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The Effects of Interface Management Tasks on Crew Performance and Safety in Complex, Computer-Based Systems: Overview and Main Findings

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The Effects of Interface Management Tasks on Crew Performance and Safety in Complex, Computer-Based Systems: Overview and Main Findings

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ABSTRACT

The primary tasks performed by nuclear power plant operators are process monitoring and control. To perform these tasks in a computer-based system, operators must perform secondary tasks such as retrieving information and configuring workstation displays. These are called “interface management tasks.” Demands associated with interface management tasks may be excessive under some circumstances and potentially affect plant safety. The objective of this research was to evaluate the effects of interface management tasks on crew performance and safety using published literature, discussions with subject-matter experts, site visits, and simulator studies. We found evidence of two forms of negative effects: (1) primary task performance declines because operator attention is directed toward the interface management task, and (2) under high workload, operators minimize their performance of interface management tasks, thus failing to retrieve potentially important information for their primary tasks. Further, these effects were found to have potential negative effect on safety. The results of this study are reported in two volumes. Volume 1 provides an overview of the major findings. Volume 2 describes the detailed analyses that were performed. The results form the technical basis for human factors engineering guidelines for the review the interface management aspects of human-system interface designs, to help ensure that they do not compromise safety.

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PREFACE

This report was prepared by Brookhaven National Laboratory (BNL) for the Division of Systems Analysis and Regulatory Effectiveness of the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research. It is submitted as part of the requirements of the project *The Development of Human-System Interface Design Review Guidance for NUREG-0700, Revision 2* (JCN W6546), specifically for Task 6, Develop and Evaluate New Design Review Guidance for Selected Topics. The NRC Project Manager is Paul Lewis (301 415-6767; PML1@nrc.gov) and the BNL Principal Investigator is John O'Hara (631 344-3638; ohara@bnl.gov).

ACRONYMS

BNL	Brookhaven National Laboratory
EPRI	Electric Power Research Institute
HFE	human factors engineering
HSI	human-system interface
NRC	Nuclear Regulatory Commission (U.S.)
SAR	safety analysis report
VDU	video display units

1 INTRODUCTION

Nuclear power plant operators are supervisory controllers. At a detailed level, their primary tasks include activities such as monitoring steam flow, starting pumps, and aligning valves. At a general level, primary tasks involve several generic cognitive tasks: monitoring and detection, situation assessment, response planning, and response implementation. In old control rooms, operators "walked the boards" to perform their primary tasks from a standing position. The control rooms are typically very large workspaces with spatially dedicated human-system interfaces (HSIs); i.e., alarms, displays, and controls. In this context, spatial dedication means that individual HSI components are always in the same place and visible to operators in their vicinity. Operators integrate and interpret information based on their training, experience, and crew communication.

By contrast, more modern, computer-based control rooms provide many HSIs on video display units (VDUs). These HSIs often lack spatial dedication and may or may not be visible on the VDU screen at any one time. They exist in a virtual rather than physical workspace. The typical workplace is usually much more compact and includes workstation-like consoles for seated operators. The underlying digital instrumentation and control systems are capable of providing much more data to operators than spatially dedicated displays. The information systems may have thousands of display pages.

To successfully perform these primary tasks, operators must perform secondary tasks such as accessing information from workstations. Such tasks are called "interface management tasks" and are actions performed by the operator to interact with the HSI rather than with the plant. Thus they are not directly related to the primary tasks. General interface management tasks include:

- Configuring - Setting up the HSIs of a computer workstation in a desired arrangement, such as assigning the soft functions on a multifunction display.

- Navigating - Access and retrieval of a specific aspect of the HSI of a computer workstation, such as a display or control.

- Arranging - Adjustments made to the operator's view of the information. It can occur at several levels, across and within displays, such as arranging items within a display page or window.

- Interrogating - Questioning the HSI to determine information regarding its status, such as the relationship of the current display to the rest of the display network or the latest file date. Also included in this category is the use of help systems.

- Automating - Setting up shortcuts to make interface management tasks easier.

In part, these tasks are necessitated by the fact that operators view only a small amount of information at any one time through their VDUs. The characteristic of limited viewing area sometimes has been referred to as the "keyhole effect" (Woods et al., 1990, 1994). To access information through the keyhole, personnel must perform interface management tasks.

As operational experience with these computer-based HSIs develops, there is increasing concern that the interface management demands may be excessive under some circumstances when compared with more conventional interfaces. This additional workload may interfere with the operators' ability to monitor and control the plant and it may detract from their ability to handle process disturbances. Thus, interface management tasks potentially may affect plant safety. Since there has been a steady increase in the use of computer-based displays and controls in nuclear power plants (NPPs), the issue of interface management was identified as a potential safety concern.

The U.S. Nuclear Regulatory Commission (NRC) reviews the human factors engineering (HFE) aspects of control rooms to ensure that they are designed using human factors engineering principles. These reviews help protect public health and safety by ensuring that operator performance and reliability are appropriately supported. Guidance to support these safety reviews is contained in the *Human-System Interface Design Review Guidelines*, NUREG-0700, Rev. 2 (NRC, 2002).

To address the potential concerns regarding interface management, the NRC undertook research to better define the effects of interface management on personnel performance and plant safety. The results are described in two report volumes. Volume 1 (this volume) provides an overview of the major findings of the study and their implications. Chapter 2 addresses the effects of interface management on task performance. Chapter 3 addresses the effects of interface management on plant safety. Chapter 4 discusses the implications of the findings for HSI design and evaluation. Conclusions are presented in Chapter 5. Volume 2 is the basis for this overview and describes the detailed analyses and evaluations that were performed. The results of this study were used to provide the technical basis for HFE design review guidance development (reported separately in O'Hara and Brown, 2001).

2 THE EFFECTS OF INTERFACE MANAGEMENT ON TASK PERFORMANCE

This chapter addresses the effects of interface management on personnel task performance. The discussion is divided into two sections: the first addresses the development of a model to describe the potential effects of interface management on task performance based on a cognitive analysis of their demands. Then analyses are discussed to determine whether there is support for the potential effects in complex, real-world, computer-based systems. In the second section the effects of HSI design features on the performance of interface management tasks are identified.

2.1 Model of the Effects of Interface Management on Task Performance

Model of Interface Management Effects

To model the potential effects of interface management tasks on primary tasks, an analysis was performed within the framework of theory and research on human information processing and cognition.

To adequately perform any task, two conditions need to be satisfied: (1) there must be sufficient cognitive resources available to do the task, and (2) there must be adequate information available (Norman and Bobrow, 1975). Cognitive resources are devoted to processes associated with long-term memory, working memory, and attention. According to multiple-resource theory (Wickens, 1991), there is only a finite amount of cognitive resources available for task performance. This relationship has been referred to as a performance-resource function. Simply stated, tasks are performed well when there is a match between the resources demanded and the resources supplied. When the resources demanded exceed those supplied, performance declines. In addition to cognitive resources, operators need information (data) to perform their tasks. That is, no matter how many cognitive resources are available, if the data available is too limited, task performance can suffer.

The situation is a bit more complicated when two tasks are involved. This is referred to as a dual-task situation. In a dual-task situation, resources can be devoted to one or the other task, or they can be divided between them. Typically in high workload situations, when resources are devoted to maintain performance on one task, performance on the other declines (Wickens and Carswell, 1997; Wickens and Seidler,1997).

In considering the applicability of this research to such real-world tasks as supervisory control (primary task) and interface management (secondary task), one significant difference emerges. Much of the research on dual-task tradeoffs is based on laboratory studies examining how attention is allocated between two tasks that are relatively *independent*, i.e., performance of one is not dependent on the other. However, primary and interface management tasks are *dependent*. Personnel must perform interface management tasks in order to retrieve the information relevant to the ongoing activities. These tasks rely on many of the same cognitive resources and use many of the same HSIs (e.g., a mouse may be use to both start a pump and retrieve displays). Thus primary and interface management tasks, while dependent, compete for the same resources. That is, cognitive resources have to be shared between the primary and interface management tasks and the operator has to decide on how to allocate resources between them.

Based on these considerations and the dependent nature of the two classes of tasks, two hypothetical dual-task performance effects under cognitively demanding situations were defined:

- *Resource-limited effect* - Interface management tasks draw cognitive resources away from primary task performance, and primary task performance becomes resource-limited and declines.

- *Data-limited effect*- Primary tasks consume most of the cognitive resources leaving little for Interface management performance. Since the primary tasks are dependent on interface management tasks, primary task performance becomes data limited and declines when interface management tasks are not performed.

General Evaluation of Interface Management Effects

These effects were then evaluated to determine whether they described actual effects involving interface management tasks in complex systems. To evaluate the effects, we used the following sources of information (1) literature analysis, (2) interviews with subject matter experts from many industrial domains, (3) walkdowns of scenarios in seven process control facilities, and (4) two simulator studies focused on HSI issues (Roth and O'Hara, 1998; O'Hara, et al., 2000).

We found that very few studies have been performed specifically examining this issue in complex task domains. We did, however, find evidence for effects of interface management on performance across a variety of data sources. Evidence of the resource-limited effect was evident in high-workload, cognitively demanding situations. Across a wide variety of industrial domains, performance on primary tasks has been shown to decline when too much attention is directed to secondary tasks.

Evidence was also found for the data-limited effect. Operators manage workload by prioritizing all their tasks - primary and secondary tasks. Interface management tasks are not prioritized as highly as primary tasks and frequently are not performed. Operators will use several strategies to minimize interface management demands, such as configuring their workspace as a spatially dedicated one. Operators often prefer to use the displays that are currently presented, rather than try to retrieve the best displays for the task.

Interestingly, operator reluctance to perform interface management tasks also was observed when workload was not high. This may be the result of HSI complexity (e.g., operators do not know where information is) or a lack of skills necessary to perform interface management tasks (e.g., operators do not know how to configure a display). Operators frequently commented that training in interface management strategies is deficient or absent.

Thus, interface management tasks may create barriers between operators and plant information, even when the effort to retrieve information is not high. Operators may not access information if they do not feel that it will be worth the effort. During periods of high workload, such as major transients, operators may decide to not access additional information because the retrieval effort may detract from the operators' primary task of analyzing current conditions and stabilizing the plant. Also, selecting new displays may disrupt ongoing tasks or may interfere with current information being used. There also are times when operators may not realize interface management tasks are necessary. In some cases, the operators may not access information because they do not know that it exists. Thus, information may not be monitored if the operator forgets to retrieve it or if the operator has an incorrect understanding of plant condition and decides that it is not needed.

2.2 The Effect of HSI Design on Interface Management

Control rooms typically have specific HSI design features for the performance of interface management tasks (such as dialog formats and navigation features). While these features have impacts on task performance, we found that interface management demands stem significantly from the overall design of all HSI resources, e.g., as alarms, displays, and controls. Within that context a number of HSI design topics are discussed below, including:

- General Design of HSI Resources
- Concept of HSI Use
- Display Design
- Viewing Area and the Number of VDUs
- HSI Flexibility

General Design of HSI Resources

Interface management demands stem from the design of the main aspects of the HSI such as alarms, displays, and controls, as well as the design on the HSIs interface management features, such as means to navigate the information system. The HSI characteristics most associated with the interface management demands are the amount of information, display formats used to present information, organization of displays in a network, visual display device area, and HSI flexibility. Computer-based control rooms equipped with digital instrumentation and control systems typically provide much more real-time information than is found in conventional control rooms. While the volume of information increases considerably, it is available through the limited viewing area of workstation VDUs. The characteristic of the limited viewing area sometimes is referred to as the "keyhole effect." The consequence of the keyhole effect is that at any time most of the information is hidden from view, i.e., the operator has only a glimpse of the current plant information through the display devices. Therefore, operators must know what information and controls are available in the virtual information space, where they are, and how to navigate and retrieve them. If insufficient viewing area is available for operators to perform their tasks, they may have to frequently repeat navigation tasks. A problem related to the keyhole effect is that access to controls and displays tends to be serial, e.g., only a few controls can be accessed at one time, in contrast to the parallel presentation of controls and displays in conventional control rooms. Finally, in conventional control rooms, displays and controls are predominantly spatially dedicated. They have fixed locations that cannot be changed in form or function. By contrast, computer-based HSIs are flexible; they can be configured and can function in various operating modes.

The detailed design of HSIs has been found to affect interface management task performance as well. However, except in a few cases, such as menu design, there has not been a great deal of research comparing different HSI design characteristics for such performance. In addition, the operators' mental models of the HSIs, especially the display network organization, are significant considerations in interface management task performance.

Concept of HSI Use and the Number of VDUs

Operators often do not use HSIs in ways that designers expect. They adopt numerous strategies to create workarounds and aids to correct for limitations in designs (Cook, Woods, and Howie, 1990; Woods, Johannesen, Cook, and Sarter, 1994; Vicente et al., 1997). If the data-limited effect accurately characterizes an effect of interface management, then an interesting paradox is created. As noted above, control rooms are designed with vast amounts of data, available through hundreds and sometimes thousands of displays, viewed by the operator through a limited number of display devices. Designers may expect that operators will use the flexibility of the computer-based interfaces to configure the HSI in such a way that it is ideally tailored to the unique demands of the current situation. However, as we have seen operators frequently prefer not to do that. Being reluctant to perform such tasks, they instead configure their HSI as a spatially dedicated one. This behavior is a part of their workload management strategy.

Display Design

In computer-based control rooms, the most common method of representing information is by functions and systems. Organizing displays in such a manner was effective in older control rooms because the spatial dedication allowed operators to scan the boards. However, limiting display organization in this way may not be effective for computer-based control rooms (Heslinga and Herbert, 1995). For routine operations that occupy the vast majority of an operator's time, accessing the information they need can be a difficult, effortful task. The reason for this is that for more routine tasks, operators' information needs are not centered along the system hierarchy. Since tasks typically cut across many systems, operators need to access many displays to retrieve task information. When the viewing area is limited, they are required to perform many Interface management tasks. In particularly bad situations, operators may be forced to make repetitive transitions among displays, an action that is sometimes referred to as display thrashing (Henderson and Card, 1987).

Viewing Area and the Number of VDUs

We found operators' concern about limited display area to be a very common issue and one that transcended domain application. This likely is related to a number of factors including: (1) the desire to have information presented in parallel, (2) reluctance to perform interface management tasks, and (3) poor information system design. The trend to pack more and more information and functionality into computer-based systems, while at the same time reducing the ability to display information makes operational tasks difficult. In fact, in hybrid control rooms where operators have a choice to use "old fashion," spatially dedicated HSIs or computer-based HSIs operators will frequently opt for the spatially dedicated HSIs, when in difficult situations. Thus, while the number of VDUs may have seemed reasonable to the designer when considering the flexibility and interface management and configuration resources provided in the control room, it is not ideal to the operator who is attempting to minimize this aspect of workload in order to maximize the time available to perform primary tasks. The operators may rather have more VDUs so that their initial "set-up" can display all the information they will need.

HSI Flexibility

The flexibility of computer-based HSIs is frequently problematic for operators. One reason is reduced automaticity. The amount of resources a task requires is related to the degree to which performance is automated. When there is a good match between the task information available and the operator's mental model, performance becomes somewhat automatic, i.e., requires very little attention and cognitive resources. By contrast, when the situation is unclear, operators must engage in a lot of decision-making which requires significantly more cognitive resources. When HSIs are spatially dedicated, operators can use automatic information processing capabilities, such as scanning and pattern recognition, to rapidly assess plant situations. The flexibility of computer-based HSIs and their general lack of spatial dedication causes interface management tasks to be more dependent on controlled information processing. The flexibility also makes it easier for operators to mistake one display for another, and may cause them to improperly assess a situation or operate the wrong piece of equipment.

Flexibility increases the need for interface management tasks and also for operators to make decisions about the HSI. In this sense, interface management tasks are more cognitively demanding and require that the operator have more knowledge and skills related to using the HSI than is required of operators in conventional plants.

3 THE EFFECT OF INTERFACE MANAGEMENT ON PLANT SAFETY

This chapter addresses the effects of interface management on plant safety. Although interface management tasks may affect primary task performance, it does not necessarily follow that this effect has an impact on plant safety. Therefore, a safety significance analysis was performed to examine this relationship.

3.1 Human Actions and Human Error

The potential mechanism by which interface management tasks can impact plant safety is through their impact on human actions that are important to safety. If the types of effects discussed in the previous chapter lead to human errors in the performance of risk-important actions, then safety can be affected.

Human errors can be explained on the basis of a relatively small number of cognitive mechanisms (Norman, 1981, 1988; Rasmussen 1986; Reason, 1988, 1990). The error mechanisms typically relate to the human information processor's response to factors such as unfamiliar situations, high workload, and disruptions of ongoing actions. Under such circumstances, people use heuristics (information processing short cuts) to cope with the demands.

As discussed in Chapter 2, interface management effects have the potential of increasing the likelihood of human errors through a number of means:

- Risk-important actions can be directly affected by the tasks that operators are required to perform when engaging in interface management, such as by (1) delaying the completion of risk-important actions, (2) distracting the operator from important information needed to perform the risk-important actions, and (3) interrupting the task sequence for the performance of risk-important actions.

- Risk-important actions can be affected by a failure to perform interface management tasks. Possible reasons for this failure include (1) not being aware that important information is hidden from view, (2) knowing information is available, but, because it is hidden from view not knowing its importance or misinterpreting it, and (3) knowing information is available, but choosing not to retrieve it because of high workload or general reluctance to engage in interface management tasks. With respect to the latter, during periods of high workload, such as major disturbances, operators may decide to not access additional information because the retrieval effort may detract from the operators' primary task of analyzing the situation. Also, selecting new displays may disrupt ongoing risk-important actions or may interfere with current information being used.

- Interface management tasks can be performed incorrectly and lead to misinterpretations or errors such as operating the wrong control due to confusion resulting from a lack of spatial dedication.

- Similarity of HSI features that are used for risk-important actions and interface management tasks can lead to errors. For example, accidental operation of plant equipment may occur if the operator actions required to control equipment are not sufficiently different from those for performing interface management tasks.

3.2 Safety Analysis

The safety significance analysis methodology used had been developed in earlier NRC research addressing the potential safety significance of computer-based HSI technology in hybrid control rooms (O'Hara, Stubler, and Higgins, 1996). It is an adaptation of the approach to digital upgrade safety evaluations that was developed by the Electric Power Research Institute (EPRI, 1993) using the 10 CFR 50.59 process. The EPRI methodology was endorsed by the NRC in Generic Letter 95-02 (NRC, 1995). While the 50.59 process has changed since our study was conducted, the analysis still serves as a useful research tool.

A subject matter review team was established with expertise in human factors, HSI design, nuclear plant operations, probabilistic risk assessment, and safety analysis report analysis. The team performed an evaluation of a hypothetical plant modification that embodies the HSI technology and issues involved in interface management. The baseline configuration was a typical, conventional control room design and the plant modification was a computerized display and procedure system with soft control capability. The modification was developed based on the HSI characterizations obtained from the site visits.

The review team was briefed on the hypothetical plant modification and the types of human performance issues that can be associated with computer-based systems. They were asked to evaluate the proposed modification using a set of questions adapted from the EPRI methodology. They generally addressed (1) failure modes that are caused or aggravated by personnel actions, and (2) failure modes and equipment characteristics that have negative effects on personnel performance. The SMEs were asked to indicate whether the response to each of the primary question is "likely" or "not likely" taking into account the supplemental considerations. The SMEs were also asked to provide an explanation of their evaluations.

Following the evaluation of the seven primary questions, an overall assessment of whether the modification was "potentially safety significant" was made. An indication of "likely" to any of the primary questions results in the identification of the modification as "Likely to be potentially safety significant."

The evaluation form was first completed by each evaluator independently, then the evaluators met as a group to discuss their assessments and arrive at a consensus. A final evaluation form was compiled.

The results of the safety evaluation indicated that the plant modification involving interface management issues was "likely to be potentially safety significant." With respect to the individual questions, the review team concluded that:

- It was "likely" that the proposed modification could increase the probability of occurrence of an accident evaluated previously in the safety analysis report (SAR)

- The proposed modification could increase the consequences of an accident evaluated previously in the SAR

- The proposed modification could increase the probability of occurrence of a malfunction of equipment important to safety evaluated previously in the SAR

- It was "likely" that the proposed modification could increase the consequences of a malfunction of equipment important to safety that was evaluated previously in the SAR

- The proposed modification could create the possibility of an accident of a different type than any evaluated previously in the SAR

- It was "not likely" that the proposed modification could create the possibility of a malfunction of equipment important to safety when the malfunction is of a different type than any evaluated previously in the SAR

- It was "likely" that the proposed modification could reduce the margin of safety as defined in the basis for any technical specification.

This evaluation means that if HSI systems are not adequately designed and implemented, interface management effects may increase the probability or consequences of an accident or a malfunction of equipment important to safety.

Such an evaluation does not mean that the types of plant modifications represented by the characterization are *necessarily* unsafe. It means that its human performance concerns associated with interface management have the potential to compromise plant safety and, therefore, should a review of such a modification be necessary, HSI review guidance addressing interface management will be needed by NRC staff to help ensure that the modifications do not compromise safety.

4 DISCUSSION

The implications of this research for design and evaluation of HSIs are discussed below. The discussion addresses minimizing the need for and effects of interface management. Also addressed is the improvement of HSI features for performing interface management tasks.

4.1 Minimizing the Need for Interface Management

HSIs should be designed to minimize the need for interface management tasks, especially under high workloads. Approaches to accomplishing this objective are discussed below.

Information System Design

As noted earlier, interface management demands are, in part, an artifact of poor design of other HSI resources, such as displays, alarms, and controls. One approach to minimizing interface management demands is to improve the design of these aspects of the HSI. Some examples of candidate approaches are discussed below.

Displays that provide better support for task performance will help minimize the need for interface management tasks by bringing more task-relevant information together in single displays. This will help minimize the need for operators to access multiple displays and place them on individual VDUs or on individual windows within a VDU. An example of a task-based display is a display that is structured according to operational or emergency procedures an operator must follow (O'Hara, Higgins, et al., 2000).

Mass-data displays may represent another approach to help minimize interface management demands. These displays contain more information on individual display pages than is typical. However, at least initially, dense displays are considered undesirable. Thus a tradeoff is created between distributing information over many less-dense displays that require a lot of navigation and packing displays with data potentially resulting in a crowded appearance but requiring less navigation. It has been found that displays which initially appear crowded to operators can become well liked and effective in supporting performance as operators gain experience with them (Roth, Lin, et al., 1998).

This discussion should not be interpreted to suggest the other forms of representation (e.g. function- and system-based) are not needed. They are needed for overall monitoring of system state, fault diagnosis, and handling situations that are unplanned and unanticipated by designers. The point is that for the types of activities that take up most of the operator's time, the absence of task-oriented displays impairs crew performance.

The organization of display networks should be easily understood by operators so they readily know the location of information in the computer system. The organizational structure should also minimize the need for navigation.

Determining the Number of Displays

There are advantages to limiting the number of VDUs in a control room from a design perspective. Fewer VDUs (or more properly less display area) means smaller control rooms, more simplicity in that there are fewer HSIs to integrate, less cost for equipment, and a lower maintenance burden. In operational environments with significant space and power limitations, such as air and space craft, designing HSIs with fewer VDUs may be a logistical necessity. However, except in these specialized situations, the advantages of fewer VDUs may not be justified when considering the significant increase in time operators spend navigating among displays (especially during emergencies), and considering the likelihood that during emergencies operators will believe that they do not have time to navigate among displays. Thus, the advantages of fewer VDUs may be offset by an almost inevitable decrement in operator performance.

By increasing the number of VDUs, operators can display more information at any one time, thus reducing the demand to remember information from one display to another and reducing the need for interface management tasks to retrieve and configure information. With additional VDUs operators can also have the opportunity to use some VDUs as spatially dedicated displays so they can put overview displays or specific information, such as parameter trends, that may be important to the current ongoing task.

When designing a control room, one of the first details is the overall control room configuration i.e., the number and location of computer workstations and their hardware such as VDUs, keyboards, and the number and location of other hardware items such as alarms and switches. The number of monitors is decided before a complete understanding of what information will be presented to the operator or how it will be presented. These types of decisions are often made before input from operational crews is obtained. There is only a loose coupling between information needs, information presentation, and display area needed to support operations.

Determining the appropriate amount of display area should include determining the information that will be needed at one time by the operators, the arrangement of information within display pages, the arrangement of pages within the display network, and the means used to access the information. It should also take into account the coordination of activities across crew members. For example, some displays may be shared by multiple operators at a workstation, which may reduce the total number needed. Alternatively, additional display devices may be needed to present group-view displays to support communication and coordination among personnel. When HSI design requirements are developed, these factors should be evaluated to determine the number of VDUs that will reduce the workload associated with accessing information during peak workload conditions. Designs should reflect the fact that interface management tasks may not always be performed.

HSI Flexibility

The system should be sufficiently flexible to enable operators to recover from difficult situations or to adjust the HSI in situations where personal preference can positively impact performance. Operators should be able to develop novel information displays for unusual circumstances. However, flexibility should be constrained so that working with the system does not become a complex decision-making task and so that operators do not have to frequently redesign HSIs to get the information they need.

4.2 Improving Interface Management Design

Improving HSI Predictability

To support the performance of interface management tasks, the HSIs should be designed to capitalize on the speed and power of the operators' automatic information processing capabilities; i.e., well-learned responses that require little attention. Design features that increase the predictability of the HSI enable such automatic processes to develop. An example is organizing display networks so operators can easily understand them and so that information can be readily located and retrieved.

Enhancing Navigation Functions

Providing enhanced navigation features and functions such as including landmarks within displays to indicate where in the overall information system the operator is looking, embedding links to additional information within the information displays the operator is currently using, and providing history functions (a history function maintains a list of displays the operator has recently retrieved) to facilitate navigation to previously viewed displays.

Automatic Interface Management Features

Automating aspects of interface management may reduce interface management workload. For example, if there is an alarm for a specific component, the HSI might provide an icon on the VDU screen that, upon operator request, automatically retrieves the relevant equipment display. Predetermined information groupings also may help to reduce interface management demands.

Interface Management Training

Training in interface management strategies may enhance overall performance of both primary and interface management tasks. When computerized workstations are used, the efficient performance of secondary tasks (interface management) is very important to primary task performance. We have observed numerous instances in which training on interface management has not been fully developed, and the result has been poor performance.

5 CONCLUSIONS

Interface management tasks can affect the performance of primary tasks, such as by making them resource-limited or data-limited. Thus, interface management tasks may create barriers between operators and important information. Since NPP personnel tasks can support risk-important actions, the interface management effects have the potential to impact plant safety.

The interface management demands stem both from the design of HSI resources such as alarms and displays, as well as the design of interface management aspects themselves such as workstation configuration and display navigation features.

An identification of the HSI characteristics and functions that can contribute to interface management effects provides the technical basis for the development of design review guidelines that will reduce the probability of error and make the HSIs more error-tolerant. The use of the information reported here for guidance development is discussed elsewhere (O'Hara and Brown, 2001). The guidelines have been incorporated into the NRC's *Human-System Interface Design Review Guidelines* (NUREG-0700, Rev. 2) and will be used by the NRC staff to ensure that HSI designs do not compromise safety.

6 REFERENCES

Bennett, K., Nagy, A., and Flach, J. (1997). Visual displays. In G. Salvendy (Ed.), *Handbook of Human Factors and Ergonomics* (Second Edition). New York, NY: Wiley-Interscience.

Cook, R., Woods, D., and Howie, M. (1990). The natural history of introducing new information technology into a high risk environment. In *Proceedings of the Human Factors and Ergonomics Society - 34th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

EPRI (1993). *Guideline on licensing digital upgrades* (EPRI TR-102348). Palo Alto, CA: Electric Power Research Institute.

Henderson, A. and Card, S. (1987). A multiple, virtual-workspace interface to support user task switching. In *Proceedings of the CHI'87 Human Factors in Computing Systems Conference*. New York, NY: Association for Computing Machinery.

Heslinga, G. and Herbert, M. (1995). Experiences with advanced systems for human-machine interaction. In *Proceedings of the 6th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design and Evaluation of Man-Machine Systems*. Cambridge, MA: Massachusetts Institute of Technology.

Norman, D. (1988). *The psychology of everyday things*. New York, NY: Basic Books.

Norman, D. (1981). Categorization of action slips. *Psychological Review, 88*, 1-15.

Norman, D. and Bobrow, D. (1975). On data-limited and resource-limited processes. *Cognitive Psychology*, *7*, 44-64.

NRC (2002). *Human-system interface design review guideline* (NUREG-0700, Revision 2). Washington, D.C.: U.S. Nuclear Regulatory Commission.

NRC (1995). *Use of NUMARC/EPRI Report TR-102348, Guideline on licensing digital upgrades, in determining the acceptability of performing analog-to-digital replacements under 10 CFR 50.59* (NRC Generic Letter 95-02). Washington, D.C.: U. S. Nuclear Regulatory Commission.

O'Hara, J. and Brown, W. (2001). *Human-system interface management: Human factors review guidance*. Upton, New York: Brookhaven National Laboratory.

O'Hara, J., Brown, W., Hallbert, B., Skråning, G., Wachtel. J., & Persensky, J. (2000). *The effects of alarm display, processing, and availability on crew performance* (NUREG/CR-6691). Washington, D.C.: U.S. Nuclear Regulatory Commission.

O'Hara, J., Higgins, J., Stubler, W., and Kramer, J. (2000). *Computer-based procedure systems: Technical basis and human factors review guidance* (NUREG/CR-6634). Washington, D.C.: U.S. Nuclear Regulatory Commission.

O'Hara, J., Stubler, W., and Higgins, J. (1996). *Hybrid human-system interfaces: Human factors considerations* (BNL Technical Report J6012-T1-4/96). Upton, New York: Brookhaven National Laboratory.

Rasmussen, J. (1986). *Information processing and human-machine interaction: An approach to cognitive engineering.* New York, NY: North-Holland.

Reason, J. (1990). *Human error.* New York, NY: Cambridge University Press.

Reason, J. (1988). Modeling the basic error tendencies of human operators. *Reliability Engineering and System Safety*, *22*, 137-153.

Roth, E. and O'Hara, J. (1998). *Integrating digital and conventional human-system interface technology: Lessons learned from a control room modernization program*. (BNL Report J6012-3-4-7/98). Upton, New York: Brookhaven National Laboratory.

Roth, E., Lin, L., Thomas, S., Kerch, S., Kenney S., and Sugibayashi, N. (1998). Supporting situation awareness of individual displays and teams using group view displays. In *Proceedings of the Human Factors and Ergonomics Society – 42nd Annual Meeting* (pp. 244-248). Santa Monica, CA: Human Factors and Ergonomics Society.

Vicente, K., Mumaw, R. and Roth, E. (1997). *Cognitive functioning of control room operators*. Toronto, Canada: University of Toronto.

Wickens, C. (1991). Processing resources and attention. In D. Damos (Ed.), *Multiple task performance.* London: Taylor & Francis.

Wickens, C. (1994). *Context, computation, and complexity: Applications to aviation display system design*. Urbana-Champlain, Illinois: University of Illinois.

Wickens, C. and Carswell, C. (1997). Information processing. In G. Salvendy (Ed.), *Handbook of human factors and ergonomics* (Second Edition). New York, NY: Wiley-Interscience.

Wickens, C. and Seidler, K. (1997). Information access in a dual-task context: Testing a model of optimal strategy selection. *Journal of Experimental Psychology: Applied*, 3, 196-215.

Woods, D., Johannesen, L., Cook, R., and Sarter, N. (1994). *Behind human error: Cognitive systems, computers, and hindsight* (CSERIAC SOAR 94-01). Wright Patterson Air Force Base, Ohio: Crew Systems Ergonomics Information Analysis Center.

Woods, D., Roth, E., Stubler, W., and Mumaw, R. (1990). Navigating through large display networks in dynamic control applications. In *Proceedings of the Human Factors Society - 34th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Woods, D., Johannesen, L., Cook, R., and Sarter, N. (1994). *Behind human error: Cognitive systems, computers, and hindsight* (CSERIAC SOAR 94-01). Wright Patterson Air Force Base, Ohio: Crew Systems Ergonomics Information Analysis Center.