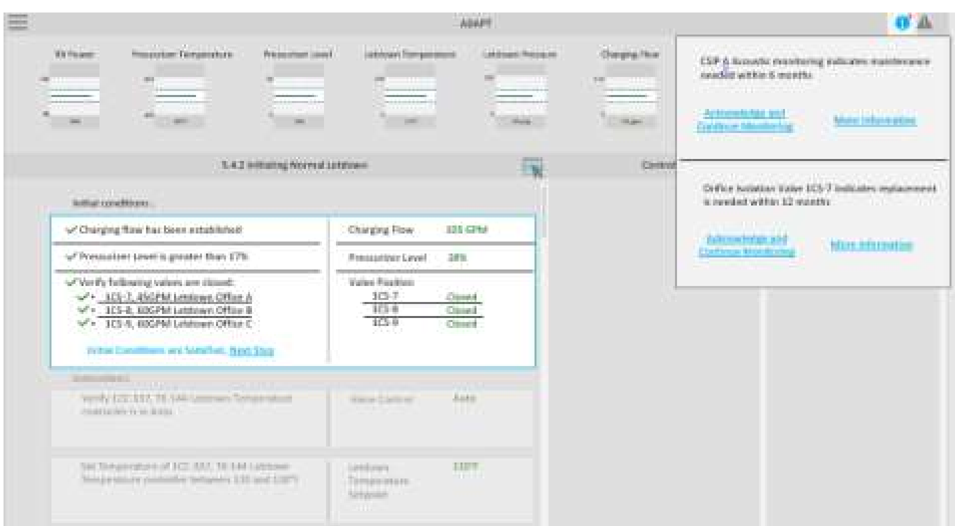

Figure 13. Online monitoring maintenance notifications

Online monitoring can be used to diagnose immediate needs with the use of advanced sensors and data analytics and guide the operator through actions based on the equipment failure. In Figure 14, the loss of VCT level has triggered an alarm recommending that the operator they switch to an abnormal operating procedure.

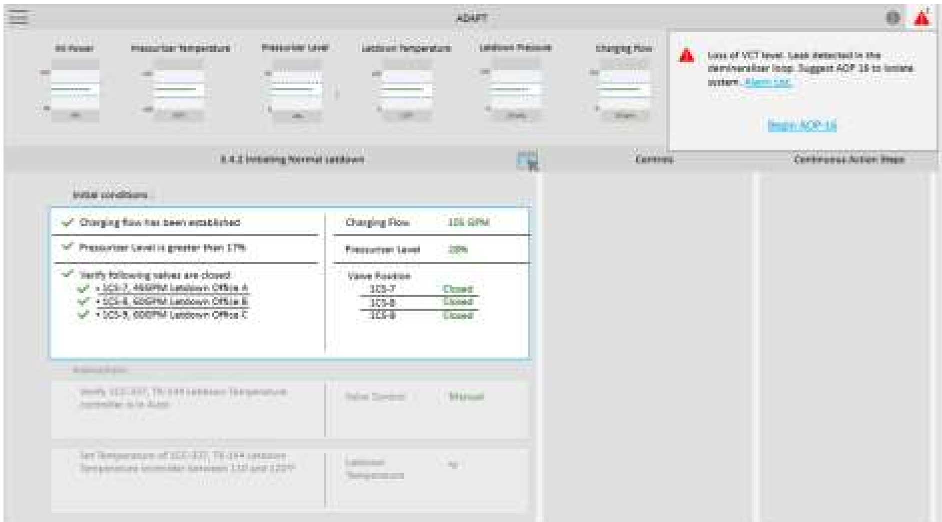

Figure 14. Online monitoring alert

2.3.2 Decision Support

The advanced procedure system monitors process parameters continuously and procedure logic is automatically evaluated. Clear instructions are provided to operators to guide them through which conditions are met based on process parameters and which actions operators will need to take. Decision support is also provided to operators through the alerts and notifications, which alert the operator to conditions which require operator's attention. The decision support tool utilizes plant data, alarm and event information, analytics, and additional sensor input, and additional plant information to support the operator. The example in Figure 15 alerts an operator potential maintenance condition. The operator can acknowledge and continue with their current task or select more information to identify maintenance needs and schedule or plan maintenance.

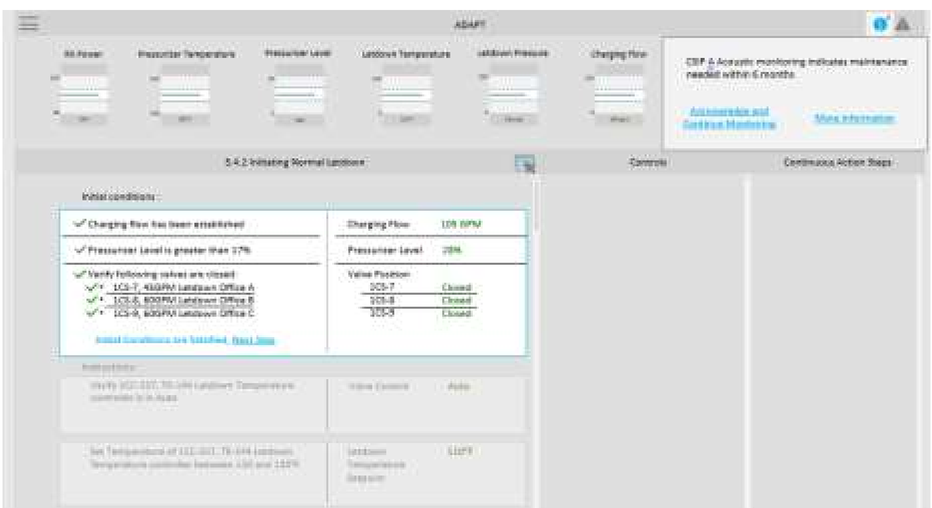

Figure 15. Decision support notification to operators

Another area that decision support will alert the operator is when an unexpected action occurs. For instance, in the example is Figure 16 an operator places the controller in manual rather than automatic as the procedure directs. An alert to an unexpected action alerts the operator that he has deviated from the procedure step. The operator may have reason to perform manual control actions over automatic and will be provided an alert to override the procedure step recommended action.

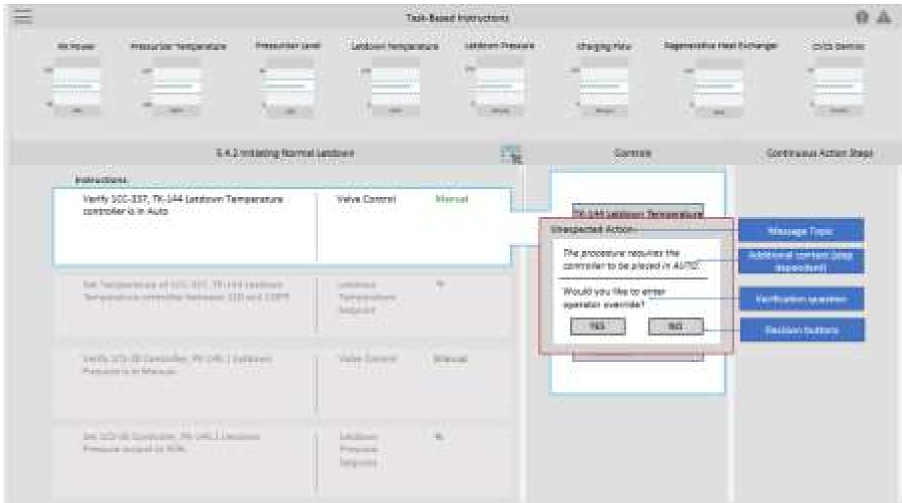

Figure 16. Unexpected action notification

Online monitoring provides additional sensors and instrumentation to process equipment. Having the additional process parameters will provide decision support to operators if a process variable is out of range and will recommend actions to be taken. The example in Figure 17 shows that after opening valves and instrumentation identifies the downstream flow is lower than expected. Decision support can inform the operator to open an alternative valve, or to notify field operators to check the field, which can be done directly from the interface.

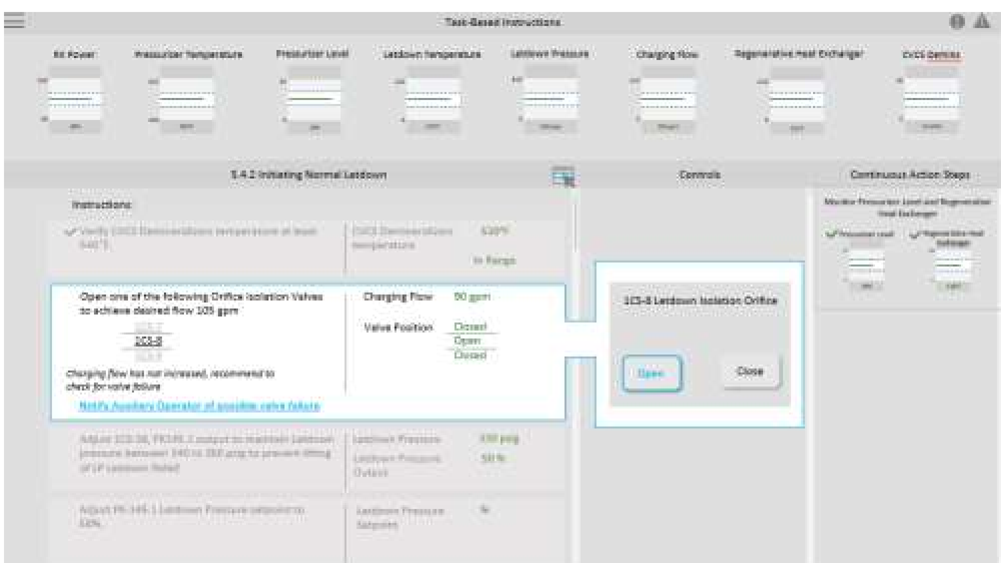

Figure 17. Field action decision support from valve failure

3 Design Process

ADAPT is a new conceptualization of the control room in which a single operator, supported by greater automation, manages the control room. ADAPT integrates new technologies (e.g., online monitoring and advanced procedures) to facilitate streamlined NPP operation and maintenance. We are using the iterative design process to take ADAPT from the conceptual stage to a functional prototype, which will provide the framework for the nuclear industry to adopt the concept.

In accordance with the approach described in the Guideline for Operational Nuclear Usability and Knowledge Elicitation (GONUKE; Boring et al., 2015), the ADAPT prototype was developed in consultation with subject matter experts (Kovesdi et al., 2020). The motivation for this workshop was to obtain focused feedback form subject matter experts to inform the next iteration of the design. We conducted semi-structured interviews with operators that provided feedback on the layout, information content, information presentation, task workflow, and level of automation.

3.1 Addressing Design Themes

The conceptual design of ADAPT and related display systems were informed largely by both general display design principles and context-/task-specific design input from subject matter experts (SMEs) collected in a series of semi-structured interviews and informal conversations. Figure 18 is adopted from INL/EXT-20-57862, which illustrates the primary design inputs used to initiate the design of ADAPT.

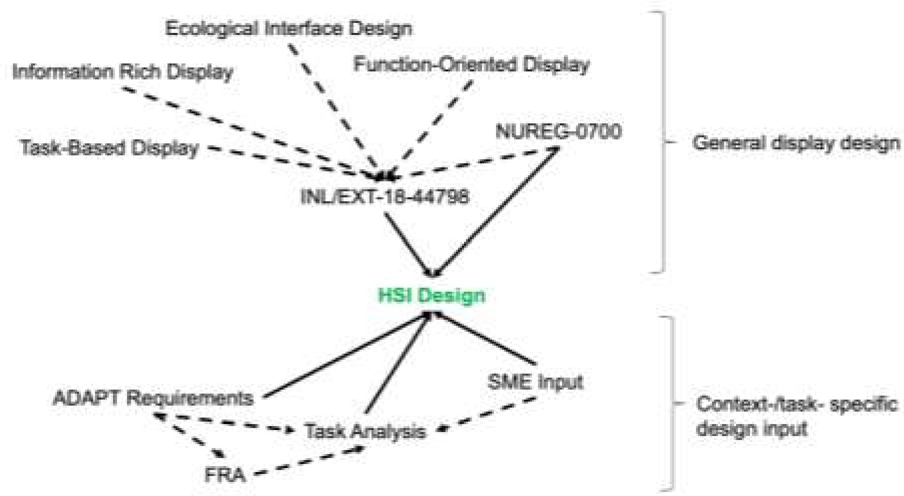

Figure 18. (Recreated from INL/EXT-20-57862) Inputs into the initial design of ADAPT

In following 'good HFE practice[1]' that promotes a human-centered approach through iterative design that champions the voice of the user, this work sought to collect design input from representative licensed operators to not only understand their impressions of ADAPT, but to capture specific domain knowledge that centered around five generalized design themes: [1] layout, [2] information content, [3] information presentation, [4] task workflow, and [5] level of automation (LOA). These five themes addressed key aspects of interface design, system functionality, and usability to which specific design assumptions and trade-offs from the initial conceptual design needed further clarification. The goal of this workshop was to validate the reasoning for the changes implemented in ADAPT. The following sub-sections provide greater detail of the 5 thematic drivers of the workshop.

3.1.1 Layout

The workstation in the ADAPT concept is drastically different from the existing control boards in US plant, reducing the control room to a single workstation with four screens. The plant overview display system provides continuous indication of overall plant status to indicate the plant's health and performance. The task overview display system provides task-specific information to support rapid assessment of the associated plant systems and sub-systems involved in the task being performed; consequently, only relevant information concerning the specific system was provided in the task overview screen. The task-based display system allowed operators to work through the task by providing task-relevant indications, procedures, and soft controls of the associated plant equipment to perform a task. Finally, the secondary

[1] The term 'good HFE practice' refers to the application of ISO 13407 (Human-centered design processes for interactive systems) among the practices cited in many HFE resources including by not limited to Boring and colleagues (2015), Lee and colleagues (2017), as well as Kovesdi and colleagues (2018), which focuses making systems usable through a broader multi-disciplinary approach that places strong emphasis on active involvement of users, human-centered automation, and iterative design.

task display screen was meant to be a flexible workspace in which operators could have additional information.

Our goal was to validate the reasoning underlying the changes made to the organization of the workstation. With the two monitoring displays at the top and the two interactive displays at the bottom, this arrangement was designed to provide the operator easy access to the controls while comfortably monitoring the information in the read-only screens. Another important question concerned the layout of the task-based display screen. Within this screen, the instructions appear in the left column. The soft controls are located in the middle column. In the right column, continuous actions are presented (e.g., out-of-range alerts, decision support). The decision to organize these features was driven by the assumption that the operator could work through the instructions while receiving alerts about problematic values. The soft control and decision support would provide the operator with support. We needed operator feedback on whether this assumption was correct.

3.1.2 Information Content

The goal of ADAPT was to create a new human-system work relationship that promotes operational and maintenance efficiencies in a way that reduces the workload for the operator. Thus, within the ADAPT concept, the level of information processed and monitored is shared by the operator and ADAPT system. Consequently, ADAPT does not reproduce plant information in a way that is analogous to a traditional analog control board from a U.S. NPP. Rather, data that is collected through multiple streams such as advanced sensors and real-time communication with the field are processed and presented in a way that provides meaningful insight through decision support and visualizations. To this point, the collection of additional data streams requires ADAPT to utilize increased levels of automation such that cognitive burden (workload) is optimal for the operator. This balance between presenting information to the operator and automating was a significant consideration for the design of ADAPT. As such, the aspect of *information content* focused on understanding whether the information included in the display screens was the information needed by operators. Thus, questions generated prior to the workshop sought to establish a technical foundation for the selected content on the display screens.

We queried operators on the streamlined instructions in the task-based display screen. Unlike traditional, paper-based instructions, operators do not need to consult gauges and dials on the control boards to verify conditions are met in the procedure. The operator will be notified that conditions are met (i.e., the end-result of the computer verifying conditions) before moving to the next step. The design team decided to streamline the instructions to reduce the cognitive burden on the single operator during a procedure. Operators were asked to provide feedback on whether or not they felt comfortable with this approach. If operators were not comfortable with the approach for a variety of reasons, it could indicate that workload was not being reduced or a different problem was being introduced. Another critical question concerning information content was the dynamic nature of the screens. For example, the plant overview screen updates depending on the state of the plant. When the plant is in an abnormal state, the operator is presented with significantly more information. The design team decided that including only relevant information would benefit the operator's ability to control the plant. Operators provided feedback on whether they were comfortable with the dynamic screens (e.g., Are they distracting? Are the necessary parameters included in the different screens?).

3.1.3 Information Presentation

The ADAPT concept presents information in a novel format (e.g., the use of advanced visualizations like relationship trends and balance charts, as well as repurposes procedural content in a human-centered format). This work sought to understand if operators were able to understand the information being conveyed. Additionally, identifying other issues such as the manner in which the information is presented was sought to ensure optimal usability.

The design team employed novel formatting to improve the ease of interpreting indicators on the displays. For example, balance charts were used to display the relationship between feedwater and steamflow. Another critical departure from typical displays was presenting information concerning reactor vessel, pressurizer, and steam generator in an inter-related manner. For example, for the reactor coolant system, temperature and pressure are presented in an inter-related manner. The design team chose this format because they wished to provide the relationship between these two variables. This type of change could also be confusing to operators, who might prefer variables to be presented as individual trends. Within the task-based display, the design team also chose to present the "return to active step" information by creating an icon rather than a label. The icon was meant to make this action easy and quick for the operator. On the other hand, icons are not always straightforward. Consequently, we sought feedback on whether this icon clearly communicated what it was intended for.

3.1.4 Task Workflow

The ADAPT concept transforms the way in which the plant is operated. Specifically, the inclusion of advanced capabilities like online monitoring, real-time collaboration with the field, decision support, and integration display systems completely change the concept of operations such that the operator is put in a supervisory role. The workflow of tasks is fundamentally changed. Understanding the extent to which this new task workflow meets task requirements is important for all display systems of ADAPT. Moreover, the task-based display system was of specific focus as it provides the interface between operator and controlling plant systems. Here, operators would work through a procedural/task protocol using this screen. Because procedures in ADAPT are not displayed in a manner that corresponds one-to-one to paper procedures, it was important that we validate that the workflow is intuitive and supports the task. Furthermore, we needed to assess if the overall organization did not increase human errors.

The dynamic nature of the screens inevitably changes the content of the screen compared to static paper instructions. The dynamic instructions only present information that is relevant to the current tasks and conditions. The decision to only have relevant information was meant to reduce cognitive workload; consequently, the screens would need to update as the situation changed. The flipside of this decision is to have all information available and be presented in a consistent manner. Here, the design team needed to know what the trade-offs were in reducing cognitive burden versus having all information available in a consistent manner.

Within ADAPT, alerts and notifications are used to draw the operator's attention to important information. To increase focus on the task at hand while reducing overall workload, the ADAPT system continuously monitors process parameters in the background, but only presents information relevant to the current task in the task-based displays. Therefore, it is necessary to use alerts and notifications to enhance situational awareness of abnormal conditions that are not related to the current task at hand.

3.1.5 Level of Automation

A critical feature of the ADAPT concept is the increase of automation to reduce operator workload. Consequently, the initial design incorporated features that presented the operator with streamlined monitoring (e.g., less information is presented under normal plant conditions) and control (e.g., the system would notify operator that a specific protocol should be implemented). Essentially, we are proposing a new human-system relationship within the control room. The system monitors the state of the plant and alerts the operator if a decision needs to be made. This level of automation could be disorienting to the operator. They might prefer having greater control. We sought operator feedback on the level of interaction and control they are comfortable with. Another issue that impacts workflow is situational awareness. Greater automation can potentially lead to more mind-wandering, which could workflow. The design team chose a level of automation that was intended to reduce workload while maintaining situation awareness, and the team needed to evaluate whether the operators agreed.

4 DESIGN WORKSHOP

4.1 Method

4.1.1 Participants

A total of eight (8) licensed operators from a commercial U.S. NPP participated in the workshop. Of these eight operators, there was a total of five (5) senior reactor operators (SROs) and three (3) reactor operators (ROs). All operators gave informed consent before participating in the workshop.

4.1.2 Data Collection

This section describes development of the interview questions and overall task flow for each session.

4.1.2.1 Question Development

The purpose of the design workshop was to collect operator feedback on the ADAPT concept, based on a generic nuclear power plant. This feedback was collected to support design decisions, where there were either [1] certain assumptions made or [2] alternative design approaches for a feature or function with equal technical basis. Listed, are key themes of areas to which the workshop delved into specific questions where there were certain assumptions of alternative design approaches requiring operator input (i.e., refer back to Section 3.1 for details).

- The **layout** of ADAPT workstation and each display system within the integrated control room.
- The **type (or content) of information** offered by ADAPT; to provide a technical basis for selecting the information presented on each display system.
- The **format of information (i.e., presentation)** presented on ADAPT's display systems; to collect feedback on the usefulness of novel graphics such as *balance charts* (mass/flow or pressure/temperature) and *mini trends*.
- The **task workflow** offered by ADAPT; to verify if the workflow offered by ADAPT's display systems is logical and does not introduce human error traps.
- The selected **LOA** used within ADAPT to identify task-related information based on plant and field information automatically collected.

Specific questions were developed to elicit feedback on each of these areas for a specific system in ADAPT. The chord diagram in Figure 19 provides a mapping between the thirty-two (32) interview questions developed and the key design themes. In this chord diagram, the numbered segments on top refer to the specific interview question. The color of the segment refers to the ADAPT system of interest (e.g., red being used for general ADAPT feedback, orange referring to the plant overview display system, green referring to the task overview display system, and blue referring to the task-based display system).

The colored links refer to the inter-relationship between the specific interview question and the theme being addressed by the question; though, it should be emphasized that in certain circumstances, a question located in a system specific section (e.g., plant overview display system) may have implications across ADAPT. For example, specific questions focused on the format of a certain display element on the plant overview display system also apply to related systems such as the task overview display system where applicable. The framework provided in Figure 19 is used in this report to further describe the interview questions, shown in Table 9 through Table 12, respectively. These tables outline the exact questions used in the workshop.

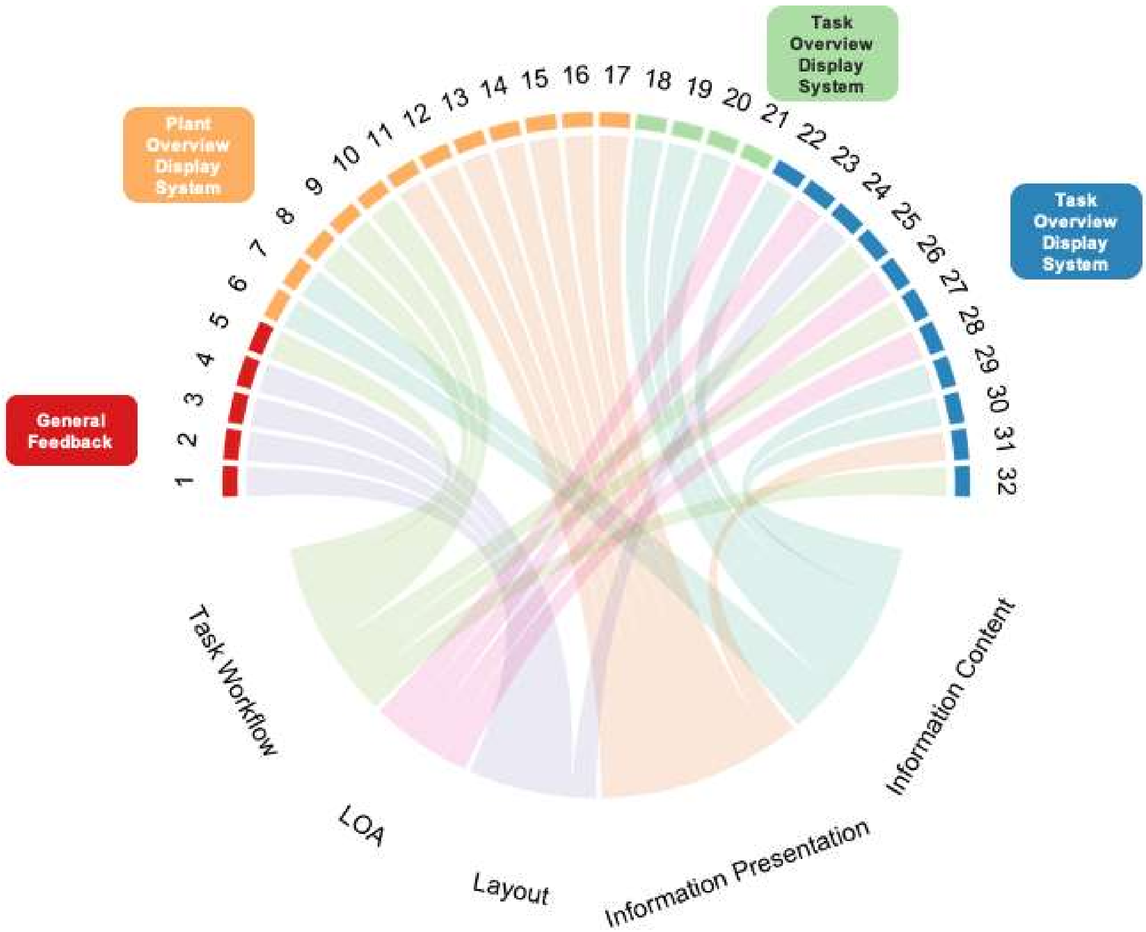

Figure 19. Mapping of key themes to interview questions used in the workshop

4.1.2.2 Interview Protocol

Two-hour blocks were planned with operators the week of March 24-27th, 2020. There were designated roles in executing the interview sessions. The *facilitator* provided the overview of ADAPT and verbally administered the interview questions. The *notetaker* recorded feedback from the operators during the interview and wrap up portions of the session; notes were collected using a standardized template in a spreadsheet. Further, additional LWRS researchers supported each session by taking additional notes (i.e., using the spreadsheet template), as well as by asking follow-on questions throughout the course of the facilitated discussion.

The sessions were completed remotely via video conferencing software and each session followed a task flow, similar to that shown in Figure 20. These activities are described in more detail next.

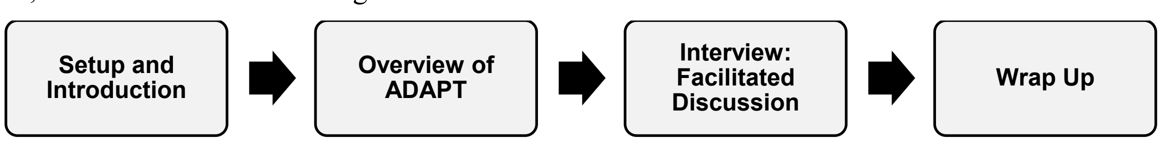

Figure 20. Design workshop task flow

Setup and Introduction

Upon connecting to the web meeting and ensuring a reliable internet connection, the dedicated facilitator greeted the operator and reminded them that the session was completely voluntary, and their feedback would be used to inform the design of ADAPT[2].

Overview of ADAPT

The facilitator provided an overview of the underlying philosophy and key capabilities that comprised ADAPT was provided to operators. This overview was provided in conversational form but also utilized a standardized presentation of ADAPT to ensure key functionality was consistently provided across sessions. An example of the verbiage used by the facilitator is shown below:

- *"The concept we are presenting here will demonstrate how taking plant data from the control system and the field and applying advanced analytics could reduce operations and maintenance costs. We have used technology that is already available or part of current R&D projects as the basis for the concept. This concept would require an increase in the amount of plant information that is collected and integrated to understand plant status. It would also require sophisticated data analytics and increased automation. We want you to use your imagination and your expertise on how the plant is operated now, to help us design how the plant will be operated in the future."*

Interview: Facilitated Discussion

The semi-structured interview questions shown in Section 4.1.2.1 were verbally administered by the facilitator within the context of the selected storyboards (i.e., select steps from an operating procedure) to help facilitate conversation for each interview topic. These storyboards included:

- Initiation of normal letdown
- Online monitoring with vibration and acoustic monitoring that triggers a notification
- Online monitoring with vibration and acoustic monitoring that triggers an alert

While the interview portion generally followed the sequential order of the question structure, the discussion followed a less rigid approach, allowing the conversation to be more freeform, to ensure that the feedback from operators was complete. Each session focused more on the *quality* of responses (i.e., richness of the qualitative feedback) as opposed to *quantity* of questions answered (see Appendix A for a detailed outline of operator response characteristics). To this end, operators six and seven were interviewed in parallel during a single session; this arrangement was completed based on their availability to participate in the workshop. An important point here is that the purpose of this qualitative data was intended to elicit SME feedback on aspects of ADAPT's design, as opposed to a quantitative evaluation that requires experimental control.

Wrap-Up

Upon completing the semi-structured interview, the session concluded with the facilitator asking the operator if there is anything that he or she wanted to cover that was not discussed in the interview. This provided an opportunity for the operator to share any comments or feedback that was not specifically part of the facilitated discussion.

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[2] An Institutional Review Board reviewed informed consent was administered to operators during the session and sent to them via email at the end of each session. Operators signed and electronically returned these forms upon accepting to participate in the interview.

4.1.3 Qualitative Data Analysis

The nature of the data collected from the workshop was qualitative in nature, and exclusively comprised from the freeform text-based notes recorded from commentary made by operators. To this end, a systematic process known as thematic analysis was done to transform the freeform notes collected in separate spreadsheets into actionable themes (i.e., findings) driven in part by the nature of the content and overarching aims of the workshop (Kuniavsky, 2003). The following sub-sections describe this systematic process used to take the freeform notes collected by individual researchers into the findings described in Section 4.2. Figure 21 illustrates the process used to perform thematic analysis on the rich text-based data collected.

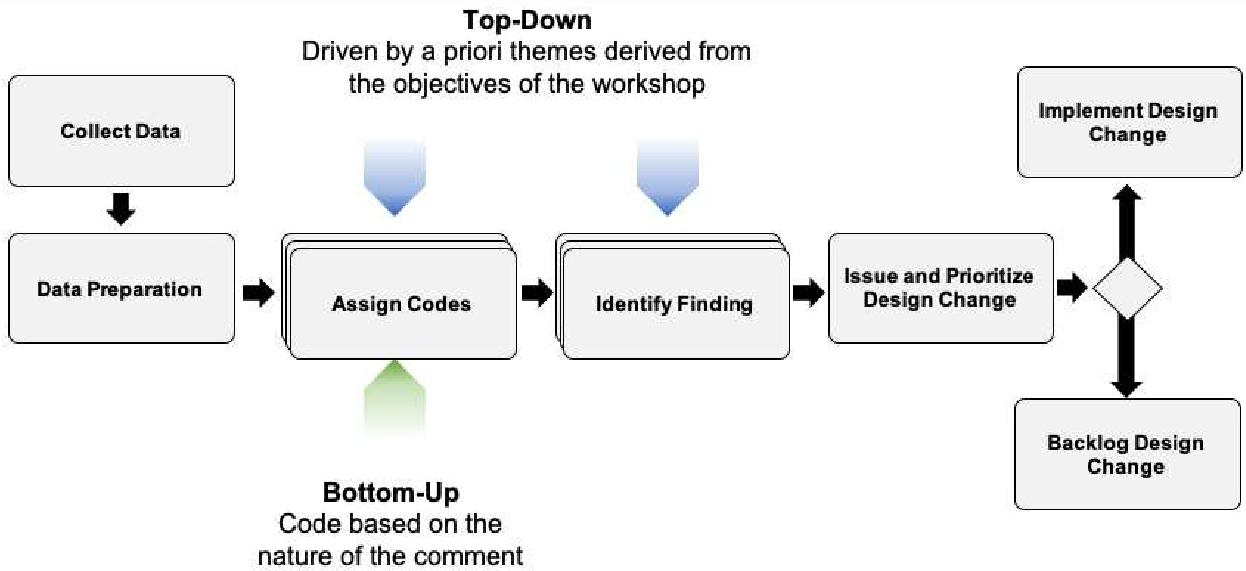


Figure 21. Qualitative data analysis process

4.1.3.1 Data Preparation

Notetakers recorded the qualitative data for each session in a separate spreadsheet that followed a specific template (i.e., based on the question structure described in Section 4.1.2.1). The dedicated notetaker and supporting notetakers used a separate spreadsheet, naming the file based on their initials and operator identification number given. These files were then aggregated into a master dataset using a custom script developed in R. The aggregated dataset was used as the primary resource for qualitative data analysis described next.

4.1.3.2 Assign Codes: Tagging and Grouping Qualitative Data

Next, the text-based data was grouped into commonalities based on the focus of the comment. These groups, also known as *codes*, comprised of simple tag names that characterized the nature of the comment. In some cases where the comment from the operator was fairly complex, multiple codes were assigned to a single comment. The advantage of coding comments as such, as opposed to simply summarizing comments by question, is to uncover possible themes that may reside across multiple questions. That is, by assigning codes to comments cross the entire dataset, commonalities in operator responses across questions can be identified for a more thorough qualitative analysis. It should be emphasized, that the codes created were nonetheless guided by the a priori themes described in Section 3.1.

4.1.3.3 Identify Findings

The qualitative data with assigned codes were further analyzed by comparing the codes assigned and further grouping based on their degree of commonality. This process was inherently subjective in nature, requiring the researcher to utilize existing knowledge of human factors and conjunction with the overarching workshop objectives and a priori themes to create actionable findings. Furthermore, the accuracy and reliability of the assigned codes and findings were ensured by having multiple LWRS researchers perform independent analyses of the data (also shown in Figure 21 for 'Assign Codes' and 'Identify Finding'), which was later shared and consolidated. The approach ultimately ensured that qualitative data analysis was thorough and accurate.

4.1.3.4 Issue and Prioritize Design Changes

Finally, these identified findings were then transferred into a prioritization matrix where the LWRS research team assigned priority (e.g., low, medium, high) to each finding and then determined whether the finding should be implemented or backlogged from the subsequent design iteration. The priority assignment was subjective in nature (i.e., not formally based on risk profile), though focused on the likely benefit of proposed design recommendation to overall operating performance and safety.

4.2 Results

4.2.1 Findings

This section describes the detailed findings from the workshop. Each sub-section is divided by the sub-system within ADAPT. Within these sub-sections, there is a summary table that highlights key findings from the detailed results below. The detailed findings present a summary title, a tag for the referred theme (Section 0), and detailed description of the finding with applicable/representative quotes captured during the session.

4.2.1.1 General Findings

Table 2. Highlight findings from general feedback for ADAPT

Highlight Findings: General Findings
• Operators expressed the need for the ADAPT concept to support multi-tasking; operators commented that there are times when multiple tasks and procedures are active at once. • Operators generally requested the ability to veto decision support from ADAPT; operators wanted to have the 'final say' in making key decisions and performing plant actions. • Operators preferred having the ability to develop custom displays to support their task needs; having the ability to customize trends with specific tailored parameters would support the current way operators monitor the plant. • The use of the secondary-task display system was thought of as an acceptable method for seeking detailed plant information that is currently provided on the plant computer systems (e.g., Emergency Response Facility Data Acquisition and Display System - ERFDADS). • Some operators commented that the ADAPT workstation should contain more HSI screens to support multi-tasking activities. For instance, a concept of six monitors was proposed by one operator.

Task Workflow

Finding 1: Desire for multi-tasking capability

Most operators (n = 6) expressed the need for the ADAPT concept to support multi-tasking. The general rationale was that there are times when operators must perform multiple procedures (or tasks) concurrently. Operators commented the multi-tasking can take place in all conditions, but is notably prevalent in abnormal and emergency situations, as well as outages (e.g., OP7 - *'During an outage, there may be six different tasks going on at once'*).

LOA

Finding 2: Level of automation (balancing operator control with decision support)

The topic concerning level of automation was elicited by operators at different points throughout the interviews. Notably, the capability of allowing the operators to override the automation as needed was suggested by operators (n = 4). While operators were generally positive towards the use of automation to aid as a decision support tool, they wanted to have the 'final say' in making key decisions and performing plant actions. Specific comments are summarized below and are categorized based on the display system where the comment was recorded.

Plant Overview Display System.

An assumption made in the design of ADAPT was that alerts and notifications could be used to support in detecting a change in plant conditions. Researchers asked operators if this assumption acceptable. Two

(2) operators commented that the use of alerts and notifications would be helpful, but ultimately wanted 'the final say' when deciding or performing a control action.

Task Overview Display System.

Researchers asked if the underlying automation philosophy of ADAPT's task overview display system to automatically change information based on plant conditions and task requirements was desired or not. One (1) operator commented that this automated behavior 'works well when everything is going good.' However, the system would need to allow the operator to override when the automation is not working correctly. OP6: *'If there is a computer glitch, [I] would [want] the ability to go manual.'*

Task-Based Display System.

During the semi-structured interview questions related to the task-based display system, two (2) operators explicitly mentioned that they desired an ability to view the logic and/or information used by the automation to provide recommendations and equipment status. For instance, one operator suggested having the ability to override the task-based display system in situations where an indication may have malfunctioned or be out of serve (i.e., lockout tagout). This operator (OP8) desired an ability to 'click on the value to override or get more information,' as needed. He also wanted the ability to see all possible steps provided (e.g., including the steps 'N/A-ed') to approve or veto. To this end, another operator (OP3) also commented that he wanted to view all possible steps provided by the task-based display system so that he could approve or veto the recommendations given by the system. In this sense, the ability to preview the procedure (see above) was important, as well as having the ability to ultimately agree to the recommendations given by ADAPT.

Information Content

Finding 3: Desire to customize displays with information (interface flexibility)

Operators commented that they desire having the ability to develop custom displays to support their task needs (n = 4). For instance, operators commonly referred to their current software that allows them to create custom trends for specific plant variables that they wish to monitor. A common rationale was that operators each look at different information to make decisions about the plant. Thus, having this capability to customize trends with specific tailored parameters would support the current way operators monitor the plant. To this end, the operators had a positive response to the secondary task display system.

- OP1: *'For the most part, 75% of us use the same indications. There are a few who are experienced see other things.'*

Information Content

Finding 4: Desire for capability to drill into more detailed information

Operators commonly commented that they desired to see detailed information about the plant as they referenced their existing ERFDADS and PI systems (n = 7). Operators mentioned that they were 'used to seeing lots of information.'

- OP3: *'On PI, operators set up programs that monitor slight changes all over (e.g., 50 points being monitored).'*

Operators commented that they can readily understand the status of primary and secondary side equipment from these displays. They suggested using ERFDADS (or equivalent) as a resource for developing overview displays. The use of the secondary-task display system was thought of as an appropriate location for this information.

Layout

Finding 5: Desire to have additional HSI screens

Two (2) operators commented that more screens on the ADAPT workstation would be desired. The basis for more screens was related to their need for multi-tasking. These operators mentioned that the use of more screens would support monitoring, particularly in multi-task situations. One operator explained that the task overview and task-based display system could be duplicated across the addition of two new displays (i.e., in a 2 x 3 display format).

- OP5: *'You're not only combining two people in one, but also the amount of information into one. Unless we get a lot better with automatic controls, we will probably need more screens.'*

4.2.1.2 Plant Overview Display System

Table 3. Highlight findings for the plant overview display system

Highlight Findings: Plant Overview Display System
• Operators initially wanted to have additional information, when initially asked about their impressions of the design philosophy for presenting only relevant indications specific to assessing and monitoring the current health and safety of the plant. Operators commonly referred to wanting more information like they have on their existing plant computer systems. • The parameters presented on the plant overview display system to rapidly assess plant health were generally complete, with some plant-specific exceptions. • The use of alerts and notifications to assist the operator in detecting a change in plant state was generally acceptable; although, operators preferred having ultimate control in diagnosis. • Operators were not familiar with the two-variable relationship format. The traditional trend format was generally preferred to display plant variables. • Operators were generally positive towards the mass balance charts; they currently use a similar format in their current operations. Although, the application of this format for power balance was not inherently clear. • Researchers asked operators what plant conditions should require individual overview screens. While there was not a complete consensus, there was partial consensus on designing for [1] steady state (normal operations), [2] reactor startup, [3] reactor shutdown, and [4] abnormal conditions.

Information Content

Finding 6: Overall philosophy of the plant overview display system is new to operators

The overall design philosophy of the plant overview display system is to only show information that is required to verify if the plant is in a normal or abnormal condition, as well as monitor key parameters within a given condition. Operators were asked if the concepts of the plant overview display system accomplished this philosophy and if there were concerns.

Operators generally preferred having more information on the plant overview display system than what was presented for normal operations (n = 5). These operators referred to their plant computer systems such as ERFDADS or PI when described the level of detail preferred in an overview. Representative comments included:

- OP4: *'We have the ERFDADS. I would just have that displayed.'*
- OP5: *'Right now, operators might probably prefer this, [the] abnormal display. To me, more information is better even for an overview screen. [I am] used to looking at ERFDADS and PI that have a lot of information. Bunches of numbers and charts. ... Having all of [the information] on one picture without having to click around is better. It's more comforting to have it all on one screen.'*

Information Content

Finding 7: Most operators found the plant overview information to be complete, though some operators suggested additional plant-specific information

Researchers explained the underlying philosophy of the plant overview display system regarding the selection of information on the display. To this end, operators were also asked if the content presented on the plant overview display system was generally complete (i.e., not plant specific), specifically for normal operations.

Four (4) operators mentioned that the content was generally complete, with a few exceptions that were plant specific (i.e., OP1, OP5, OP6, and OP7).

- OP1: *'The only other thing [parameter] is condenser pressure ([i.e., used] in [the] monsoon season). [This parameter] lets us know if steam is sent our way based on wind conditions. We come down in power to keep condenser pressure [, using condenser pressure]. [It] makes sense having this [parameter] in [a] dedicated location. ... Other than condenser pressure. Those are the things that give idea to plant is very normal.'*

- OP5: *'Those would be the major plant parameters we monitor. There are some other monitors (not sure how busy we want to make it), possibly charging letdown flow for PVGS. Other than that, this is a good overview.'*

Though, an additional two (2) operators commented that the plant overview for normal operators was overly simplistic, particularly for certain situations such as down powering where there are discrete stages requiring the use of other parameters (i.e., OP4 and OP8).

- OP4: *'The normal ops plant overview is way too simplistic.'*

- OP7: *'For up/down power… Struggling with the overview being generic (but not sure if it is too simple, or too generic) there are stages of shutdown that he is looking for.'*

Task Workflow

LOA

Finding 8: The approach for alerts and notifications was acceptable, though preference was made to ultimately keep the operator in charge

An assumption made in the design of ADAPT was that alerts and notifications could be used to support in detecting a change in plant conditions. Researchers asked operators if this approach was acceptable or not. Generally, operators were positive towards the receiving alerts and notifications to support detecting changes in plant conditions (n = 3). Although, these operators preferred having control in determining a change in plant state, as opposed to ADAPT automatically changing display information (see General Finding #3).

- OP1: *'The alert would be very helpful. A screen to change automatically would not be preferred. Would be very useful to have this alert. For example, need context if left workstation. Having a message of what the system is trying to tell us would be very important.'*

- OP2: *'It's nice that it is there but you can ignore it if you want.'*

- OP3: *'Does this automatically change? Does the operator make the determination that they are in new procedure or the equipment? I think I would prefer that the operator makes this determination. Maybe the software can give alert or notice but the operator should have final say. I like the approach of ADAPT; we normally have an overview up and then there's an event. We have to then manually change all trends to dive into situation.'*

Information Presentation

Finding 9[3]: Operators generally were more familiar with individual trends over the multi-variable relationship trends

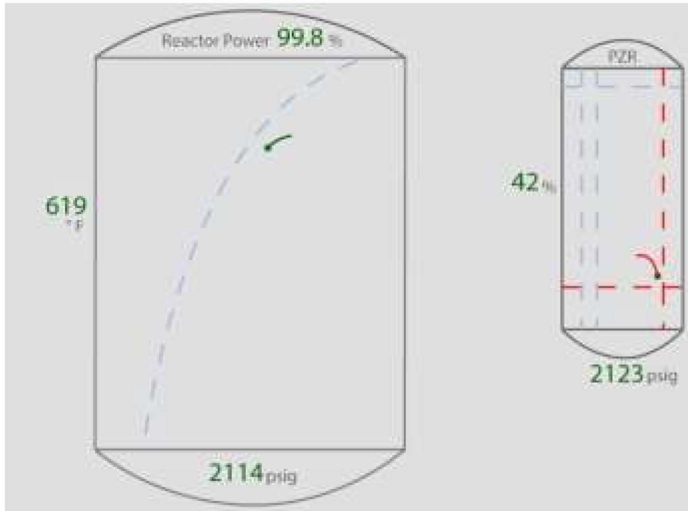


Figure 22. Example relationship trends presented on the plant overview display system

Operators were asked about their impressions with the relationship trends used on the two overview displays.

"The reactor vessel, pressurizer, and steam generators utilize a unique format for visualizing parameters that are related. Do these "relationship" graphics convey meaningful relationships in a way that displaying these graphically separately (e.g., individual trends) would not? Would you prefer this format or separate trends? Why?" - See Figure 22

Overall, operators generally commented that they preferred traditional (one variable) trends rather than the (two-variable) relationship format (n = 7). Operators commonly referred to their existing experience where they rely on the use of traditional trends.

- OP1: *'For the most part, would prefer trends. We are used to seeing the trends.'*

In addition to familiarity with trends, other concerns regarding the relationship format pertained to [1] the sensitivity of axes, [2] location of the numerical readout displays, and [3] number of variables needed to input into the format. For instance, OP3 commented that the changes in 'core parameters' at 100% power are very small in which they use tighter monitoring bands for monitoring. OP3 was concerned that the relationship format could depict these subtle changes given the format shown. OP5 was initially confused about the nature of the numerical readout displays for each of the variables on the graphic. That is, he was not sure if the numbers would relocate based on the state of the variables represented on the graphic. OP5 thought that it could be potentially misleading to see pressurizer level displayed at the bottom of the graphic when in fact pressurizer level was high, or if pressurizer pressure was on the left and pressure was in fact high. OP5 thought a more 'neutral' location was needed to depict these values if presented in this format. Finally, OP6 and OP7 commented that in some conditions, there may be more than two variables inter-related that require monitoring. In such cases, the existing format would need to be revisited.

[3]Finding 9 was also applicable for the Task Overview Display System.

Information Presentation

Finding 10: Operators were familiar with the balance chart format for some parameters

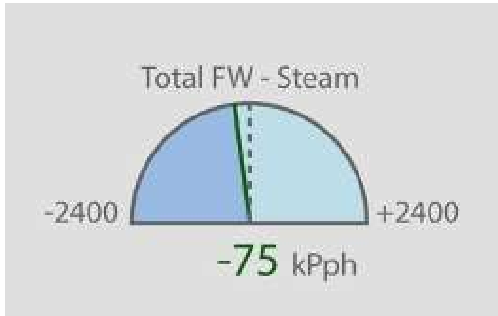


Figure 23. Example balance chart presented on the plant overview display system

Operators were generally positive towards the format of the balance chart (n = 5). Operators commented that the balance chart format was familiar to them (Figure 23), as their existing display systems use similar formats to depict relationships like mass balance. However, one (1) operator was initially confused with the application of the balance chart with presenting power balance of the reactor and turbine output (OP1 - *'What are we measuring there?'*).

Information Content

Finding 11: There was partial consensus on designing for [1] steady state, [2] reactor startup, [3] reactor shutdown, and [4] abnormal conditions

ADAPT's plant overview display system was designed to present plant-level information in a context-dependent manner, based on the different conditions of the plant. To inform the number of possible conditions to design for, researchers asked operators what conditions should be considered.

Four (4) of the operators provided feedback on the number of plant conditions to design for. While there was not a firm consensus on the number of conditions that require plant overview displays, there were some conditions that were identified by more than one operator. These conditions are summarized below (Table 4).

Table 4. Identified plant conditions for designing plant overview displays

Condition	OP1	OP2	OP5	OP8
Steady-State* (Normal)	X	X		
Reactor Startup*	X	X		
Reactor Shutdown*	X	X		
Low Power	X			
Bringing the Turbine Online	X			
Abnormal Operating Condition*	X	X	X	
Ability to Customize the Overview per Condition				X
**Some consensus observed*				

Task Workflow

Finding 12: Response planning and implementation strategies for parameters approaching a 'non-critical' boundary

Researchers asked OP1 what general actions are typically planned and taken to stabilize a parameter value that is being monitored and is approaching a particular boundary that is not associated with transitioning into an AOP or EOP.

OP1 commented that operators' response planning and implementation strategies are largely context dependent. There are certain actions that are taken outside of the scope of a given procedure and are initiated before any alarm threshold, such as routine adjustments to common parameters like steam generator level, pressurizer pressure, and volume control tank (VCT) level.

Contrarily, there are other situations where operators let a parameter reach an alarm threshold; in these cases, constant manipulation of the parameter is not preferred due to the response characteristics of the parameter or the length of the task itself. For example, in cases where there might be a leak in the safety injection (SI) tank, the feedback of the leak is significantly delayed and the process of remediating the situation is greatly involved.

4.2.1.3 Task Overview Display System

Table 5. Highlight findings for the task overview display system

Highlight Findings: Task Overview Display System
• The overall task overview display system concept and format was positively received by operators. The underlying design philosophy of including information from the procedures was generally at a sufficient level of detail needed for monitoring equipment related to a task. • Using the procedures and related documentation such as piping and instrument diagrams (P&IDs) were considered a strong design basis to develop task overview displays.

Information Content

Finding 13: The task overview display system was positively received by operators, providing a sufficient level of detail for the task

The overall layout and level of detail of information on the task overview system was well received by all operators. A common theme described by operators was that the task overview display system provided the right amount of information needed to monitor key parameters related to the task being performed when used in conjunction with the other display systems of ADAPT (n = 7). That is, operators commonly mentioned that they would likely use the task overview display system to monitor equipment being affected by the task and would also utilize the task-based display system and secondary display system to perform the task and additionally monitor detailed information. Operators described how they would interact with the task overview display system within the context of their existing work, where they perform tasks on the control board and use their plant computer systems to monitor of specific parameters at certain points within the task.

Other display characteristics that were positively received from the task overview display system included the mimic format (n = 4) and the use of trends for specific parameters (n = 3). Operators who explicitly commented that the mimic format was useful mentioned that they could easily follow the flow paths and gain an understanding of where the equipment was generally located in relation to the broader system; the operators were familiar with the mimic format based on their experience and training. Representative comments included:

- OP1: *'[The] flow paths are like the ones we work with. We would be able to quickly adapt.'*
- OP4: *'Currently operators have access to mimic diagrams to see the system on a workstation. There is no controlling from the mimic.'*

Information Content

Finding 14: Use of procedures and related material as a design basis

Researchers asked operators what specific resources could be used to inform the development of specific task overview display system screens; the concept shown was developed through a combination of identifying parameters presented in the procedure, as well as from SMEs. As previously highlighted, operators were generally positive towards the amount of information on the display. Further, two (2) operators explicitly commented that the basis followed was appropriate in developing task overviews.

- OP1: '*If you use this as a basis for task-specific screen, [I] want to see everything [about] how you're touching and what it is affecting. This a good base model for letdown.'*
- OP4: *'[You] need to start with [the] P&ID and then [the] procedure as resources. [The] key things to monitor are [the] parameters but generic flow here shows enough information.'*

4.2.1.4 Task-Based Display System

Table 6. Highlight findings for the task-based display system

Highlight Findings: Task-Based Display System

Indications Pane

- The indications pane was acceptable, despite having redundant information. Operators generally were positive towards the application of this pane and commented on its use as a resource for at-a-glance information for parameters specific to the task at hand.

Procedure Instructions

- The indications pane was considered to be useful for monitoring task-relevant parameters; the redundancy in these parameters across displays was acceptable to operators.
- The desire to preview the procedure by scrolling through the course of actions prescribed in the procedure was important to operators.
- The procedure instructions pane appeared logical and usable; operators specifically liked the location of the soft control pane directly next to the active step.
- The desire for having the step numbers was largely driven by operators' existing mental model; for instance, operators commented how the numbers support communication with field operations. Though, steps numbers were generally not considered as useful when researchers explained ADAPT's operating model such as providing real-time communication with field operators and capability of mirroring field operations from the control room.
- The active step orientation button was seen as useful; though, some operators did not understand immediately what the intent of the icon was without having background.
- Re-allocating verification actions to automation was acceptable to operators; in this sense, verification of equipment in a correct state would be omitted from operator required actions.
- Additional to previewing the procedure, having a manual override capability, and providing status of equipment health were important features.

Continuous Action Pane

- Operators found the continuous actions pane to be a useful feature, particularly when working in abnormal situations requiring use of AOPs and EOPs.

Alarms and Notifications

- The proposed system behavior for alerts and notifications possibly occluding a portion of the indications pane was considered acceptable by operators.
- During the onset of an alert, operators identified a need for ADAPT to maintain the trajectory of an in-progress procedure to ensure the plant is in a safe state while attending the new condition.

Information Content

Finding 15: The indications pane was acceptable for providing redundant task-relevant indication for monitoring

Operators were generally positive towards the use of the top pane region of the task-based display system being used for the indications pane (*n* = 5); the redundancy across displays for these indications was considered acceptable. These operators expected that the parameters shown in the indication pane would provide a comprehensive suite of parameters specific to the task (i.e., procedure) being performed. Two of these operators (*n* = 2) further suggested that the format of these indications could be simplified to only a numerical readout.

– OP5: *'Maybe just numbers, not necessarily trends, that would be helpful.'*

The rationale for simplifying the indications pane was primarily based on holistic use of the task-based display system in conjunction with the secondary display system. That is, operators preferred to be able to use the secondary display system to view detailed information of specific parameters such as trends and select backup/control indications. In this content, the indications pane on the task-based display system would serve to provide at-a-glance status of these indications within the context of the task at hand.

- OP8: *'…As long as they don't take up a big part of the screen and are small and [I] can glance at [the indications,] then that is good.'*

Task Workflow

Finding 16: Desire to preview a procedure

Four (4) operators commented that they would desire to have the capability of previewing the procedure before execution. A common rationale was that operators wanted to understand what actions they needed to perform before executing. This feature was noted as particularly important for unfamiliar tasks where consequences are high to which the operator must have a clear understanding of his/her action's impact to the plant. Operators mentioned that previewing even steps that are not inherently applicable would be desired.

- OP2: *'[I like the task-based display system] as long as I have an option to look at those steps so I can check that it is doing what it is supposed to be doing.'*
- OP3 commented that *'ultimately the operator is owning the license and has to know and agree with these things. Hence, preview is important.'*
- OP4 commented that he wants to be sure the procedure *'is going to do what he needs it to do.'*
- For example, OP7 commented that he would like the capability to preview ahead during less familiar tasks to understand the impact to the plant; more familiar tasks may not require as much preview. OP7 further commented that in some tasks, there is a need to plan ahead so that a sequence of actions can be completed in a timely manner (i.e., needing to anticipate the set of actions and their impact to the plant). OP7 preferred seeing all available steps: *'my opinion is to see every step, leave it greyed out or something, but I want to know the option and that it was there.'*

Layout

Finding 17: The layout of the procedure instructions appeared logical and usable with having the step, process value, and soft controller collocated

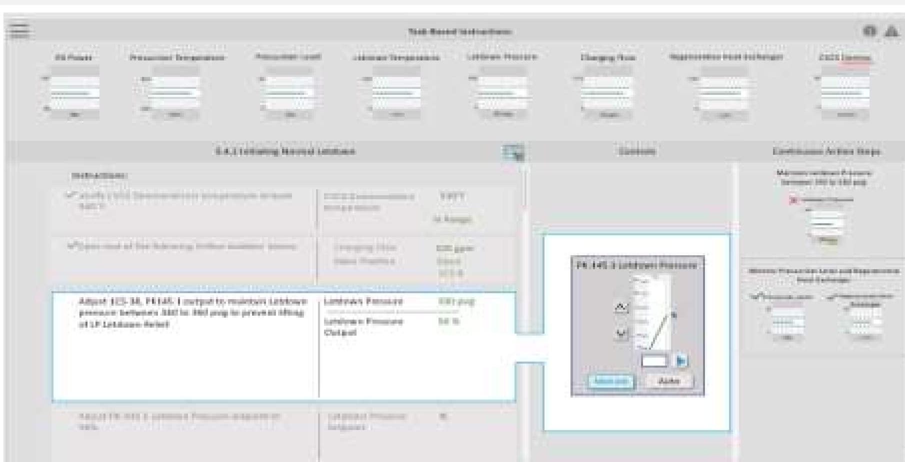


Figure 24. Layout of the procedure instructions pane of the task-based display system

Researchers asked if the layout of the procedure instructions pane (Figure 24), where there is the procedure step embedded with the process value and soft controller to the right, made sense from an operational sense. Generally, operators were positive towards this layout (n = 4). These operators commented that the grouping of step, process value, and soft controller '*cuts down on human error*' (e.g., OP5).

- OP2: *'I like how it is setup. I like how the controller is there.'*
- OP5: *'This looks great. Cuts down on human error. Placekeeping [is] built in.'*

Information Content

Finding 18: Operators initially had mixed opinions with showing the step numbers; those who preferred numbers initially based their opinion on their existing conduct of operations

There was initially a mix in preference for showing the procedure step numbers and not showing the numbers. That is, four (4) operators initially commented that they preferred seeing the step numbers. Their basis was in support of how coordination with field operations is currently done at their plant (i.e., the step number provides a common reference point for the control room and field).

- OP4: *'[There] may be difficulties coordinating with field work should there not be numbers.'*
- OP6: *'Based on our plant, it would be nice to have those step numbers and knowing what procedure you are in. We have to communicate with people in the field to perform specific steps.'*
- OP8: *'Step numbers would be helpful. I need them to coordinate.'*

Though, when LWRS researchers clarified that the underlying conduct of operations would fundamentally change within ADAPT such as by leveraging technology in a way that improves communication with the field, two (2) of those operators mentioned that the existing design 'made sense within this framework.' For instance, having the ability to track in real-time where an auxiliary operator is in a procedure from the control room using the ADAPT task-based display system would ultimately meet the same requirement as the step numbers in current day operations.

Information Presentation

Finding 19: The active step icon was perceived as useful but was not immediately intuitive to some operators.

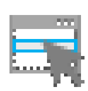


Figure 25. Action step icon in the task-based display system

Operators generally thought that the feature of being able to return to the active step upon a single click was useful (n = 5). However. when researchers introduced this question by asking operators if it was intuitive what the active step icon (Figure 25) was intended to do (i.e., without formally introducing them to this feature), some operators (n = 3) did not immediately understand what the intent of the icon was for.

- OP3: *'I don't know. Is that [for] expand?'*
- OP5: *'...Not sure what that icon does.'*
- OP7: *'...Looks like picture of what you have on the screen.'*

Task Workflow

LOA

Finding 20: ADAPT's philosophy of re-allocating verification steps to automation, where plant equipment in the correct state would be omitted from operator verification, was considered acceptable

Researchers discussed with one operator (OP5) the underlying philosophy of ADAPT's task-based display system where the system omits certain steps that do not require immediate action, based on having data from the plant. For example, in some procedures there are steps to verify that certain plant equipment is in a given state. With the use of online monitoring data, ADAPT's philosophy is to essentially omit procedural steps that do not require the operator to take action. If the equipment is in the correct state, then the operators will proceed forward in the procedure; however, if the equipment is not in the correct state, then ADAPT will provide the correct course of actions needed. The intent of this philosophy is to reduce burden on the operator. However, within this new concept of operations, it is important understand certain circumstances to which this underlying philosophy is no longer useful. Hence, researchers followed on to this discuss by asking if there were any situations where ADAPT's philosophy may not work (i.e., see Q32 in Table 12).

OP5 did not identify specific situations where ADAPT's philosophy of omitting verification steps would not work (i.e., OP5 was generally positive towards this approach). Though, OP5 did note important ways in which operators interact with their existing procedures that could serve as design input for ADAPT. OP5 mentioned that there are times when the operators must perform a series of steps (e.g., two or three) in a row where the steps are read and then performed within a timely manner (e.g., operating multiple equipment of the same type in sequence). In the existing control room, there are physical indications and controls on the control board; however, the way in which these activities are performed digitally may be cumbersome if designed improperly such as in a way that requires excessive or untimely clicking.

OP5 closed this discussion by favoring the use of automation in this context such as by automating control sequences, providing lockouts where operators can only perform actions in the acceptable timeframe, as well as track actions made by multiple operators.

Information Content

LOA

Finding 21: Procedure preview, manual override, and equipment indications were important features and functions to ensure operators continue to check the integrity of data provided by ADAPT

Researchers asked operators how to ensure that they continue to check the integrity of the data provided by ADAPT such as when the task-based display system provides a recommendation course of action (from the procedure instructions) as opposed to showing the step logic. One important feature that operators identified in supporting operator cooperation is having the ability to preview the procedure (refer to Finding 16). Additionally, operators ($n = 3$) commented that having the ability to override the automation (e.g., see Finding 2) with the ability to have direct indication of the plant equipment's integrity (e.g., an indication to show that it is in maintenance, in lockout tagout, etc.) would be important features to help verify data integrity.

Information Content

LOA

Finding 22: The continuous action pane with trends was perceived as useful, especially in abnormal situations that require using AOPs/EOPs

The continuous action pane was positively regarded ($n = 3$). Specifically, the capability of monitoring multiple parameters within the context of the task was desired by these operators. The trend format was generally preferred over alternative formats such as a numerical readout. Operators preferred having the ability to manually pull up these indications. Lastly, continuously applicable steps, that would be used in the continuous actions pane, were identified to be most frequent in AOPs and EOPs.

– OP2: *'I like it [continuous action pane] because it shows that your actions are having an effect (referring to the embedded trends). I like trends rather than just seeing status. Most people I know like trends.'*

– OP4: *'The way AOPs and EOPs are designed, there are continuously applicable steps. [It] would be cool to have continuously applicable steps come up.'*

– OP5: *'I like having the parameters there in green, having the parameter pulled in wherever and then having those trends for continuous monitoring. Maybe you could have an 'X' at top right [of the pane] and everything shifts up. Then there is a little icon [for continuous monitoring where] you can then close it out when needed. This way I can pick what I want to watch.'*

Task Workflow

Layout

Finding 23: The proposed system behavior for alerts and notifications possibly occluding a portion of the indications pane was acceptable for operators

During the onset of an alert or notification, a visual cue on the top right pane of the task-based display system is presented for each signal type. The operator has the ability to hover over the icon to retrieve more information. One potential concern with this behavior is that the new opened window can obscure the view of a subset of trends on the indications pane. As such, researchers asked if the proposed behavior was acceptable or not.

Operators were generally fine with the proposed behavior of an incoming alert or notification, so long as the window could be closed ($n = 5$).

– OP3: *'We have things like this all the time and it does not bother me. This would have minimal impact.'*

– OP4: *'(No concern) …. Not as long as it can be made to go away.'*

Worth noting, one operator (OP7) who had no concern with the described system behavior suggested having the alerts and notifications located in the bottom right where there would likely be more room.

– OP7: *'[I am] fine with [this] behavior, but why not bottom right corner? Maybe [have the] ability to drag this to corner if needed?'*

Further, an additional operator commented that he did not like having the alert or notification occlude a portion of the indications pane (OP5). He suggested having the alert or notification appear in the secondary task display system.

- OP5: *'I would not want my alert popping up on instructions. It can cover up redundant information to the left.'*

Task Workflow

LOA

Finding 24: A need to maintain the trajectory of an in-progress procedure to ensure the plant is in a safe state while attending the new condition

During the onset of an alert, requiring immediate action, ADAPT's philosophy is to replace the existing procedure with the correct procedure that addresses the new condition attributing the alert after the operator acknowledges the alert. Researchers asked if the proposed workflow and LOA was appropriate to operators.

One consideration brought up by two operators ($n = 2$) was the need for ADAPT to maintain the status of the procedure in process (before the incoming alert). Relating to Finding 1, these operators highlighted the need for ADAPT to allow for multi-tasking, as well as joint collaboration between operator and automation to potentially complete the 'in progress' procedure to a point where the plant is in a safe state while attending to the new circumstance.

- OP2: *'What happens to the procedure I was in when the alert comes up? What happens to maintaining the first procedure? Will it do it automatically? Does it completely ignore the previous procedure? That could be a problem. It would need to maintain everything that you already completed in the first procedure. There have been sometimes in the simulator where this has happened. One person would put the first procedure into a safe condition and then help the second person with the AOP. If there are three people, then one person stays with the first procedure. The other two works on the AOP. They try to stick to one thing at a time though.'*

4.2.2 Prioritization of Design Feedback

Table 7 captures the design prioritization used to guide modifications to the design of ADAPT based on feedback from the workshop. In this table, the first column refers to the sub-system of ADAPT that the finding refers to. The second column refers to the finding number, which corresponds to the findings described in Section 4.2.1. The third column refers to whether the finding created a need for implementing a design change (YES) or not (NO). Findings that fit neither criteria contain 'NA.' The classification of the findings was largely consensus based, from the LWRS research team. In all cases, a description for the bases on these classifications is provided in the rightmost column. For detailed descriptions of the design changes (marked as YES), refer to Section 4.3.

Table 7. Design prioritization matrix resulting from the design workshop

System	Finding Number	Implement Status	Justification/ Design Modification
General ADAPT	1	NO	**Desire for multi-tasking capability** The underlying automation philosophy is to reduce cognitive burden for the operator by providing only the most critical task, given the plant conditions. As such, the complexities of time sharing between tasks is minimized through ADAPT's decision support capabilities. This philosophy shall be validated in future evaluation activities such as performance-based tests like operator-in-the-loop simulation.
	2	YES	**Level of automation (balancing operator control with decision support)** ADAPT's automation philosophy has been designed such that decision support is provided, but responsibility is shared with the operator and positioned such that the operator has final say. This philosophy is reflected across each display system and is illustrated in the next section.
	3	YES	**Desire to customize displays with information (interface flexibility)** Functionality to create custom trends is provided in ADAPT and will be shown in the secondary task support display system. Additionally, custom notifications created are visually represented on the overview display systems, shown in detail in the next section.
	4	YES	**Desire for capability to drill into more detailed information** Similar to Finding 3, ADAPT offers the secondary task display system that provides access to custom and detailed plant information such as custom trends, plant historians, P&IDs, plant equipment status, and other information that's not inherently applicable for the active task at hand.
	5	NO	**Desire to have additional HSI screens** One primary driver for a desire for additional HSI screens was based from a need to multi-task. However, the underlying philosophy of ADAPT is to reduce cognitive burden through advanced automation that transforms that way in which operators perform tasks (see Finding 1 above). This philosophy shall be validated in future evaluation activities such as performance-based tests like operator-in-the-loop simulation. At least one output in future evaluations will be further understanding of whether more screens are needed.

System	Finding Number	Implement Status	Justification/ Design Modification
Plant Overview Display System	6	NA	**Overall philosophy of the plant overview display system is new to operators** Finding 6 captured impressions of the plant overview display system. Operators commented that they are familiar with their existing display systems that provide more detailed information. Although, it is unclear to what extent ADAPT's new philosophy influences human-system performance without formal performance-based testing. No explicit design recommendations were generated from this finding.
	7	NO	**Most operators found the plant overview information to be complete, though some operators suggested additional plant-specific information** Operators generally commented that the information on the plant overview display system was complete. Though, additional plant specific parameters were identified such as condenser pressure, which is specific to PVGS and is used seasonally. Since the focus of the workshop was to collect generalized findings, these plant specific suggestions were omitted at this time.
	8	**YES**	**The approach for alerts and notifications was acceptable, though preference was made to ultimately keep the operator in charge** While not explicitly demonstrating during the workshop, the existing ADAPT concept ultimately places the operator in charge in initiating transitions across displays based on changing plant conditions.
	9	**YES**	**Operators generally were more familiar with individual trends over the multi-variable relationship trends** Operators were most familiar with standard time series trends. Further operators were concerned that the alternative relationship trend may not show subtle yet meaningful changes in a way that is clear. LWRS researchers reviewed alternative design formats that provide a high-level (i.e., showing the complete range of the parameter and important thresholds), as well as a local-level view of the parameter (a meaningful scaled window of the parameter that clearly shows subtle yet meaningful changes). One concept that came from reviewing operators' needs was a combined format, defined as a 'fisheye' format, of the total range and selected window that shows a local view of the parameter. The next section describes this new concept in detail.
	10	NA	**Operators were familiar with the balance chart format for some parameters** Operators offered their impressions of the balance chart shown on the overview displays. This finding did not create a need for a design modification to ADAPT.
	11	**YES** (PARTIAL)	**There was partial consensus on design for [1] steady state, [2] reactor startup, [3] reactor shutdown, and [4] abnormal conditions** LWRS researchers are in process for developing the different plant modes that define these different plant overview displays. Currently, considerable work has been done for steady state and abnormal conditions.

System	Finding Number	Implement Status	Justification/ Design Modification
	12	NA	**Response planning and implementation strategies for parameters approaching a 'non-critical' boundary** Finding 12 was specific to understanding operational context for managing oscillating and changing parameters that do not invoke an alarm. While no design modification was created from this finding, the finding documents possible variants in ways to which operators may interact with ADAPT in performing monitoring actions.
Task Overview Display System	9*	YES	See Finding 9 above.
	13	NA	**The task overview display system was positively received by operators, providing a sufficient level of detail for the task** Finding 13 captured impressions of the task overview display system, which was well received. The finding did not identify a need for any design modifications to the task overview display system.
	14	NA	**Use of procedures and related material as a design basis** Finding 14 was specific to the methodology used to inform the design of the task overview display system, as opposed to generating design-specific feedback. The finding suggests that the use of procedures and related materials like P&IDs are valuable resources for informing the design of these displays.
Task-Based Display System	15	NA	**The indications pane was acceptable for providing redundant task-relevant indication for monitoring** Finding 15 captured impressions of the indications pane located on the task-based display system, which was well received. The finding did not identify a need for any design modifications to the task-based display system.
	16	YES	**Desire to preview a procedure** The capability of scrolling to preview a procedure along with the task overview display was already an intended design feature of the task-based display system. As a result, the finding did not identify a need for any design modifications to the task-based display system.
	17	NA	**The layout of the procedure instructions appeared logical and usable with having the step, process value, and soft controller collocated** Finding 17 captured impressions of the layout for the procedure instructions pane located on the task-based display system, which was well received. The finding did not identify a need for any design modifications to the task-based display system.
	18	YES	**Operators initially had mixed opinions with showing the step numbers; those who preferred the numbers initially based their opinion on their existing conduct of operations** The primary basis for including step numbers was to support communication to the field, providing a common reference point between control room and the field. The fundamental operating model for ADAPT is to enhance communication through advanced capabilities such as real-time communication, which not only supports such placekeeping, but also enables sharing live video feed and other information to added context. Alternatively, added features such as an option to show/hide step numbers (or a common reference point) was considered.

System	Finding Number	Implement Status	Justification/ Design Modification
	19	NO	**The active step icon was perceived as useful but was not immediately intuitive to some operators** Operators favored the capability to reorient to an active step of scrolling the procedure. However, the icon for this control was not immediately understood when researchers asked. It should be noted that no formal familiarization was provided to operators (which would be expected in actual application) of ADAPT and its features. Further, operators were provided static screenshots of ADAPT, which loses rich information afforded through interaction with a functional prototype. Future evaluation activities will revisit the usability of this icon when presented in a dynamic context.
	20	NA	**ADAPT's philosophy of re-allocating verification steps to automation, where plant equipment in then correct state would be omitted from operator verification, was considered acceptable** Finding 20 captured OP5's impression of the automation philosophy for handling verification activities. The finding did not identify a need for any design modifications to the task-based display system.
	21	YES	**Procedure preview, manual override, and equipment indications were important features and functions to ensure operators continue to check the integrity of data provided by ADAPT** As highlighted in Finding 2, ADAPT's philosophy is to apply a human-centered approach to automation, which emphasizes integration by careful understanding of the task requirements and capabilities of the automated system and operator. In this context, the operator is considered the supervisor to the automated processes initiated through ADAPT. While ADAPT provides decision support to the operator using advanced capabilities including online monitoring of equipment that collects real-time data, the operator is positioned to make the ultimate decision and plant action. Under this framework, ADAPT enables the operator to override the automation when deemed necessary. Information that is important for the operator to make executive decisions are provided from the display systems in ADAPT. Such information includes but is not limited to maintenance notifications (e.g., lockout tagout), condition-based alerts, and alarms.
	22	NA	**The continuous actions pane with trends was perceived as useful, especially in abnormal situations that require using AOPs/EOPs** Finding 22 captured impressions of the continuous action on the task-based display system, which was positively received. The finding did not identify a need for any design modifications to the task-based display system.
	23	NA	**The proposed system behavior for alerts and notifications possibly occluding a portion of the indications pane was acceptable for operators** The proposed system behavior of the alert and notification region and its effects on occluding part of the indications pane did not pose a problem for operators since the incoming window can be easily closed and the trends are redundant across the other display systems. The finding did not identify a need for any design modifications to the task-based display system.

System	Finding Number	Implement Status	Justification/ Design Modification
	24	YES	**A need to maintain the trajectory of an in-progress procedure to ensure the plant is in a safe state while attending the new condition** The current philosophy of ADAPT is to prioritize each condition and suggest to the operator to attend to the more pertinent through the alert and notification pane. This philosophy leverages automation in way that will bring the plant to a safe state in the current procedure to avoid additional burden to the operator. See the next section for details.

4.3 Design Updates to ADAPT from Workshop

4.3.1 Updates to the Overview Displays

Figure 26 shows the normal overview display, which would automatically shift to the abnormal overview in Figure 27 when operators confirm the notification from the task-based display. The modifications to some of the display elements and layout are listed in Table 8.

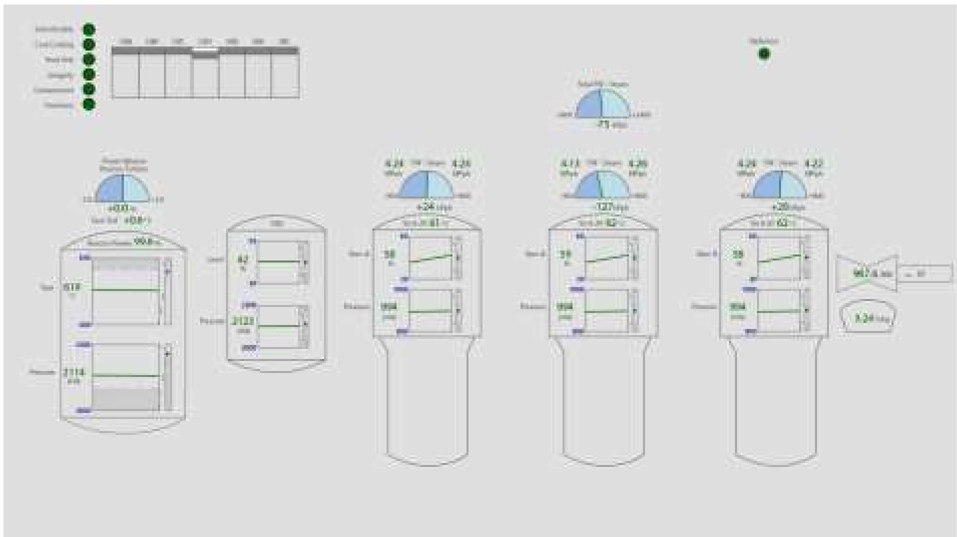


Figure 26. Second iteration of the plant overview display system under normal operations

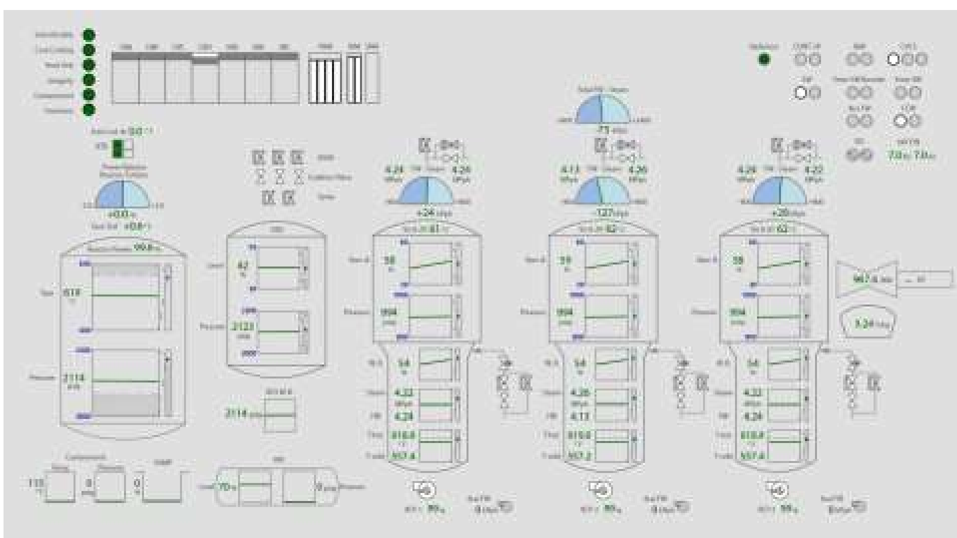
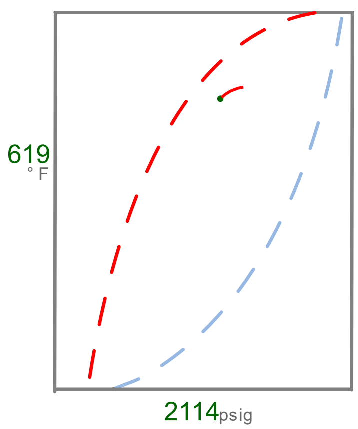
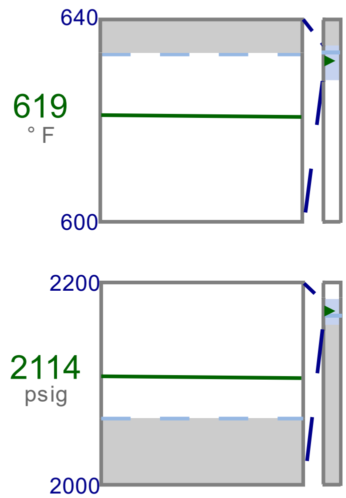
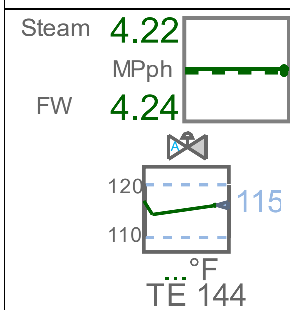
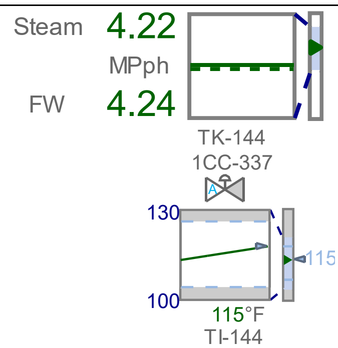
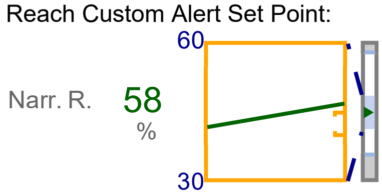
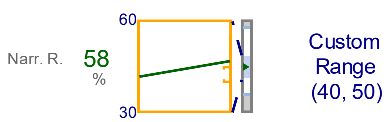
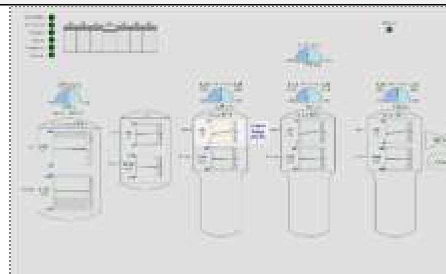


Figure 27. Second iteration of the plant overview display system under abnormal operations

Table 8. Design updates in the overview displays

First Iteration Display Elements	Second Iteration Display Elements	Justification
		In the first iteration, we used a single plot to represent the temperature and pressure with temporal trajectory because of the relationship between temperature and pressure. In the second iteration, temperature and pressure were plotted separately. During the workshop, operators have mentioned that they were not familiar with the two-variable relationship format, and the traditional trend format was preferred. It is consistent with the previous research that operators had worse performance in detection and diagnosis with pressure-temperature display than analog display (Vicente et al., 1996). All the process data are displayed independently.
		In the second iteration, the process data element has the capability to zoom-in. Operators have stated that they sometimes look at small changes, which is barely noticeable from a standard range trend plot. The detailed explanation of trend plot is shown in Figure 28.
NA Previously, the overview displays did not have this feature built in.	Reach Custom Alert Set Point:   Hover Over: 	In the second iteration, the overview displays show the alerts which operators set in the secondary task display. Operators mentioned that they preferred to have the capability to custom the alert set point, which is narrower than the system's alarm set point. In some cases, they would like to act on earlier before triggering the alarm.

First Iteration Display Elements	Second Iteration Display Elements	Justification
		

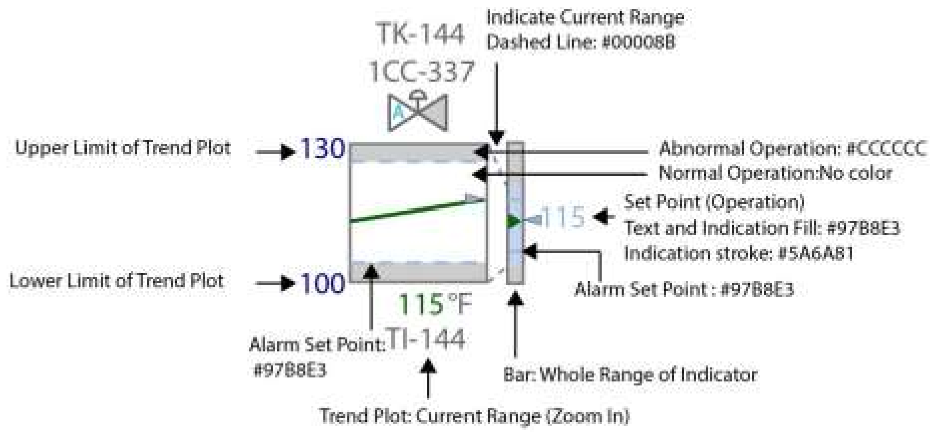


Figure 28. Explanation of trend plot for process data with zoom-in function

The process data trend plot is an IRD with indications of alarm setpoint, operation set point, temporal information, zoom-in range, and the overall range. Some of the features may not be shown depending on the characteristics of the control or process data. For example, the design of the sump level in Figure 28 is not modified because a small fluctuation of the sump level would not indicate the changes in system dynamics.

In the task overview, we removed information that the operator's indicated were not immediately relevant to the task. For the example scenario shown, each individual seal injection flow has been removed because there is no need to monitor it when restoring the normal let down after maintenance. Additional indications for excess letdown have been added, as it describes dynamics of the sub-system. One operator has stated that temperature and pressure are usually the leading indicators. The additional information added in the task overview display is a refinement for restoring normal let down under maintenance task, not due to the changes in the design concepts.

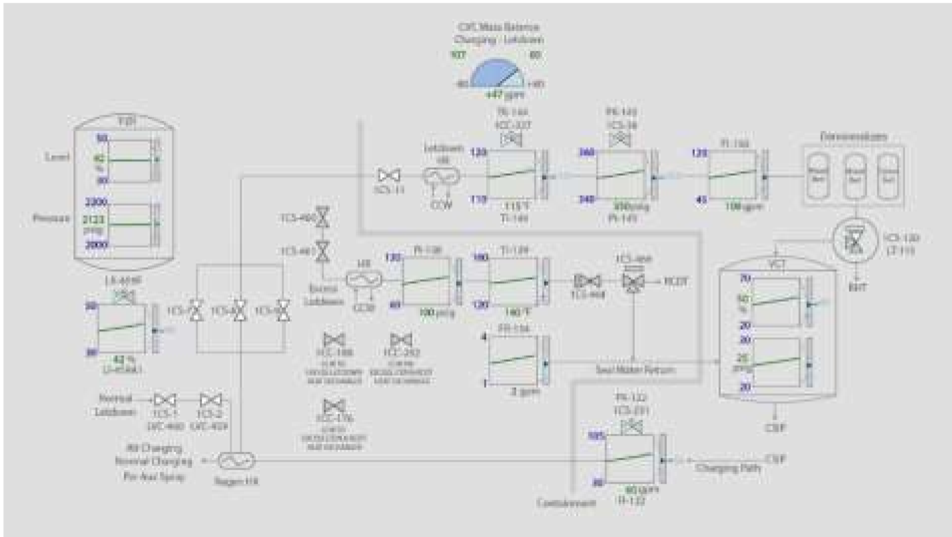


Figure 29. Second iteration of the task overview display system for restoring normal letdown after maintenance

4.3.2 Updates to the Task-Based Display System

4.3.2.1 Toggling Step Numbers

The decision to not show step numbers in the initial design was somewhat controversial. Four operators stated that step numbers should be shown, while the rest suggested they were not needed. Of the four that wanted step numbers displayed, each expressed concern about coordination with the field or other organizations. When the philosophy of ADAPT was further explained to describe the ability to coordinate with the field (i.e. automatic place keeping), operators determined step numbers were less important than they originally suggested but that it still might be useful to refer to them at times. Consequently, ADAPT was updated to provide options for multiple design features including whether or not to show step numbers while navigating the procedure. The default option is to not display the step numbers.

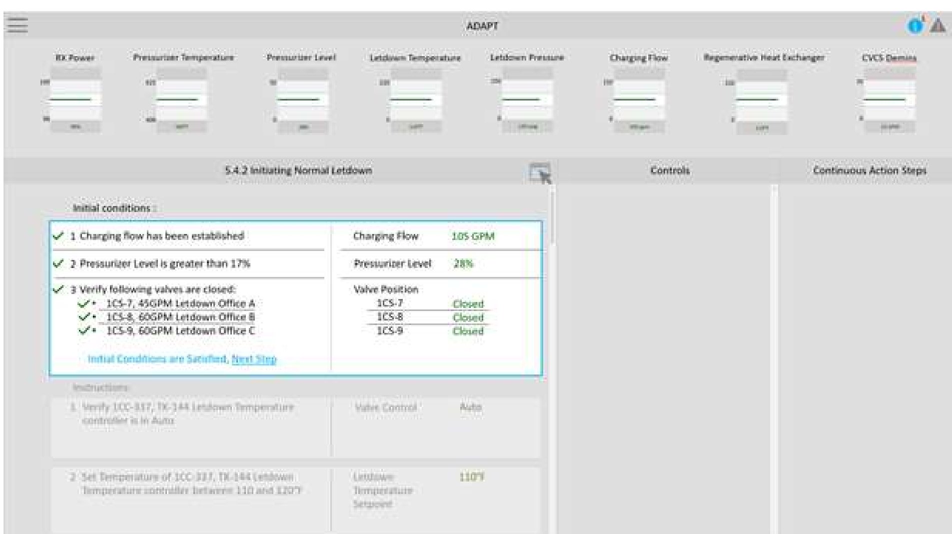


Figure 30. Step number display turned ON

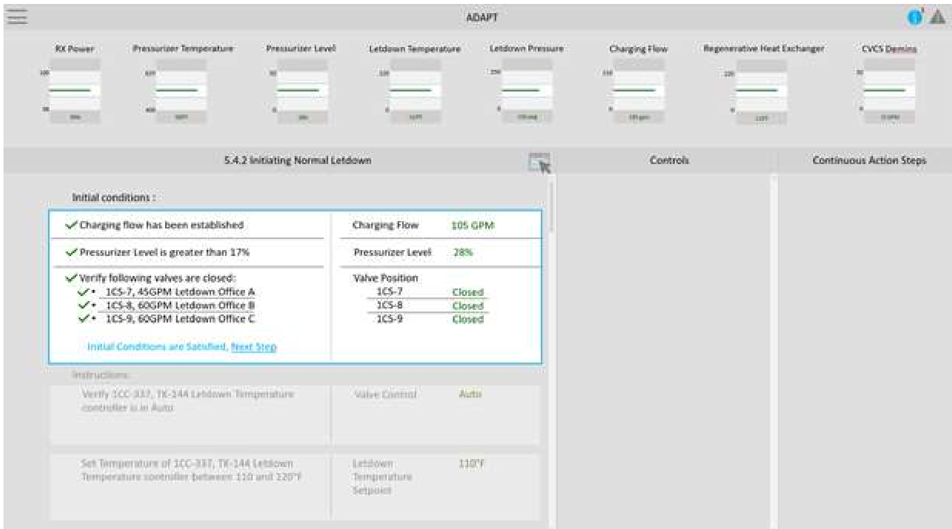


Figure 31. Step number display turned OFF

4.3.2.2 Manual Override of Automated ADAPT Functions

The design philosophy and functionality presented within the dynamic instructions section of ADAPT were strongly influenced by the computer-based procedure design philosophy described by Le Blanc and Oxstrand (Oxstrand, Le Blanc, & Bly, 2016). From this philosophy, the user is guided through the procedure and any additional information that is needed to perform the step is available when relevant. Additionally, logic supports the operator to ensure the correct path of execution is followed. During the workshop, multiple operators expressed general approval for this philosophy but mentioned the need for an operator to occasionally override the system (e.g. equipment failure). To accommodate this, a manual override feature was included in the functionality of ADAPT. Operators are able to enter override two ways; by performing an action that deviates from the task instructions or by accessing the controls menu and clicking the override button. When entering override by deviating from the procedure, an 'unexpected action' message appears to ensure the operator actually wants to enter override and that the procedure deviation did not occur unintentionally.

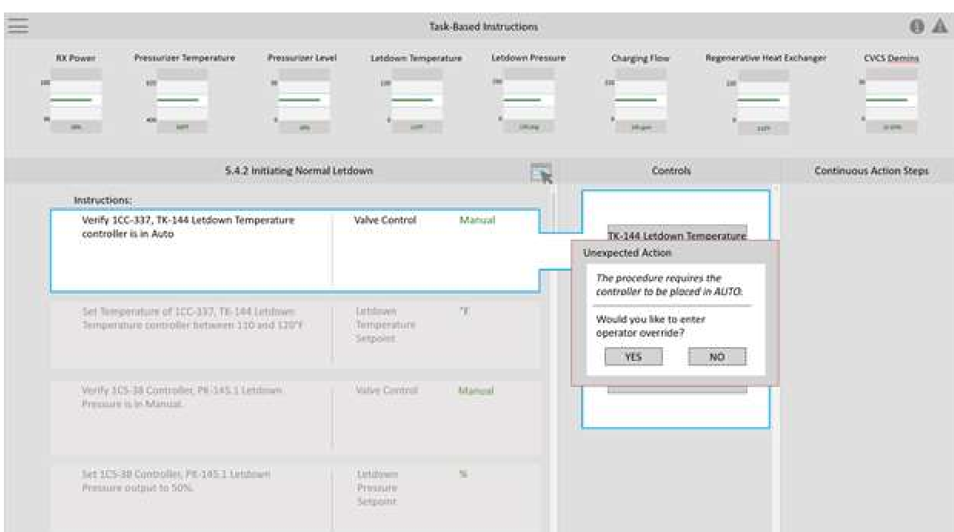


Figure 32. Initiating an override of task instructions: Unexpected action message shown

Operators can accept this action and proceed with the override or reject this action and continue executing the procedure under normal conditions. An operator does not have to take a deviating action to enter override, however. Override control is also available through the controls menu (i.e. clicking on 'override step conditions' button). The same message will appear to ensure the operator wishes to enter override.

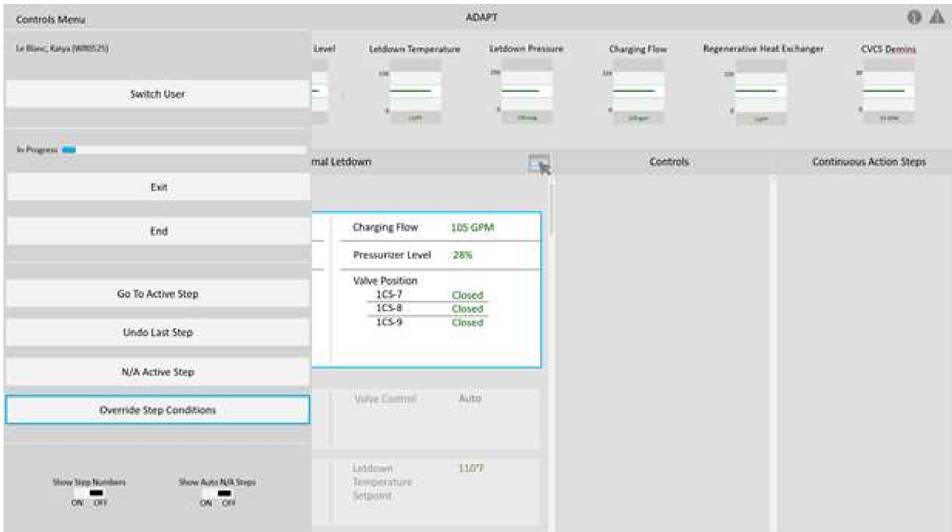


Figure 33. Initiating an override through controls menu

4.3.2.3 Presenting Equipment Status

One operator mentioned the need for equipment indications such as maintenance and lockout-tagout to notify operators that equipment is not operable. The operator said that in their current operations on overview screens they use indications to show that equipment is under maintenance or under lockout-tagout to inform control room operators to not place the equipment into service. The philosophy of the ADAPT concept uses icons for maintenance and lockout-tagout to inform operators which equipment is out of service. Maintenance and lockout-tagout icons are used on both the task and plant overview screens.

4.3.2.4 Managing Multiple Plant Conditions: Human-Automation Collaboration

Two operators mentioned when managing multiple plant conditions, the need to bring the in-progress procedure to a safe state while attending to the new plant condition. Operators said they had concerns when switching to another procedure while the current procedure is in progress. The ADAPT system will pause the in-progress procedure and notify operators when new plant conditions require operator attention. Operators are able to continue the in-progress procedure until they have reached a hold or safe point or determine whether the in-progress procedure is more important to complete before selecting the recommended procedure. Once the operator decides to attend to the new plant condition procedure recommendation, the in-progress procedure would pause and the new recommended procedure would populate on the task-based display system.

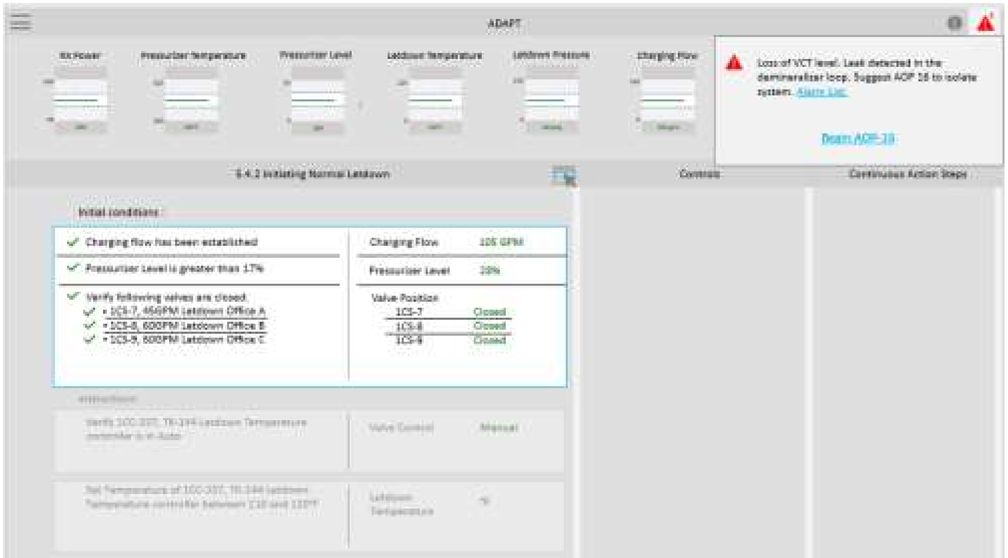


Figure 34. Alert notification to begin recommended procedure AOP 16

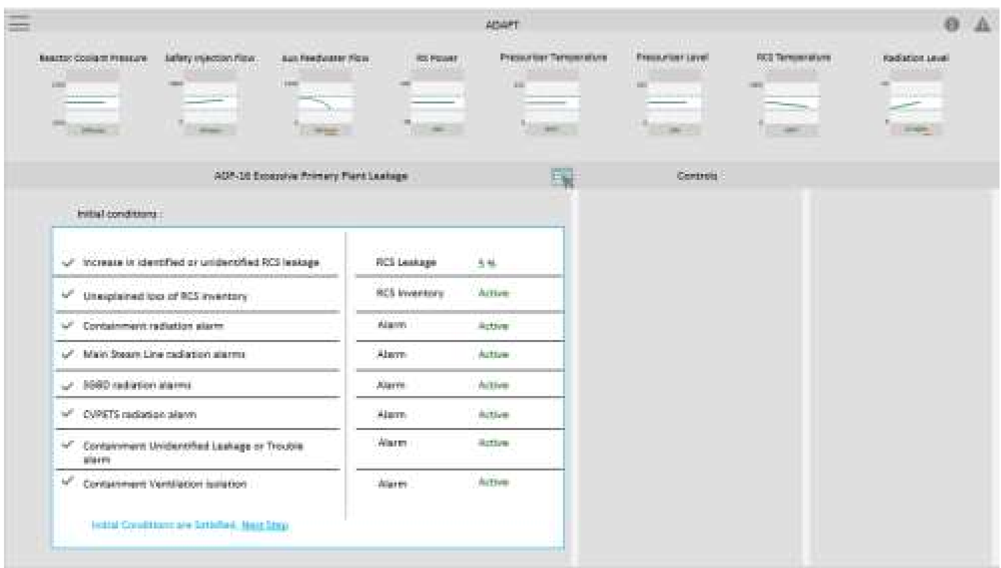


Figure 35. Initial conditions for AOP 16

The workflow shown in Figure 34 illustrates the operator beginning to initiate normal letdown where the first action is to verify the initial conditions from the previous procedure. In this illustration, an incoming condition occurs (i.e., a leak in the demineralizer loop causing VCT level to decrease), which is presented as an alert to the operator. The decision support capability provides a recommended course of action for the new condition (e.g., to begin AOP 16), as well as a description of the detected fault and diagnosis (i.e., a loss of VCT level due to a leak in the demineralizer). Here, the operator is provided access to related alarms (e.g., 'Alarm List') and the option to begin AOP 16. The operator can choose to begin the AOP 16 procedure, based on this guidance provided by ADAPT. Once AOP 16 is selected the current in-progress initiating normal letdown procedure will be paused and the AOP 16 indications, instructions, and continuous monitoring will be made available to the operator (Figure 35).

5 DESIGN GUIDANCE

Process plants themselves differ greatly. But, even within the nuclear industry, each plant has unique features that would impact the content of ADAPT displays. Design guidance provides decision making support when populating the ADAPT display content. Simply replicating the content of this example across the industry would not result in the operational benefits proposed here. By prescribing a set of guidance and design criteria, this advanced control room concept can be adopted by any plant.

Rasmussen and Vicente (1989) argued that a display should support the handling of errors and plant variants rather than attempt to eliminate them, and this philosophy is employed in the ADAPT concept. Each display supports an aspect of operator duties by providing the right information, at the right time, alongside the needed controls. The criteria used to build each display is discussed here to support replicability in other plants. These criteria assume a degree of information and data connectedness within the plant, and discussion of how plant information is brought into the control room is not the focus of this work. This section discusses how the operator is supported by the workstation design.

To review, the plant overview display, task overview display, and task-based instruction display are the primary displays with a prescribed convention to their design. The secondary task display is personalized by the plant or operator during operation. It serves as an auxiliary space to pull up custom information unique to operator needs or operating style. It is recommended this space be available to accommodate differing operator strategies but does not abide criteria beyond that recommendation.

5.1 Overview Displays

Criterion: Overview graphics should integrate complex system information, represent relationships, and enable rapid value recognition and comprehension.

Criterion: The content of an overview support rapid recognition of system status and awareness of following implications

Generally defined as a summary of information for processes of the system of interest, presented to the operator in one display (Le Blanc, K. et. Al., 2018), overviews are useful when information from a complex system can be integrated to enhance operator awareness of changing plant conditions. Effective overviews minimize the need for operators to combine information, make calculations, or search for information to determine the condition of the system displayed. All relevant information to determine system status-at-a-glance should be included in the same overview screen (i.e., see NUREG-0700, Rev.2).

Many concepts describe how to design graphics (IRD, EID, Dull-Screen). LWRS has synthesized many designs in single document and has applied the resulting philosophy here (Le Blanc, K. et. Al., 2018). The objective is to display information in an actionable, comprehensive way. The intent of the display can impact how and what information is presented. For instance, the plant overview during normal operating status is meant to signal to the operator of a potential problem but not offer true diagnostic capabilities. The task-based display presents highly detailed, task-specific information with diagnostic capability but not high-level plant health information for status monitoring. The information presented should support the display's purpose.

Content and graphic selection is paramount to a successful display. Making the right selection is aided by having a clear intention behind each overview. Clearly defining the intent of each display allowed experts to accurately build the content and constrain the human factors and graphic design needs. To design with intent while accommodating the multitude of control room situations ADAPT uses four displays. Each display supports part of the operator's role in the control room.

5.2 Plant Overview Display System

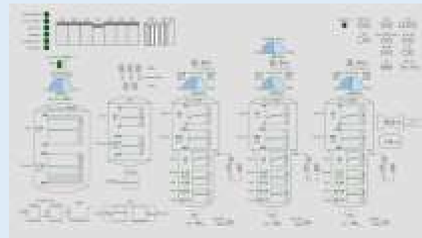
Criterion: Use leading indications to minimize display content but maximize operator awareness and recognition of evolving plant statuses.

Leading indications are the foundation of a plant overview display. Not meant to be diagnostic, leading indications, like a canary in a coal mine, serve to cue the operator of impending trouble. Based on overview information the operator knows where to investigate the source of the issue. As issues progress, or the plant enters a less frequent status, the overview can transition to include greater detail. However, it is critical to be discriminant in selecting information for the plant overview. It is meant as a reference, a display to orient the operator towards the condition of the plant. Detailed plant information is available in the task-based display and is augmented by the task overview. Any other information the operator on duty requires can be supported by the auxiliary display for custom investigation.

Criterion: Maintain consistent placement of plant values

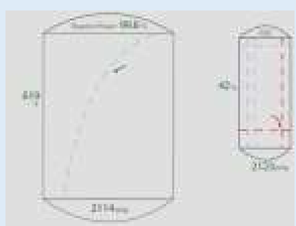
As more indications are added, keeping plant indications in consistent screen locations will minimize confusion and search time. Most plants will likely have a similar base set of leading indicators with additional unique indicators to accommodate individual plant characteristics. A plant expert should make the determinations with review from expert operators. Notice in the abnormal plant overview the additional information is added around the already existing normal plant over information. Any information the operator was monitoring before entering abnormal status remains where the operator expects to find it for a smooth transition. Adhering to this criterion also emphasizes the first criterion to use only information necessary on the normal operation plant overview. The display can quickly be filled with information required for other plant statuses.

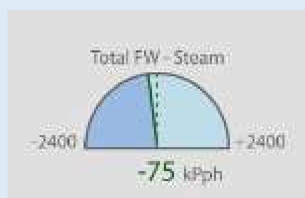
Criterion: Augment information to support different plant statuses

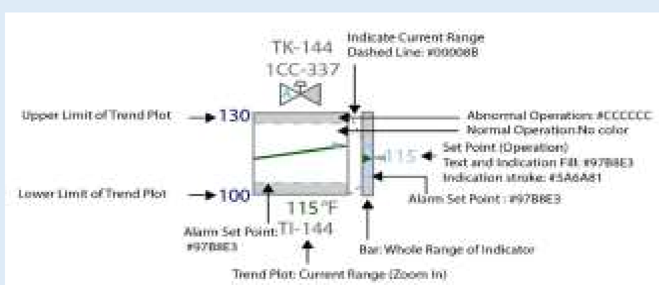


The plant overview display supports operator plant awareness at all times. The plant overview may adapt to different plant statuses. In the example, a normal and abnormal plant status overview was presented to experts for review. Plant experts should determine how many plant statuses should be represented for an individual plant overview display. The overview is built with expected parameters for the status it represents. Doing so serves a few purposes. The graphics used in the display can help inform the operator of expected plant values. More informative, relevant diagnostic information is built into the display. Noise from irrelevant alarms that typically flood current control rooms can be filtered to only those informative to the operator. These characteristics sharpen the plant picture for the operator for at-a-glance determinations and subsequent actions.

Criterion: Use graphics that clearly delineate expected from unexpected plant values







Digital displays going beyond single-sensor single-indication philosophies must balance confusing information in an overworked graphic and graphics that describe the nature of information presented. Unclear graphics require mental operations in the moment to understand the state of the system, an outcome contrary to the goal of ADAPT. However, providing graphics that align with operator needs can optimize recognition and comprehension.

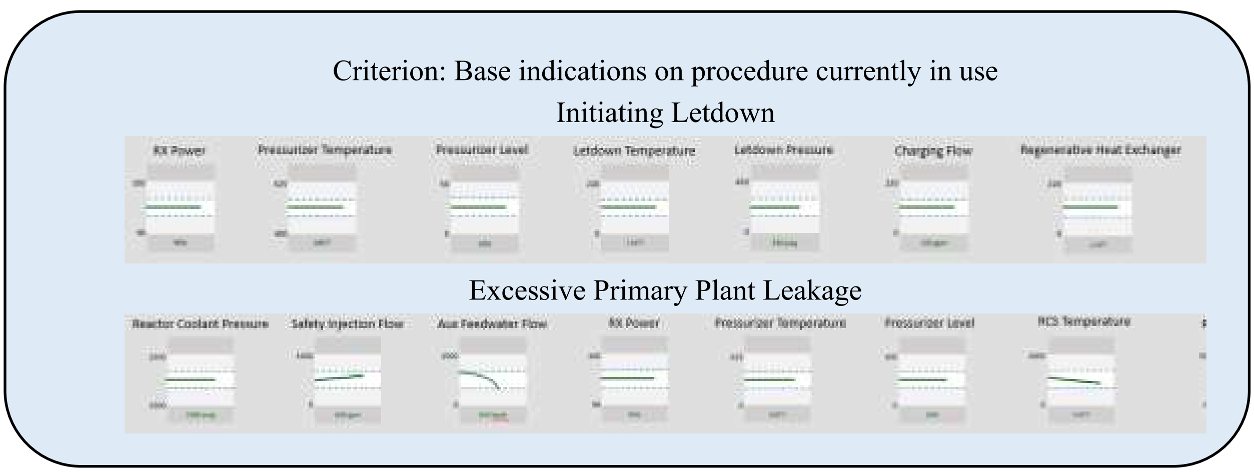
In the design presented to operators during the workshop, the operators were confused by trends representing two values at once (y-axis and x-axis each representing a plant value where typically, in trends, the x-axis represents only time). Operators instead preferred two individual trends. The feedback meant removing an integrated display to show potential relationships for two trends that, if designed right, take advantage of emergent features. The result is an informative graphic by different means. The graphic on the top right was successful in representing operator mental models. It was kept in the second iteration as an integrated graphic. Maintaining this flexibility and awareness of tradeoffs is part of making ADAPT successful.

5.3 Task-Based Display System

The task-based display system is the control center. It is how operators interact and control the plant. Operators carry out procedures, monitor task specific indications, access control faceplates, and receive decision support for plant actions. This display is detailed and supports the operator at the equipment manipulation level. This display integrates equipment controls with procedures. Operators receive notifications and plant alarms via a notification system. Decision support is provided here. The advanced analytics within ADAPT act as a peer review when carrying out tasks within the control room.

This display's success is reliant on the clarity and availability of task overview display support and vice versa. The keyhole effect, referring to the operator focusing on too little available information at a single moment, is mitigated through several design considerations. Procedure construction providing exceptional task clarity. Immediately available task-relevant information reduces search time or relying on memory for to assist decision making. Decision support that synthesizes information, plant values, calculations, and tables to reduce workload and provide suggestions for operators. Continuously available trends and plant information related to the procedure remain visible for reference anytime during the procedure. Lastly, the task overview display show task-at-hand's impact on the larger system.

5.3.1 Indication Pane



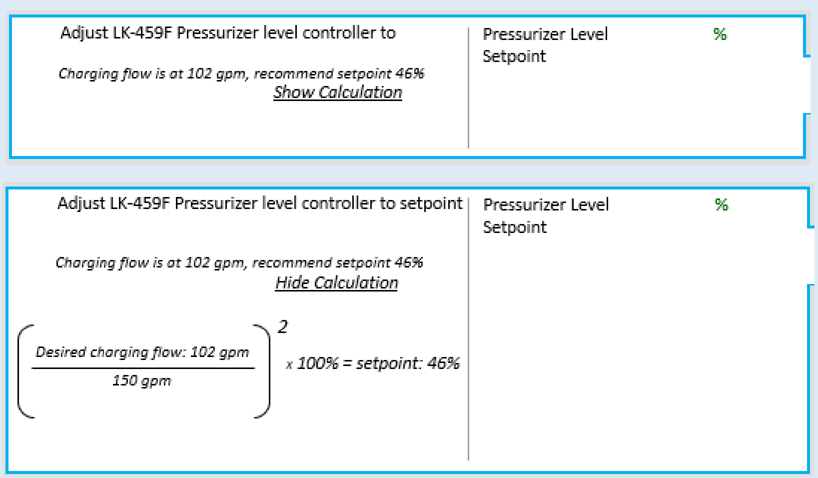
Common practices in main control rooms is marking indications and controls required in an upcoming procedure. Especially if the task is uncommon, time-critical, complex, or a combination of all three there is value in having prepared information. The indication pane on the task-based display supports that context by using the procedure to pre-populate the most used indications for monitoring. Indications that support time-sensitive tasks or require continuous monitoring take priority over frequency of use alone. As displayed, the indication pane automatically switches with the procedure being performed. The information is likely redundant with information in the task overview display and possible the plant overview. However, its location in the pane also serves to cue operator expectations for the procedure being performed. Note that locating this information in the task-based display cues the operator on the procedure. Locating this pane on either overview would not have the same effect in focusing the operator's attention on the procedure.

5.3.2 Procedures

Criterion: Instructions are clear and obvious

The procedure design must provide the operator with clear, unambiguous instruction. ADAPT uses a variety of features to support that aim. Based in a decade of computer-based procedure research (EPRI, 2005; IEEE, 2009; Le Blanc et al., 2015; Oxstrand, et al., 2014) design elements including place keeping, salient current step, consistent step construction, live process values embedded in the step, and decision support keep the operator on track and apprised of their immediate tasks. ADAPT's procedure design removes artifacts required in paper-based procedure while using the advantages of a connected plant. Advantages that include real-time plant information, communication with field operations, and procedure logic to guide appropriate tasking.

Criterion: Maximize digital capabilities in instruction design



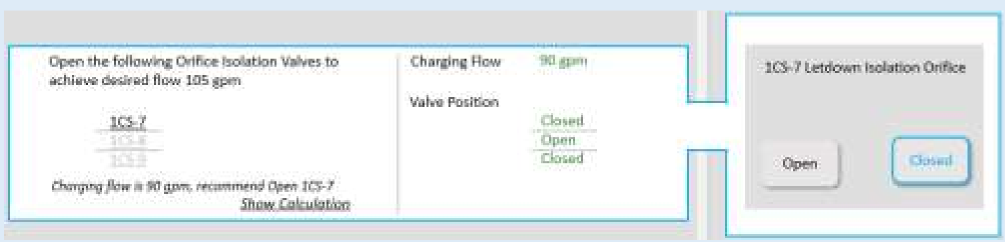
Inspired by the HABA-MABA concept (Fitts, 1951), all calculations, estimates, tables, and any other functions humans are bad at should be allocated to automation. The operator should receive the meaning of the data, and not have to rely on his own interpretation of the data itself. However, the operator ultimately commands the system making all final decisions. The capability to see how information was generated should exist if the information an operator receives does not match his understanding or expectation. Allowing the operator to compare knowledge-in-the-head to knowledge-in-the-system builds a collaborative environment. It also compensates for any data shortcomings of the connected plant.

Criterion: System analytics provides "peer" check of actions contradictory to step logic

As part of a human system collaborative environment, ADAPT has error prevention strategies to avoid accidental commands for operators acting contrary to decision support or procedure logic. ADAPT can verify plant status with step requirements, the system can act as a digital peer check for the operator to ensure best actions are taken. Part of remediating errors rather than preventing them entirely, this function is a compromise of ultimate operator authority and advanced system analytics. This function adds the chance to feedback decision justifications to continue improvement of ADAPTs implementation.

5.3.3 Controls

Criterion: Step relevant controls are automatically brought up when step is activated



Step-relevant controls are made available alongside the step. The colocation affords easy comparison of current system state, desired state, and how to match the two if disagreement exists. Adhering this criterion minimizes control search time, potential to use an incorrect controller, and supports faster, but still correct, step execution. Note, other controls can be called up on the secondary task display should the operations call for it. ADAPT in its complete implementation implies no other control should be needed.

The task-based display system alone provides the operator with the right information, at the right time and supporting suggestions based on ADAPT's plant knowledge. The operator is expected to confirm ADAPT's plant knowledge with his own to ensure proper plant operation. The task-based display alone does not support the operator's wider awareness of the system in operation. The task-overview display is tailored to support operator situation awareness relevant to the higher-level goal of the tasks taking place below in the task-based display.

5.3.4 Monitoring and Decision Support

Criterion: Use advanced technology to reduce operator burdens

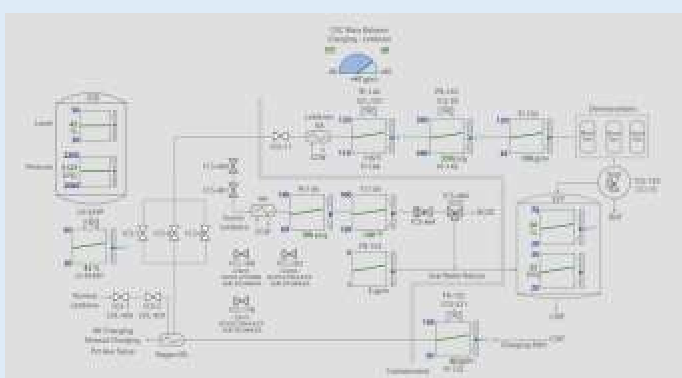
A connected plant offers opportunities to reduce operator burden. Communication, status monitoring, maintenance needs, and equipment malfunctions are a few areas with options to decrease overall operator workload.

Equipment status monitoring coupled with procedure analytics allows supporting functions such as "Continuous Action Steps." Paper procedures relied on multiple steps peppered in the procedure to remind operators to check equipment statuses. That burden is better placed on the analytics in ADAPT. Such tasks can be set to alert the operator when action is needed but otherwise remain in the background while more important tasks are carried out.

Operations can notify field operations automatically and subsequently follow steps taken to perform maintenance directly from the workstation. Connecting dynamic field instructions with main control room operations can provide more accurate, real-time notifications of plant statuses as impacted by other work occurring in the field. Equipment monitoring also supports maintenance recommendations either routine or immediate and unexpected.

5.4 Task Overview Display System

Criterion: Minimize keyhole effects by supporting tasks with system information



ADAPT brings the entire control room to a single workstation. The obvious risk is reducing the amount of information immediately and always available to the operator that a traditional MCR offers.

Mitigating this issue is a Task Overview display system that provides diagnostic and relevant information regarding the subsystem the operator's current task involves. Instead of the operator seeking out system information, the right information is brought to the operator. It affords a wide-angle view of task impact and equipment being operated.

Verification of actions taken in the procedure is available in the task overview display. Also available is upstream and downstream consequences of each action. The subsystem overview is vetted by experts to determine what elements are necessary to support the task being carried out in the task-based display. Recommended is using each procedure as the initial frame of reference for developing the task overview. Integrating information from other plant systems may be necessary to the task in some cases. The task overview should also reinforce the operator's mental model of the system at hand. Displaying information already represented is appropriate since it is critical to having the information at hand in a predictable location. The operator should refer to each screen for different purposes. The redundancy of an indication should not have bearing on the decision to display it.

6 Conclusions

This report describes the ADAPT concept, and a workshop to collect operator feedback on the design. The methods and results are presented in detail, and changes to the design based on the feedback are documented. The final section described initial design guidance for implementing the concept with examples, illustrations, and the basis for the guidance. The guidance presented here, along with the philosophy presented in Kovesdi et al. (2020) provides the framework and design guidance for implementing a concept like ADAPT in a nuclear power plant. Future work will focus on further investigation of the concept and will culminate in pilot implementation of the concept.

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Appendix A: Interview Questions

Table 9. General ADAPT feedback interview questions

Theme	Question	Basis
Layout	A fundamental philosophy for ADAPT is to provide relevant information for the task at hand. There are four displays that serve as different viewpoints of the plant. *The plant overview* provides continuously available indication of overall plant status to facilitate accomplishing your tasks safely and efficiently. *The task overview* provides context-specific task information that is relevant for monitoring to safely and effectively perform a task. The *task-based display* presents task-relevant indications, procedure instructions, and additional monitoring and decision support. This display 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 that aren't related to the task at hand and navigates them to instructions to carry out the tasks to diagnose and resolve the issue. Q1. What are your impressions of the ADAPT configuration (i.e., is the overall concept and layout sound or not)?	Basis: Understand operators' impression with the underlying concept of operations of ADAPT (i.e., to provide relevant task-specific information)
Layout	Q2. Does the overall layout of the displays appear to be organized logically on the workstation?	Basis: Targeted question that queries whether operators think ADAPT is logically arranged.
Layout	Q3. Does it make sense or not to have two read only overviews continuously visible (above)?	Basis: Follow-on question that queries whether operators think having two overview displays makes sense.
Layout	Q4. Does it make sense or not to have two interactive displays (below)?	Basis: Follow-on question that queries whether operators think having two interactive displays makes sense.
Task Workflow	Q5. The interface changes based on conditions. Do you see any issue with this? Probe Questions • Does it make to have a dedicated place for information on the screen (e.g., reactor power)?	Basis: Targeted question that queries if having dynamic information on the overviews makes sense from an operational perspective. Alternatively, operators may request having all information available in a consistent manner.

Table 10. Plant overview display system interview questions

Theme	Question	Basis
Information Content	Our intention with this overview is to show only the information needed to verify that the plant is in a normal condition. The overview shows only information needed to monitor to tell if the plant is going to an abnormal condition. Q6. Does this accomplish this? Is there a concern with this approach? Note: Explain to operators that they would receive a notification prior to the overview displays changing (as needed).	Basis: Targeted question that queries if the plant overview display system clearly shows the state of the plant (e.g., normal or abnormal).
Information Content	Q7. Did we select the right parameters for the plant overview? Are we missing any parameters	Basis: Targeted question that queries if the information provided on

Theme	Question		Basis
		(i.e., please think generally and not specific to your plant)?	the plant overview display system is complete.
Task Workflow	Q8.	An assumption made in the design was that alerts and notifications can be used to support you in detecting a change in plant conditions. Is this assumption acceptable?	Basis: Targeted question that queries if the use of alerts and notifications is appropriate for cueing the operator to a change in plant state.
Task Workflow	Q9.	The plant overview will adapt based on plant mode conditions. What conditions should we design for (i.e., how many Plant overviews should there be)?	Basis: Targeted question that queries the number of states to design the plant overview display system for.
Task Workflow	Q10.	When some values are approaching an ‘out of range’ boundary and it does not fulfill an Abnormal Operating Procedure (AOP), Emergency Opertaing Procedure (EOP) or Alarm Procedure (AP) condition, what actions do you typically take to stabilize the value? How long does it usually take to respond to this kind of situation?	Basis: Understand how operators act towards stabilizing parameters that are not necessarily in alarm threshold territory.
Information Presentation	Q11.	The reactor vessel, pressurizer, and steam generators utilize a unique format for visualizing parameters that are related. Do these “relationship” graphics convey meaningful relationships in a way that displaying these graphically separately (e.g., individual trends) would not? Would you prefer this format or separate trends? Why?	Basis: Query whether operators prefer the inter-related visualization or separate trends.
Information Presentation	Q12.	Reactor Vessel: Can you describe the relationship between reactor coolant system (RCS) temperature and pressure? What is the best way to present this relationship? Probe Questions • Does this relationship differ based on varying plant states? Describe. • Does the current design clearly show this relationship? • Would separate trends for pressure and temperature better show this relationship? • Are the variables on the correct axes? • During normal operation, do you need to know the sub-cooling line? Are you trying to maintain the pressure and temperature around the sub-cooling?	Basis: Follow-on question for Q11 that queries specifically the relationship between temperature and pressure for RCS and how this information should be displayed across plant states.
Information Presentation	Q13.	Power Balance: Is the Power Balance Reactor-Turbine diagram presented in a way that is meaningful to you?	Basis: Follow-on question for Q11 that queries specifically if the balance chart for power balance is meaningful.
Information Presentation	Q14.	FW-Steam: Are the feedwater (FW)-Steam diagrams presented in a way that is meaningful to you?	Basis: Follow-on question for Q11 that queries specifically if the balance charts for FW-Steam is meaningful.
Information Presentation	Q15.	FW-Steam: Would you also like FW-Steam trended?	Basis: Understand where trends are needed.
Information Presentation	Q16.	Steam Generators: Can you describe the relationship between temperature, pressure, and water level for the steam generators? What is the best way to present this information?	Basis: Follow-on question for Q11 that queries specifically the relationship between temperature, pressure, and level for the steam

Theme	Question	Basis
	Probe Questions • Do you use this information to compare differences between steam generators? • Does the current design clearly show this relationship? • Would separate trends be preferred?	generators and how this information should be displayed.
Information Presentation	Q17. Are there other indications that are needed for normal operations that is not currently on this overview?	Basis: Verify with operators that the information on the display is complete.

Table 11. Task overview display system interview questions

Theme	Question	Basis
Information Content	The purpose of the task overview display system is to provide task-specific information to enhance situation awareness of the state of the systems and sub-systems relevant to the task. The intention of this screen is to support predefined tasks within a procedure. Q18. What sources of information should be considered in this display? Probe Questions • We used procedures and SMEs to collect this input. • Are there other resources that can be used to identify parameters for this display? • Frame based on how they design their Pi displays. • Goal: Need to understand what resources should be considered other than the procedure to inform the display. We need to develop a set of rules to design task-based displays and overviews.	Basis: Targeted question that queries what resources can be used to develop task overview displays? to develop a set of rules to design task-based displays and overviews.
Information Content	The existing screen was designed for initiation of normal letdown. The philosophy used was to only show indications that were relevant from the procedure (i.e., the charging system is not drawn out). Q19. Is this approach acceptable? How often would you like to have additional information? How would you like to get this information? Probe Questions • In your opinion, should this mimic show other sub-systems of the chemical volume control system (CVCS)? Why? • What are your thoughts on the way the flow paths are presented? • Is it clear what equipment is inside containment and what equipment is not? Is this important? • Is there a general (i.e., 'hard and fast') rule that comes to mind in determining	Basis: Targeted question that queries what information is important and not important for the mimic display on the task overview display system.

Theme	Question	Basis
	what information to present on the task overview mimic? • How would you prefer to find more information? Toggle to a detailed? Navigate to a display?	
Information Content	Q20. From an overview perspective, what do you need to know about? – Heat Exchangers – Pumps – Valves	Basis: Targeted question that queries what information is most useful for determining the health and status of heat exchangers.
LOA	The current design of the task overview display system has the information change automatically based on plant conditions and task requirements. Q21. Is this behavior desired or not desired? Probe Questions • Would it be desired to change this display manually? Describe. • Are there any concerns with this display automatically changing? • What involvement would you want to have if the system changed displays automatically (e.g., no notifications, notification with ability to confirm veto, complete manual control, etc.)?	Basis: Targeted question to understand if the LOA for changing display information is appropriate.

Table 12. Task-based display system interview questions

Theme	Question	Basis
Information Content	Indication Pane: Some of the information in this pane is redundant across ADAPT (e.g., shown on the overviews). Q22. Is the redundancy acceptable? Probe Questions • Is there a better use of this space?	Basis: Targeted question that queries if information redundancy is appropriate.
LOA	Procedure Instructions: The system automatically evaluates the step logic and presents the results. Q23. How do we ensure that operators are checking the values that the system provides? Do we need to? Probe Questions • What does it mean to you to maintain situation awareness when the system provides information to you? • What is most important to maintain situation awareness in this context?	Basis: There is no reason for the operator to verify in ADAPT. How do we ensure operator just steps through the procedure? Note, there was an alternative design that time constrains each step. Targeted question to understand the appropriate LOA for step logic.
Layout	Procedure Instructions: We have the step text and a process value to the right. Q24. Does this layout make sense? Probe Questions • Is the process (i.e., live) values next to the instructions distracting or not?	Basis: Targeted question that queries on whether the layout makes sense.

Theme	Question	Basis
	• If I asked you to rearrange the information (indication panel, verifying procedure steps, controls, continuous actions), how would you do it to improve your workflow? And why?	
Task Workflow	Notifications: When an alert or notification comes in, it is presented in the top right corner of the display. The operator is able to hover over the cue for more information; the hovering may obscure one or more of the trends in the indication pane. Q25. Is there a concern with this feature? Probe Questions • Do we need dedicated space for notifications and alerts?	Basis: Targeted question that queries if occluding the trend information in the indications pane presents a possible human error trap. This information will be used to understand if a dedication pane is needed.
LOA	Notifications: When an alert that requires immediate action comes in, the system will replace the existing procedure with the correct procedure needed for the new condition upon the operator acknowledging the alert. Q26. What should the workflow be for either choosing this recommended procedure or some other procedure?	Basis: Understand the workflow for transitioning procedures based on changes in plant conditions.
Task Workflow	Verifying Task Instructions: The first steps are to verify the initial conditions. Q27. If we have the information, we need to verify these conditions from the control system, what would you like to see? Probe Questions • Would it be okay to simply state the conditions are met and move to the next step? • When we have a group of steps that need to be verified, would you prefer to step through each condition separately or see them as one group? • What if it is a couple of verification steps in the middle of the instructions part of the procedure? • The actual values are displayed to the right of the step text, how do you feel about this layout?	Basis: Understand the acceptable workflow and LOA for task instructions.
LOA	Continuous Action Steps: The system will monitor procedure-based conditions and alert the operator to actions he needs to take. Q28. Should we present the continuous action steps in the procedure when it first appears? Would it be disorienting to have the system alert operators without first seeing the instructions? Probe Questions • Should we maintain the trends on the continuous action step panel, or simply	Basis: Question to understand the format of information in the continuous action step pane.

Theme	Question	Basis
	have a list of conditions that are being monitored • What if we have the indications on the indication pane already?	
Information Content	We do not present the original step text verbatim. We rephrase them to extract the conditions we are checking, and monitoring and then presenting the actions based on the evaluation of conditions (see step 8): Maintain the following: pressurizer level between 17%- xx% regenerative heat exchanger temperature below the high temperature alarm at 525° Fahrenheit (F) Adjust controller 1CS-231, FK-122.1 Charging Flow to maintain pressurizer (PZR) level and Regenerative Heat Exchanger (HX) temp Q29. Rephrasing Instructions: Do you see any problem with this approach? Do you have any suggestions to improve it?	Basis: Question to understand the whether the phrasing and presentation of task instructions is appropriate.
Information Content	We removed step numbers because we only present relevant steps and actions based on task and conditions (which would mean different step sequences based on conditions). Each step has a unique identifier, and coordination with field operators will happen directly through the interface. Q30. Step Numbers: Do you see any challenges with not having procedure steps?	Basis: Question to understand the if removing the step numbers is acceptable.
Information Presentation	Q31. Active Step Icon: Is it intuitive what the icon will do?	Basis: Question to understand if the active step icon is intuitive.
Task Workflow	If a step starts with an action verb such as ensure, open, set etc., the system will assume an action needs to be taken, and will present the current conditions and direct the operators to change the condition If a step starts with verify, the system will assume that an action will not be taken and will simply direct the operator to move on because the condition is met (if it isn't met, it will direct the operator to the appropriate contingency). Q32. Basis for Step Instructions: Are there any situations where this approach will not work?	Basis: Question to understand if the workflow (i.e., step logic) is appropriate to operators.

Appendix B: Response Characteristics from the Operator Workshop

The table below outlines the specific questions administered to each operator session. The 'X' denotes that the question was administered in a given session.

	Question	OP1	OP2	OP3	OP4	OP5	OP6 & OP7	OP8
General Feedback	1	X	X		X	X	X	X
	2	X		X	X	X	X	X
	3	X				X		X
	4	X						
	5	X				X		X
Plant Overview	6	X			X	X	X	X
	7	X			X	X	X	X
	8	X	X	X		X		X
	9	X	X			X		X
	10	X				X		X
	11	X	X	X	X	X	X	X
	12	X			X	X	X	X
	13	X			X		X	X
	14	X			X	X	X	
	15	X			X			
	16							
	17							
Task Overview	18	X	X		X		X	
	19	X	X	X	X		X	X
	20		X	X	X	X		X
	21					X	X	X
Task-Based Display System	22		X		X	X	X	X
	23		X		X	X	X	X
	24		X		X	X	X	X
	25		X	X	X	X	X	
	26		X	X	X		X	
	27		X	X	X	X	X	X
	28		X		X	X		X
	29						X	
	30		X	X	X	X	X	X
	31			X	X	X	X	X
	32					X		