CONF-970625--2
BNL-NUREG-64193

Human Factors Considerations in Control Room Modernization: Trends and Personnel Performance Issues

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Abstract: Advanced human-system interface (HSI) technology is being integrated into existing nuclear plants as part of plant modifications and upgrades. The result of this trend is that hybrid HSIs are created, i.e., HSIs containing a mixture of conventional (analog) and advanced (digital) technology. The purpose of the present research is to define the potential effects of hybrid HSIs on personnel performance and plant safety and to develop human factors guidance for safety reviews of them where necessary. In support of this objective, human factors topics associated with hybrid HSIs were identified. A human performance topic is an aspect of hybrid HSIs, such as a design or implementation feature, for which human performance concerns were identified. The topics were then evaluated for their potential significance to plant safety. Twelve topics were identified as *potentially* safety significant issues, i.e., their human performance concerns have the potential to compromise plant safety. The issues were then prioritized and a subset was selected for design review guidance development.

Keywords: Human factors, Man-machine system, Human-System Interface.

I. INTRODUCTION

Advanced human-system interface (HSI) technology is being integrated into existing nuclear power plants (NPPs) as part of modifications to control systems and HSIs. The new HSIs are predominantly based on digital technology. The result of this evolution is that hybrid HSIs are created; i.e., HSIs containing a mixture of analog and digital technology. While the introduction of advanced HSI technology is generally considered to enhance system performance, there is also the potential to negatively impact human performance, spawn new types of human errors, and reduce human reliability. Thus, it is important to consider the potential effects of this trend on personnel performance. Hybrid HSI performance effects associated with hybrid HSIs stem from both the new technology itself, as well as, its interaction with the analog technology. The effects can be related to: (1) *personnel role* - a change in the role of personnel in the plant (a change in functions and responsibilities of plant personnel, e.g., caused by a change in plant automation due to replacement of a plant control system); (2) *primary tasks* - a change in the way that personnel perform their primary tasks (those involved in performing the functional role of the operator to supervise the plant; i.e., process monitoring, situation assessment, response planning, and response execution and control); (3) *secondary tasks* - a change in the methods of interacting with the HSI and the demands it imposes (Secondary tasks are those the operator must perform when interfacing with the plant, but which are not directed to the primary task, e.g., navigating through displays, searching for data, choosing between multiple ways of accomplishing the same task, and deciding how to configure the interface); (4) *cognitive factors* - a change in the cognitive factors supporting personnel task performance (e.g., situation awareness and workload); and (5) *personnel factors* - a change in the required qualifications or training of plant personnel.

The purpose of this research project is to better define the effects of hybrid HSIs on personnel performance and plant safety and to develop human factors engineering (HFE) guidance to support the safety reviews performed by the U.S. Nuclear Regulatory Commission (NRC). Should a review of plant modifications involving a safety significant aspect of hybrid HSIs be necessary, such guidance will be needed to provide the NRC staff with the technical basis to help ensure that the modifications do not compromise safety. In this paper, the identification of human performance topics and their safety evaluation is discussed. Human performance topics are aspects of hybrid HSIs, such as a design or implementation feature, for which human performance concerns have been identified. The paper will summarize the results the topic identification, safety evaluation, and prioritization (see [1] and [2] for more detail).

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II. METHODOLOGY

Human performance topics were defined by first identifying the types of HSI technology changes that are occurring. Once identified, the potential effects of the changes on personnel performance were examined. This information was obtained from several sources: literature, interviews, and site visits. A review of the national and international HFE literature pertaining to system

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design descriptions, HSI-related human performance research, and operational events (provided by the NRC) was performed. The review included literature from the following domains: nuclear power, fossil power, process control, medical systems, aviation, and the general HFE research literature. An additional source of information was interviews with plant personnel, vendors and regulatory authorities. The interviews were conducted both over the telephone and during selected site visits, which provided the added ability to observe hybrid HSI technologies during field operations and personnel training. Lastly, site visits to facilities utilizing hybrid HSIs were conducted to provide an opportunity to discuss operational and maintenance experience with plant personnel and to observe operators' use of such interfaces. The sites included two NPPs, two fossil power plants, and two petro-chemical facilities.

While human performance concerns may be identified, it does not necessarily follow that they are safety significant. Thus, the topics were evaluated using a safety significance analysis methodology to identify those topics that represent potentially safety significant issues; i.e., which have the *potential* to compromise plant safety. Two examples of how hybrid HSIs could potentially impact safety follow [3]. In the first example, a keyboard entry coupled with a mispositioned system panel switch led to the lockup of a microprocessor-based overhead, annunciator system that went undetected for over one hour. Subsequent investigation revealed that the annunciator system could be locked up if an operator initiated a specific input twice while the system was connected to the wrong computer port. In another event, an operator assumed manual control of a full-range digital feedwater control system during power ascension, and tried to "bump" open the feedwater valve using a series of short intermittent key presses. However, the operator was unaware that each press corresponded to only about 0.1% demand, and the series of key presses translated into negligible changes in valve position demand. As a result, the plant tripped on low steam generator level. A contributing factor was that the feedback provided by the new digital controller to the incremental manual manipulations was not as clear as the floating needle indication of the former analog system.

The analysis methodology was based on the considerations described in 10 CFR 50.59 [4]. Some topics were described as modifications that may be made to existing plants, such as the installation of a computer-based procedure system, and the potential personnel performance effects of the modification were identified. Other topics were concerned with the design and implementation issues that impact human performance. A determination of potential safety significance was made based on criteria adapted from the Electric Power Research Institute's guideline on licensing digital upgrades [5]. A determination that a topic is potentially safety significant means that its human performance concerns have the *potential* to compromise plant safety. Such a determination does not mean that plant safety is necessarily compromised nor that a specific implementation cannot be done acceptably. Following the analysis, the issues were prioritized based on (1) the degree to which the topic addressed performance directly involved in the operation of the plant versus personnel involved in supporting roles, and (2) the degree to which the topic addressed HSI components that are primary sources of information and control capabilities for operators.

A peer review of the analysis was conducted to obtain an independent evaluation of the analysis and prioritization of the topics. There were five independent reviewers who were selected with special expertise in digital I&C, risk analysis, human factors, human reliability analysis, NPP operations, and operator training. Reviewers were also selected based on their knowledge and experience in the area of HSI upgrades and effects on personnel performance and plant safety. The peer reviewers were asked to indicate whether they agreed with the overall BNL assessment of the potential safety significance of each topic and whether they agreed with the prioritization of the topics. Following the peer review, a final prioritization of the topics was developed based on the peer review input.

III. FINDINGS

Based on the literature review, interviews, site visits, and event data, we found that there is an evolution from large control rooms with spatially dedicated displays and controls to compact, workstation-like consoles with computer-based controls and displays. Specific trends were identified in the following areas: increased automation of plant control functions and computerization of many HSI subsystems, including alarm management systems, information and display systems, controls, procedures, and operator support systems. The human performance considerations associated with the trends in HSI technology are discussed below. In addition, design and implementation considerations are also addressed.

A. Human Performance Considerations

1) Changes in Automation: Plant control system upgrades can provide higher levels of automation than the original design; for example, full-range feedwater control systems. Changes in automation can have a major effect on the operator's role, defined as the integration of the responsibilities that the operator performs in fulfilling the mission of plant systems and functions. Since automation has been predominately technology driven, changes in automation often fail to result in a coherent role for operators. In addition, concerns have been identified regarding the design of the HSIs that link personnel to automated systems. Even when a process is fully automated, personnel must still monitor its performance, judge its acceptability, and when necessary assume control. HSIs have been lacking in their ability to support these personnel task demands. Automated systems have generally been designed with inadequate communication facilities which make them less observable and may impair the operator's ability to track their progress and understand their actions. In one case this problem led to operators defeating or otherwise circumventing a properly operating automated system because they believed it was malfunctioning.

The overall effect of technology-centered automation and inadequate HSI design is that human performance may be negatively affected. Automation can increase the complexity of

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the plant and problems can arise because the operator lacks a good mental model of the behavior of the automated system, i.e., how and why it operates.

Many problems associated with human interaction with automated systems have been attributed to poor situation awareness which is difficult to maintain when the operator is largely removed from the control loop. In such conditions operator alertness may suffer. Conversely, the workload associated with transitions from monitoring automated systems to assuming manual control during a fault in an automated system can be very high. Further, there may be an erosion of the required skills for tasks that have been automated. Since NPP designs still require the operator to assume control under certain circumstances and to act as the last line of defense, the consequences of poor integration of the operator and the automated system can be significant.

2) Alarm System Design and Management: The alarm system is one of the primary means by which process abnormalities come to the attention of plant personnel. Advanced, computer-based alarm systems are available as upgrades and include characteristics such as: alarm reduction processing, different techniques for making alarms available to operators (dynamic prioritization, suppression, and filtering), a wide variety of display devices and presentation formats, increased controls for interacting with alarm systems, and flexibility of alarm features (such as setpoints). The operational experience and research on the effects of these features on operator performance have revealed mixed results. For example, when computer displays were first used to present alarms, operators were unable to effectively use the alarm systems under periods of high alarms because of scrolling message lists and limited display area. Further, while considerable effort has been devoted to alarm reduction techniques, studies are not conclusive on their effectiveness. One problem may be that designers have set alarm reduction goals in terms of percent of alarm reduction. While this might seem reasonable, it may not relate to the operator's use of the system and, therefore, might not noticeably improve crew performance.

3) Information Design and Organization: In conventional control rooms, the large spatially-fixed arrangement of indications present individual parameters as separate pieces of information. Data integration and interpretation are accomplished by the operator based on pattern-recognition, training, and experience. Computer-based display systems provide many ways for data and information to be processed and presented in an effort to make the information more immediately meaningful. The human performance considerations can be grouped into two broad categories: (1) display formats, and (2) display management and navigation.

Display Formats - Graphic displays provide different representations of the plant's functions, processes, and systems. To make information more meaningful, efforts have been made to map displays to underlying cognitive mechanisms such as perceptual processes and mental models. If achieved, such displays should approach properties of direct perception, i.e., immediately understood with little need for interpretation. However, this places a significant burden on the designer both to anticipate the information needs at various levels of abstraction (e.g., physical to functional), and to map them into appropriate display formats that correspond to the operator's mental models. While research has shown that display formats can have a significant effect on performance, the identification of the appropriate format for different tasks needs to be addressed.

Graphic displays also contain many more elements (e.g., abbreviations, labels, icons, symbols, coding, and highlighting) than do conventional displays. As displays convey more information at multiple levels of abstraction, the complexity of both the elements and the displays become greater. Therefore, generalization of guidelines, such as for the use of color, needs to be assessed for alphanumeric and simple displays to more complex graphic forms such as configural and ecological displays. The relationships between graphical and coding elements may be complex and the effects of relatively new graphical techniques, such as animation, need to be addressed.

NPP display pages typically are composed of a variety of formats. Considerations include: (1) how these formats should be combined to form display pages, (2) how different display formats might interact within a display page, and (3) how complex information should be divided to form individual pages.

Display Management and Navigation - Digital instrumentation and control systems usually have the capability to present much more information than was available in analog systems. This information is typically presented on a limited number of video display units (VDUs). To address the mismatch between information available and display area available, information is usually arranged into a hierarchy of display pages. New display systems may contain thousands of display pages. Display management and navigation tasks involve those activities that operators perform to access and use the information in these displays. The problem with display management and navigation is that it sometimes has been found to impose a significant workload on the operator which is not related to the primary task of monitoring and supervising the process. For example, when the information needed by operators exceeds the display area available, the operator may be required to make rapid transitions between screens, try to remember values, or write values on paper. These secondary tasks will compete for cognitive resources which would be better allocated to the primary task. The human performance concerns include: the demands placed on the operator's memory for remembering display locations, the inability to quickly access needed information, and delays in accessing needed displays. In addition to increased workload and distraction, these problems can increase operator response time. Factors that contribute to the display navigation demands include tradeoffs between density of information contained in an individual display and the number of displays in a display network, the arrangement of the displays within the network, the number and types of paths available for retrieving data, the cues for directing information retrieval, and the flexibility of software-driven interfaces that allows information to be displayed in a variety of formats and locations.

4) Soft Controls: In conventional control rooms, spatially-dedicated control devices are the predominant means for providing control input. They are always in the same location and always provide the same control function. Soft controls are control devices that are defined by software; thus, a control may change as a function of the display screen presented. Several concerns have been identified including ease of using soft controls as compared to hard controls, absence of tactile and aural feedback, loss of dedicated spatial location of controls, limited display surfaces on which to present soft controls, navigation to controls during configuration tasks and emergency situations, accuracy in mapping between the display schematic and subsystem components, response time and display update rate of complex systems, reliability of soft interfaces for critical tasks, and environmental factors (e.g., glare).

In addition, specific problems have been identified related to feedback and time delays, control-display relationships, serial access of controls, potential confusion between process controls and display and navigation controls, the degree of precision that can lead to increased operator workload, and an increased potential for error. For example, computer-based display devices may provide new mechanisms for introducing unintended actions (slips), such as access of the wrong control, accidental actuation, errors in input values, and capture errors.

5) Computer-Based Procedures (CBP): Plant procedures provide instructions to guide operators in monitoring, deciding on appropriate actions, and controlling the plant. CBPs provide a range of capabilities that can support these tasks and reduce demands associated with the paper-based medium. Some of the human performance concerns identified for CBPs include the loss of situation awareness in terms of losing the big picture of operations because only a portion of the procedure can be observed at one time, and losing a sense of location with regard to the total set of active procedures. Navigation within one procedure, or between multiple procedures, and related supporting information can also be time consuming and error prone.

The appropriate level of automation of CBP systems is another question. While paper procedures require the operator to monitor plant indications, CBPs often contain plant indications. The operators may become over reliant on the CBP information and may not feel the need to look at other sources of information in the control room. Important information presented by other indications may be missed.

During a total loss of the CBP, special demands may be imposed on operators as they attempt to control the plant using backup systems. The transfer from CBP to paper procedures may be challenging, especially if their presentation formats are different, such as switching from text to flowchart formats.

6) Computerized Operator Support Systems (COSS): COSSs assist operators with cognitive tasks such as evaluating plant conditions, diagnosing faults, and selecting response strategies. They are often knowledge-based systems, such as expert systems. While most of these applications have been used off-line, on-line systems for diagnostics are emerging. Despite the development of many COSSs, there has not been a great deal of experience with operational aspects of their use. Several experimental evaluations of the value of expert systems to reactor operators have been inconclusive. Problems have been identified related to: the task relevance of the information provided, level of explanatory detail, the complexity of the COSS information processing, lack of visibility of the decision process to the operator, lack of communication functions to permit operators to query the system or obtain level of confidence information regarding the conclusions that have been drawn. In addition, poor integration into the rest of the HSIs has limited the usefulness of COSSs.

7) Maintenance of Digital Systems: The maintenance of digital equipment places new demands upon personnel capabilities and skills. Recent events in NPPs and other complex systems indicate the importance of digital system maintenance on system performance and safety. A review of fault tolerant digital control systems indicated that inadvertent personnel actions, including maintenance, was one of the two leading causes of failures of redundant computer-based systems. Recent failures of digital systems in U.S. NPPs illustrate how inadequate integration of software-based digital systems into operating practices and inadequate mental models of the intricacies of software-based digital systems on the part of technicians and operators caused systems to become inoperable. The events also show the susceptibility of software-based systems to failure modes different from analog systems. Errors associated with such activities as troubleshooting, programming, and loading software are significant problems. This topic may become increasingly important as utilities use the on-line maintenance capabilities of digital control systems to reduce the duration of plant outages. A greater understanding is needed of the task demands and error modes associated with maintenance on digital systems.

8) Configuration Control of Digital Systems: For many digital control systems, logic configuration can be performed rapidly via an engineering workstation. The use of such workstations for configuration poses questions regarding the types of safeguards that are needed to maintain the integrity of the control system. Errors due to a lack of awareness of the mode (e.g., configure versus test) of the configuration workstation are possible. Undesirable changes may be made without detection. Also, safeguards for access to the configuration workstation and related equipment need to be considered.

9) Staffing and Crew Coordination: There is a trend in process control industries toward reduced overall staffing levels through the implementation of multi-unit control rooms, compact computer-based control consoles, and automation. However, while computer-based technologies can reduce operator workload in some situations (such as during normal operations), they may increase workload in other situations (such as when there are automated system failures). In addition, these technologies are likely to change the ways in which crew members interact, communicate, and coordinate their activities. Therefore, a greater understanding is needed on how these effects relate to staffing levels.

10) Acceptance and Training: When plants are modified, two factors are important to making the transition to new technology: training and operator acceptance. The training process may need to adapt to frequent changes (since digital systems can be more easily modified than conventional systems) and the diversity of HSI technology in hybrid plants. It will also need to address a broader range of skills needed to use hybrid interfaces and the potential for negative transfer between conventional and advanced technology. Operational experience has also shown that operator resistance to HSI modifications is not uncommon.

11) Design Analyses and Evaluation of Hybrid HSIs: Hybrid HSIs may have unique design considerations that need to be addressed, including: functional design requirements of the new system (and their relationship to the functional requirements of the systems they replace), unique characteristics of the new technology, integration with the existing HSI, evaluation techniques, and the assessment of the impact of the modification on the plant's design basis and related analyses.

12) Upgrade Implementation and Transition: The method by which HSI modifications are implemented may affect human performance demands and the opportunity for errors during the transition period between operation under the old and new HSI. During the modification process, interim periods may occur in which the HSI has characteristics that are more challenging to operators than either the original configuration or the final configuration.

B. Safety Significance of Hybrid Topics

Safety significance was determined by the methodology described in Section II. As part of this work, the topics of Alarms and the display management and navigation aspects of Information Design and Organization were screened-out from further analysis because they are already being addressed by other ongoing NRC research. Two of the topics were combined prior to the assessment and prioritization steps due to the similarity of their concerns. As a result, the original set topics was reduced to 10. Applying the safety significance analysis methodology, all of the 10 topics were identified as potentially safety significant and were prioritized.

The independent peer reviewers generally agreed with the analysis. The assessments and comments provided by the peer reviewers indicated agreement that all 10 topics were potentially significant to safety. There was also a reasonable degree of agreement regarding the priorities of the topics.

A final ranking was performed using a combination of BNL and peer reviewer rankings. Based on these considerations, the following were identified for guidance development: (1) Design Analyses, Evaluation, and Implementation of Hybrid HSIs (combination of the Design Analyses and Evaluation of Hybrid HSI and Upgrade Implementation topics); (2) Computer-Based Procedures; (3) Information Design and Organization; (4) Soft Controls; and (5) Maintenance of Digital Systems.

IV. DISCUSSION

There are important human performance considerations associated with hybrid HSIs. The topics identified generally have the potential for broad impact on the types of human actions that are important in the plant, such as process monitoring, fault detection, situation assessment, response planning, and response execution. These effects were found to be potentially safety significant, meaning that their human performance concerns have the potential to compromise plant safety. Several common themes were identified during the analyses:

1. User needs are often inadequately addressed in the design of computer-based systems, e.g., the need for information in the context of current tasks, goals, and objectives for operations, maintenance, and configuration personnel, and the need for feedback from control actions.
2. Computer-based system's can add to plant complexity. Having a good mental model or understanding of the computer-based system is essential to proper monitoring, supervision, and maintenance. Failure to account for this aspect of CBPs tends to lead to poor situation awareness and a sense of being out-of-the-loop.
3. Computer-based systems, especially automated systems, alarm processing systems, and COSSs, are often not sufficiently observable. The reasoning basis of these systems is not clearly presented and communication facilities are not adequate to enable operators to ask questions or otherwise verify system performance.
4. There is an overall trend away from spatially dedicated HSIs, which support parallel processing of information, toward virtual work spaces and serial access to information and controls. This may result in greater cognitive workload and more time spent performing secondary tasks.
5. Personnel concerns, such as training and acceptance, are significant considerations in the introduction of new technology.

Based on a prioritization of the topics, the following topics were identified for further human factors engineering guidance development: (1) Design Analyses, Evaluation, and Implementation of Hybrid HSIs (combination of the Design Analyses and Evaluation of Hybrid HSI and Upgrade Implementation topics); (2) Computer-Based Procedures; (3) Information Design and Organization; (4) Soft Controls; and (5) Maintenance of Digital Systems. Development of the guidance is currently underway using the methodology developed for NUREG-0700, Revision 1 [6]. This guidance will be included in Revision 2 to the document.

VI. ACKNOWLEDGMENTS

This research is being sponsored by the U.S. Nuclear Regulatory Commission. The views presented in this paper represent those of the authors alone, and not necessarily those of the NRC. The authors wish to extend our gratitude to the facility personnel, subject matter experts, and peer reviewers who shared their knowledge and expertise with the project staff.

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