Light Water Reactor Sustainability Program

Benefits of Advanced Control Room Technologies: Phase One Upgrades to the HSSL and Performance Measures

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ABSTRACT

Control room modernization is an important part of life extension for the existing light water reactor fleet. None of the 99 currently operating commercial nuclear power plants in the U.S. has completed a full-scale control room modernization to date. A full-scale modernization might, for example, entail replacement of all analog panels with digital workstations. Such modernizations have been undertaken successfully in upgrades in Europe and Asia, but the U.S. has yet to undertake a control room upgrade of this magnitude. Instead, nuclear power plant main control rooms for the existing commercial reactor fleet remain significantly analog, with only limited digital modernizations. Previous research under the U.S. Department of Energy's Light Water Reactor Sustainability Program has helped establish a systematic process for control room upgrades that support the transition to a hybrid control room. While the guidance developed to date helps streamline the process of modernization and reduce costs and uncertainty associated with introducing digital control technologies into an existing control room, these upgrades do not achieve the full potential of newer technologies that might otherwise enhance plant and operator performance. The aim of the control room benefits research is to identify previously overlooked benefits of modernization, identify candidate technologies that may facilitate such benefits, and demonstrate these technologies through human factors research. This report describes the initial upgrades to the HSSL and outlines the methodology for a pilot test of the HSSL configuration.

ACKNOWLEDGEMENTS

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ACRONYMS

AOP

APS   Alarm Presentation System

BARS

BOP   Board Operators

CPS   Computerized Procedures System

DCS   Distributed Control System

DOE   Department of Energy

EOP   Emergency Operation Procedure

EPRI   Electrical Power Research Institute

FIR   Fixation to Importance Ratio

FOG   Free Open Ghost

FY   Fiscal Year

gPWR   Generic Pressurized Water Reactor

HIS   Human System Interface

HRP   Halden Reactor Project

HSSL   Human Systems Simulation Laboratory

INL   Idaho National Laboratory

JADE   Java Application Development Environment

LWR   Light Water Reactor

LWRS   Light Water Reactor Sustainability

NASA TLX   National Aeronautic and Space Administration Task Load Index

NPP   Nuclear Power Plants

OPAS   Operator Performance Assessment System

R&D   Research & Development

RO	Reactor Operator
SA	Situation Awareness
SABARS	Situation Awareness Behavioral Rating Scale
SACRI	Situation Awareness Control Room Inventory
SAE	selective attention efficiency
SAGAT	Situation Awareness Global Assessment Technique
SART	Situation Awareness Rating Technique
SI	Safety Injection
SME	Subject Matter Experts
SPAM	Situation Present Assessment Method
SRO	Senior Reactor Operator
SWAT	Subjective Workload Assessment Technique
U.S.	United States
WPF	Windows Presentation Foundation

1. **INTRODUCTION**

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

Control room modernization is an important part of life extension for the existing light water reactor (LWR) fleet. None of the 99 currently operating commercial NPPs in the U.S. has completed a full-scale control room modernization to date. A full-scale modernization might, for example, entail replacement of all analog panels with digital workstations. Such modernizations have been undertaken successfully in upgrades in Europe and Asia, but the U.S. has yet to undertake a control room upgrade of this magnitude. Such technology remains the sole province of new reactors such as the four AP1000 plants currently under construction in the U.S. Instead, NPP main control rooms for the existing commercial light water reactor fleet remain significantly analog, with little evidence of digital modernizations. There have, of course, been select upgrades in the U.S. such as behind-the-boards modernization of crucial sensors, wiring, and controls. Additionally, there are a number of like-for-like replacements of obsolete or worn out components on the control boards such as like-for-like annunciator system replacements. There have also been several distributed control system (DCS) replacements for systems such as turbine control, feedwater, or chemical and volume control. These upgraded components and systems have typically addressed an immediate need to replace equipment that is past its usable life. Such upgrades rarely represent an encompassing or systematic vision for control room modernization and instead address primarily matters of equipment obsolescence.

As noted in *EPRI TR-1010042* (Electrical Power Research Institute, 2005), control room upgrades are scarcely an all-or-nothing undertaking. While it may be viable for one plant in a regulated market to complete a full-scale digital upgrade, the cost, expertise, and time required for such an upgrade is significant. The downtime required to replace a sizeable portion of an existing main control room well exceeds the outage cycle of a plant. In a commercial electricity market such as the U.S., it is challenging to justify the lost revenue of taking the plant offline to modernize the control room. Control room modernization, such as the fully digital control rooms found in some chemical and process control facilities, does not significantly decrease the cost of operating the plant, nor does it necessarily increase the safety or reliability of the plant. A commercial NPP's operating license requires a prescribed crew complement, regardless of the underlying technology in the control room. Further, the plant already operates at extremely high safety and reliability margins, and gains through digitization are likely to be minimal. Thus, the modernization of the control room becomes a sunken cost to the private utility, and there is little perceived benefit to the effort and cost required to replace the control room.

A survey of 11 U.S. utilities conducted by the Idaho National Laboratory (INL; Joe et al., 2012) revealed that there is a general desire among utilities to replace the existing control room with a fully digital modernized control room[1]. However, the reality is that most utilities will only achieve modernization in a stepwise fashion—gradually digitizing one system at a time and creating a hybrid analog-digital control room. Further the end-state modernization is likely to be a hybrid control room that leverages as much advanced technology as possible, but not a fully modernized control room. Of the utilities surveyed, 50%

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[1] It is important to note that the participants who were surveyed were mainly operations staff rather than management and leadership, so the opinions expressed in this survey may not reflect the plant's official position.

identified cost as a significant upgrade barrier to a fully digital control room, while 20% identified the regulatory process as a barrier. The U.S. commercial nuclear fleet presents a unique situation for upgrades: while there is desire to upgrade, practical constraints such as cost (primarily through lost revenue) and regulations prove formidable hurdles to the upgrade process.

Previous research under LWRS has helped establish a systematic process for control room upgrades that supports the transition to a hybrid control room (e.g., Boring et al., 2014; Boring and Joe, 2014; Hugo et al., 2013; Ulrich et al., 2014). There are limits to the processes outlined in these guidelines. While the guidance developed to date helps streamline the process of modernization and reduce costs and uncertainty associated with introducing digital control technologies into an existing control room, these upgrades do not achieve the full potential of newer technologies that might otherwise enhance plant and operator performance. The aim of the control room benefits research presented here is to identify previously overlooked benefits of modernization, identify candidate technologies that may facilitate such benefits, and demonstrate the benefits of these technologies through human factors research. This report describes the first phase of research in this project including the first phase upgrades to the HSSL and the design of the pilot study to evaluate those technologies.

2.   Upgraded HSSL configuration

The Human Systems Simulation Laboratory (HSSL) houses a full scale, full scope, and reconfigurable virtual nuclear power plant (NPP) control room simulator.

2.1 Generic Pressurized Water Reactor Simulator

The Generic Pressurized Water Reactor simulator (gPWR) is a generic nuclear simulator developed by GSE Systems, Inc. The gPWR is a full-scope model based on an existing 3-loop Westinghouse NPP currently operating in the U.S., and can simulate a wide range of scenarios (i.e., normal, abnormal, and emergency operations). Given these capabilities, the gPWR can be used for training operators, developing and testing procedures, and as a research platform to study various human factors R&D topics (http://www.gses.com/products/gpwr-nuclear, retrieved 13 May 2015).

2.2 Layout/configuration of HSSL

The HSSL houses a full scale, full scope, and reconfigurable virtual NPP control room simulator. The simulator consists of fifteen bays that each have 3 forty-seven inch LCD screens (measured diagonally). The bottom two LCDs have touch-screen capabilities via infrared overlays. A Dell OptiPlex desktop computer running Microsoft Windows 7 Professional is housed inside each of the bays, and acts as the client to the simulator software code running on a secure server. The server room houses backend servers that allow for rapid image deployment via Free Open Ghost (FOG), Windows Server 2008 R2 for different plant models and configurations, and Microsoft Hyper-V utilization to satisfy virtualization needs. The bays are perched atop lockable wheels for mobility, maintainability and convenience. Because of these features, the control room can be reconfigured into almost any NPP control room layout.

Other resources used in the HSSL include virtual machines, an air-gapped network infrastructure, FOSCAM wireless IP cameras for video capture, and Peavey wireless lavaliere microphones for audio capture. Blue Iris software is used to record and synchronize the audio and video feeds.

The control room is capable of running different NPP simulations, though it is most commonly running GSE's gPWR. As shown in Figure 1, the layout of the reconfigurable bays is currently in an L-shaped configuration, and it will be assumed to remain so when additional displays are installed to support the Westinghouse technologies.

Figure 1. The Human System Simulations Laboratory

There is also an observation room in the HSSL, in which resides a Dell OptiPlex computer that serves as the Instructor Station for the simulator. From there, all simulator activities are controlled, including: powering on the bays, starting the simulator, loading initial conditions, inserting a malfunction scenario, and powering down the bays. The core of the system is run by GSE Systems Java Application Development Environment (JADE) simulator platform. Additional details on the installation and start up of the HSSL simulator can be found in Boring et al. (2012) and Boring et al. (2013).

2.3 New Control Room Technologies

As previously mentioned, the goal of the LWRS Benefits project is to demonstrate how improved plant operations and avoided problems would be economically beneficial to NPP owners, and how these improvements are enabled by new control room technologies that are made effective by good human performance engineering and R&D. To facilitate this R&D project, INL will acquire and install new technologies in the HSSL. The new technologies/systems are the Westinghouse Computerized Procedures System (CPS), the Westinghouse Alarm Presentation System (APS), and Task Based Displays developed by the Halden Reactor Project (HRP). These three technologies are summarized below.

2.3.1 Computerized Procedures System (CPS)

Recognizing an opportunity to enhance the safety and efficiency of NPP operations, Westinghouse developed CPS to display to the senior reactor operator (SRO) the procedure steps and other relevant information interactively on a computer screen. The underlying conjecture is that the dynamic interaction between the SRO, CPS, and the NPP's response to control actions will enable the entire crew of operators to operate the NPP even more effectively than they already do (Lipner & Kersch, 1994). This enhancement in the performance of operators would be realized through more accurate and timely presentation of more detailed and integrated plant status information in a centralized location, thereby improving the operators' situation awareness and reducing cognitive workload. For example, because the CPS continually monitors the NPP for crucial data, it can help guide operators through appropriate action responses from normal to emergency plant operations. Thus, the CPS should enable the SRO to work efficiently and more accurately by analyzing real-time plant data and diagnosing the proper course of action.

As documented in Lipner, Mundy, and Franusich (2007), the CPS display has three primary windows: 1) an overview flowchart of the procedure steps, 2) a text summary of the procedure step, and 3) the underlying logic for the procedure step. These three main windows are labeled as 60, 62, and 64 in Figure 2 below.
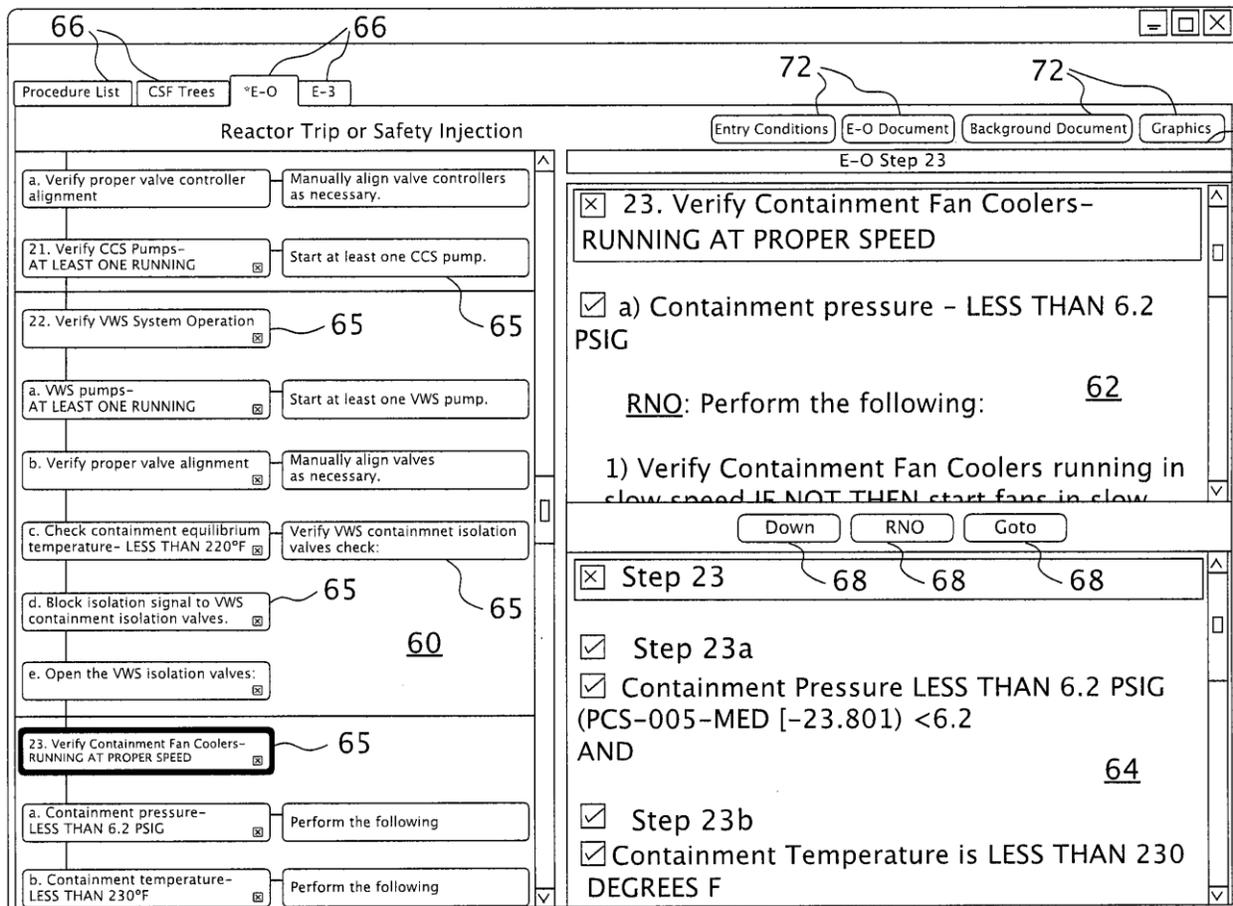
Figure 2. Drawing of the Westinghouse CPS (from Lipner, Mundy, & Franusich, 2007)

Always visible buttons (72 in Figure X) display information on the procedure's entry conditions, a digital copy of the procedure, and additional background documents and graphics that provide relevant contextual information to the SRO. Additional context sensitive buttons (68 in Figure X), allow the SRO to navigate through the steps of the procedure. Tabs in the upper left corner of the screen (66 in Figure X), link to other procedures, a master list of procedures (i.e., Procedure List), and CSF Trees that present continuously updated information on six different safety critical functions or parameters.

The CPS will interact with the HSSL simulator and read the same data points as it normally would in a plant. This can be done using a variety of different computer languages. In the past, communication and interaction with the simulator and new third party software was done via Windows Presentation Foundation (WPF) using DLL interface libraries for .NET (Lew, et al., 2014). Depending on what language the CPS is written in and what platform it uses, the same approach and underlying logic will be used to accomplish this task.

In terms of physical location in the HSSL, the CPS will be displayed on one or two 24-30" monitors at the SRO station. Figure B shows a conceptual layout of the HSSL with the additional technologies. The SRO station/desk can comfortably support multiple displays without obstructing the SRO's view of the control room or operators. This configuration will adequately meet the needs of the SRO, allowing him or her to visually view the legacy control boards without obstruction. The CPS displays are labeled as 8 and 9 in Figure 3.

Figure 3. Mock-up Showing Potential Location of CPS Displays (8 & 9) on the SRO Workstation

2.3.2 Westinghouse Alarm Presentation System (APS)

Westinghouse's advanced alarm management and presentation systems, originally called AWARE (Carrera & Easter, 1991), and now called APS, were developed both for use in advanced control rooms, and as a back fit solution to overcome some of the challenges with alarms systems currently installed in U.S. NPPs (while still retaining the best features of those legacy systems). The ability to reconfigure and customize the APS system allows it to meet existing NPP needs and the needs of the operator.

Specifically, given the advantages and disadvantages of the legacy alarms systems, the Westinghouse advanced alarms systems are a hybrid of overview alarms, using the same kind of tile-based structure in existing NPPs (see Figure 4) and audio alerts, while also providing detailed information provided on additional displays, which are located on the SRO's desktop or workstation (see Figure X). In the AWARE system, these two components were referred to as the Overview Panel and the Support Panel, respectively (Carrera, Easter, & Roth, 1997). APS refers to these as the wall panel client and workstation client, respectively. The wall panel client is designed to provide all the operators an overview of the information using a combination of the standard alarm tile layout that facilitates pattern recognition, and additional supporting information such as running counts of the number of new, acknowledged, cleared, and suppressed alarms.

APS Primary Panel

PXS	RCS	CVS	CNS	WLS	PMS	DAS	CCS		PSS	VLS	VAS	VES	VZS	VDS	VWS
PCS	IIS	RNS	VUS	WGS	PLS	RMS	SWS		SSS	VCS	VRS	VBS	VNS	VVS	VYS
	SMS	SFS	FHS	WRS	DDS	SJS				VFS	VHS	VXS	VIS	VPS	
	RXS		MHS	WSS	MES	OCS						VTS	VGS	VQS	

SAFEGUARDS ACTUATION	ADS STAGE 4	CONTAINMENT ISOLATION	MAIN FW ISOLATION	NEUTRON FLUX	RCS HOT LEG FLOW	MAKEUP	CNMT PRESSURE
REACTOR TRIP	ADS STAGE 1-3	CVS MAKEUP ISOLATION	STARTUP FW ISOLATION	OTDT MARGIN	PRESSURIZER	LETDOWN	CNMT FLOODUP
RCP TRIP	IRWST INJECTION	CVS LETDOWN ISOLATION	STM LINE ISOLATION	OPDT MARGIN	RCP	BORIC ACID TANK	PCS RECIRC LOOP FLOW
TURBINE TRIP	IRWST RECIRCULATION	AUX SPRAY ISOLATION	SG RELIEF ISOLATION	CORE EXIT TEMPERATURE	STEAM GEN 1	COMPONENT COOLING	PCCWST PCCAWST
DIVISION TRIP	RX VESSEL HEAD VENT	RNS CNMT ISOLATION	SG BLOWDN ISOLATION	ROD INSERTION LIMIT	STEAM GEN 2	RCS PRESSURE	CMT
FUNCTION TRIP	PASSIVE CNMT COOLING	CNMT AIR FILTER ISOL	STEAM DUMP BLOCK		MAIN STEAM	NORMAL RHR	IRWST
LCO	CORE MAKEUP TANK INJECTION	REFUELING CAV ISOLATION	BORON DILUTION BLOCK		PRIMARY SAMPLING	RCS HOT LEG LEVEL	ACCUMULATORS
	PRHR HX ALIGNMENT	MCR ISOLATION	PZR HEATER BLOCK		COOLING TOWER	SPENT FUEL POOL	OPER DEFINED PRIMARY

New:0 Acknowledged:0 Cleared:0 Equipment:0 Suppressed:0   BY SH NU CA QU   UA MA   Healthy

Figure 4. Westinghouse APS wall panel client (retrieved from http://www.westinghousenuclear.com/Portals/0/operating%20plant%20services/automation/human-system%20interface/NA-0057%20Alarm%20Presentation%20System.pdf, 13 May 2015)

The workstation client not only has telemetry with the wall panel, but it also presents the alarms in list format so that more detailed information and the timing of the annunciation can be shown. Additionally, while it is possible for the alarm system to support multiple wall panels, it may not be desired (or even possible given the amount of available physical space) to have a 1:1 replacement of the legacy alarm tiles. In fact, since the alarm tiles are virtually represented on the wall panel, they do not require their own dedicated space like legacy alarm tiles. The SRO can control which set of alarms are displayed on the wall panel from the workstation client. Given this, an NPP's operations organization may choose, for example, only 2-4 wall panel displays, and only show the alarm tiles that they deem to be most important for a given mode of operation (e.g., normal operations, low power/shutdown, startup, refueling). To display secondary alarms on the wall panel displays, the SRO would simply select on the workstation client the alarm bank(s) he or she wishes to project on the wall panels.
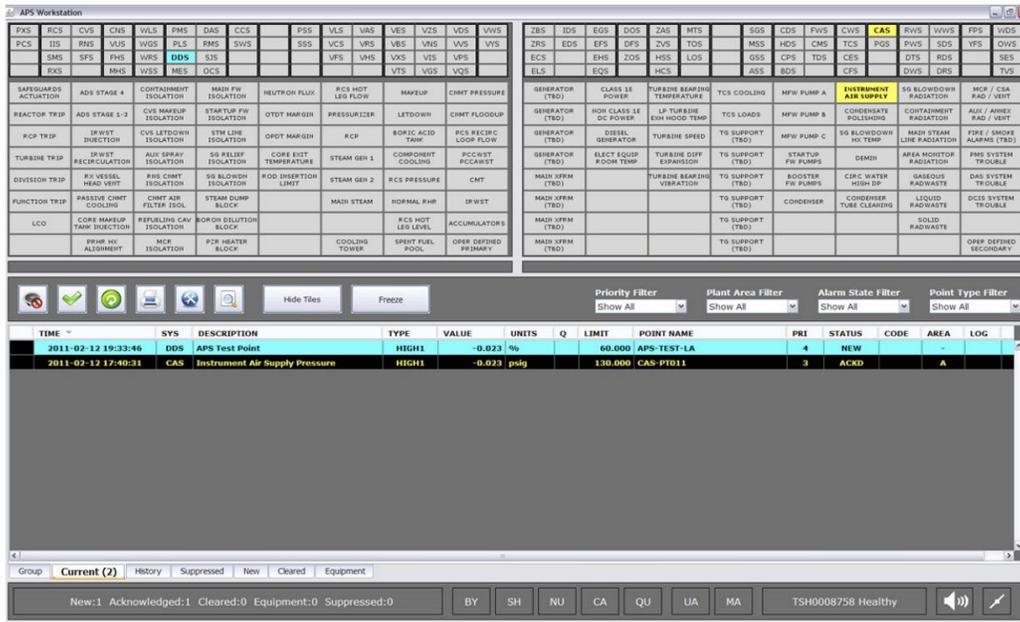
Figure 5. Westinghouse APS workstation client (retrieved from
http://www.westinghousenuclear.com/Portals/0/operating%20plant%20services/automation/human-
system%20interface/NA-0057%20Alarm%20Presentation%20System.pdf, 13 May 2015)

Additional customizable functionality has been implemented in APS. For example, various plant
customizable alarm prioritization algorithms have been programmed into the system, thereby allowing the
NPP's operations organization determine how alarms can be potentially presented (e.g., customizable
colors and shapes) and/or filtered (i.e., suppression schemes for managing nuisance and consequence
alarms) depending on their relevance or importance.

Thus, from the outset (Carrera & Easter, 1991, pg. 1389), the Westinghouse advanced alarm systems have
been designed to facilitate the operator's ability to monitor and make decisions by:
1. Alerting the operator to off-normal conditions, which is the primary function of an alarm system.
2. Aiding the user in understanding that condition, by using both pattern recognition in the alarm tile
   presentation, and by providing more detailed information to the SRO on the workstation client.
3. Aiding the user in focusing on the most important issue through customizable alarm presentation,
   prioritization, filtering, and suppression.
4. Providing corrective action guidance to the operator. This can occur in multiple ways, such as:
   a. When an annunciator alerts the operator of the NPP's current operational state, it
      provides general guidance on what corrective actions may need to be taken.
   b. When an advanced alarm system is programmed to alert operators when automatic safety
      systems to do not actuate, "as expected following a reactor trip." (Roth & O'Hara, 2002,
      pg. 28).
   c. When the alarm system is programmed to alert the operators of unexpected alarms after a
      reactor trip or after transients.

Other benefits of the workstation client are that it provides pop-up navigation menus, tabbed interfaces,
custom alarm layouts, and alarm history. The APS software is Operating System-independent because it
is written in Java. Additionally, because the APS workstation client can be displayed on commercially
available LCD screens, the overhead costs are minimal, and replacements can be acquired easily.

Similar to the CPS, the APS will interact with the HSSL simulator and read the same data points as it normally would in a plant using a variety of different computer languages. INL will leverage past experience connecting third party software to the gPWR to connect the APS to the gPWR (e.g., Lew et al., 2014).

As shown conceptually in Figure 6, the APS workstation client will be displayed on one or two 24-30" monitors at the SRO workstation (labeled as 6 and 7) in the HSSL alongside the other benefits technologies to be installed. To accommodate the wall panel displays, equipment can be moved or reconfigured in the HSSL as needed. However, despite the advantages of reconfigurable bays, limitations begin to present themselves in terms of physical space. The height of the bays in their current configuration is approximately 91.25", which leaves roughly 30" of space between the bays and the ceiling. The current 47" displays used in the bays are approximately 26" in height, which leaves roughly 4" of room from the ceiling, if the same sized displays are used for the APS screens and they are mounted above the bays. Thus, as seen in Figure 6, the preliminary estimates indicate that the wall panel client can be shown on large displays above one or two of the bays (labeled as 2 and 3) so that it will be easily visible to the SRO and ROs.

Figure 6. Mock-up Showing Proposed Location of APS Workstation Client (6 & 7) on the SRO Desk and APS Wall Panel Clients (2 & 3) in the HSSL.

In lieu of mounting the APS wall clients to the top of the bays, other options that have been investigated include independent, height adjustable display mounts, or ceiling or wall mounts. Advantages of the

independent mounts include mobility, configurability, and inexpensive overall cost, while cons remain somewhat insignificant. Although ceiling or wall-mounted displays are aesthetically ideal, the cost of such an effort is significantly higher than the previously described mobile mounting options.

If the space above the bays proves to be too constrained for the wall client displays, the possibility of deploying more displays as needed has been discussed as well. Alternate locations may be possible since the APS displays are relaying similar information as the legacy annunciators, and there are several options in the HSSL for locating the wall client, including on the back panels of the control room (see Figure 7). Generally speaking, APS screens placed in low traffic areas provides flexibility in display sizes and display options. For example, a projector is being considered as an option for the APS wall panel displays, which would be mobile and placed practically anywhere in the HSSL.

Figure 7. Proposed Alternate Location for the APS (AWARE) Wall Panel Clients in the HSSL

2.3.3 Task-Based Overview Displays

Human factors researchers with operations experience at the Halden Reactor Project , in partnership with INL, developed a number of task-based overview displays. These operator support displays were developed based on HRP's extensive experience in Human System Interface (HSI) design, and their long R&D history developing large overview displays for advanced NPP control rooms. Like large overview displays, these task-based overview displays were designed to display to the reactor operators and board operators (RO and BOP) and SRO the most critical indicators of the plant's state given its mode of operation (e.g., normal, abnormal, and emergency operations). However, these displays were also

designed to have a smaller physical footprint than a large overview display, such that they would be more suitable for installation and use in U.S. commercial NPP control rooms. In fact, Jokstad et al., (2014) states, "All displays are designed to fit a single screen on the HSSL panels, with a resolution of 1920x1080 pixels." (pg. 18).

In total, the HRP developed four screens for the task-based overview display system:
1. An operator support display for the RO during normal mode operation.
2. An operator support display for the RO once safety injection (SI) has been actuated.
3. A normal mode operation display for the BOP.
4. An emergency operation procedure (EOP) mode display for the BOP.

These screens are shown below in Figure 8 - Figure 11. A description of what each object on the screen is can be found in Jokstad et al., (2014).
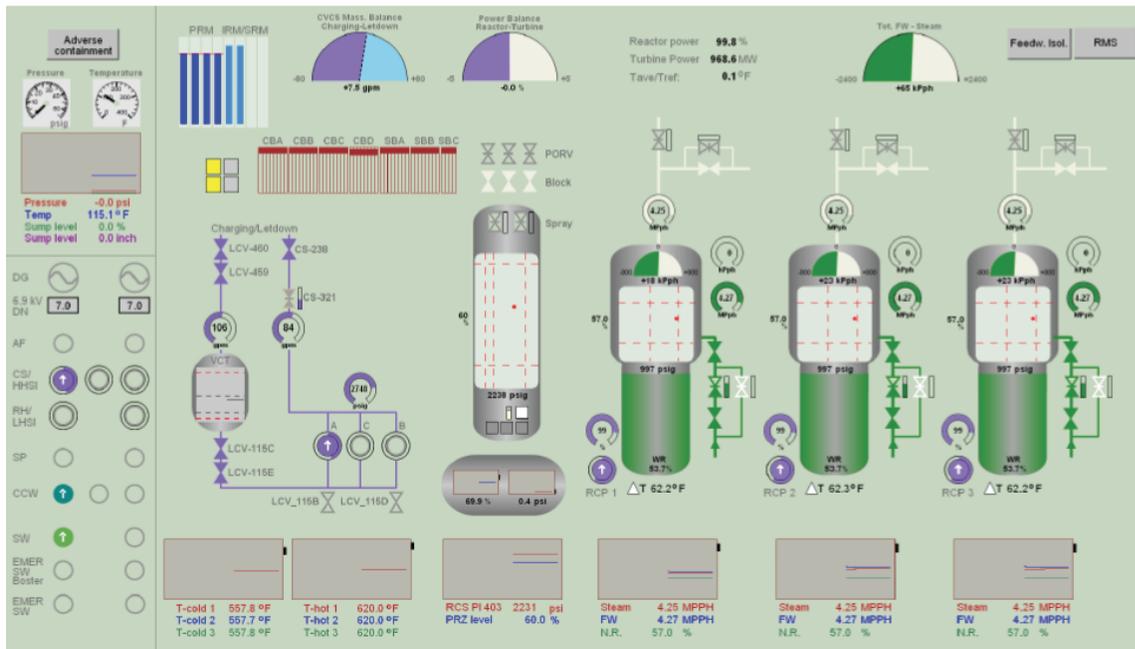
Figure 8. RO Normal Operations Operator Support Display
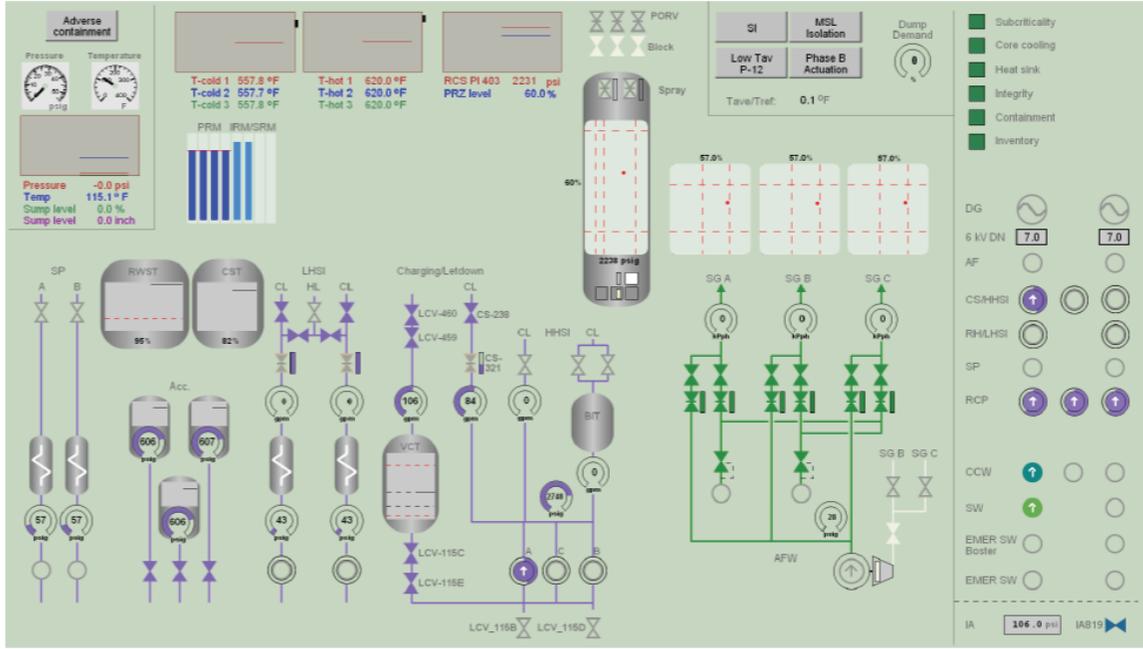
Figure 9. RO Post SI Operator Support Display
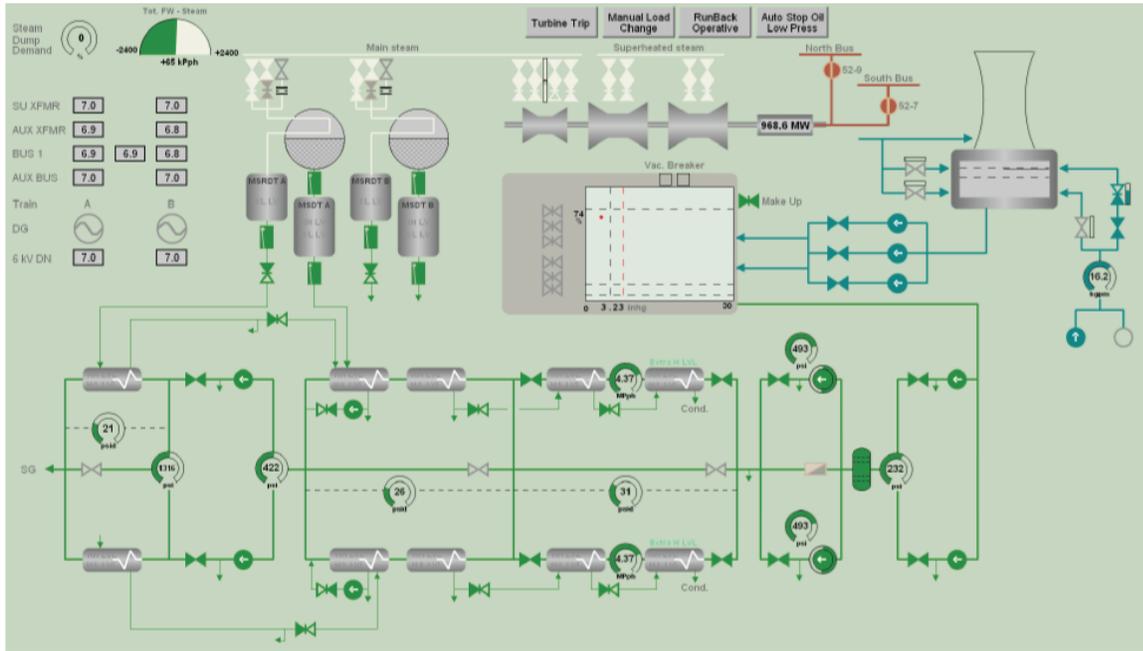
Figure 10. BOP Normal Operations Operator Support Display
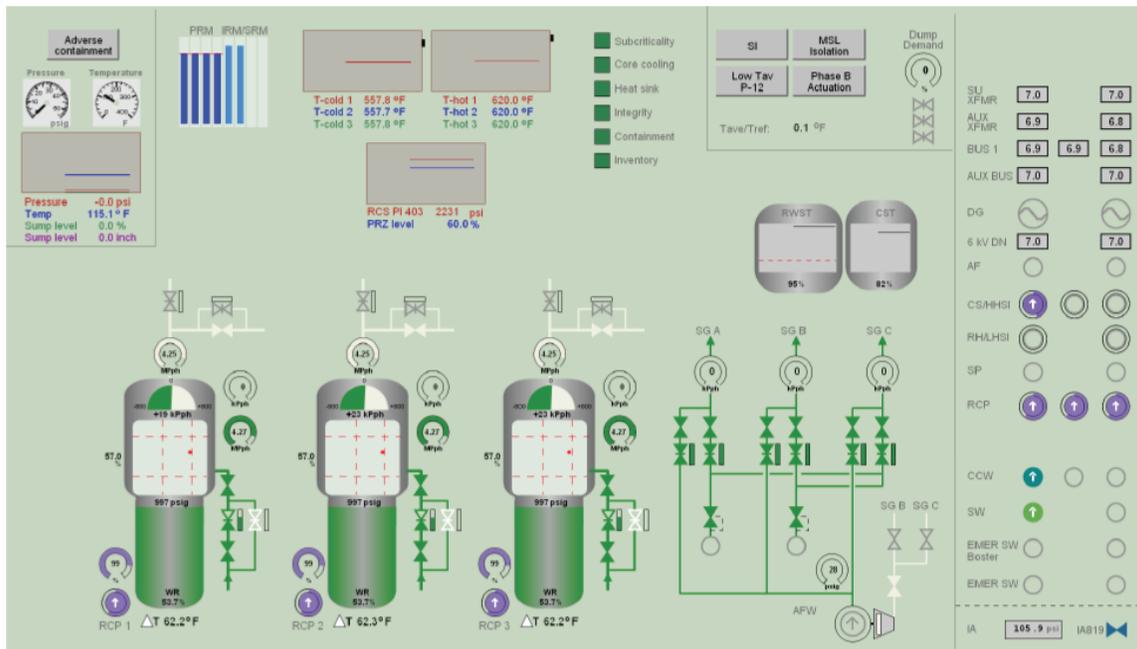
Figure 11. BOP EOP Operator Support Display

Like the Westinghouse APS, these task-based overview screens only display indicators. No control actions can be taken from these displays. In fact, the RO and BOP are not even able to control which of the two displays they are presented. The SRO has a display and input device on the SRO desk that provides telemetry with the board mounted displays, and allows her or him to change which screens are displayed to the RO and BOP.

In November 2014, HRP staff visited INL to help install the overview displays in the HSSL. Testing the displays at this time with the gPWR simulator running confirmed that they interact as expected with the HSSL simulator. Details on how this was accomplished and what computer languages were used can be found in Jokstad et al. (2014).

With respect to physical location in the HSSL, INL is exploring the feasibility of mounting the task-based overview displays above the existing simulator bays as well. The proposed location of the displays (labeled as 1 and 4) can be seen in Figure 12. This option is similar to the one INL is exploring for the Westinghouse APS wall client displays, provided that sufficient space over the bays is available to install the task-based overview and APS displays. If it is not possible to locate the task-based overview displays over the bays, alternate locations in the HSSL will be evaluated. The display and input device the SRO uses to control the RO's and BOP's task-based displays will be located on the SRO desk, which is labeled as 5 in Figure 12.

Figure 12. Mock-up Showing Proposed Location of HRP Task-Based Overview Displays (1, 4, & 5) in the HSSL

3.   General Approach to Research

This section describes the general approach to the series of evaluation studies that will be conducted to demonstrate benefits of control room technologies. This work is intended to be conducted across three years and the results of previous phases of the research will provide input to the next phases.

3.1 Industry Partner

The research team will work closely with a utility partner to conduct this research. The team will identify a host NPP and/or utility to collaborate. The partner will then host baseline studies in their training simulator (if possible) and provide operating crew to participate in evaluation studies in the HSSL. They will also provide access to process experts to advise on scenario design and the simulation model to use in the HSSL.

3.2 Scenario Development

Scenarios will be developed specifically to test the benefits of the candidate technologies selected. The scenarios used will be tailored specifically to the technologies used, and the proposed benefits of those technologies. In general, the researchers anticipate developing scenarios to evaluate:

- Normal, routine activities

- Unanticipated activities

- Anticipated transients

- Anticipated design basis accidents

- Beyond design basis accidents (contingent on expected upgrades to HSSL)

3.3 Phase One

The first phase of the research will be a pilot test of the evaluation methodology that will be conducted in the HSSL. Several of the near-term candidate technologies will be installed in the HSSL and integrated into an existing simulation model. The researchers will then evaluate performance with and without the candidate technologies. Participants for the first phase of research will be licensed operators (if available) or an ad hoc sample of retired operators and/or nuclear engineering students. The purpose of the pilot test is to test and refine the experimental methodology in preparation for the next phase of the research. This phase will occur in Fiscal Year (FY) 2015.

3.4 Phase Two

The second phase of the research will be a baseline measure of performance carrying out the scenarios that are developed to test the technologies. This baseline will be conducted in the host plant's training simulator using the host plant's operating crews. The researchers will measure several operating crews' performance, SA, workload, and team performance for each of the scenarios. This phase will be conducted in FY 2016.

3.5 **Phase Three**

The third phase of the research will evaluate the candidate technologies in the HSSL. The host plant's simulation model will be installed in the HSSL, and the candidate technologies will be integrated into the simulations. The researchers will invite operating crews from the host utilities to conduct the scenarios in the HSSL with and without the candidate technologies. If resources allow, the researchers will compare performance, SA, workload, and the other metrics described in Section 4.4 using the technologies in the HSSL to an established baseline performance without the technologies in the HSSL and performance in the host plant's training simulator. This phase will be iterative; each successive study will build on the results of the previous studies. The near-term technologies will be tested first and, as they become available, the farther term technologies will be integrated and tested. This phase will commence in FY 2016 (as resources and availability of industry partners allow) and continue as new technologies are made available for study purposes.

4. PHASE ONE RESEARCH PLAN

Section 3 provided a general overview of the approach to conducting this research; this section provides a detailed description of the research activities planned in phase one of this research. The purpose of the phase one study is to test the initial configuration of the upgraded HSSL. That is, to ensure it is fully operational and to obtain preliminary data for the performance benefits of using the technologies compared to the existing analog control rooms. Another objective is to refine the study design and the performance measures to ensure sensitivity, diagnosticity, and validity of the performance measures used for future phases of the research.

Le Blanc et al. (2014) described several important features of conducting research for NPP control room modernization including:

- Goals of the study. As stated above, the goals of the study are to test the initial configuration, refine the performance measures and provide preliminary evaluation of the phase one technologies. This study is a pilot test of the configuration of the HSSL and the performance measure capabilities.

- System technology. The technologies being evaluated in this study are described in section 2. Section 4.1 maps the technologies to the proposed benefits and the performance measure that will be required to assess those proposed benefits.

- Design stage. Some of the technologies (i.e., the Westinghouse systems) to be evaluated in this study are mature; however, their use in the context of a hybrid control room has not been tested. Because this research is intended to assess advanced technologies in new contexts, it is considered to be early in the design stage.

- System fidelity. The HSSL (described in section 2) is a full-scale, full-scope simulator, which means it has high system fidelity. However, the first phase research will be conducted with operators from an operating NPP, and the plant model used will be a generic plant (due to the fact that the upgrades are made to the gPWR plant model). This will limit the system fidelity of the particular plant used, but will be addressed by extensive training of the participants before conducting any experimental scenarios.

- Environmental fidelity. This study will be conducted in a full scale, full scope simulator. Therefore the environmental fidelity will be relatively high. However, there are several important differences between the HSSL environment and the host plant's control and training simulator. One example of that difference is the fact that the controls are presented on a glasstop simulator instead of actual hard controls. This may affect the operator's performance. The effect of the performance measure apparatus (e.g., the mobile eye tracking device) will also influence the environmental fidelity.

- Location of the study. As discussed above, the majority of the studies in this research project will be conducted at the HSSL rather than the plant's control room or training simulator, limiting the environmental fidelity of the study.

- Nature of the users. As stated above the users will be highly trained NPP operators, but they will be operating an unfamiliar plant. The users in this study are described in more detail in section 4.2.

- Types of measures. The types of measure need to be tailored to the goals of the study. Section 4.4 describes the approach to designing measures and the specific measures that will be used in this study.

- Types of Scenarios. The scenarios used in this study are tailored to make the best use of the technologies installed in the HSSL and the proposed benefits of those technologies. Another important feature of scenario design in this study is the operator's experience on scenario. The approach to scenario design is discussed in section 4.3.

4.1 **Technologies**

As described in section 2, the research team identified three near-term technologies to install in the HSSL: Task-Based overview displays, Computer-Based Procedures and Advanced Alarms. LeBlanc et al., (2014) reviewed the proposed benefits of the candidate technologies that will be used in all phases of this research. The proposed benefits of the three technologies that have been implemented in the HSSL are summarized in Table 1.

Table 1. Proposed Benefits of Technologies in the upgraded HSSL.

Overview Displays	- Reduced workload (physical and cognitive) - Enhanced SA - Enhanced detection of off-normal conditions - Enhanced crew coordination
Advanced Alarm Systems	- Reduced workload - Enhanced diagnosis - Increased efficiency
Computer Based Procedures	- Enhanced performance - Reduced errors - Enhanced efficiency

4.2 **Utility Partner**

The research team has identified one utility partner to participate in this research. The utility operates one three unit site. Managers at the utility have indicated that they have interest in going beyond like-for-like replacement of obsolete equipment and have an end-state vision of a fully modernized control room utilizing advanced technology. The utility will provide process experts, trainers, and operating crews to help execute this research. The utility partner will provide the following resources.

- Support from training organization to help develop scenarios
- Support from training organization to help develop training on the new technologies (proficiency for study purposes only, not equivalent to licensing)
- Support from the operations organization to provide operators for simulator studies both at the participating utility training simulator and at the HSSL at INL
- Access to the training simulator and operators for a baseline study
- Access to process experts to help develop performance measures and scenarios

- Plant simulator model for use in HSSL

For the phase one study, the utility will send two operating crews to INL to participate in the study in the HSSL.

4.3 **Scenario Design**

Scenarios will be designed based on the capabilities of the technologies utilized and the proposed benefits of those technologies. The team has selected the set of procedures to be computerized in the Westinghouse CBP system based on a two emergency scenarios. The scenarios selected are a steam generator tube rupture and a feedwater or main steam line break. These scenarios are ideal for testing the Westinghouse EOPs, and the Westinghouse advanced alarms. A Steam generator tube rupture scenario is also ideal for testing the transition between the Halden normal operations overview displays to the safety injection overview displays. The researchers will inject additional malfunctions and complications into the basic scenarios in order to address the fact that licensed operating crews routinely practice emergency scenarios such as the steam generator tube rupture scenario. The researchers will work with process experts and trainers from the host plant to identify realistic and challenging additions to basic scenarios.

4.4 **Performance Measures**

The benefits of the technologies will be demonstrated primarily by comparing metrics of performance conducting the scenarios with and without the candidate technologies. Based on the list of proposed benefits of the technologies installed in the HSSL, the main measures of performance are Plant performance, Operator Performance, Operator Situation Awareness, and Operator Workload Because a secondary objective of the phase one study is to refine the experimental methods and performance measures, the research team will use a larger suite of performance measures than will be used for future phases of the research. Because the scenarios used in the first phase of the research will be emergency scenarios, the performance measures will be tailored to assess the benefits of the technologies under emergency conditions.

4.4.1 Plant Performance

The main goal of all nuclear power plant personnel (operators, managers, maintenance crews, etc.) is to safely and efficiently generate electricity. The most direct way to measure how an operator's performance will impact the objective of the plant is to measure plant performance. Plant performance comprises the effect an operator has on the system and the system's direct effect on performance. The main plant performance metric in this study will be discrepancy score. Ha and Seong (2009) describe a method to measure the discrepancy between the prescribed values of important plant parameters. The important parameters and the acceptable ranges of those parameters will be identified for the two scenarios selected by process experts. Once the parameters and ranges have been defined, the following formula will be used to calculate a discrepancy score.

- Discrepancy at time t, $D_i(t) = \begin{cases} \frac{X_i(t) - S_{Ui}}{S_{Ui} - S_{Li}}, if\ X_i(t) > S_{Ui} \\ 0,\ if\ S_{Li} \leq X_i(t) \leq S_{Ui} \\ \frac{S_{Li} - X_i(t)}{S_{Ui} - S_{Li}}, if\ X_i(t) < S_{Li} \end{cases}$

  - S_{Li} = lower bound of parameter i

  - S_{Ui} = upper bound of parameter i

  - $X_i(t)$ = value of parameter i at time t

- Average discrepancy for parameter i $= \sum_{t=0}^{T} \frac{D_i(t)}{T}$

4.4.2 Human Performance

Human performance and plant performance are related, but human performance does not always have an observable effect on plant performance in all circumstances. Sometime plant performance is acceptable even when aspects of human performance (e.g., SA and workload) are below acceptable levels, and vice versa. For this reason, in order to fully understand the impact of advanced technology on performance, both plant performance and human performance must be carefully considered.

Human performance comprises behavioral and cognitive elements. Behavioral aspects of human performance can be characterized as the observable actions the human takes on the system along with any observable communication between other crew members (for example, a verbal indication that a certain diagnosis has been made, or that a particular procedure will be entered). The behavioral component of human performance will be primarily evaluated objectively using the Operator Performance Assessment System (OPAS; Skranning, 2004). Other aspects of human performance (such as SA and Workload) are not directly observable, and a combination of objective and subjective measures will be used to assess them.

4.4.2.1   Operator Performance

The main metric for identifying human performance, OPAS, is a computer-assisted, hierarchically structured, real-time measurement system that assesses system and operator performance against predefined standards of performance and predetermined goals that are established when the simulator scenario is being formulated by subject matter experts in advance of the experiment. The subject matter experts decide or determine what the main goal is for a given scenario, and then further identify sub-goals that must be accomplished in order to achieve the main goal. Sub-goals are further divided into actions that the operator must perform to achieve the sub-goal. The operator actions and sub-goals are differentially weighted on a 5-point scale to reflect their importance in achieving the associated sub-goal (for operator actions) or main goal (for sub-goals).

4.4.2.2   Situation Awareness

Situation awareness is an important concept both in nuclear process control and Human Factors research (Burns et al., 2008). The field of aviation coined the term situation awareness (SA) during the First World War (Patrick et al., 2006. Research on SA in nuclear process control, has revolved around effective interface design to support operators in rapidly achieving and maintaining SA while monitoring and operating the plant.

There are multiple competing models with different conceptualizations of the SA construct. Of the competing models, Endsley's model is the most widely accepted within the human factors field and a number of practitioners have adopted her three-level SA model (1995a). Endsley's three-level model defines SA as the "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (1995a). Level one consists of identifying the elements in the environment, level two consists of integrating the elements into a comprehensive representation in relation to task goals, and level three consists of projecting the future states of the integrated elements within the environment. The model is hierarchically organized such that each level requires the successful completion of the level below it. This hierarchical Self-rating is one basic technique used for evaluating SA. The self-rating technique consists of individuals rating themselves on multiple dimensions of their subjective SA post simulation. The situation awareness

rating technique (SART) uses ten dimensions to rate SA (Taylor, 1990). The ten dimensions of SA in the SART are instability of the situation, complexity of the situation, variability of the situation, arousal, concentration of attention, division of attention, spare mental capacity, information quantity, and familiarity with the situation. Individuals rate themselves on a seven-point scale for each dimension of SA. The ease of administration and lack of intrusion on the primary task are the two main advantages of the self-rating technique. However, the self-rating technique collects participant data after the trial has ended, which potentially causes a number of issues. Self-ratings may be distorted due to an individual's biased perception of their performance during the simulation (Endsley, 1995b). Furthermore, individuals must remember their mental state when rating themselves on the various dimensions, which confounds self-ratings with working memory and recall abilities. When rating the different dimensions of SA, individuals must condense dynamic moments of SA throughout the simulation into a single average value for each SA dimension. Additionally, the subjective self-report ratings may not necessarily correlate with performance during the simulation. Participants can potentially rate themselves highly on the SA dimensions; however their performance may have in fact been poor.

Observer ratings are another subjective measure widely used to evaluate SA. The observer rating technique consists of subject matter experts (SMEs) observing and rating participants' SA during the simulation (Salmon et al., 2009). The SME rates the participants' SA on predefined observable behaviors. Observer ratings are advantageous since they require minimal intrusion on the primary simulation task and can be conducted in industry with professionals completing real life tasks as opposed to completing simulations. An example of an observer rating technique is the Situation Awareness Behavioral Rating Scale (SABARS) used by Matthews and Beal (2002) to measure SA of infantry soldiers in field training exercises. Bias in the observation and recording are potential disadvantages of the observer rating technique. Replication of experiments is virtually impossible without the original subject matter expert, which makes comparisons between studies and disciplines difficult.

The freeze probe technique is the most widely used objective SA measurement. The freeze probe technique consists of administering SA related queries while the simulation is suspended or frozen (Endsley, 1995b). The queries to evaluating SA are created by first conducting a detailed cognitive task analysis to ensure that the SA related queries meaningfully relate to SA deemed necessary for the successful completion of a given task (Endsley, Selcom, Hardiman, & Croft, 1998). In complex tasks, subject matter experts are consulted both during the task analysis and to evaluate the relevance of the generated SA related queries. The individuals responses reported during the freeze probe are compared to the actual state of the system at that particular point in time, as defined by the experimenter, to yield an overall SA score for a task. SA query responses may contain information about the value of a component with relatively static properties, such as an alarm that is either in the on or off state. Additionally, the responses may contain information about the rate and direction of change for a component with more dynamic properties, such as a speedometer in a car. Scores from multiple tasks can be used to quantify the amount of SA at various time points during the simulation. The primary benefit of the freeze probe technique is the immediate objective SA assessment periodically throughout the simulation as opposed to measurements of SA at the end of the trial. SAGAT is an example of a well-known freeze probe technique designed with queries that specifically evaluate SA at each of the three levels of Endsley's SA model. (Endsley, 1995b). Queries from the SAGAT developed for use in aviation consist of questions concerning a pilot's knowledge of the aircraft's airspeed, altitude, attitude, and location (Endsley, Selcom, Hardiman, & Croft, 1998). The SAGAT developed for use within the military aviation domain contains the same queries found within the general aviation domain in addition to combat queries such as the location, altitude, airspeed and potential threat level of other aircraft (Endsley, Selcom, Hardiman, & Croft, 1998). There is more evidence correlating performance with the SAGAT freeze probe technique than any other SA measurement (Salmon et al., 2009). Despite the strong correspondence between assessed levels of SA and performance, the validity of the freeze probe technique is questionable. Skeptics have criticized the SAGAT and its underlying freeze probe methodology due to the potential

invasion on the primary simulation task. Furthermore, the freeze probe query captures other factors in addition to SA. Disambiguating working memory and recall from SA construct as assessed with the freeze probe queries is not possible (Salmon et al., 2009). The SA information must be retained in working memory while the simulation is frozen and the queries are administered. Newer techniques sensitive to different cognitive aspects of SA are needed to isolate SA construct for an accurate assessment.

The real-time probe technique is another SA measure that relies on providing participants with SA related queries (Salmon et al., 2009). Unlike the freeze probe technique, the real-time probe does not suspend the simulation. This technique was developed to mitigate the intrusion on the primary task induced by suspending the simulation. The content of the answers and the response time in providing the answers are used to generate a score for the level of SA. The situation present assessment method (SPAM) is an example of a real-time probe technique used to evaluate SA in air traffic controllers (Durso et al., 1998). The SPAM is remotely administered over the telephone to air traffic controllers. The response times for correct answers are used to assess the level of SA. A shorter response time reflects the air traffic controller with a high level of SA since the air traffic controller can mentally recall the information or efficiently direct his or her attention towards the necessary indicator to retrieve the information quickly. Longer response times reflect lower levels of SA since the air traffic controller cannot mentally recall the information and does not efficiently locate the information quickly. The time that it takes the air traffic controller to answer the telephone provides mental workload information. Longer times to answer the telephone reflect higher levels of mental workload on the assumption that the air traffic controller is more engaged in controlling aircraft in his or her airspace and cannot immediately answer the telephone. The mental workload indicator provides an additional component for analysis, since SA has been shown to differ by the amount of mental workload (Soliman, 2010). The real-time probe suffers similar issues as the freeze probe. The queries intrude upon the primary simulation task. Completing the secondary task of answering probe questions concurrently with the primary task still involves a potentially significant amount of distraction. Additionally, cognitive elements such as working memory are indiscriminately captured by the real-time probe. As with the freeze probe technique, there is no way to differentiate these cognitive elements from the SA construct.

In the complex and automated systems found in nuclear process control, the operators' role has shifted away from a manual controller towards a more supervisory role in which the operator monitors the automation and occasionally takes action as necessary (Sheridan, 1992). A critical component of the supervisory monitory is efficiently sampling critical pieces of information and making accurate diagnoses of the plant status and any upsets. In relation to situation awareness, this information foraging required for accurate diagnoses falls within the perception and comprehension levels of Endsley's three-level model. The projection of future states is important to test potential hypotheses accounting for a plant upset, but this is largely a mental process occurring within the mind of the operator. Eye tracking can be used to examine the more measureable perception and, to a lesser extent, the comprehension components of Endsley's three-level model (Ha & Seong, 2014).

Specifically, eye tracking can be used to examine the elements within the interface the operator is actively perceiving, attending to, and processing while foraging for diagnostic information. Eye tracking is based on the premise that an individual's visual fixation point is directly linked to their attentional allocation. Though attention can be covertly directed away from an individual's fixation point, this is an effortful process that must be consciously pursued unlike the innate yoking of attentional resources towards the individual's visual fixation point. As a result, researchers can infer cognitive processing of the visual element residing within the individual's fixation point. This provides researchers with a window into the operator's mind by tracking an individual's fixation points on particular visual elements of the interface. There are a few different approaches to quantifying an individual's attentional allocation while sampling information. Ha and Seong provide two related models called the fixation to importance ratio (FIR) and

the selective attention efficiency (SAE) (2010). Both of these models quantify the number of fixations, and duration of fixations in relation to predefined importance assigned to the visual elements contained within the interface. This quantified approach is valuable, because it can provide objective assessments of where the operator's attention allocation was directed, which in turn can be used within an SA framework to understand what elements the operator used to acquire SA. FIR and SAE comparisons against traditional SA measures, such as freeze-probe and real-time probe techniques can help researchers understand how the perceptual component of Endsley's model may contribute to shortcomings an operator might experience at the comprehension and projection levels measured by the traditional techniques.

In a general sense, eye tracking provides two specific benefits for examining SA, which other commonly used techniques cannot always adequately provide. First, the common self-reporting data many SA studies rely upon suffers the disadvantage of being subject in nature, which can result in inaccurate representations of the individuals true SA (Ha & Seong, 2014). The participant may not have accurately reported the interface elements they were perceiving and using to generate their SA model. This could occur because after completing the scenario, the participant now has access to information that they were still acquiring while completing the scenario. For example, the participant is fully aware that a steam generator tube rupture scenario was the focus of the scenario, however at the beginning of the scenario they were still arriving at this conclusion and sample other visual elements unrelated to a steam generator tube rupture. Since they are biased by the knowledge of the full nature of the scenario at the time of their self-report, they may report more attention focused on steam generator relevant visual elements when in reality their attention was more distributed towards other irrelevant visual elements. Another way to conceptualize the biasing nature of self-report data following scenario completion is to consider how the participant reduces the entire scenario experience into the reported experience. The participant aggregates the entire experience, which ultimately induces bias since the participant cannot report their experience at each significant point in time during the scenario. In contrast eye tracking is an objective measure that will faithfully record the individuals gaze information throughout the scenario. In addition to the objective nature of eye tracking measures, the continuous nature also provides accurate data on the participants SA experience throughout the trial (Ha & Seong, 2014). Unlike the self-reporting post scenario completion, the eye tracking provides data at each point which eliminates any bias due to the participant aggregating each significant time point during the self-reporting. Lastly, eye tracking is relatively unobtrusive. The participant simply performs the task as they normally would while the eye tracing equipment logs their gaze information. Given the complexity of interfaces typically included in SA studies, any reduction in intrusiveness from measures bolsters the validity of the study as a faithful representation of actual operator experience.

SA will be assessed in this series of studies using a modified freeze probe questionnaire like SAGAT. The Situation Awareness Control Room Inventory (SACRI) is a modeled after SAGAT, but designed for NPP control rooms (Hogg et al., 1995). The INL researchers will work with process experts to develop a simplified SACRI questionnaire so that it addresses the most important parameters for the scenario, but is minimally intrusive. SA will also be assessed with eye tracking using Ha & Seong's (2014) FIR and SAE metrics. The objective SA measures will be complemented with the subjective SART inventory.

4.4.2.3   Workload

Broadly speaking, workload is a human factors measurement construct that is meant to be a representation of the degree to which the human's capabilities are (and are not) consumed by the task they are performing. If the task requires the person to exert considerable physical and/or mental effort to complete the task to be performed, then it is said that his or her workload is high. If the task requires little physical and/or mental effort to complete the task, workload is low.

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In the context of physical activities, this general conceptualization of workload makes sense in that a person can exert only so much physical effort before becoming fatigued. Their physical resources become depleted. Additionally, there are some physical tasks that are beyond the physical capabilities of people (i.e., the demand for physical effort by the task outstrips the person's physical abilities). For mental activities, there is general consensus that these resource depletion and resource availability-to-demand formulations are also correct in that cognitive theories of attention and mental processes have demonstrated that there are limits to how long people can attend to or mentally perform complex tasks, and that there are some mental tasks that are beyond the mental (e.g., information processing) capabilities of people.

It is important to note, however, that while the resource depletion and resource availability-to-demand formulations are linear conceptualizations of workload, the relationship between workload (especially mental workload) and performance is *not* linear. The relationship between performance and workload follows the Yerkes-Dodson Law (Yerkes & Dodson, 1908), where optimum performance is seen at moderate levels of workload, with performance decreasing as workload becomes too high or too low.

For this benefits R&D project, the focus is on mental workload. The operating context of the NPP control room has aspects of nominal physical activity, but given that that virtually all of the key performance tasks involve operators interacting with instrumentation and control systems in the control room that require expert mental processing by operator, the emphasis and concern is about the operator's mental workload.

There are a multitude of measurement approaches for mental workload, in large part because it is a theoretical cognitive concept that cannot be observed in the same direct ways as physical workload can. Wilson and Eggermeier (2006) classify measures of workload according to the following taxonomy: primary task measures, secondary task measures, subjective measures, and physiological measures. As the name implies, primary task measures assess the person's performance while they perform the main task set before them. Specific primary measures include speed, accuracy, and how well they perform relative to predefined standards of perfect performance. Secondary task measures assess how well people can manage the workload of an additional non-primary task introduced concurrently with the primary task, and are primarily intended to assess the degree to which a person may have spare mental workload capacity. Like primary task measures, secondary task measures are non-physiological objective measures of workload and performance. Many subjective measures of workload are also available, including the subjective workload assessment technique (SWAT) and NASA task load index (NASA-TLX). Subjective measures rely mostly on self-report or an observer's inference of the performer's workload. Subjective measures can be used both as primary and secondary task measures. Finally, physiological measures rely on the observed correspondence between physiological changes in a person's body and changes in cognitive (and physical) activity. Common physiological measures of workload include heart rate, eye blinks, electrical brain activity (i.e., electroencephalograms), and cortisol levels (typically measured through saliva samples).

Workload will mainly be assessed using the NASA TLX. Workload will also be assessed with blink rate and blink duration using mobile eye trackers. Physical workload will be assessed using a pedometer to determine how much the operators need to walk around the control room to find the information they need. In control room operations, physical workload is often minimal, and is not assumed to contribute significantly to overall workload. However, one indication of increased efficiency of overview displays is that it will allow the operators to monitor relevant conditions without walking around the room as much as they do with the traditional displays. This will be demonstrated using a pedometer.

4.4.3 Summary of Performance Measures

Table 2 presents the technologies used in the upgraded HSSL the benefits of those technologies, and the corresponding performance measure that will be used to assess the benefits.

Table 2. Description of relationship between technologies, benefits, and performance measures.

Technology	Benefits	Corresponding Performance Measures
Overview Displays	- Reduced workload (physical and cognitive) - Enhanced SA - Enhanced detection of off-normal conditions - Enhanced crew coordination	- NASA TLX, blink rate and duration, step count - SACRI, SART, FIR, SAE - Time-to-initiate AOP - BARS
Advanced Alarm Systems	- Reduced workload - Enhanced diagnosis - Increased efficiency	- NASA TLX - Time to diagnose - Time to complete tasks
Computer Based Procedures	- Enhanced performance - Reduced errors - Enhanced efficiency	- Discrepancy Scores - OPAS - Time to complete procedure

4.5 Experiment Design

The goal of this study is to pilot the upgraded HSSL configuration (i.e., to make sure the technologies function properly, are properly integrated into the HSSL, and function together well), and refine the performance measures. Another goal is to provide some preliminary insight into the benefits of the technologies.

4.5.1 Variables

The independent variable in this study is the HSSL configuration. The independent variable will have two levels: with and without the technology upgrades. For the first phase study, the independent variable will be manipulated between participants. The main reason for a between participants design is that once the participants encounter the experimental scenarios, it will no longer be novel, and they will know exactly what to expect.

The dependent variables are the various performance measures described in section 4.4. Performance will be compared with and without the technology upgrades on each of the performance measures.

4.5.2 Experimental Protocol

Prior to conducting any scenarios, the operating crews will be extensively trained on how to operate the gPWR. INL researchers will work with trainers from the host utility and personnel from the simulator vendor (GSE systems) to develop 1-2 days of training.

Following the training, the crews will conduct the experimental scenarios. The two operating crews will be randomly assigned to one of the two conditions (with or without the upgraded technology). Following the assignment, both crews will be trained on how to use the advanced technology. This is to ensure that both crews get the same amount of training. Only the crew that is assigned to the upgraded technology condition will use the enhanced technology during the experimental scenario. The other crew will be told they won't use the technology, but they will have a chance to experience the technology informally following the experimental session.

During the experimental session, plant parameters will be recording using the simulator logs. Two observers will be using the computer-assisted OPAS system to observe operator performance. Each crew member will be fitted with a mobile eye tracker to measure blink rate, blink duration, and gaze patterns. Each participant will also be given a pedometer and told to reset it immediately prior to the scenario starting. Finally, the freeze probe SA questions will be administered periodically throughout the scenario (about 4 times). All of the other subjective self-report measures (e.g., the NASA TLX and SART) will be administered at the end of the scenario.

5. **Future Work**

The results of this study will serve to refine the performance measures and evaluate the upgraded HSSL configuration for the second phase of research. During the second phase, the same general process will be followed. The main difference will be that the experimental studies will be conducted using the host utility's plant-specific simulator. The simulator model will be installed in the HSSL and the upgraded technology will be configured to work with the plant simulator in the HSSL. The INL researchers will design a baseline study to be conducted at the plant's training simulator. The same scenarios will then be conducted in the HSSL with and without the upgraded technologies. The baseline study will serve as a comparison condition to determine potential performance differences that are simply due to using the glass top simulator in the HSSL. Future phases of this research will evaluate progressively more advanced technologies using the same basic process.

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