DESIGN THEMES FOR FUTURE HYBRID NUCLEAR POWER PLANT CONTROL ROOMS

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ABSTRACT

As nuclear power plants (NPP) control rooms are updated and new technologies added, a new hybrid control room is set to emerge and with it new safety implications for design. This paper highlights two technologies determined to be highly relevant for control room modernization: overview displays and computer-based procedures. Control room operators were observed in the simulator, while conducting abnormal and emergency scenarios. Additionally, operators were observed and interviewed in the control room during normal operations. Design themes for both of the technologies are discussed. Results revealed ten main design themes for overview displays, including observations of the system used currently in order to provide overview information. The results revealed three main design themes for computer-based procedures that were more directed at an envisioned world, since these technologies are not deployed currently. This evaluation elicited considerations for requirements for future control room system designs and recommendations for hybrid NPP control rooms.

Keywords: Overview displays; human-machine interface; qualitative; interface design

1. INTRODUCTION

The nuclear power plant (NPP) operator is not only responsible for the plant's health, but for maintaining critical safety functions that protect the facility, its workers and the public. The NPP main control room's displays and controls are effectively the operator's sensors and actuators that enable the operator to monitor, diagnose and manipulate plant conditions. Traditional analog human-system interfaces are distributed throughout the control room, usually organized by NPP

subsystem and function. However, because of display salience, an experienced operator can often scan the entire control room and gain plant status situation awareness (Mumaw et al., 2000).

NPP infrastructure modernization efforts within the existing plant fleets are currently underway, which presents new opportunities and imperatives for the incorporation of digital control-display technology that improves or at least maintains plant safety. These new NPP control room displays must support operator situation awareness and decision-making for safety, while ensuring effective and efficient management of plant performance at a tolerable cognitive load. Specific modernization efforts being considered as potentially valuable are overview displays and computer-based procedures.

Overview displays have been touted as supporting operators' ability to quickly and easily gather information regarding plant status; thus, improving situation awareness and communication among team members, which is critical during emergency or abnormal events (Braseth, et al, 2009; Ulrich et al, 2012). While NPP specific design standards for individual interface display components exist (NRC, 2007), these standards do not address the emerging needs of operators as overview displays, beyond recommendations related to font size, colors, etc., and minimal guidance related to the integration of other digitized system components into operators decision making activities. Additionally, overview displays are common in other industries (e.g., oil and gas, NASA mission control); however, they have provided limited utility (Ball, 2008).

Another technology intervention the NPP industry has recognized, as a safety enhancement is computer-based procedures (CBP). Computer-based procedures may be able to assist operators in place keeping, gathering required information automatically, permit easier navigation and adherence to the steps than existing paper-based or soft-copy (e.g., Adobe PDF files) procedures. There has been research around using CBPs to enhance operator performance in nuclear power for a number of years, however the deployment and implementation of CBP limited. In addition, research focused on how operators want to interact with these technologies remains scarce (Le Blanc & Oxstrand, 2013).

The presented exploratory observation and interview-based study provides insight into the functional requirements operators will require in order for these technologies to be effectively integrated into the NPP control room. The observations during training and normal operations were focused on understanding how crews perform in a typical nuclear power plant control room (e.g., simulator), particularly interactions with the current displays and control under normal, abnormal and emergency conditions. The primary goal of the integrated observations and interviews was to identify aspects of the operator activities that can benefit from the implementation of digital overview displays and computer-based procedures. In addition, this research was intended to derive and extend the current design guidance for the development of overview displays and computer-based procedures.

2. METHOD

Participants

The NPP operator participants included individuals who were a few months out from receiving their licensure to those with 30+ years of working at the plant. The older operators frequently were retired Naval submarine NPP operators, but the demographics of the younger operators varied from a recently retired Naval submarine NPP operator to those with scientific and engineering oriented undergraduate degrees. The majority of the observations occurred in the simulation center, as part of ongoing training with abnormal and emergency events; however, observations were also conducted during normal plant operations. Interview participants

consisted of five reactor operators (RO), one shift manager, and one shift technical advisor (STA). Control room personnel were opportunistically interviewed, while they were conducting their shift training or work duties.

Procedure

Three researchers conducted all training and normal plant operation observations and interviews. Three different training scenarios, included one with a hostile act, one that was a reactor startup, and a final scenario with a steam generator tube rupture were observed. The researchers were allowed to watch from either the simulator control room monitoring center or from the simulated control room itself. Simulation instructors were available to answer researchers' questions regarding specific interactions or events that occurred during the simulation. All researchers observed the pre-session trainer overview discussion. All researcher notes were transcribed and coded after the conclusion of all observations and interviews. Observations of scenarios were between 35 minutes to 3 hours.

The normal operations observations and interviews were conducted with the various control room personnel, while they completed their normal shift work. Individual personnel interviews lasted between 15 minutes to over an hour, and were interrupted by typical shift responsibilities. Upon receiving permission from the control room personnel, researchers used an interview guide specifically focused on overview displays and computer-based procedures. Specific interests included a current system composed of distributed displays that is frequently used in a manner similar to overview displays and the associated functionality and limitations. Interview questions also queried personnel regarding their expectations for large screen overview displays and information requirements for that type of system. Finally, a series of questions elicited feedback regarding the potential content and best uses of computer-based procedures.

Two team members qualitatively coded the resulting data for design requirements. The two coders iteratively met to confer on a categorization scheme and to resolve categorization discrepancies. Both researchers coded all of the observation and interview transcripts.

3. RESULTS

The qualitative results are decomposed into a number of relevant human factors considerations by overview displays and computer-based procedures. Each primary categorization is further decomposed into specific relevant observations and feedback that can impact system design.

Overview displays

The observed NPP control rooms do not specifically incorporate large overview displays; however, an existing reporting system on existing computer screens was frequently repurposed and effectively functioned as an overview display. This system incorporated six digital displays distributed around the control room; thus, the following results view this system as a distributed overview display system.

The displays need to be *viewable* throughout the control room. Given the configuration of the distributed displays, operators were observed whom had certain information (e.g., trend charts) displayed on one monitor, and other information displayed on a second monitor across the room. One operator was observed sitting in the center of the room gathering general trend information from the distributed displays and when detailed information was required, physically walking to the particular display that had the necessary information displayed.

The *layout* of the overview displays directly impacts personnel's situational understanding, cognitive workload, and decision-making. Given that the current system displays are not designed specifically for use as system overview displays, control room personnel commented on a number of attributes they deem necessary for true overview displays. The information layout on the digital displays needs to match the physical system boards. Previous systems depending on the usage information were reported as having missing information from the system or the layout was reversed from the board layout. The existing system also limits what information can be displayed concurrently when compared to the information operators required to support their responsibilities. For example, the feedwater system is displayed as a mirror image of the actual physical control room board layout. Some limits are necessary to ensure that a consistent layout is provided, but the personnel wanted systems that also provide flexibility. It is quite cumbersome with the existing system to locate the information that may be needed or desired within the layout.

It is important that the displays, whether centralized or distributed provide the necessary *overview content*. The data collection activities confirmed results from the existing literature that cites trend charts as an important element of overview displays (Burns, et al, 2008). A limitation of the observed existing system is that only a small number of trend charts, with few data points can be displayed simultaneously. Further, it is critical that overview displays, whether centralized or distributed provide the ability for personnel to understand the currently displayed information easily and "at-a-glance", while completing other primary tasks. The STA regularly walks the systems and needs to know what is going on quickly during that data collection activity; thus, even if the distributed displays are set to display differing information, the STA must be able to quickly assess the system state across the screens. For example, one operator mentioned that at the start of the shift, he walks the boards to verify all information states, but also to verify that the distributed displays contain the information he expects them to contain, particularly when trend charts containing different information are displayed on multiple displays. This verification is important for his ability to look across the control room from a centralized location and assess the current system state. All interview participants frequently mentioned this criterion for overview displays.

The existing system is difficult to *navigate* when seeking to access information. For example, the system can require a complex series of steps to "drill down" into the system in order to access information. Further, the amount of available information is very broad, which can make recalling where desired information is located within the system difficult. As a result, a large number of steps and a long period of time can be required to access the desired information.

A concern raised regarding the representation of the NPP system on overview displays was the shear system *complexity.* This system complexity had a direct impact on the system mimics provided on the existing boards, often resulting in abstractions of the complexity. Thus, a concern mentioned by several interviewees was that digital displays may still be unable to represent accurately and effectively the very complex subsystems.

The *usage context* dramatically impacts the frequency with which the displays are used for overview purposes. It was observed that during normal operations, the displays were primarily used to provide trend charts that were checked on a regular, but low frequency basis. However, the usage of the displays to provide overview related information increase significantly during the abnormal and emergency training simulation observations. Thus, operators thought that procedure specific screens (e.g., startup) in an overview display will support their work.

The existing system was developed in the early-1990s, a time when the computer processing and interface display capabilities were significantly limited compared to today, which leads to limitations related to the system's *flexibility*. The system provides a number of preset displays; however, operators found that these displays were not designed for working on a specific task; thus, necessitating opening multiple screens during the course of a single task. The current system allows operators to customize some of the presented data on some displays (e.g., trend charts),

but does not necessarily support fully customized combinations of data points. Further, if the operator customizes a screen and leaves the particular screen to complete another task, the customized screen is "forgotten" and the operator must dedicate time to recreating the screen content. There exist no means of "saving" the screen content for use later. Further, one is unable to access historical data that is no longer displayed on that particular screen, such as information that has moved off the end of a displayed trend chart. It is noted that such historical data is available via other systems in the control room. All of these aspects can directly impact decision-making.

The existing system also fails to provide sufficient *decision support* capabilities. Decision support systems typically integrate current and historical information that can be used by the system for predictive modeling, a critical aspect for making decisions that ensure the NPP system safety. The plant has an industrial standard historical data management system that permits access to historical data points, but it is not integrated with the digital display system. Thus, personnel must integrate information across multiple systems and calculate, either by hand or by self-developed spreadsheets, predictions for certain procedures. The existing system does not provide personnel with tools that allow them to combine the current system state with predictive models in order to understand the positive or negative potential outcomes of different system manipulations.

The inclusion of new *information sources* and *communication mediums* was deemed important when developing new overview displays. An important concern for many operators was the ability to visually check on areas in the physical plant to ensure it was safe to proceed with particular actions and to verify the safety of distributed personnel. Thus, the inclusion of camera feeds and the control of their field of view throughout the plant were important to achieve this objective. Further, instantaneous communication mediums, such as WIFI-enabled texting, were viewed as valuable capabilities.

As with any intelligent system, there is a concern about personnel becoming *over reliant* on overview displays, which can result in *skill degradation*. This concern has been demonstrated to be legitimate with the existing systems. It was reported that during prior training sessions, when certain non-safety critical systems were disabled, personnel failed to successfully complete the emergency recovery procedure. During one of the observed scenarios, the personnel were presented with such a system failure and were able to identify how to obtain the necessary information to complete the scenario successfully without the non-safety critical system that they frequently used as if it was an overview display.

Computer-Based Procedures

For all types of actions in the control room(e.g., regularly scheduled maintenance to emergency procedures), the current procedures that need to be performed are directed by binders containing paper-based procedures. For example, for any regular maintenance, the procedure is printed and the control room operator, often times in collaboration with a field operator, works through the paper procedure to complete the tasks. This approach requires the field operator to return to the control room to complete the procedure. Computer-based procedures (CBP), while in existence at other industrial plants are not yet prevalent in NPPs. The presented results are interview-generated data design themes the operators view as necessary for successful integration of CBP.

An important aspect of CPB functionality will be that it is *flexible*, which speaks directly to developing something beyond a flat file, or even a slightly enriched format (e.g., PDF forms). One operator actually tried to complete a routine procedure via an Adobe PDF file using his tablet. Due to the inflexibility of the flat-file PDF procedure, he quit and went back to paper. Current paper procedures allow operators to record notes, in addition to recorded values and other necessary and relevant information. Additionally, operators were acutely aware that during

emergency procedures the plant state will likely require deviation from the written procedure (e.g., beyond design basis) that must be documented. Other important requirements for flexibility include place keeping and documenting skipped steps accurately.

Like overview displays, the CPB's *content* was mentioned frequently as a concern. Specifically, operators viewed the CBP's as an opportunity for providing real-time system information directly associated with the procedure steps, which was viewed as a means to improve their efficiency and accuracy when completing a procedure. This information may be system component values or values that operators normally calculate by hand or by using other computer based systems. Further, alarm specific CBP can include set point information and allow the operators to see the parameter ranges and the steps required to address the alarm. The ability to integrate data from multiple sources and display it collectively in a context relevant space on the CBPs was deemed of high value to operators. These aspects all have the potential to contribute to improving operator decision-making.

Additionally in terms of content, operators felt that CBP could be used to navigate alarm procedures that occur during operations. The operators expressed interest in using technology to help them complete the alarm procedures and even use smart alarms directly connected to the procedures both bring them up and to help prioritize.

The inclusion of *new technology* on which the CBP can be implemented was discussed. Tablet-based procedures were viewed as a viable and preferred means to accessing and completing procedures. Operators felt current alarm procedures binders can be physically replaced with a tablet (the alarm procedures binder for a particular board are currently housed on the front of that board). They felt each binder could be replaced with a tablet that would be located where the current binder is held and dedicated to that board. Further, operators thought a tablet-based version of surveillance or routine maintenance had the potential to improve efficiencies by incorporating real-time information from the field personnel directly, via text or video feed in order to be proceed with the next steps.

4. DISCUSSION

This qualitative evaluation employed standard human factors observation and interviewing techniques to understand how NPP personnel interact and use the technology in the control room to accomplish their work, with a specific focus on overview displays and computer-based procedures. Additionally, this evaluation elicited new considerations for requirements for future control room system designs.

The observed plant does not formally have overview displays; however, it does have a system that operators use as if it is an overview display system. The digital displays associated with this system are relatively small individual computer monitors that are distributed throughout the entire control room and are not shared. The system displays can be supplemented with additional information that operators feel is missing or can be made more graphically oriented to facilitate information processing and decision-making. Many of the "rules" governing traditional large overview displays do not apply to the distributed displays that are effectively being used as distributed overview displays in the current NPP control room.

Centralized, large wall-based overview displays can provide additional information, but appear to have their limitations. Perhaps a better alternative is to provide larger distributed displays specifically designed as overview displays that provide the information operators feel is missing from their makeshift overview displays. Trend charts have been noted as an important element of large overview displays, the operators specifically requested more trend charts and the ability to have more flexibility in manipulating and customizing the data contained in the trend charts. Further, the operators seem keen to have information more readily accessible.

Computer-based procedures were very appealing to the operators, especially if the computer-based procedures incorporate real-time system information (e.g., PID controller temperatures),

historical trend generation, and communication with personnel in the field for all procedures. Two other concepts held great appeal: replacing station paper manuals with dedicated mobile electronic devices and smart alarms connected directly to the alarm procedure documents.

Overall, the implementation and use of newer technologies appealed to operators. The current standard for evaluating technologies and training operators on those technologies occurs in the simulated control room. The majority of the time operators spend in the simulator is focused on responding to abnormal or emergency procedures, while the bulk of the operators' work in the actual control room is conducting routine operations that create safe power generation. Designing and evaluating technology based on these highly infrequent extreme events may create technologies that are irrelevant. Further, these new technologies may be burdensome to operators during normal operations, which can potentially increasing workload, hinder decision-making and negatively impact situation awareness.

As thousands of NPP control operators prepare to retire, the next generation of operators will have "grown up" using computer-based and mobile electronic-based technologies daily (Nuclear Energy Insight, 2011). Further, as aging NPP technology degrades and is replaced with new technology, it becomes feasible to provide more digitally based information. It is absolutely necessary to understand the existing control room technology, but it is also absolutely critical to understand how the next generation of technology savvy operators expects to conduct their work processes. Thus, future research will further examine the impact of distributed digital overview displays and computer-based procedures on operators' performance with a focus on operator situation awareness, cognitive workload and decision-making.

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