NUREG/CR-6749
BNL-NUREG-52638

Integrating Digital and Conventional Human-System Interfaces: Lessons Learned from a Control Room Modernization Program

Brookhaven National Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

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Manuscript Completed: August 2001
Date Published: September 2002

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NRC Job Code W6546

ABSTRACT

This study examined the impact of introducing advanced human-system interfaces (HSI) into a conventional nuclear power plant control room. The advanced HSIs include a computer-based procedure system, an advanced alarm system, and a graphic-based plant information display system. The impact of the new systems on the cognitive functioning of individual crew members and on the structure and functioning of the crew as a team was examined. Information on crew performance was obtained by observing crews during full-scope training simulations of plant disturbances. In addition, interviews were conducted with operators and other utility and vendor personnel. The general findings were that the new HSIs provided positive support for crew performance, reduced workload, and were well accepted by the crews. One of the more interesting and significant effects introduced by the advanced HSI systems was on crew structure and communication. The computer-based procedure system enabled the shift supervisor to access plant state information directly, reducing the need to ask board operators for plant parameter values. In turn, the board operators had access to a richer source of plant state information via the advanced alarm system and graphic-based plant information system than previously was available, enabling them to monitor plant state more broadly. These changes have potential implications for human performance and reliability. The fact that crews use multiple independent sources of information and multiple independent perspectives may increase the crew reliability by increasing the probability of detecting and correcting errors in situation assessment, thus reducing the potential for errors of intention. However, the improvement in human performance and reliability depends on the crew's ability to effectively communicate and maintain a shared situation awareness. The study provides illustrative cases where successful performance is dependent on effective communication among crew members. While this study began exploring these issues, further research is required to establish how new HSIs affect crew structure, communication, decision-making and reliability. The lessons learned from this investigation will be used to support human factors guidance development addressing these topics.

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(continued)

ACKNOWLEDGMENTS

The authors wish to express their sincere gratitude to the Westinghouse design personnel and Nordostschweizerische Kraftwerke AG (NOK) utility personnel who granted us permission to conduct this study and who gave generously of their time and patience while it was being conducted. Specifically we would like to thank Garry Brassart, Jim Easter, Mel Lipner, Craig Watson, and Mike Halverson of Westinghouse and Fritz Portmann and Eberhard Wyrsch of NOK. Special thanks is given to the utility operators who provided insightful comments and perspectives on the new systems and to the vendor's training instructor whose knowledge and understanding significantly contributed to the study.

Thanks are also extended to our NRC colleagues Joel Kramer and Paul Lewis who made it possible to conduct the study and who provided thoughtful comments on the development, conduct, and interpretation of the study.

Finally, we wish to thank Mary Anne Corwin for her technical editing and improvement of the report.

ACRONYMS

AAS	advanced alarm system
BNL	Brookhaven National Laboratory
CBP	computer-based procedure
CRT	cathode ray tube
EOP	emergency operating procedure
HFE	human factors engineering
HSI	human-system interface
I&C	instrumentation and control
GDS	graphic display system
LOCA	loss of coolant accident
MSIV	main steam isolation valve
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
PWR	pressurized water reactor
RCS	reactor coolant system
RNO	response not obtained
SG	steam generator
SI	safety injection
SRO	senior reactor operator
VDU	video display unit
V&V	verification and validation

1 INTRODUCTION

The Human-System Interface Design Review Guideline (NUREG-0700, Revision 1) (O'Hara, Brown, Stubler, Wachtel, and Persensky, 1996) was developed to provide human factors engineering (HFE) guidance to the U.S. Nuclear Regulatory Commission (NRC). It describes those aspects of the human-system interface (HSI) design review process that are important to the identification and resolution of human engineering discrepancies that could adversely affect plant safety. NUREG-0700 also provides detailed HFE guidelines for the assessment of HSI design implementations.

In the development of NUREG-0700, Rev. 1, several topics were identified as "gaps" because there was an insufficient technical basis upon which to develop guidance. One such topic is the integration of advanced HSI technology into conventional nuclear power plants (NPPs). The NRC is currently sponsoring research at Brookhaven National Laboratory (BNL) to: (1) better define the effects of changes to plant HSIs brought about by the application of digital technology on personnel performance and plant safety and (2) develop human factors engineering (HFE) guidance to support safety reviews in the event that a review of plant modifications involving a safety significant aspect of HSIs is necessary. Such guidance is currently being integrated into NUREG-0700 and will be used to provide NRC staff with the technical basis to help ensure that the modifications do not compromise safety.

Based upon literature, interviews, and site visits, changes in HSI technology and the potential effects those changes have on personnel performance were identified (O'Hara, Stubler, and Higgins, 1996). The topics were then evaluated and prioritized with respect to their potential safety significance (Stubler, Higgins, and O'Hara, 1996). Based on this analysis, several topics were included in those selected for guidance development, including computer-based procedures (CBPs) and information design and organization. In addition, the NRC has developed guidance for advanced alarm systems (Brown, O'Hara, and Higgins, 2000) and interface management.

The purpose of the study described in this report was to develop lessons learned related to these topics based upon a study of the integration of advanced HSIs into a NPP that currently uses primarily conventional HSIs. In connection with a computer replacement, the Swiss utility Nordostschweizerische Kraftwerke AG (NOK), modernized the control rooms at Beznau. The two units are two loop, 350 MWe pressurized water reactors that began operation in the late 1960s and early 1970s. The modifications were designed by Westinghouse and include a CBP system, an advanced alarm system (AAS), and a graphic based plant display system. Operating crews were trained on the use of these systems at the Westinghouse Waltz Mill Site in Madison, Pennsylvania. The training was conducted in a full-scope dynamic plant simulator and involved using the computerized HSI to respond to dynamic plant disturbances. The control room modernization project represented a unique data collection opportunity to address human performance issues associated with regard to the new HSI technologies and but also any related issues such as the design, evaluation, and implementation of the new systems. The latter are critical to the successful introduction of new technology.

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The information obtained was based on observations of crews during their initial training with the new systems and interviews with operators and other utility and vendor personnel. The lessons learned will be used to support guidance development in the topic areas.

2 OBJECTIVE

The objective of this study was to obtain information and lessons learned regarding a wide range of topics related to the integration of advanced HSI technology with conventional technology in a control room modernization program, and more particularly, to identify the strengths and weaknesses (opportunities for improvement) of the specific technologies:

- Computer-based procedure system
- Alarm system
- Display system
- Systems-integration across the new systems and with the existing HSIs

In addition, information on the following general topic areas was sought:

- Scope and objectives of the HSI modernization program
- Design goals, basis, methods, and evaluation
- Implementation and transition to the new systems
- Impact on operator training
- Impact on crew operations, staffing, qualifications, communication, and coordination
- Configuration, maintenance, and upgrade

An area of particular interest in the study was the impact of the new HSIs on crew performance. Early discussions with designers of the HSIs and plant management suggested that the combination of new HSIs strongly impacted how the operators functioned as a crew. The CBP system was developed for the plant's emergency operating procedures (EOPs). It provided the shift supervisor with the plant parameter data required for him to work through the procedures. This had two direct effects: (1) it reduced the need for 'low level' communication between shift supervisor and the board operators that was previously required to provide the shift supervisor the plant parameter data called out in the procedures; and, (2) as a consequence, it freed the board operators' cognitive resources. The board operators no longer needed to serve as the 'eyes' of the shift supervisor. It should be noted that these CBP-related observations may reflect the fact that it was EOPs that were computerized and not some simpler type of procedure.

The AAS and graphic display system (GDS) also created new sources of information that, if utilized, could improve the crew's understanding of, and response to, plant conditions.

The utility, recognizing the opportunities afforded by the new computerized system, instituted a change in crew structure and distribution of responsibilities. Instead of the traditional crew structure, where board operators only take action at the direction of the shift supervisor and function essentially as one cognitive unit, the utility decided to allow the board operators to work independently and in parallel with the shift supervisor. For the immediate post-trip actions, the shift supervisor works through the procedures, while the board operators assess plant conditions based on the AAS (as well as the graphical display system and traditional board indicators).

2 OBJECTIVE

We were interested in exploring the impact of the new HSIs and crew structure on crew performance. The new crew structure has the potential to increase the reliability and effectiveness of the crew. This is because the board operators, by working independently from the shift supervisor (using different information sources and methods), may provide an additional, independent (redundant and diverse) check on plant state and appropriateness of response actions. However, the improvement in crew performance and reliability depend on effective communication among crew members. Paper-based procedures necessitate communication between the shift supervisor and the board operators. By providing plant parameter data directly to the shift supervisor, the CBP eliminates that forcing function. The question is, how do the new HSIs impact crew communication and, in turn, the ability of the crew to maintain a shared understanding of the state of the plant and of the procedures.

It is possible that the CBP could improve communication and the ability of the crew to maintain a high level of situation awareness by shifting the content of communication to a higher level. With paper-based procedures the focus of communication is on the status of individual parameter values. It is possible that CBP could shift the content of communication to a higher level that more directly addresses the status of the plant relative to the goals of the procedures and achievement and maintenance of safety functions. It is also possible that by removing the forcing function to communicate, the CBP results in reduced communication and a consequent loss of situation awareness among crew members. A reduction in communication per se is not a signal of degraded team performance. It is possible that more effective teams, in some cases, actually talk less than less effective teams (Orasanu and Fischer, 1992; Orasanu, 1994). The key is that the more effective teams know what information needs to be passed to their team-mates and when. One of the goals of this study was to explore the impact of the new HSIs, particularly the CBP, on crew communication.

We were interested in obtaining the operator's perspective on the impact of the new HSIs on (1) cognitive load, (2) roles and functions, and (3) communication among team members. In addition we were interested in how the changes in cognitive load, operator roles, and communication affected the situation awareness of each of the crew members and the quality of team decision-making.

We were also interested in the impact of the new HSIs on the ability of crews to work through emergency response procedures in pace with dynamically evolving emergency scenarios.
Of particular interest was the impact of the new HSIs on the ability of crews to monitor the effectiveness of the emergency procedures in handling emergency scenarios as well as the ability of the crews to detect and respond to cases where the actions specified in the emergency response procedures are not fully appropriate to the specific situation. Several studies examining both actual and simulated incidents have shown that conditions sometimes arise where response guidance in the procedures are not fully appropriate to the situation (Kauffman, Lanik, Trager,

and Spence, 1992; Wreathall, Reason, and Dougherty, 1993; Roth, Mumaw, and Lewis, 1994). In those cases the ability of the crews to recognize that the actions specified in the procedures are not fully appropriate to the specific plant conditions and to take corrective action are important cognitive activities. Roth, Mumaw, and Lewis (1994) showed that with paper-based emergency response procedures, operator crews actively monitor the appropriateness of procedural steps to the evolving plant conditions and occasionally will deviate from the literal interpretation of a procedural step when it is determined to be necessary to achieve the goals intended by the procedural step and/or to maintain plant safety. We were interested in determining how CBP affected operators ability to monitor the effectiveness of the procedures, and detect and respond to situations where the actions specified by a procedural step were not fully appropriate to the situation.

It is important to point out the limitations and constraints of the study. First, the observations were made during the first training week using the new systems. Thus, we were observing operators using the HSIs early in their learning curve. Second, the systems were not completely debugged at the time the study was conducted. Thus many of the specific problems encountered by the crews were known to management and were in the process of being corrected. Third, the scope of the scenarios was limited to relatively straightforward events from a cognitive perspective. Since the operators were being exposed to the HSIs for the first time, the training staff felt that for pedagogical reasons, it was important to use simulator scenarios that were straightforward and that and exercised a core set of procedures. Thus, use of the HSIs was not observed in the full range of complex situations that could arise.

In addition, as will be discussed in the next section, the study relied on interviews and naturalistic observational methods. No systematic manipulations of HSI features and characteristics were attempted and no quantitative assessment of performance was obtained.

The main objective of the study was to capture lessons learned from the introduction of these new HSIs to serve as a source of input to designers, implementers, trainers and evaluators of new HSIs. A goal of the study was to gain an understanding of operators' perception of the computerized HSIs relative to traditional hardwired control boards. We were interested in gathering information on which aspects of the new HSIs the operators felt were clear improvements over traditional hardwired control boards as well as which areas they felt introduced new challenges or raised new issues. The study aimed to provide information on what features of the new computerized HSIs appeared to be most beneficial to the operators, to identify areas that designers, implementers and evaluators of new HSIs need to pay careful attention to, and to identify areas where further research is required.

3 METHODOLOGY

3.1 Participants

The main participants in the study were five crews of professional NOK operators observed and interviewed between July and September of 1997. The crews varied in size between four and six. Each contained minimally a shift supervisor, reactor operator, a turbine/balance-of-plant operator, and shift engineer.

The observations and interviews took place in a full-scope training simulator. The operators were at the simulator for a week of refresher training.

In addition to the observation and interviews of the crews, interviews were conducted with:

- Utility head of operations
- Utility head of training
- Vendor project manager
- Principal designer of the CBP system
- Principal designer of the AAS
- Principal designer of the graphic display system
- Principal training instructor

3.2 Simulator

The simulator was Westinghouse's full-scope training simulator of a pressurized water reactor (PWR) in Madison, Pennsylvania. The control room was modified to include the new CBP, AAS, and display systems.

In addition to the standard control board with analog indicators, there was an Alarm Overview Panel made up of vacuum-fluorescent display devices installed at the top of the control board for presentation of advanced alarm messages.

There were also five workstations distributed around the control room. Each workstation had two visual display units (VDUs) for a total of 10 VDUs. One pair of VDUs was at the shift supervisor's desk. A second pair was located in the back of the room and was intended for use by the shift engineer. The three remaining pairs of VDU were located by the control board and were intended to be used by the board operators. The total number of VDUs was the same as in the actual control room.

3.3 Advanced HSIs

A brief description of each of the three advanced HSIs follows (references to additional information are provided). While the systems were mature enough to support initial training, it should be noted that the CBP and AAS were still in the final stages of implementation and, so, were still undergoing fine-tuning and corrections to the databases.

3.3.1 Alarm System

The AAS is composed of two main components: (1) an Overview Panel and (2) a Support Panel.

The Overview Panel is composed of a set of alarm message windows presented at the top of the control board. The alarm message windows are vacuum-fluorescent eighty-character alpha numeric display devices that display computer-generated alarm text messages. The alarm windows are analogous to engraved tile light boxes of current annunciator systems, but allow for changes in the text presented in the alarm window.

The alarm system attempts to preserve some of the strengths of a conventional tile-based annunciator system, namely the value of having multiple, parallel-presented, dedicated position, alarm windows, while taking advantage of the flexibility afforded by use of computer-generated alarm text.

The Overview Panel is composed of 254 alarm message windows. This is approximately one-third to one-fourth the number of tiles in the usual annunciator tile system. At the time of this study, the database for the AAS contained a total of approximately 6000 distinct alarm messages. The alarm messages are grouped and assigned to alarm windows on the Overview Panel based on a plant function organization scheme.

Only one alarm message can be displayed in an alarm window at a time. However, it is possible for more than one alarm message associated with a given alarm window to be active at the same time. Therefore, a prioritization scheme was defined to determine which alarm message will be displayed in an Overview Panel window when more than one alarm message is active. The alarms not displayed are stored in a queue of active alarm messages associated with a given Overview Panel alarm window. If there are alarm messages in the queue, a symbol appears in the alarm message window to alert the operators that queued messages exist. The lower-priority alarm messages in the queue can be accessed from the Support Panel.

The AAS consisted of Westinghouse's advanced alarm system called AWARE. Additional information regarding the AWARE system design can be found elsewhere (Carrera et al., 1996; Easter and Lot, 1991; Levett et al., 1995). A key feature of this AAS that distinguishes it from other computer-based alarm systems is that it is organized functionally. The alarm layout is based on a functional goal-means decomposition of the plant (Rasmussen, 1986). Further, prioritization among alarm messages is only performed within narrowly-defined queues of alarms that all relate to the same plant function. No attempt is made to prioritize alarms across functions. This contrasts with many other computerized alarm systems that assign each alarm a predefined indication of urgency for operator action, with some alarms always coded as "high" urgency for action and other alarms always coded as "low" urgency. In this alarm system, operators do not have to consciously consider relative alarm priority. The alarms that appear in the alarm windows at any given point in time are expected to be addressed by the operators.

The Support Panel is displayed on the dual-headed VDU workstations. One display provides a reduced version of the Overview Panel that allows the user to see in which areas there are alarms. From the Support Panel, operators can also access all active alarms in a queue. They can examine the list of alarm messages whose priority did not permit them to be displayed on the Overview Panel or that have been recently "bumped" off the Overview Panel by messages of higher priority. They can also see the logic behind any alarm message, the set-points and inputs to the logic, and various parsings of the chronological alarm message list.

In addition to the AAS, there were two other alarm systems available to operators. One was the original tile-based alarm system that was implemented at the time the plant was built. The tiles are typical of conventional alarm tiles that are organized into matrices by plant functions and systems.

The third alarm system encompassed a set of "base" alarms that came with the plant computer upgrade as a standard feature. This alarm system is a VDU message list display that is chronologically organized. It is accessible from the two-headed workstation VDUs. While the alarm processing and alarm display capabilities are more sophisticated in the AAS, the base alarm system had greater coverage in that it contained alarm setpoints associated with every plant parameter on the plant data highway.

3.3.2 Computer-Based Procedure System

The EOPs were implemented in Westinghouse's Computerized Procedure (COMPRO) system. Additional information regarding the COMPRO system design can be found elsewhere (Lipner, 1994; Lipner and Kerch, 1994; Lipner and Orendi, 1992).

The CBP is based on the standard PWR two-column format EOPs. The CBP uses the written procedures as the basis for textual displays. Prompts guide the operator step-by-step through the EOPs.

The CBP is connected to the plant computer database. As a result, it is able to present the operator with current plant parameters. Key features of the CBP include:

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- Resolution of procedural step logic for the operator and indication of whether a high-level step is satisfied or violated;

- Presentation of the detailed sub-steps and supporting plant parameter data that provide the basis for whether the high-level step is satisfied or violated;

- If a high level step is violated, the contingent step information is presented in the adjacent column (i.e., the "Response Not Obtained" column);

- Indication of when criteria to transition to another procedure have been met and provision of a link to the new procedure;

- Continuously monitoring of plant parameters associated with the following procedure elements, and alerts the operator when associated criteria are satisfied:

  - Fold-out pages
  - Critical safety functions
  - Continuous action steps
  - Notes and Cautions

These functions are performed by the operator in paper procedure use and impose additional monitoring and memory demands.

The CBP is completely user-paced and user-directed. It is user-paced in the sense that the system only advances to the next step at the prompting of the user. It is user-directed in the sense that it is the user who has ultimate control and responsibility for how the procedures are utilized. While, the CBP indicates whether a procedural step is satisfied or violated, and what action this implies (e.g., taking a control action at the board, following the steps in the Response Not Obtained column, transitioning to another procedure) the operator can always override the CBP. While the CBP presents procedural steps sequentially, there are navigation facilities that allow the operator to get to any step in any EOP procedure at any time.

The CBP operates on a double monitor workstation. The procedural information appears on the first VDU and supporting or supplementary procedural information appears on the second VDU (e.g., graphs, critical safety-function status trees). The procedural information VDU is divided into four areas, which appear from top to bottom as follows:

- Pull down menus
- Parallel information
- Current procedure information
- User prompts

The current procedure information area provides the status of the current high level step and the supporting sub-steps. The two-column format of the EOPs is preserved. If the high level step is violated, then the contingency actions in the 'response not obtained' (RNO) column appear. If the high level step is satisfied, the information in the 'RNO' column is not displayed unless the operator requests to see it.

The parallel information area is used to display information that needs to be monitored in parallel (e.g., status of the critical safety functions, fold-out page criteria, and cautions).

The user prompt area is the primary navigation mechanism. Phrases such as 'continue to Step X' or 'Transition to Procedure X Step Y' are displayed in this area to indicate the recommended next movement within the EOPs. The user moves through the EOP steps by clicking in the 'prompt' area.

The pull down menu provides a mechanism for accessing supplemental information as well as a mechanism for navigating to any procedural step in any procedure at any point in time.

The CBP was used by the shift supervisor who was the senior reactor operator (SRO) on the crew. Since the CBP was connected to the plant computer, the shift supervisor could go through the procedure without having to ask board operators for the values of plant parameters.

There was no automatic control of plant equipment by the CBP and no soft controls associated with either the CBP or the Graphic Display System. Control actions could only be made by operators at the control board. Thus, when the procedures specified control actions to be taken, the shift supervisor had to instruct the operators to carry them out.

3.3.3 Graphic Display System

The graphic display system contains a variety of display types including:

- Graphic process displays that provide plant parameter information organized around plant system mimics
- Predefined trend displays of key plant parameters
- Operator-defined tailored trend plots of chosen plant parameters

Additional information regarding the general approach to the display system design can be found elsewhere (Easter and Watson, 1997).

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There are several navigation mechanisms to bring up displays of interest including:

- Hierarchically organized pull-down menus
- Pokefields that allow direct access from one display to another related display by clicking on a pokefield within the first display
- Paging (up/down/left/right) between displays

Another key feature of the Graphic Display System is that it includes zoom and pan capabilities. This allows the operators to 'blow-up' areas of interest to see more detail or to make it visible from farther away.

The Graphic Display System is accessible from any of the workstation VDUs. It is implemented in a windowing system that allows operators to bring up multiple displays in different windows on a given VDU. The size and location of the display windows can be manipulated and overlapped. Operators can switch between displays and retrieve those that were hidden.

3.3.4 Operations Philosophy and Philosophy of Use of the HSI Systems

The introduction of computer-based HSI systems into the control room changed the amount of plant state information available to operators. It also changed the accessibility of the information to different members of the crew. In particular, CBP provided the shift supervisor with the plant state information required to work through the procedural steps. It was no longer necessary for the shift supervisor to ask the board operators to read plant parameter indications off the control board and say them aloud in order for the shift supervisor to determine whether a procedural step is satisfied or violated. The CBP provided that information directly.

This change in technology introduces the opportunity to change the traditional roles assigned to crew members in responding to emergencies. This became apparent to plant management during the simulator testing of the HSI systems that occurred several months prior to the beginning of the training period. At the time of the study, plant management was in the process of developing a philosophy of use for the HSI systems.

At the time our observations were conducted, the philosophy of use that had been developed and trained was as follows:

- Following a trip, the shift supervisor was to utilize the CBP to work through the EOP steps. He did not need to ask the board operators for plant state information. He could work independently of the board operators until a control action was needed, at which point he would ask the board operators to take the actions. Minimal guidance was provided with respect to requirements to communicate progress through the EOPs to the board operators. In general, the shift operator was asked to call out "important steps" including any procedure transitions.

- During the first EOP immediately post-trip (the Reactor Trip or Safety Injection procedure referred to as E-0), the board operators were told to focus on monitoring the AAS. The AAS provided alarm messages if any of the automatic safety equipment that was supposed to turn on following a trip did not come on. The operators were told that if any alarms came in indicating that automatic systems had not come on as required, they should take appropriate manual control actions to recover the systems. They were not required to inform the shift supervisor or get his approval prior to taking the control actions.

  All operators were responsible for attending to all alarms. In general, it was understood that the reactor operator would tend to focus on reactor related alarms, and the balance-of-plant operator would tend to focus on secondary side alarms. In this stage of the introduction of the new systems, there was no specific rule about division of responsibilities.

- The shift engineer was responsible for monitoring the critical safety functions and maintaining a broad overview of plant state. His role was to provide advice to the shift supervisor and ensure that any procedure transitions that were made were appropriate to the plant situation.

3.4 Interview Questionnaire

A principal source of data was crew and other personnel responses to interview questions. Prior to the actual data collection, an extensive list of interview topics was developed. The topic list was based on general findings and issues identified in an earlier phase of the project (O'Hara, Stubler, and Higgins, 1996), the general experience of the authors, and comments on a draft set of questions by utility, vendor and sponsor personnel. In addition, background discussions were held with the vendor personnel to gain a better understanding of the control room modernization program and the detailed design considerations of the individual HSI systems.

This complete list of topics was broad and addressed detailed considerations of each area identified in the study objectives. This list and the detailed considerations under each topic is contained in Appendix A. Addressing such diverse topics required interviews with a range of both vendor and utility personnel. The specific subset of questions addressed in interviews with operators is contained in Appendix B.

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3.5 Study Procedures

3.5.1 Simulator Exercises and Observations

The crews were observed and interviewed during their regularly-scheduled week of refresher-training on a high-fidelity training simulator. This one-week training session was the first time the operators were being trained on the use of the AAS and CBP in a high fidelity plant simulator.[1] The operators were already familiar with the Graphic Display System since it had been installed in the plant for several years and was routinely used.

During the training week operators utilized the computerized HSIs to respond to simulated accident scenarios. For pedagogical reasons all the accident scenarios run during the first week of training with the new HSIs were designed to be familiar events that exercised a core set of procedures and were straightforward to diagnose and respond to.

Each of the crews was observed over a two-day period. Typically, one observer attended the training session on the third and fourth day of the training week. This allowed the operators to gain some familiarity in the use of the HSI systems prior to the observation sessions.

Each crew was observed in four training exercise scenarios: A steam line break outside containment, a steam generator tube rupture, a small break loss of coolant accident (LOCA), and a loss of all feedwater event. Each scenario typically included a main malfunction that led to a reactor trip as well as several additional small complicating malfunctions (e.g., a controlling Pressurizer Pressure channel failed high).

Following a trip, the shift supervisor was responsible for using the CBP to work through the EOP. The board operators were responsible for monitoring and responding to the AAS and taking control actions at the board.

The shift engineer played a role equivalent to that of a Shift Technical Advisor. He was typically called out of the control room prior to the reactor trip (so that he would not be aware of the early evolution of the event) and then called back in approximately 10 minutes into the event.

For each crew, one scenario was included where the computer system failed and the operators had to transition from use of the new HSI systems to use of the analog HSIs only. The scenario was a small break LOCA. The crew used the CBP, AAS and Graphic Display System through Step 10 of E-0, the initial post-trip EOP procedure. At that point, all the computerized systems

[1] Prior to full-scope simulator training, the crews were given preliminary training on the basic design of the CBP and AAS. This included both classroom and limited-scope simulator training.

were turned off and the crew was told that they had lost the plant computer. In the case of the EOPs, the shift supervisor had to transition from the CBP to the paper procedures.

Crews were observed unobtrusively from the instructor's area. Although crews were aware of the observer's presence, a one-way viewing capability allowed the observer to view crew performance during training scenarios without disruption or distraction to the crews. The observer came into the simulated control room during the post-scenario exercise debriefing when the training instructor discussed what went well and what could have been done better with the crews. The debriefing also included discussions of strengths and weaknesses of the computer-based HSI systems in supporting operator performance in the scenario. The observer posed clarifying questions during the debriefing.

The observations were qualitative, i.e., no formal data collection was attempted. The observations provided the opportunity to see how the operators interacted with the new systems and each other. In addition, they provided the opportunity to observe and document cases that illustrate the kinds of complexities that can arise in accident situations and how the new HSIs impacted the ability of the crews to identify and respond to those complications. These notes often provided information to discuss during operator interviews.

3.5.2 Interviews

Operators were interviewed in crews. The crews were typically available for one hour at the end of each of the two days. Given this limited amount of time, no effort was made to address each question in Appendix B with each crew. Instead, for individual crews, questions were selected based on (1) the overall goal to address all questions across crews, (2) the unique events that occurred for a particular crew, and (3) the aspects of the new HSIs that the crews felt were important.

The primary purpose of the interviews was to obtain the operators' perspective on how they used the new HSI systems and how the new systems had affected their performance as individuals and as a team. Questions probed the perceived impact of the new systems on operator workload, situation awareness, distribution of tasks and responsibility among team members, and communication and coordination among the team members.

Other topics that were covered included:

- Whether they felt the available display real estate was sufficient and how it was utilized

- The extent to which they understood and had confidence in the software processing

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- How they felt about the training they had received on the new systems and what additional training they felt would be desirable

In general, the interviewer attempted to elicit reactions to the new HSI systems from the perspective of the shift supervisor, the board operators and the shift engineer.

4 RESULTS

The observations of crew performance and crew interview comments provided complimentary and reinforcing perspectives on how the operators utilized the new HSIs. They provided the basis for drawing broader conclusions about the impact of HSI systems on operator performance, implications for training, and the technology introduction process.

4.1 Observations

In general, operators were able to handle the emergency scenario exercises and had no difficulty using the computerized HSIs to handle the events.

4.1.1 Use of the AAS

The board operators utilized the Overview Panel alarm messages to detect plant malfunctions. Consistent with their training on philosophy of use, the board operators focused on the AAS during E-0. If an alarm message came in indicating a failure of an automatic system, they took the appropriate manual backup action without getting approval from the shift supervisor.

Consistent with training, all operators attended to all alarms on the Overview Panel. There seemed to be no clear division of labor with respect to which operators acknowledged which alarms.

The Alarm Support Panel, available from the workstation VDUs, was generally not used by the board operators. Board operators generally did not check the Alarm Support Panel to see what lower-priority active alarms were present but not displayed on the Overview Panel. In the case of one of the crews, the turbine/balance-of-plant operator, who had a lower workload during the scenario, did have the Alarm Support Panel displayed on one of his VDUs and consulted it.

The Alarm Support Panel was used mainly by the shift supervisor and the shift engineer. Shift supervisors typically consulted the alarm overview display or a display that provided a chronological listing of alarms.

4.1.2 Use of the CBP

In all the scenarios we observed, the shift supervisors were able to utilize the CBP to work through the EOPs with little trouble. They were able to keep pace with the event and transition smoothly between procedures.

Prior work in human factors and human computer interaction (Elm and Woods, 1985; O'Hara, Stubler, and Higgins, 1996; Roth, Mumaw, and Stubler, 1992; Woods and Watts, 1997; Roth, Malin, and Schreckenghost, 1997) suggested that operators might become disoriented due to the narrow 'keyhole' provided by a computerized procedure as compared to paper (i.e., because they can see fewer steps at a time with computerized procedures than with paper) and/or that they might experience difficulties navigating among procedures (i.e., the 'getting lost' problem). No evidence of getting disoriented, losing place in the procedure, or having difficulty finding or navigating to other procedures was observed during the study. Shift supervisors appeared to be able to move readily within and across procedures.

Cases were observed where the procedures (as presented by the CBP) gave operators the option to take actions or make procedure transitions that were inappropriate to the situation.[2] In those instances, operators were able to detect that the indicated action was inappropriate and override the CBP. These cases are discussed in greater detail in the section on illustrative cases.

4.1.3 Use of the Graphic Display System

The main type of display that operators utilized during the emergency scenarios were trend graphics. Operators rarely selected system mimic displays (process displays).

Operators tended to put up multiple trend plots on their VDUs. It was not unusual to see operators divide a VDU screen into two windows and place four trend plots in each. Since each trend plot could have up to four parameters trended, this meant that operators could have up to 32 parameters trended per VDU.

One crew was observed to put up a unique trend display that they had tailored themselves. The operators used the "zoom" feature to create a bold graphic display that allowed them to monitor a parameter trend from a distance. The parameter they were monitoring was Tave. They used one color trend (blue) to define the target value (Tref) and a second color trend (red) to define the parameter value (Tave). They modified the display so that the trends were represented not as thin lines but as solid color areas. As a result, the relative change in shape of the two colored areas provided an indication of the relative value Tave to Tref, and the change over time that could be easily seen and interpreted from a distance.

The display created independently by the operators illustrates two interesting points. First, it provides an example of an 'ecological interface' (Vicente and Rasmussen, 1992) that is designed to make emergent and perceptually salient information that is of importance to the user. In this case, the operators were interested in the difference between Tave and Tref, and how that difference changed over time. They exploited the relative shape of the colored areas for Tave and Tref to make the difference between the two values perceptually salient. Second, it provides

[2] These cases were similar to the types of situations that have been observed to arise with paper-based procedures (e.g., Roth, Mumaw & Lewis, 1994).

an example of how users tailor computerized systems to their needs in ways that are not always anticipated by system designers. This phenomenon has been observed repeatedly (e.g., Roth, Mumaw, Vicente, and Burns, 1997; Vicente, Mumaw, and Roth, 1997). Vicente has coined the term "finishing the design" to describe the phenomenon (Vicente, Mumaw, Roth, and Burns, 1996).

Operators rarely modified or pulled up new displays once a scenario was started. Rather, they tended to select a set of trend plots to display at the start of the session and kept those up throughout the session. This supports the point that operators are reluctant to engage in interface management tasks when workload gets high preferring instead to go with the information that is available rather than taking the time and effort to retrieve new information (O'Hara, Stubler, and Nasta, 1997).

4.1.4 Utilization of Available VDU Display Real Estate and Coordination of HSI Systems

The AAS, CBP and Graphic Display System all included displays that could be brought up on any of the workstation VDUs. One of the questions of interest was what displays different crew members chose to put up and how they utilized the VDU display real estate available to them.

Operators generally packed the available VDU display real estate with information. Operators were observed putting up multiple windows per VDU, occasionally overlapping and/or covering up one display with another. Covering up information by overlapping or covering one display with another was not found to create any problems.

As mentioned previously, board operators tended to put up multiple trend displays on their workstation VDUs.

The shift supervisors put up the CBP on one VDU. The other VDU was used to display information on plant state. Typically, the shift supervisor would put up an alarm display in one window and some trend displays in a second overlapping window.

The shift engineers, because of their broader range of responsibility, were observed to make the most intense use of the two VDU screens allocated to them. For example, in one case a shift engineer was observed displaying the CBP on one VDU so that he could monitor the critical safety functions (which are displayed at the top of the CBP screen). He placed two more windows on the same VDU that presented plant parameter trends. These two windows were overlapped on top of the CBP display so that the critical safety function display on the CBP was still visible. On the second display was a chronological list of alarms in one window, a set of additional trend plots in a second window, and an overview system mimic display.

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4.1.5 Crew Structure and Division of Responsibility

Observation of operator performance during the scenarios indicated that they followed the operations philosophy presented during training; i.e., during E-0, the shift supervisor and control board operators operated in parallel and largely independent of each other. When the board operators took manual action when alarm messages indicated that automatic systems had not come on as required, they generally informed the shift supervisor of the action they took, but this was not always the case (see critical incident described below).

The shift supervisor worked through the procedures using the CBP. There appeared to be considerable variability between shift supervisors in the extent to which they communicated with the board operators as they worked through the procedure and what they communicated to them. One shift supervisor tended to read out loud all the high-level steps, indicating whether the step was satisfied or violated. Other shift supervisors only called out 'important steps' such as procedure transitions, steps where actions were to be taken , and the step goals (e.g., 'we are leaving this procedure because we have to stop safety injection'). A third style observed was a shift supervisor who tended to paraphrase and summarize procedural steps to keep the crew informed of his progress. He would state the problem (what is wrong), the solution path, and the current goal (of the portion of the procedure they were in). He would also read major procedural steps and procedure transitions.

4.1.6 Transitioning from CBP to Paper EOP

Each crew was observed during a scenario where a failure of the plant computer was simulated, so that all the computer systems failed and operators had to revert back to conventional board indicators and paper procedures. The training objectives of the scenario were to provide practice and to assess whether:

- The shift supervisor would pick up the paper-based EOPs and continue through the EOP steps from where he left off with the CBP
- The shift supervisor would pull out the fold-out page and monitor it in parallel with following the procedure in effect
- The shift engineer would pick up the paper status trees and begin to monitor the critical safety functions manually
- The board operators would coordinate with the shift supervisor to provide him the plant parameter information needed to follow the procedures that would have been provided by the CBP

The crews successfully demonstrated all these behaviors. The operators made the transition smoothly and had little difficulty handling the events either before, during, or subsequent to losing the HSI systems.

In the debriefing that immediately followed the scenario where the computerized systems were lost, operators indicated that they had no trouble responding to the scenario without the computerized procedure but that they did miss them. One crew elaborated on the features of the HSI systems that they missed. They indicated that the capability they missed the most was the trending capability of the Graphic Display System. Next they missed the CBP, especially its support with respect to automatic calculation of subcooling, automatic monitoring and alert of critical safety function, and automatic monitoring of foldout pages. One shift engineer indicated that he missed the AAS and CBP that helped him get quickly oriented when he is called in late in the event. These comments reflect the opinions of the crews in general.

4.2 Illustrative Cases

One of the areas of particular interest was the ability of crew members to maintain awareness of:

- The state of the plant
- The state of the procedure (i.e., where they are in the procedure and what they are trying to achieve)
- Whether the procedurally-directed actions are appropriate to the current situation

Roth, Mumaw, and Lewis (1994) demonstrated that these are important cognitive activities that operators engage in when handling emergencies with paper procedures. An important question is whether the new computerized HSIs enhance, leave alone or interfere with these important cognitive functions of operators.

The existing literature has raised concerns that CBPs might interfere with the ability of operators to follow the logic behind the procedure and detect situations where the procedures do not fully apply (e.g., Elm and Woods, 1985). Reasons given include that CBPs provide a narrower 'key hole' on the procedure (i.e., show fewer steps at a time) and that they potentially reduce communication among operators. In the observations, we looked for illustrative cases that provided evidence regarding whether or not the operators demonstrated the ability to monitor the appropriateness of the procedure to the current situation and overrode it in cases where it was inappropriate.

Since the new HSIs were expected to impact communication among the crew, we also looked for cases that illustrated good communication as well as cases that illustrated breakdowns in communication and consequent loss in situation awareness. These cases help illuminate the impact of the new HSIs on team communication and team situation awareness.

Illustrative cases related to these issues are discussed below.

4.2.1 Cases Where Crews Correctly Chose to Redirect the CBP

In the large majority of the scenarios observed, the CBP provided correct information and indicated actions for operators to take that were appropriate for the situation. In those cases, the shift supervisor worked through the procedure smoothly and the crew was able to handle the event effectively.

Three cases were observed, however, where the CBP provided misleading information and/or specified inappropriate action.[3] In all those cases that we observed, the operators correctly detected that the indicated action was inappropriate to the situation and overrode it. This demonstrates the crews' ability to maintain broad situation awareness, monitor the procedural path, and detect when an action indicated by a procedural step is not fully appropriate to the situation. It also demonstrates that the operators recognized that the CBP was a tool to support them and they were comfortable redirecting it when they judged it was appropriate. This is consistent with the design philosophy of the CBP.

The three cases are briefly described below.

Case 1: Steam Line Break Outside Containment Scenario

This case illustrates a situation where operator judgment was required to override an action specified by the CBP, and they did so methodically and conservatively.

When the crew got to the safety injection (SI) termination criteria step, the CBP indicated that the criteria for terminating SI was not met. The operators cycled through the procedure loop twice and the CBP still indicated that the criteria for terminating SI was not met.

The shift engineer determined that it was appropriate to terminate SI based on indications from the Graphic Display System and the conventional plant HSIs. After discussion, the shift supervisor announced to the crew that they would terminate SI and that they could reinstate SI if it was needed. The crew double-checked that SI was not needed and then terminated it. They

[3] As is described below, these cases resulted from a literal interpretation of the paper-based procedures, and would occur with computer-based procedures as well if they are followed literally (cf. Roth, Mumaw, and Lewis, 1994).

then moved through the CBP. Thus, this is a case where the crew correctly determined that SI should be terminated even though the procedure indicated that the literal SI termination criteria had not been fully met.

The issue here was that the procedural step criteria asked if a parameter was 'stable or increasing.' Since the plant was cooling down, the parameter was slightly decreasing (but the decrease was accounted for by the cooldown). The procedures (whether paper-based or computerized) do not consider all the plant data that the operators use in making their determination (e.g., the EOP does not take into account decay heat).

As has been observed with paper-based procedures (Roth, Mumaw, and Lewis, 1994) some procedural steps require operator judgment to determine whether the step has been satisfied. In those cases, operators utilize their knowledge of the plant state and the intent of a procedural step in determining whether a procedural step is satisfied. Case 1 illustrates that the same types of situations can arise with CBPs and that operators are able to recognize those situations and redirect the procedure path just as they would with paper-based procedures.

Case 2: Small Break LOCA

This is a second case where the operators decided to redirect a procedural path. It provides another instance demonstrating the importance of operators' to use multiple divergent sources of information as double-checks. In this case, they used Graphic Display System trends and board indications to independently evaluate the action specified by the CBP. It also illustrates the importance of crew communications and joint decision making in monitoring the appropriateness of the solution path and ensuring that the actions taken are appropriate. Further, it provides an instance demonstrating that situations can arise where the actions specified by the CBP are not fully appropriate given the local context.

The crew was in Procedure ES-1.2 when they reached procedural Step 5 to initiate reactor coolant system (RCS) cooldown. By technical specifications, the system must not cool down at a rate greater than 55 degrees per hour. The CBP computed the cooldown rate over the last hour and determined that it was at a ramp of 55 degrees or less. Thus the CBP determined it was acceptable to initiate cooldown. The CBP resolved the step logic to indicate that the operators should dump steam to cool down.

The shift supervisor asked the board operators to use the steam generators to cool down based on the CBP step. The board operators decided that this was not a good idea based on the trend of the current cooldown rate. They saw that the rate was greater than 60 degrees (when taken over a shorter period of time) and that they were already cooling down rapidly because of SI flow. Therefore, they decided not to increase cooldown rate. Although they had not yet exceeded the tech spec cooldown rate when averaged over an hour at that point in time, if they increased the cooldown rate, the resulting trajectory may have exceeded the tech spec cooldown rate when averaged over an hour at a later point in time.[4] The crew discussed it, and decided to override the CBP and redirect the procedural path.[5]

Interestingly, the training instructor indicated that other crews when coming across the same situation, followed the recommendation of the CBP and took action to increase the cooldown rate. In the instructor's opinion, increasing the cooldown rate was the wrong action to take in that situation. While the observers in the study did not directly observe any cases of this type, the instructor's comment suggests the existence of cases where operators failed to recognize a situation where they should have overridden a CBP recommendation.

Case 3: Small Break LOCA

This is a case where the CBP directed the crews to transition to a function restoration guideline for a spurious reason (a failed sensor). The crew recognized that they should not be in that procedure and exited it. It provides an additional example of the ability of the crews to utilize available control room resources to maintain broad situation awareness and provide an independent check on the appropriateness of procedural directives.

In this scenario, a single channel failure from power range was failed high (sensor failure).[6] At a later point, the plant tripped due to the LOCA. When the operators went through the CBP, a critical safety function became red and the CBP indicated that the criteria had been met to transition to Procedure FR-S.1, entitled 'Response from ECR to Nuclear Power Generation.' The red path was spurious and strictly due to the failed sensor input.

The shift supervisor transitioned to FR-S.1. When in FR-S.1, a procedural step indicated to emergency borate. The crew recognized that emergency boration was not required and that they were in the wrong procedure. The crew recognized they did not have a critical safety function

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[4] The CBP in computing cooldown rate, computed the rate over the past hour. This turns out to be an insensitive predictor of future cooldown rate. It may be that a more accurate predictor would result if a shorter temporal period were used (e.g., last 5 minutes), but it is also possible that more factors (e.g., what else is going on at the time, or is likely to happen next) need to be considered in projecting cooldown rate.

As was demonstrated in this case, operators take more factors into account in predicting future cooldown rate. Most importantly, they consider current and upcoming activities that are likely to contribute to cooldown rate (e.g., SI injection will cool down the plant). The computerized procedure does not do this. There is often a great deal of human judgment involved in steps that on the surface seem like they would be straightforward to program.

[5] This scenario has only one coolant pump running. If only one coolant pump is running it is especially important to cool down slowly.

[6] Normally when this scenario is run, the channel is taken out of scan by the training instructor after the malfunction is detected so that it does not effect the remainder of the scenario. On this occasion, the instructor didn't take the channel out of scan.

violation. They recognized that the red path was due to the failed channel and checked other parameters to establish definitively that the critical safety function was not violated.

This case provides another illustration of the importance of the crew's understanding of plant state, the objectives of the procedures, and the consequences of actions in identifying situations where the actions specified by the procedure are inappropriate and should be overridden.

During the debriefing, the crew also provided some evidence that there were difficulties in team communication, and in both individual and crew situation awareness during the scenario. The shift engineer indicated that he recognized all along that they were not really in a red path. But he did not realize that the crew was in FR-S.1 until Step 4, when the procedure indicated that emergency boration should be initiated. This meant that the transition to FR-S.1 had not been effectively communicated to the crew.

There is also some evidence that the shift supervisor may have not been aware of the transition to FR-S.1. What apparently happened was that the CBP, once out of E-0, automatically checked the status trees. It computed a red path.[7] As a consequence, the button at the bottom of the screen normally used to go on to the next step switched to become the button to transition to FR-S.1.[8] It is possible that the shift supervisor transitioned to FR-S.1 without realizing it. He may have just thought he was pressing the 'Next Step' button. The shift supervisor's recollection was that CBP 'automatically' transitioned to the FR-S.1 procedure.[9]

It should be noted that the difficulties that the shift supervisor had in recognizing the transition to the FR-S.1 may well have been due to lack of familiarity with the CBP interface since it was early in the training period. The main point of the case is not that the shift supervisor inadvertently transitioned to an inappropriate procedure but that the crew recognized they were in the wrong procedure and recovered. This is an important cognitive function that arises with paper-based procedures and needs to be preserved when shifting to the new computerized medium.

The ability to detect and correct an inappropriate procedure transition depended on the knowledge of the board operators regarding plant state, and the appropriateness of procedural actions under different plant conditions. Most importantly, it depended on the ability of the

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[7] It should be noted that the CBP does display the status of the critical safety function as a bar graphic. The critical safety function bars are coded for data quality. Had the shift supervisor noticed the data quality coding, he would have realized that the critical safety function "red path" criteria had not been met and was a function of poor data quality (i.e., the failed sensor).

[8] In actuality, the button to transition to another procedure differs in shape and position from the button to move on to the next step. The shift supervisor may not have noticed the difference, possibly due to the fact that it was early in the training process.

[9] The CBP does not automatically transition to another procedure, so this would not have been possible.

board operators to actively monitor the plant state and evaluate the appropriateness of actions requested by the shift supervisor.

In summary, these three cases provide illustration of the operators' ability to recognize when they are on a wrong procedural path and to take action to redirect the procedural path. This is an important cognitive function that has been observed with paper-based procedures and needs to be preserved when computerizing the procedures.

These three cases reveal that:

- As in the case of paper-based procedures, situations can arise where the CBP provides misleading information and/or indicates inappropriate action.
- In these cases, operators are able to recognize that the CBP is off-track and redirect it.
- The operators double-check the CBP by utilizing the other control room systems (alarms, graphic displays, board indicators).
- Communication among crew members and team decision making are important contributors to the ability of crews to detect these situations and determine appropriate action.

While only three cases were directly observed during the study, discussion with the training instructor indicated that these cases are not isolated examples; other similar cases have arisen with other crews. While in the three cases directly observed in the study, the crews correctly detected when the CBP was off track and redirected it. The training manager also indicated that there was at least one case where a crew did not detect that the CBP was off-track and followed the actions it specified. In that specific situation the actions were inappropriate.

4.2.2 A Case Illustrating Importance of Good Crew Communication and Crew Situation Awareness

In general, crews effectively communicated among themselves and maintained good situation awareness. That is, shift supervisors kept crews informed of progress through the procedures, and the board operators kept the shift supervisor informed of their actions.

There was one case that arose during the study where a significant communication breakdown occurred. The board operators failed to communicate to the shift supervisor that a major malfunction had occurred and that they had taken an important action in response that had terminated the malfunction. As a result, the shift supervisor remained unaware throughout the scenario that a major malfunction had occurred that the crew had detected and corrected. Given that the malfunction had been corrected, the failure in communication was not a serious problem, but the case is discussed because it illustrates the importance of keeping everyone in the crew informed of major malfunctions, actions, and changes in plant state.

In this event, a steam line break occurred outside containment. The board operators identified the break early in the scenario, partly based on the AAS alarms (the alarm message: 'SG Pressure Not Normal') and closed the main steam isolation valves (MSIVs).[10] As a result, when the CBP went through the E-0 procedure, everything looked normal. The shift supervisor was not told about the steam generator problem by the board operators and could not find out from the CBP because by the time the CBP reached the step that checked for this condition, the problem had been corrected. As a result, he did not see or hear about the steam line break and was not aware of it throughout the scenario. When the shift engineer arrived, he was able to detect that the steam line break had occurred based on the alarm history and the panels.

This example illustrates the importance of good crew communication in ensuring accurate situation awareness on the part of all crew members. Neither the board operators nor the shift engineer informed the shift supervisor that a steam line break had occurred and had been terminated. This is an important piece of information that the shift supervisor should have been made aware of.

This example highlights the need for board operators to be cognizant that they need to take an active role in keeping the shift supervisor aware of actions they take and major changes in plant state. Board operators need to keep the shift supervisor informed of plant changes and major actions in conventional control rooms as well. Effective communication on the part of the board operators becomes even more important in computerized control rooms where information may be more compartmentalized. For example, in this case, the primary information source for the shift supervisor was the CBP, and information about the steam line break and the corrective action taken was not available through that medium.

The example also illustrates the value of having multiple sources of redundant information in the control room and multiple crew members observing the information from multiple perspectives. While no one informed the shift engineer that there had been a steam line break, he was able to personally assess the situation based on the alarm history and the board indications. In contrast, the shift supervisor, who had only access to the CBP, had no way of knowing that a steam line break had occurred and been terminated.

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[10] Closing MSIVs early is a good idea in a steam break outside containment because of concern for the safety of people. Some crews close the MSIVs as soon as they get an SI, early in E-0. This is acceptable at this plant.

4.3 Operator Interviews

A summary of the operators' responses is provided below. Operator opinions on the individual HSI systems are presented first. In each case, the positive aspects of the computerized system that operators mentioned are presented first, followed by opportunities for improvements that the operators mentioned. The operator comments presented are generally close paraphrases of what the operators said. In some cases, we quote the operators' own words. In those cases, we use quotation marks to indicate a direct quote.

As pointed out in the introduction, the new HSIs had recently been installed at the plant and were still undergoing testing and fine tuning. Many of the limitations mentioned by the operators were known to the designers and utility management and were in the process of being addressed. Nevertheless, these limitations are worth documenting here because they represent the types of issues that can arise in the introduction of a new computerized system that should be addressed in design and evaluation of new systems.

It should also be noted that some of the suggestions for improvement that were mentioned by operators and are reported below may not be practical or may not be the best design solution for dealing with the issue. The comments are reported because they serve as pointers to interface design issues that may be worth further exploration.

4.3.1 Advanced Alarm System

Positive Aspects

Reduced Number of Alarms

A positive feature repeatedly mentioned is that the AAS reduces the number of alarms relative to the original tile-based system implemented at the plant.

Post-Trip Support

A strength of the AAS that was repeatedly mentioned is that it provides alerts when automatic safety systems do not come on as expected following a reactor trip (e.g., failures in SI, failures in Reactor Trip, failures of the instrumentation and control (I&C) system, a pump problem, a valve problem). This allows the board operators to detect a problem and take corrective action promptly.

Unexpected Event Detection

It was felt that the AAS was most useful in aiding operators to detect when an event was not proceeding as expected (e.g., when automatic systems did not come on as expected, when there were secondary malfunctions or complications). As one operator put it, "It is a good help for the out of the ordinary."

Messages are Specific

The alarm system provides more specific alarm messages (e.g., exactly what channel has failed) than was possible with the traditional tile system. Operators said this reduces the mental and physical activity required to localize a problem in comparison to the original tile based alarm system. As one operator stated, "It makes some connections that we had done before in our head. Before (in the case of a channel failure), we had to look at more parameters to determine the channel failure."

Functional Organization

Operators indicated that the functional organization of AAS is helpful. After a trip, they can focus on the center panels of AAS to get information on the reactor protection.

An operator commented that the old tile-based alarm system was not organized in terms of goals, but operators still thought that way. Operators think in terms of plant protection goals. In contrast, the old alarm system was organized by physical location. The operator indicated that the AAS organization is very helpful.

Understanding of Plant State

Operators indicated that the AAS enhances their understanding of plant state.

<u>Opportunities for Improvement</u>

Number of Alarm Messages Can Be Reduced

While operators said the AAS reduces the number of alarms relative to the original tile based system, they still felt there were too many alarms. Comments made were:

- In some cases, many alarm display windows light up at once, and it is hard to read them all.

- In some cases, there may be many messages in a queue and only one is presented in the alarm display window (the highest priority message). The operators indicated that they did not have time to go back and look at the other messages in the queue on the Support Panel.

- When many alarms come in, it is hard to figure out which is the newest alarm.

Operators felt that the AAS logic needed to be refined to further reduce the number of alarms. It should be noted that the utility was in the process of doing this.

Indications of Status and Expected Conditions Need Not Be Alarmed

Operators felt that some of the alarm messages that come up on the Overview Panel are 'status indicators' that alert operators to conditions that are appropriate and expected given the event. They thought these alarms should not be presented. A repeated comment was that alarms should only be displayed on the Overview Panel to alert operators to unexpected abnormal conditions.

Examples operators gave of unnecessary alarms include:

- When there is an SI, there is an alarm that comes in to indicate that two main feedwater pumps have tripped. The operators felt it was not necessary to have this alarm since they expect these pumps to trip on SI.

- An alarm message comes up saying that steam dumps are open in situations where the steam dumps should be open. In an operator's own words, "The operator knows he is using the steam dumps. The message should not come in. It is taking away time from the operator in order to read the message."

- When an operator shuts down a pump, they felt there does not need to be a message that indicates the pump was stopped.

- When auto makeup comes on, they felt they did not need an alarm.

- If there is high temperature in a system and blowdown actuates, they felt an alarm is not needed to indicate that it actuated. Operators indicated it would be better to create an alarm if blowdown does not actuate in this situation.

Operators generally felt that while these types of messages provide information that, as one operator put it, 'is nice to know,' there are a lot of other messages that come on at the same time. In another operator's words, "The important messages can get lost among the less important messages."

Operators repeatedly mentioned that systems that come on as expected, especially systems that are manually operated, should not result in alarm messages. One operator said, "An operator under high workload conditions does not want status messages telling him that systems are coming on as expected. He only wants to be alerted to the unexpected – if a system is supposed to come in and it doesn't."

It should be noted that at this plant a distinction had been made between status messages and alarms, and the general intent was to place status messages on the Support Panel and only alarms on the Overview Panel. However, the design team that included operations staff had decided that some status messages were sufficiently important that they should appear on the Overview Panel. The operators interviewed appeared to disagree with this decision.

Reading Alarm Messages

While the Overview Panel provides some spatial dedication cues (messages on a particular function always appear in a specific display window), the operators pointed out that, unlike the traditional tile system, there is no absolute one-to-one space dedication of alarm message to position on the alarm panel. As a result, the operators have to read the message. They cannot rely on position of the window to infer the content of the alarm message.

A second concern is that after a reactor trip, many messages are displayed in a window. When a higher priority alarm comes in, there is concern that the operator may not notice the new alarm or may forget the message that was displayed.

<u>Relation to Other Alarm Systems</u>

As noted earlier, three alarm systems are available in the control room. We asked operators what they felt the role of each alarm system was and when they used the different alarm systems.

Operators indicated that the AAS was preferable to the original tile-based system in the case of major plant disturbances and post-trip situations. The perceived benefits of the AAS in comparison to the original tile-based system appeared to outweigh the perceived drawbacks.

Interestingly, the chronological-list base-alarm system was preferred for use during normal operations. Because the base alarm system contains set points on more plant parameters than the AAS, operators indicated that it is more sensitive and provides earlier alerts for the types of small problems that arise day-to-day (e.g., minor equipment malfunctions, status changes in auxiliary equipment). However, as has been documented before, once a major plant malfunction occurs, the chronologically-organized, message-based alarm system becomes ineffective and is abandoned (O'Hara, Brown, Higgins, and Stubler, 1994).

4.3.2 Computer-Based Procedures

The CBP was used by the shift supervisor. It had a significant effect on the shift supervisor's task of working through the EOP. It also had a strong effect on crew communication and coordination because it reduced the need for the board operators to provide the shift supervisor with parameter values called out in the EOPs.

In this section, we focus on the impact of the CBP on the shift supervisor. The impact of the CBP on the team is discussed in the later section on impact of computerized systems on crew performance.

Positive Aspects

Improved Speed and Accuracy

Shift supervisors felt the CBP is a beneficial support system. They felt it allows them to work through the procedure faster and more accurately than with paper-based procedures. One shift supervisor commented that the CBP "gives you a lot of information without asking the operators. You know the information is correct, and it's faster because the operator doesn't have to run around." As a consequence, the crew is faster handling transients with CBP than with paper-based procedures. With some transients, such as a Tube Rupture, it is very important to get through the procedure quickly.

Reduced Supervisor Cognitive Workload

Shift supervisors noted that much of the 'mental overhead' associated with following paper procedures are handled by the CBP, thus reducing the shift supervisor's cognitive load. Among the things automatically done by the CBP that were mentioned by operators were:

- Plant checking is done automatically by CBP. Only if some checks fail is it necessary to go to the panel operators. With the paper version, the panel operators have to check every step.

- There are some difficult EOP steps (with complex logic); the CBP resolves the logic and identifies whether a step is satisfied or violated.

- The CBP keeps track of the status of critical safety functions, continuous action steps and fold-out page criteria.

Shift supervisors noted that they missed having the CBP in the scenario where it is unavailable and they have to transition to paper procedures.

Reduced Board Operator Cognitive Workload

From the board operators' perspective, since they no longer have to serve as the eyes and ears for the shift supervisor, they can do their jobs more efficiently without being interrupted.

Opportunities for Improvement

Opportunities to Streamline Wording

Several operators felt that the CBP provides too much detail. They did not feel it was necessary to repeat all the detailed sub-steps that appear in paper-based procedures. There was a general consensus that the power of the computer has the advantage of providing results without having to show all the details that appear in the paper-based procedures.

The primary concern was that there is too much to read. One operator pointed out that it was not necessary to transfer the entire wording contained in the paper procedures as was attempted in the CBP. The wording could be adapted to the computerized system. For example, if a step is satisfied, there is no need to present the detailed criteria; it is enough to indicate the status (e.g., Pumps running). It should be noted that the designers were careful to leave the wording of the procedures the same as the paper versions, in part to avoid changing their content which might have additional regulatory implications.

Another operator suggested that the items that are phrased as questions in the paper procedures (e.g., "Check that pressure is greater than X") could be converted to statements in the CBP (e.g., "Pressure is greater than X"). In the present system, the phraseology of the paper-based procedure is preserved.

Several operators noted that if a high-level step is satisfied, they do not feel it is necessary to read through all the sub-steps. They felt that, with the current CBP, they must page through too much to get through the sub-steps.

They feel it is unnecessary to 'double-check' what the CBP is doing by reading the sub-steps because they assume it is processing the logic correctly. One operator noted, "You want to double-check with the Board, not just by reading the details of CBP."

Wording Issues

While the conventions used by the CBP to convert the paper procedures into computerized text generally worked well, operators noted that in some cases the resulting text is awkward or confusing. An example given by one operator is a step that is intended to have operators cool down the plant, preferably by using steam-dump valves.

4 RESULTS

Narrow Field of View

One shift supervisor commented that he could not look ahead as much with the CBP as he would like to, and normally can with paper procedures. He felt that, as a result, operators really have to know the procedures because it is not easy to look ahead. He noted that he would like to see a larger window dedicated to steps so that he could see more steps in parallel (both previous steps and future steps).

Transition to Paper Procedures

One shift supervisor expressed concern that with the CBP, the shift supervisor may be less likely to keep track of what procedure and step he is on. If it was necessary to shift to paper in midstream, the shift supervisor was concerned that he might not remember what step he had been on.[11]

Suggested Modifications

Operators suggested changes or additions to the CBP as follows:

- Highlight the steps that the shift supervisor is supposed to announce to the crew
- There is added information that pops up in the parallel information window such as Cautions and Warnings that are important and should not be ignored. One operator felt the cautions and warnings would be less likely to be overlooked if they appeared in the main text window.[12]

4.3.3 Graphic Display System

Unlike the CBP and AAS, the graphic display system has no specific philosophy of use associated with emergency operations. There are no conditions under which operators are required to use it, nor specific guidance as to what displays should be used at specific times.

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[11] It should be pointed out that all instances of shifts from computerized procedures to paper procedures that were observed during the simulated training showed no deficiencies.

[12] It should be pointed out that no instances were observed during the simulated training where cautions or warnings were missed. In addition, the suggestion to move cautions and warnings into the main text window was only mentioned by one operator. The comment is reported because operators missing cautions and warnings has been a chronic problem with paper-based procedures for which there has been no adequate solution. The computer offers a new medium that has the potential to reduce the problem of missed cautions and warnings. The operator's comment suggests that the appropriate timing and placement of cautions and warning in computer-based procedures may warrant further investigation.

As a result, one of our main interests was to understand who used the graphic displays, what displays were used, and when these displays were used.

Operators indicated that each operator will select the data that he needs on his VDUs and change it as necessary. During normal operations, the shift supervisor is likely to have the base (chronological list) alarm system, trends, and a system mimic display up on the VDUs. The board operators would typically put up trends on their VDUs. One operator noted that, during normal operations, each operator would typically have two trends displayed on one cathode ray tube (CRT) and two schematics displayed on the other CRT.

<u>Positive Aspects</u>

Value of Trends

Operators indicated that trend displays are particularly useful and often used by the entire crew of board operators, shift supervisors and shift engineers. One of the operators said he tailors his own trends at the start of a shift.

Value of System Mimic Displays

Operators indicated that schematic displays are useful for performing or supervising specific maneuvers, system tests, and surveillances rather than for general monitoring of plant state. For example, the shift supervisor can see the flow path and monitor whether an operator is doing a switchover correctly. Another example is that during a surveillance of pressure channels, the operators can bring up a display with all four pressure channels in parallel. The availability of a graphic display makes it easier to check all four prior to disconnecting one of the channels, and then check the other three after one is disconnected. All the information needed is on one display.

<u>Opportunities for Improvement</u>

Navigation and Setup Requirements

It was repeatedly pointed out that operators had no time to bring up or tailor displays under real-time changing conditions. The problem was not that the menu structures were difficult to understand or use. Rather, in dynamically changing conditions, any navigation and/or setup requirements impose too great a workload.

Operator comments included:

- When a reactor trip occurs and you are in a transient, the most important parameter trends should come up automatically or with just one pushbutton. In an emergency, operators do not have time to navigate for the information. Now it can take four or five mouse clicks to get to the right trend. In dynamic conditions, that is too long.

- The problem is not one of understanding how to navigate to the right display. Operators know how to get to the right display but do not have time to do it. It takes away from monitoring.

- In emergencies, if operators have to set up a trend, they will not take the time to do so. If it is preloaded, they will look at it.

- Even though the menu system is straightforward, in a dynamic event, operators don't have time to navigate to the desired trend. If it takes time to get to the picture, operators will use it less.

Operators indicated that the utility is now in the process of creating icons allowing operators to get quickly (with one click of the mouse) to desired trend displays (e.g., trends tailored to particular transients such as a primary trip or a secondary trip).

Difficult to See from a Distance

Several operators mentioned that, while the trend displays are very useful, the trend lines are thin which makes them difficult to see from a distance. The problem is exacerbated by the fact that operators try to maximize the number of trend plots they can put on a VDU, since parameter trends are a valuable aid to monitoring.

Some operators found ways to tailor the trend plots to make them more useable from a distance. One particularly good example is documented in Section 4.1.3.

Premature Introduction

One crew felt that the graphic display system had been installed in the plant prematurely and the process of testing the displays was still going on. They felt that, as a result of possible software bugs, some of the operators may be skeptical in using it.

4.3.4 VDU Display Real Estate

Operators indicated that the screen real estate provided by the VDUs in the control room is usually sufficient. However, they did indicate that they could make good use of additional VDUs if they were available.

One of the crews discussed the use of VDU display real estate at length. The shift supervisor felt he could use more VDUs. He felt that in an emergency situation the CBP should have a dedicated VDU. He also wanted to put up trends and the AAS but did not feel he had sufficient display area to put everything up he wanted to. The shift engineer also felt he could use more than two screens. To compensate, he had to put up multiple overlapping windows. The board operators indicated that they could use more screens as well. In particular they pointed out that it is important to make the trends as large as possible so that you can see them from a distance.

A second crew indicated that they tend to use the VDUs at the Shift Engineer's workstation and the spare station for special tasks. Thus, the board operators did not limit themselves to two VDUs per operator. They used all the VDU real estate available.

4.3.5 Confidence in Software

The operators were asked whether it was easy to understand how the software processes data and what the displayed information means. They were also asked about their confidence in the accuracy of the information provided by the new systems.

The operators indicated that they did not feel they needed to understand the software processes. They felt that accurate software processing should be 'a given.' Their confidence in the accuracy of the system appeared to be a function of how accurately it performed in the past, rather than how transparent the underlying logic was. If there was a need to 'double-check' the accuracy of the computer system, they indicated that they would want to compare the output with that of an independent, redundant source of information in the control room. Related comments include:

- Operators felt that they did not need to 'double-check' what the CBP is doing by reading the sub-steps because they assume it is processing the logic correctly. One operator said "You want to double-check with the board, not just by reading the details of the CBP."

- Operators indicated that the CBP is straightforward, and it is easy to understand what it is doing. The logic behind the AAS alarm messages is less transparent.

- One operator pointed out that because there are some known problems with the current database of the AAS (messages that come on that are clearly incorrect), he was not sure how much to trust it, and therefore, would want to double-check with the original tile-based alarm system. However, he indicated that "once the little problems are ironed out," he would trust the information coming in.

4 RESULTS

4.3.6 Impact on Crew Performance

Operators were asked if they felt the new HSIs changed how they worked as a team when responding to incidents. The operators' responses are summarized below.

Board Operators Have More Responsibility

Shift supervisors as well as board operators confirmed that the new HSI systems have resulted in an increase of responsibility for the board operators. This, in turn, has increased the importance of their knowledge and skill. Operator comments included:

- "Before the CBP was introduced, the shift supervisor had the lead of the group and could supervise operators. Now, board operators have more responsibility. If the AAS alerts them to a system misalignment, they can take the action to correct it. But still, everyone must work within the rules of the EOP procedures."
- "Skills of the operator are more important than before. The board operator must know what he is doing."
- "If you have reliable operators, it is a relief for the shift supervisor. But if the shift supervisor can't be sure that operators are knowledgeable, there can be problems."
- "Board operators are not so guided by the supervisor. It is a great change for them. Before they were more guided by the shift supervisor, and now they must do the work by themselves. They may discuss with each other, but the shift supervisor is working independently."
- "With the paper version of procedures, you are guided...you know what you have to do. With the CBP, you have to watch the plant yourself."

Impact on Communication

The operators also confirmed that the HSI systems have had a strong impact on crew communication. The general consensus was that the amount of communication between the shift supervisor and the board operators went down. What the shift supervisor chose to communicate to the board operators, and the level at which he chose to communicate to them, varied across crews. It was also felt that the quality of communication between the shift supervisor and the board operators improved over the course of the week of training. The impact of crew communication on situation awareness of the various members of the crew is discussed in the next section.

Operators were explicitly asked about their communication style during the scenarios that were carried out that week. Based on a comparison of operator comments from the different crews, there appeared to be wide variability across crews in the nature of communication between the shift supervisor and the board operators. In general, shift supervisors tended to communicate with the board operators more than was strictly necessary for the shift supervisor to obtain information needed for him to follow the procedure. There was an attempt by the shift supervisors to keep the crew synchronized by requesting and/or calling out information that they felt was important for all crew members to know (i.e., that needed to be common knowledge). However, what information the shift supervisor chose to call out varied from crew to crew.

While the content of communication appeared to vary across crews, there was consensus that the quality of communication improved over the course of the one-week training period, suggesting that there was a "learning curve."

Operator comments included:

- "The major impact is on communication. It is more quiet with the CBP."
- "Communication is clearly different with CBP. The shift supervisor asks fewer questions."
- "As a result of the CBP, communication is reduced. The shift supervisor has to be careful that everyone is following along."

Communication Style Varied Across Crews

One operator explained that in this early phase of the introduction of the CBP, the operators do not have approved rules and training regarding the shift supervisor's communication. They do have a list of 'highlight' steps that should be announced. They also have guidance that they should announce transition steps and steps when actions need to be taken. In general different shift supervisors communicated with board operators at different levels of detail.

One shift supervisor said that he tended to read the high-level step titles out loud along with the 'answer' that he was getting from the CBP (whether the step is satisfied or violated), unless it was a minor step (unimportant step).

Another shift supervisor said he called out the important steps, such as transitions. He let the crew know the goal (e.g., leaving this procedure because SI has to be stopped).

Another shift supervisor indicated that he asked fewer questions with the CBP than with paper procedures and that the board operators preferred being asked fewer questions. He indicated that he would ask the crew for the values of parameters when he thought it was important for all the crew members to know the value. He said, "You ask the board operator to make sure everyone knows the answer even if the CBP gave the shift supervisor the answer."

One crew indicated that the communication style had improved over the course of the week. When asked how they developed the improved communication style over the span of the week, they indicated that the crew discussed the problem as a team, but that it was the shift supervisor who developed the more effective communication style. When asked to describe the communication style he developed, the shift supervisor said that he was not just reading out steps in the procedure. He was abstracting out the goals of the procedure and communicating those to the operators. He said that he would state the problem (what is wrong), the solution path, and the current goal – "We are doing this. And, this is our goal." He used his own words, not the explicit steps in the procedure. He would also read out when he was switching procedures and the major procedural steps. The shift supervisor and the board operators agreed that communication was improved as a result.

Communication Required Conscious Effort

Because the CBP provides the shift supervisor with the plant parameter data required to resolve procedural step logic, the inherent forcing function for communication that exists with paper-based procedures is no longer as strong. Communication between the shift supervisor and the board operators is no longer an integral a part of task performance. It has become a distinct, parallel activity that imposes its own cognitive demands on both the shift supervisor and the board operators. The shift supervisor needs to consciously remember to communicate with the board operators and decide what to communicate to them. With paper-based procedures, communication was, by necessity, at a very detailed level, with specific plant parameter values requested and passed. Computer-based procedures free the shift supervisor to communicate with the board operators at a higher level, but he must consciously decide when to communicate and what to say. In turn, because there is less constant communication, the board operators need to make a conscious effort to listen for the shift supervisor. They must also make conscious effort to report to him findings that are relevant but that he would not know about through the CBP because they are not called out in the procedures.

One shift supervisor pointed out that as a result of introduction of the CBP, the shift supervisor "needs discipline" in his communication style. He elaborated, indicating that during the scenarios he had to consciously remember that the operators don't see what he sees with the CBP and explicitly remember to keep them informed of the situation. He felt that the tendency not to communicate is potentially problematic, and therefore, should be addressed in training.

A second shift supervisor noted that sometimes with the new systems, the panel operators were monitoring independently and not paying as much attention to the shift supervisor. He indicated that on occasion, when he required the board operators to take an action, he had to say it more than once before he got their attention.

Communication Improved with Practice

Several crews noted that at the beginning of the week, crew communication had been poor; however, by the fourth day, the communication became more natural and was no longer a problem.

Impact on Situation Awareness of Crew Members

While the introduction of the new HSI systems, and in particular the CBP, clearly affected communication, the effect on operator situation awareness was less clear. Shift supervisors generally felt that their situation awareness has improved. There was more variability of opinion among board operators with respect to whether the new HSIs have positively or negatively impacted their situation awareness. The majority of the board operators felt that their understanding of plant state and their ability to effectively respond to events was improved because they had the freedom to monitor the AAS and board indicators. They also pointed out that with the CBP, while they communicated less with the shift supervisor, the board operators were able to communicate and coordinate more with each other. As a result, they felt that their situation awareness had improved. A couple of board operators felt that the reduced communication with the shift supervisor negatively impacted their ability to maintain the big picture and keep up with the shift supervisor as he worked through the procedure.

The general opinion was that situation awareness improved over the course of the training week as communication between the shift supervisor and the board operators improved.

Impact on situation awareness of shift supervisor

Comments on situation awareness by shift supervisors included:

- "With the CBP the shift supervisor has better situation awareness than without."
- "With the CBP the shift supervisor feels more in control"
- "The CBP neither helps nor hurts from the perspective of situation awareness. It is the same as with paper."

4 RESULTS

Impact on situation awareness of board operators

Many of the board operators' comments stressed improvement in situation awareness because of the attentional resources freed up by the introduction of the CBP and the improved information provided by the AAS. Comments included:

- "For board operators, it improved understanding and handling of events because they now have more attention to pay to the board." (This operator did not feel that reduced communication with the shift supervisor impaired his ability to keep track of situation).

- "Without the CBP, the board operator was so busy giving back data to the shift supervisor that he did not have the mental resources to keep track of the process. Now, the board operator has more attention to pay to the process."

- "Operators have more time to watch the panels because they do not have to provide the shift supervisor with the detailed parameter information required by the EOP steps."

- "Board operators get information from the AAS that they otherwise would not have from conventional plant indicators and alarm systems (thus improving situation awareness)."

A related comment made by one crew was that they felt the board operators coordinated among themselves better with CBP than with paper. The board operators on this crew felt that while they communicated less with the shift supervisor, they had more time and attentional resources to communicate and coordinate with each other.

Other comments suggested that the change in communication with the shift supervisor negatively impacted their situation awareness:

- One of the board operators said that he was able to follow better with the paper version because every step was said out loud. Interestingly, the other board operator in the crew disagreed, attributing the difference in opinion between them to different levels of experience. The operator who did not think the CBP reduced his situation awareness thought he was more familiar with the structure of the EOPs than the other operator.

- Several crews indicated that, at the beginning of the training week, the board operators felt they had lost situation awareness, but that by the fourth day, they felt that their situation awareness was just as good with the CBP as with paper. This is because of the increased discipline of the shift supervisor in communicating with them.

4.3.7 Training

The operators were asked their opinion of the training they received on the new HSI systems. They were asked, "Do you think, based on the training you have gotten so far, that you would feel confident using these new systems in an actual incident? They were also asked, "What additional activities or training do you think is needed before you will feel confident in using these new systems in an actual incident?"

Their answers were thoughtful and informative. While they expressed general satisfaction with the training they had received, they had a number of positive suggestions for additional types of training that would provide broader experience in use of the HSI systems. Their suggestions included:

- Training on more complex scenarios that provided the opportunity to experience a greater variety of procedures and experience using the CBP in multi-fault conditions
- Training using the plant's part-task simulator to provide more opportunity to try out the systems
- Training using a data-base of "canned scenarios" to drive the HSI (One operator said, "It would be nice if there was a way to practice using the CBP on your own, using a simple simulation or database to drive the CBP. Right now, the CBP is available at the plant, but it cannot be seen in action in the control room when everything is normal.")

Many of the operator comments focused on the need for more practice on crew-interaction skills. They felt there was a need for focused training on the new crew roles and responsibilities, communication, and coordination. One shift engineer pointed out that the board operators in that crew used the advantage of extra attentional resources to keep track of the event, but whether other board operators do so depends on their level of expertise and training. He felt there may be a need to train operators to take advantage of the attentional resources that have been freed as a result of the introduction of the CBP.

Several crews pointed out that the need to train as a crew is more important with the new HSI systems because the operators now have more freedom in how they do their job. As a result, it becomes more important to understand how your team-mates perform their tasks. As an example, the different shift supervisors verbalize the EOP steps as they went through them to different degrees. At this plant, depending on scheduling constraints, operators did not always train as a crew, sometimes they trained with operators from a different crew.

Operators also stressed the value of continuing to train in the use of paper-based procedures both as a basis for developing a deeper understanding of the EOPs and as a precaution in case they ever needed to revert back to paper-based procedures. Comments on the importance of training on paper procedures as well as the CBP included:

- "Even when the CBP is used in the plant, it will still be important to train operators to use the paper versions of the procedures. Procedures are more difficult in paper form. Operators would not want to lose that skill. It is especially important for new operators who have not had lots of training on computerized procedures."

- "If the computer fails, you will have to go back to paper, so it is important to train on the paper version of procedure as well."

4.4 Interviews with Head of Operations and Head of Training

The head of operations at the plant and the head of training were interviewed. The primary purpose of these interviews was to provide perspective on:

- The motivation for installing these new HSI systems in the plant and the benefits expected

- The impact of the introduction of these systems on operator performance from the management perspective

- The involvement of the plant personnel in the development and maintenance of these systems

- The introduction and transition process by which these HSI systems were implemented in the control room

- The impact on training

The emphasis was on learning the plant management's perspective on what things they felt worked well and what lessons were learned. Each is discussed below.

<u>Motivation for Installing Advanced Alarm System and CBP</u>

Plant management indicated that the AAS was designed to support alarm reduction. The CBP was developed in an effort to move through the EOPs faster. The plant management wanted the crews to be able to get through E-0 faster, since for some procedures and events, such as a Steam Generator Tube Rupture, it is important to get through these steps quickly. It was pointed out that paper procedures are very time-consuming; for example, indication for some of the valves to be checked is not available in the control room. With the new computer system, all the data points are on the plant data highway and are available to the CBP. Thus, it is possible to go faster.

Impact on Operator Performance

Plant management felt that operator performance using the AAS is improved because it reduces the number of alarms and covers all of the immediate action steps in E-0 and alerts the operators if automatic systems have not responded as expected.

The CBP improves operator performance because operators can move faster. The goal is to finish E-0 in ten minutes. For tube ruptures, it is important to reach pressure equalization between primary and secondary in 20 minutes. The CBP also resolves step logic and points out procedure transitions. Disadvantages include a narrower field of view than paper. In addition, operators cannot flip forward and back as easily.

With respect to the Graphic Display System, plant management indicated that operators have become so accustomed to using it that if they turned it off now, they would get protest screams from the operators. During normal operations, they mostly look at the graphic display system and not the hard-wired instrumentation. With the graphic display system, operators can detect deviations more quickly and take control actions. The Graphic display system is heavily used in checking systems and allows the operators to find a problem "before there is a problem."

Impact of HSI Systems on Crew Communication

Plant management indicated that during initial testing, they identified a potential problem with communication because it was not occurring naturally. They decided that training had to stress the importance of the SRO communicating to synchronize the crew. They initially came up with a list of "most important steps" in the EOPs and asked shift supervisors to announce them. With experience however, they found that that was not useful and it is no longer required. They now require that the shift supervisor announce all the transitions and exits from procedures.

With respect to synchronizing the crew (i.e., making sure everyone "is on the same page" and shares common knowledge), plant management felt that synchronization of the crew happens naturally due to the work that has to be performed. It was felt that once the crew exits E-0 and enters another procedure, there are action steps that require the shift supervisor to ask the board operators to take action. The shift supervisor calls out the action request and then sees the result of the action request in the CBP. It was felt that this was sufficient to synchronize the crew.

4 RESULTS

Impact of HSI Systems on Training

Plant management felt that with the new HSI systems, they have basically the same training objectives as with the older technology, but training should go faster and more efficiently. The first year, they are training crews on basic EOP procedures. In the second year, they plan to introduce more complicated transients in the procedures (such as compound malfunction transients and larger number of procedures covered).

Plant management plans to train operators on the CBP and on paper. In every training period they plan to go through one scenario where the operators will need to transition to paper procedure.

Involvement of Plant Personnel in Development and Maintenance

Plant management indicated that plant personnel were actively involved in the development and upgrade of the new HSI systems. They felt the plant had initially underestimated the level of participation of plant personnel that would be required. As the project went on, they realized the demands were greater than anticipated. They would have liked to assign more operations people to the design effort.

In terms of 'lessons learned' it was felt that it was important to have much more involvement of operations personnel in development of the HSI systems. It was also felt that it was important to install the systems in the simulator first to familiarize the operators, before installing the HSIs in the control room.

Plant management indicated that maintenance of AAS and CBP databases will be done by the plant operations staff. They indicated that the software tools to maintain the AAS and CBP are easy to use. The utility is currently trying to set up a systematic and formal approach to capture "problems and suggestions." The issues identified will be reviewed by a small group that will decide whether to make changes or not.

The plant management also expressed the desirability of establishing an "Owner's Group" to share experiences and information about the new HSI systems.

Verification and Validation Activities

The plant is currently negotiating verification and validation (V&V) requirements with their regulatory agency.

5 DISCUSSION

This study examined the impact of introducing computer-based HSI systems into a conventional nuclear power plant control room. The study examined the impact of the new systems on the cognitive functioning of individual crew members as well as on the structure and functioning of the crew as a team. The study was one of the first to look at text-based CBPs (the previous CBP studies were flow-chart based) and one of the first to look at transition to paper-based procedures upon loss of the CBP system. In addition, the process by which the systems were developed and introduced was considered. Finally, the effect of the new systems on training was examined.

In considering the results of the study, it is important to re-emphasize the constraints:
(1) the observations were made during the first training week using the new systems,
(2) the systems were not completely debugged at the time the study was conducted, and
(3) the scope of the scenarios was limited to relatively straightforward events.

In addition, the study relied on interviews and naturalistic observational methods. No systematic manipulations of HSI features and characteristics were attempted and no quantitative assessment of performance was obtained.

With these limitations acknowledged, the lessons learned from the study have potential implications for design, training, and implementation of advanced HSIs in a conventional plant. These lessons are discussed below.

5.1 Overall Impact of Introduction of Computerized HSIs

Overall the results of the study suggest that introduction of computerized HSIs positively impacts crew performance. The results show that the computerized HSIs expanded the range of data available to the operators and provided increased power and flexibility. They reduced the workload associated with gathering and integrating plant parameter information needed to work through the emergency response procedures, freeing attentional resources to more broadly monitor plant state. The operators were uniformly positive about the new HSIs and would not want to revert back to the conventional control board, alarm system, and paper-based procedures. Further, the training period to utilize the systems was minimal. The operators were able to use the HSIs to handle simulated dynamic emergency events in the first week of training on the simulator.

While the general results were positive, the study identified HSI design issues that warrant consideration in the design and evaluation of new HSIs. The study also identified HSI issues for which there is currently minimal guidance available in the human factors literature, suggesting the need for additional research. These are discussed in the following sections.

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5.2 Alarm Systems

The AAS was found to enhance the operators' awareness of the plant and to support their performance. In this regard, two especially-positive features stood out. First, the alarm messages were more specific and detailed than is possible with a conventional tile system. Second, the alarm messages after a trip were well coordinated with Procedure E-0 and allowed operators to rapidly assess whether the automatic safety systems came on as they were supposed to, or whether manual backup action was required.

The study also reinforced the need for significant alarm reduction during plant disturbances and the difficulty of achieving it. In spite of the fact that the AAS reduced the number of alarms substantially from the tile-based system originally implemented at the plant, and that this was viewed positively by the operators, operators reported that there were still too many alarms activated during a serious plant transient.

A related point that was strongly articulated by the operators is the importance of distinguishing status messages (things expected to happen) from alarms (things expected to happen that did not, and things that should not have happened but did). While it may be important to alert operators to significant changes in equipment status (e.g., an automatic safety system coming on), clear cues should be used to distinguish between alarm messages and status messages. This may include placing them in different physical locations and/or using different audio tones as alerts.

In a rapidly evolving event, operators do not have sufficient time to read alarm messages. Consequently, alarm presentation strategies should be utilized that allow operators to characterize or identify the content of an alarm without having to read the detailed text. Traditional tile-based systems achieved this goal because of the one-to-one mapping between the location of a tile and the content of the alarm (i.e., complete spatial dedication). Other approaches might be to use color or graphic symbols to enable operators to more rapidly process the content of an alarm.

The AAS design goal was to utilize the physical position of the alarm display windows to enable the operators to identify the nature of the alarm without having to read the text. While it is likely that, with training and experience, the operators' ability to establish such a rapid perceptual mapping will improve, their initial comments were that they felt they needed to take too much time to read the alarm message in order to understand the nature of the alert.

Another finding of the study is that during a dynamically evolving event, directly involved board operators do not have time to consult Support Panels to review 'overflow' (lower priority) alarms. They may do so in special cases, or later in the event during low tempo periods, but in general they rely on the alarm prioritization scheme to present them with the most important alarms they should be aware of. This increases the importance of having a robust alarm prioritization scheme that is broadly applicable across contexts. In the current study, everyone interviewed, including the operators and training instructors, appeared satisfied with the prioritization scheme.

A final 'lesson learned' related to alarm systems is that alarm system requirements differ during normal operations and emergency operations. In this plant, operators relied on the chronological-list alarm system during normal operations because it included alarm limits on virtually all the data points on the highway. It was useful for picking up early signs of minor malfunctions (e.g., equipment problems). In an emergency, the large number of alarms generated and chronological list organization made the system ineffective. For emergencies, the AAS that organized alarms into categories (in this case by plant functions) and presented the alarm categories in parallel on a physically distributed board was preferred. This general finding has been repeatedly observed (e.g., Mumaw, Vicente, Roth, and Burns, 1995).

The implication of these results is not that chronological list alarm systems are the most appropriate for normal operations. It is likely that the preference for the chronological list alarm system was due to the fact that the AAS did not include as many specific alarms relevant to normal operations. As the AAS database expands, operators may come to rely on it for normal operations as well as emergency operations. The main point to be drawn from the result is that the goals and uses of alarm systems are very different in normal and emergency conditions, and that these differences should be explicitly considered in the design and evaluation of new alarm systems.

An important aspect of the present study is that it has provided converging support for AAS design and NRC findings previously reported (O'Hara, Brown, Hallbert, Skråning, Persensky, and Wachtel, 2000). The two studies were based on different objectives, different research methods (naturalistic observation and interviews vs. controlled experiment), and different alarm system design. Despite these differences, the general lessons learned from the two studies are strikingly similar, especially with regard to the following:

- There were difficulties in achieving meaningful alarm reduction (in the other study, the number of alarms during simulated process disturbances was reduced as much as 75 percent by alarm processing; despite the considerable alarm reduction, its impact on objective performance was small).

- Spatial dedication is important.

- Message systems have limitations (as discussed in Section 4.3.1, Advanced Alarm System, and in Section 5.2, Alarm Systems; unlike tiles, which can be recognized quickly based on the operator's knowledge of their spatial location, alarm messages have to be individually read, which may create high workload when there are many alarms).

- Operators were reluctant to access alarm support in high workload situations.

- Alarm system requirements were different under normal, disturbance, and post-disturbance conditions.

5.3 Computer-Based Procedures

The most significant findings of the study relate to computerized procedures. This is an area where there have been relatively few studies, and virtually no studies that have examined text-based CBP.

The study provided a positive illustration of the ways in which CBPs can be an effective aid in helping shift supervisors work through the procedures. Observations of performance indicated that operators were able to utilize the CBP to work through the procedures in pace with the events. Interviews with operators, training instructors, and plant managers provided consistent evidence that the computerized procedures improved the speed and accuracy of following procedures.

One of the most important positive aspects of the CBP was that it reduced the shift supervisor's cognitive workload. The CBP reduced the need for the shift supervisor to get plant parameter data from the board operators. Further, the CBP performed many low-level cognitive tasks associated with analyzing and following procedures, including:

- Resolving step logic
- Keeping track of location in the procedure
- Keeping track of steps of continuous applicability
- Assessing cautions, critical safety function status trees, and fold-out page criteria.

As a result, the shift supervisor was able to work through the procedures faster and was less likely to make an error (e.g., skip a step, misinterpret a step logic, miss a transition). Shift supervisors reported that they felt 'more in control' as a result.

To the operators, these positive features appear to outweigh some of the less desirable features of the CBP system. These include the narrower 'field of view' provided by CBP (i.e., in terms of number of steps that can be viewed in parallel as compared to paper). While operators noted that the CBP provided a narrower window on the procedure and made 'looking ahead' (i.e., the ability to flip forward and back through the procedure) more difficult, they did not perceive these as serious problems.

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There was some evidence that on occasion the CBP could provide misleading information or direct the operators down the wrong procedural path. It should be noted that the problem of the procedures occasionally misdirecting operators is not unique to CBP, but occurs with paper-based procedures as well (cf. Roth, Mumaw, and Lewis, 1994). CBP may accentuate the problem, however. One reason is because the computer tends to be more precise and literal in its interpretation of steps. Steps that are left to operator judgment in paper procedures may be operationalized too narrowly when computerized.

As an example, conditions such as "stable or increasing" are sometimes difficult to specify precisely. In the written EOPs, these are left to operator judgment. In converting to computerized procedures, there is a tendency to try to define terms more precisely and in some cases the criteria used by the computerized procedure may be too narrow or may not take into account as many factors as an operator would in the situation. Operators consider not only the behavior of the parameter in question, but also: (1) other current situational factors (such as a cooldown that is temporarily decreasing pressurizer level), and (2) situations that are likely to happen in the near future (such as if the crew is about to take some action that will increase the cooldown rate) that will affect the behavior of the parameter. A prime example is that cooldown will affect RCS level and pressure, as well as SG level and pressure. While operators consider cooldown effects in interpreting and projecting parameter trends (Roth, Mumaw, and Lewis, 1994), the CBP does not.

These observations suggest that caution should be taken in computerizing procedural steps that have classically been left to operator judgment in paper procedure. One option is to follow the approach taken by paper procedures, and leave these steps to operator judgment (i.e., not resolve the step logic for the operator). The CBP examined in this study used this strategy in some cases. There was a category of steps that was defined as 'no evaluation' steps. These steps explicitly required the operator to evaluate the step. The steps were highlighted by the CBP when they came up and no evaluation was provided by the CBP for these steps.

If designers choose to computerize steps that have been classically left to operator judgment, care should be taken to ensure that the operational definition of the step is not overly simplistic and that it takes into account the variety of factors that operators do under the same circumstances. This may require input from operations and training experts, in addition to engineering expertise. Further, the resulting step logic should be subject to extensive testing.

A second factor that may make CBP more prone to misdirect operators than paper-based procedures is that operators may tend to accept the CBP assessment without sufficient reflection. If the computerized procedure says that a step is satisfied, the operator may be less likely to scrutinize and double-check that the step is in fact satisfied (Mosier, Palmer, and Degani, 1992; Layton, Smith, and McCoy, 1994; Roth, Malin, and Schreckenghost, 1997). In contrast, if the operator has to assess whether a step is satisfied on his own (e.g., as happens with paper procedures), he may be more likely to look closely at parameter values and trend information in formulating his judgment. There is a significant body of literature in domains other than nuclear power that suggest that this is the case (Layton, Smith, and McCoy, 1994; Roth, Malin, and Schreckenghost, 1997). Further our findings are consistent with this claim. In two of the three cases where the CBP was off-track, it was not the shift supervisor who detected the problem. The shift supervisor called out actions for the board operators to take. It was the board operators and shift engineer who recognized that the actions were inappropriate to the situation. The question of whether CBPs encourage complacency in the user and how to structure crews to optimize the possibility of catching when a CBP is off-track is an important area for further research.

It should be recognized that the particular CBP under study was in the early stages of introduction and that its database was still in the process of being fine tuned. Most of the specific cases observed where the CBP misdirected the operators may be corrected through changes to the database. Further, while the focus here is on cases where the CBP has the potential to misdirect, it should be stressed that overall the CBP is likely to reduce the potential for operators going off track by skipping or mis-evaluating a procedural step.

The main reason for focusing on cases where the CBP is potentially misleading is that experience with decision aids in other media and other domains suggest that situations where a decision aid provides misdirection will occasionally arise (Billings, 1996; Mosier, 1997; Roth, Bennett, and Woods, 1988; Roth, Malin, and Schreckenghost, 1997; Roth, Mumaw, and Lewis, 1994). Given that situations may arise where the decision aid is off-track, important questions are:
(1) Can operators detect when the decision aid is off track? (2) Are they able to redirect the decision aid and get back on track?

In the three cases we observed in the study, operators were able to correctly detect that the CBP direction was inappropriate to the situation and overrode it. The examples illustrate important positive features of the CBP, and raise questions about the conditions that are necessary to foster the ability of crews to detect that a CBP is off-track and redirect it.

The first point is that the CBP was designed with the recognition that the person using the CBP is the cognizant decision-maker. The design philosophy was that the CBP is a tool to support that person. As a result, it included a number of features that enabled operators to redirect the CBP when they determined it was off-track.

For example, the CBP allowed the operator to override it at any point. At any point, the operator could move to any other place in the same procedure or to any other procedure. The fact that we observed cases where operators needed to redirect the procedural path reinforced the importance of including features that allow operators to override the CBP and move to any other procedural step of their choosing in the CBP.

The second point relates to the conditions necessary to foster the ability of crews to detect that a CBP is off-track and take action to redirect it. The findings suggest the importance of having (1) multiple diverse sources of information available to operators in the control room, and (2) effective communication among the operators in order to detect and correct cases where the CBP is off-track. In some of the cases we observed, it was not the shift supervisor, but rather one of the other crew members who pointed out that the actions specified by the CBP were inappropriate given the situation. The ability of the operators to recognize that the actions specified were inappropriate depended on (1) accurate understanding of current plant state, (2) solid knowledge of the goals and assumptions of the procedures and the consequences of the actions indicated by the procedure, and (3) strong communication between the shift supervisor and the board operators, that allowed the board operators to keep track of the procedural path that the shift supervisor was on.

While the study provides suggestive evidence of the kinds of factors that contribute to the ability of crews to detect if a CBP was off-track, more research is required to fully address this issue.

The study also has implications for training. The findings highlight the importance of training operators to utilize multiple independent sources of information in the control room (i.e., alarms, graphic displays, and board indicators) to double-check the CBP. This was the training philosophy adopted by the plant observed in this study.

The study also suggests the importance of training good communication skills to make sure that the crew maintains common understanding of the current state of the plant and the objectives and current state of the procedures. Our observations reinforced the importance of developing better guidance on what makes for effective team communication. While the plant management and training staff recognized that good crew communication was important, the guidance for the operators as to what constitutes good communication was not finalized and was in development. In fact, these training sessions were being used as the basis for the guidance. As a consequence, there was wide variation among the crews in communication style. In some cases, breakdowns in communication were observed. The lack of guidance on what is good communication reflects a gap in the research literature as to what constitutes good crew communication. There is currently active research in the military on what factors are associated with high reliability crews, what constitutes effective team communication, and what training is required to develop good communication skills (e.g., Salas, Canon-Bowers, and Johnston, 1997). Additional work in this area is needed to synthesize the available research results into guidance as well as to extend the results to nuclear power plant applications.

Finally, the results reinforce the importance of operators having a thorough understanding of the goals and response strategies underlying the procedures. The crews observed in the study had detailed training on the procedures and extensive experience using paper-based procedures. This may have facilitated their ability to detect when actions specified in the procedure were not appropriate to the specific situation and override them. A question arises whether the same would be true of crews that were not initially trained with paper-based procedures. Can the shift supervisor pick up the goals and logic behind the EOPs given the narrower field of view and automatic logic resolution provided by the CBP? Can board operators pick up the goals and logic behind the EOPs given that all the procedural steps are no longer voiced aloud to the crew as happens with paper?

A question that arises with respect to CBP is what happens if the CBP system fails and the operators must revert back to paper-based procedures. Concern has been expressed in the literature about whether operators would be able to locate their place in the paper-based procedures and take-over the tasks that had been done automatically by the CBP. This study provided one of the first opportunities to examine the transition from CBP to paper-based procedures. The results indicated that operators were able to transition smoothly to paper-based procedures in a simulated failure of the plant computer. The operators were able to find their place in the paper procedure and take over tasks that had been done automatically by the CBP, such as reviewing the critical safety function status trees and the fold-out page criteria, without difficulty. It should be noted, however, that the particular scenario where the computer failure was simulated was a simple accident situation and the transition to paper occurred early in the event (while still in E-0), before many procedure transitions were made. Also these crews were highly practiced on the use of paper-based procedures, and only recently introduced to the CBPs.

While the finding that operators had no difficulty transitioning to paper under these conditions is encouraging, more study is required to determine whether transfer to paper can occur smoothly in complex situations by operators whose primary experience has been in the use of computerized procedures.

5.4 Graphic Display System

Consistent with previous research, the results reiterated the importance of trend displays to support monitoring of plant state during both normal and emergency operations (cf. Mumaw, Vicente, Roth, and Burns, 1995; O'Hara et al., 2000; Roth, Brockhoff, Rusnica, Kenney, and Kerch, 1997; Vicente, Mumaw, and Roth, 1997). The trend displays were mentioned by all the crews as the most valuable displays during both normal and emergency operations. They were also mentioned as the displays they most missed in the scenario that simulated a loss of the plant computer. Trend displays support broad situation awareness by enabling operators to see at a glance whether parameters are staying constant or changing, the direction and speed of change, and approaches to limits.

An important observation is that because of the high-tempo, dynamic nature of process control, and the need for operators to move around the plant, it is important to create displays that can be seen from a distance. Operators relied on putting up trend displays as their overview displays.

The general outline of a trend can be seen from a distance, even though the exact values cannot. Operators indicated that they wished the trend lines were thicker so that they could be viewed from farther away. To overcome this problem, operators created their own graphic display that could be readily interpreted from a distance. The display exploited the ability of people to detect changes in the shape of objects to allow operators to quickly assess from a distance the deviation of a parameter from target and the direction of change over time. This is an excellent example of an ecological interface display (Vicente and Rasmussen, 1992).

It was also found that in dynamic emergency conditions any requirement for display navigation or display set up may be too much. Any requirement for set-up or navigation is an added burden on operators during dynamic emergencies and should be minimized. While operators liked and used the trend displays, they indicated that in high tempo situations such as an emergency, they could not afford to take the time to set up a particular trend display. There was an expressed desire to predefine displays and to have them come up with just one pushbutton mouse click. This is a more general representation of the reluctance noted above for operators to access alarm support displays.

This finding is consistent with the findings of a recent NRC study of interface management, such as display configuration navigation (O'Hara, Stubler, and Nasta, 1997). That study found that operators were reluctant to engage in interface management tasks in high workload situations. O'Hara et al. have noted that this reluctance to access information not presently available and the keyhole effects created by VDU-based interfaces creates the potential for operator performance to become data-limited, i.e., crews may miss important information because it is not contained on the presently available displays.

The operators reported that the system mimic displays were also valuable, but we did not observe them using such displays often during the emergency scenarios. The likely reason is that, according to the operators, system mimics are mostly used to support specific tasks such as tests or inspections that require a detailed view of a particular system (e.g., a particular valve maneuver). It would be necessary to observe operators during normal operations in the plant to get a better assessment of how the operators use those types of displays (cf. Vicente, Mumaw, Roth, and Burns, 1996).

5.5 Confidence in Software

Operators did not appear to be concerned with following the software logic on which the HSI systems were based. Operators assumed that the software logic would be correct. They did not feel a need to double-check system logic in real time. For example, in the case of the CBP, operators did not feel a need to go through every procedure sub-step to assess for themselves whether a step was satisfied or violated. They relied on the CBP to resolve the logic correctly. Rather than retreading the same path as the HSI systems, operators preferred to double-check system conclusions using independent methods. For example, operators assessed plant state independent from the CBP based on independent sources of information such as alarms, graphic displays and board indicators. They typically did not check the specific parameters and logic used by the CBP.

The operators' approach to monitoring the performance of the computerized system is consistent with results in other studies of supervisory control of automated systems both within and outside the nuclear domain (Roth, Malin, and Schreckenghost, 1997; Tenney, Rogers, and Pew, 1995; Vicente, Mumaw, and Roth, 1997). The results have implications for the design of software systems. First, the reliance of operators on the accuracy of the software logic places additional emphasis on ensuring the accuracy of the underlying software. While operators don't want to have to 'shadow' or 'second guess' the computer system to make sure they are on track, it is important that they have confidence that the systems will generally give correct information. Second, the results emphasize again the importance of including multiple, independent and redundant sources of information in the control room to allow operators to detect problems.

5.6 Impact on Operations and Crew Structure

The introduction of new HSI systems, particularly CBPs, can affect the structure and dynamics of the team as a whole. This in turn can affect the quality of decision making. We observed that the introduction of the CBP had broad effect on the cognitive performance of individual crew members as well as on the functioning of the crew as a team. It affected the scope of responsibility of the different crew members, the communication pattern among crew members, and the situation awareness of the different crew members. The change in crew member responsibility and crew structure have implications for training as well as human performance and reliability.

The shift supervisor and board operators were able to work more in parallel. The shift supervisor concentrated on working through the procedures and the board operators concentrated on monitoring the AAS, graphics display, and control board HSIs. The change in crew structure appeared to have two consequences. On the one hand, the shift supervisor and the board operators, individually reported improved situation awareness and greater confidence in the accuracy and speed of their performance within their own locus of responsibility. Shift supervisors reported that they felt they could work through the procedure faster and more accurately. Board operators reported that they felt they were able to maintain better situation awareness of the plant state and to take appropriate control actions. On the other hand, the ability to maintain awareness of each other's situation assessment and activities appeared to require more conscious attentional effort than before.

The cognitive workload associated with following the procedures appeared to have been reduced. The shift supervisor had less need to rely on the operators to obtain information about plant state.

As a result, shift supervisors reported that they felt more in control and that they experienced improvements in situation awareness. While the computerized procedure reduced the shift supervisor's workload in some respects, it introduced a new element of workload. The new elements included the need to keep the crew informed of his assessment of the situation and the status and direction of the procedural path as he worked through the procedure. Shift supervisors reported a need to consciously remember to inform the crew of their status through the procedure and to consciously formulate what to communicate. The new communication requirement is a substantial cognitive task that appeared to improve with training and experience. Shift supervisors varied in the extent and content of their communication to the crew, and crews reported that communication improved over the course of the training week. The variance among people and across time suggests that this is a skill that can be improved with training and experience.

Similarly, the introduction of the CBP changed the cognitive load, task responsibilities, and communication requirements of the board operators. Because the board operators no longer needed to provide detailed plant parameter information to the shift supervisor, they had more attentional resources to devote to monitoring the AAS, graphic displays and control board. From this perspective, they felt they had opportunity for greater understanding of plant state and thus better situation awareness.

At the same time, the board operators were working more independently from the shift supervisor. They had more responsibility and less direct supervision. This has several consequences. First, as reported by the operators, the fact that the operators were now working more independently meant that their knowledge and skill became more important. Second, while operators reported that they felt their understanding and situation awareness of plant state was better, their ability to maintain awareness of the progress through the procedure required more cognitive effort. Procedure awareness depended on the skill of the shift supervisor in communicating to operators progress through the procedure. It also depended on the knowledge operators had of the structure and objectives of the procedures. Further, because the board operators' focus was more on monitoring the plant, they had to consciously attend to keeping track of the shift supervisor's progress through the procedures. The need to pay attention to the shift supervisor to recognize when he is communicating something important to them becomes a secondary task. One crew in particular mentioned that the shift supervisor had to occasionally repeat a request to the board operators because he had failed to get their attention the first time.

Generally, the board operators indicated that they were able to maintain awareness of progress through the procedure, particularly as the week progressed. The main point is that with the new systems, maintaining awareness of the shift supervisor's progress through the procedure becomes a separate task that requires knowledge, skill and devotion of attentional resources on the part of both the shift supervisor and the board operators. This activity needs to be recognized and explicitly trained.

There is also a need for board operators to keep the shift operator informed of key findings they observe during monitoring and important control actions that they take. While generally board operators did so, there was one case where key information was never communicated to the shift supervisor, and he was not able to pick it up from the CBP. This case highlights the importance of communication, the potential for communication breakdown, and the need to explicitly train for effective communication.

To summarize, a major finding of the study is that the new HSIs resulted in a change in the information available to the different members of the crew and the communication pattern among crew members. Because the shift supervisor and board operators are attending to separate sources of information, the need to keep each other informed to insure a common frame of reference is potentially more important, but more difficult. More research is needed to understand the factors that contribute to a shared frame of reference among crew members and to establish the impact on crew performance and reliability of the degree to which crews share a common frame of reference as opposed to maintaining different perspectives.

5.7 Implications for Training

The study raised two issues with respect to training. One deals with training on the use of the new HSI systems in handling emergencies. The focus of the training was on handling events. There was little focus of attention on training how to most effectively utilize the HSI systems in handling the events. An open question is whether operator performance in emergencies would be improved if there was explicit training on effective use of the available HSI systems.

The second training issue raised by the study deals with training crew communication skills aimed at developing shared situation awareness among crew members. The study reinforced the principle that in a control room environment, key information is distributed among crew members. The quality of decision-making depends on the ability of everyone of the team to be aware of important control actions about to be taken and to evaluate the appropriateness of the actions based on their knowledge and perspective. We observed a number of critical incidents where inappropriate control actions suggested by the shift supervisor based on the CBP were caught by the board operators or shift engineer who had different sources of information available to them. The study further highlighted that advanced HSI systems increase the level of knowledge and understanding of individual crew members through increased availability of information. On the other hand, they can increase the compartmentalization of knowledge, so that different crew members are more likely to be in possession of different information. This places an increased premium on effective communication among crew members.

We observed wide variability among crews in the extent and content of their communication. The impact of the differences in communication style on individual and crew situation awareness and quality of team decision making is not well understood. More research is required on this topic in order to provide better guidance for development and evaluation of training programs on crew decision making.

Training on Use of the HSI Systems

While operators were introduced to the features of the HSI systems, there was no effort within this timeframe to focus on how to best exploit the systems in different situations, either normal, abnormal, or emergency. The focus of simulator training was on handling emergencies properly. There was little discussion on how the HSIs were used during a scenario, or how they could have been used better. It was up to the individual crew members to decide how to use the HSIs. As a consequence, there appeared to be lots of individual variability within and between crews with respect to extent to which they used the different systems (e.g., the graphic display system) and how they used them.

The lack of explicit training in the use of the HSI systems reflects variously (a) an acceptance and/or expectation that operators will develop familiarity with the various features of the systems informally on their own; that there is no formal need to teach this type of knowledge and skill, and (b) an acceptance and/or expectation that different individuals will tailor the systems to their own personal style (e.g., that different operators will choose to put up different graphic displays or different collections of windows on their VDUs). A similar finding was observed at other plants where new computer-based HSI systems were introduced (Mumaw, Vicente, Roth, and Burns, 1995). In that study it was found that operators had developed clear strategies for managing the HSI that evolved over time and were disseminated across operators and crews, but it was all transmitted informally.

While it is important to guard against over-regimentation and to allow operators flexibility in tailoring their VDU workspace to their particular needs, there may also be value in formally introducing operators to effective ways to use the computerized system. Further, such flexibility increases the demands on operators to engage in tasks not directly related to process control. As noted above, operators are often reluctant to perform such tasks in high-workload situations.

Training and Guidance for Team Situation Awareness

The implications of the above discussion for team training include:

- It is important to train the shift supervisor to keep the crew informed as he moves through the procedures.
- It is important for operators to train as a cohesive (intact) crew, since it is important for team members to learn the specific communication styles of their team-mates

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- A useful technique may be to cross-train operators so that each is aware of the communication needs and burdens of the other (e.g., have the board operators' experience using the CBP).

- It is not clear whether the natural demands for interaction that emerge from using the procedure (e.g., the need for the shift supervisor to ask the board operators to take action) are sufficient to provide a common frame of reference, or whether more guidance on communication should be provided.

- There may be differences in training requirements between "new" crews and "refresher" training. Current crews have had the opportunity to learn the structure and logic of the paper procedures that may help them transfer to computerized procedures. The same level of expertise may have to be provided for new crews.

- It is important to train on paper procedures and on the transition from HSI systems to paper procedures.

6 CONCLUSIONS AND RECOMMENDATIONS

The introduction of computer-based HSI systems significantly affects crew structure and crew communication. These changes have implications for human performance and reliability. The fact that the crew is using multiple independent sources of information and multiple independent perspectives may increase the crew reliability by increasing the probability of detecting and correcting errors in situation assessment, thus reducing the potential for errors of intention. However, the improvement in performance and reliability depends on the ability of the crew to effectively communicate and maintain a shared situation awareness. Thus, there is need for research to better understand the implications of the types of changes in crew structure observed in this study on communication and individual and team situation awareness. The knowledge gained in such research can support the development of guidance on effective crew structures and styles of crew communication for high-reliability team performance.

Based upon the findings and issues discussed in this report, the following recommendations are made regarding future research:

1. This study examined the initial introduction of new HSIs to operators for use in handling events in a dynamic, full-mission simulation. A longitudinal investigation of how new HSI systems are implemented over time to observe full transition and operator acceptance in the plant and in training exercises is recommended.

2. The research can be extended to more challenging conditions. For example, the use of the systems for handling more complex events should be investigated. Such complex events can include situations where there are potentially misleading indicators (e.g., Roth, Mumaw, and Lewis, 1994). Another situation can be failure of the new computerized HSIs at a more cognitively-demanding time, such as when the crew is far into an event and there are multiple aspects of the EOPs being followed, with numerous steps of continuous applicability being monitored, and an extensive procedure history to transfer to paper.

3. Our study utilized naturalistic observational and interview methodologies. A more formal experimental investigation of the effects of paper vs. computerized procedures would provide the opportunity to systematically quantify the magnitude of the effects and issues discussed above. An experiment could address:

    - Quantitative differences in performance:

        - Time to complete critical steps
        - Errors of execution, such as skipping steps, missing transitions, and missing cautions

- Measure the situation awareness of crew members, such as board operators, shift supervisors and shift engineers

- Measure the effects on communication to determine:

  - What the shift supervisor should say as he reads the procedure
  - Where the acceptable limits are for a board operator taking action without alerting the shift supervisor and getting his approval
  - Where the acceptable limits are for a board operator to decide not to inform the shift supervisor that an action was taken
  - If the communication that takes place when the shift supervisor has to ask the board operator to take an action is enough to keep the shift supervisor and board operators on the same page
  - If and when there should be hold points to make sure everyone is on the same page

- Measure the ability of the crew to detect and recover when the procedure goes astray

- Measure the ability of the crew to transition to paper

4. As noted above, research addressing a better model of what constitutes good crew performance is needed to better understand the implications to crew reliability of the types of effects that were observed in this study. Understanding of the effect on crew roles and changes in communication style caused by new technology will be supported by such a model. In addition, research on effective crew structure and how best to train it will be important to providing a basis from which to develop guidance in this area.

5. Evaluation of the types of graphic displays a new HSI provides and their use in normal operations for "routine" monitoring is recommended. The types of scenarios observed in our study involved plant transitions and disturbances. As such, some of the displays that may be used in typical monitoring were not used often. An important role of operators in contributing to overall plant reliability and safety is the ability to detect and handle equipment malfunctions early, before they lead to a plant trip situation. As a result, it is important to understand the impact of the new HSIs on the types of routine monitoring that occur during normal operations.

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APPENDIX A

General Information Topics Addressed Through Discussions with Utility, Design, Operations, Maintenance, and Training Personnel

I GENERAL QUESTIONS

1 Background

- Why did the utility decide to initiate this design modification program?
  - What factors led to the decision to upgrade?
- Scope of the upgrade?
  - What are the current control room human-system interfaces (HSIs) like?
  - What control room functions are being addressed by the new systems?
  - Are any of the new systems "safety grade" or do they interface with "safety grade" systems?
- Are the new systems an enhancement or a replacement of the current control room HSIs?
  - Will the old and new continue to coexist after the upgrade?
  - Will the new system replace existing HSIs?
  - What additional capabilities are provided?

2 Design

- What are the design goals of the new system?
  - Was there a philosophy of use for the system (e.g., who uses it, when is it used, how is it used in conjunction with the existing control room systems)?
- What was the design basis of the new system (e.g., existing product lines, customer requirements)?
- Generally, how were the new systems designed and their components integrated?
- How was the software development process handled?
  - What was the requirement for software reliability?
  - How will software problems be handled once the systems have been installed?

- What was the involvement of utility personnel: management, engineering operations, training, and maintenance personnel in the design process?
- What were the considerations for integration with the rest of HSI?
  - Are any changes required in the control room HSIs due to the new system?
- From a designer's standpoint, what were/are the major benefits?
  - Are the potential benefits fully realized (and if not, what is needed to fully realize the benefits of the new system)?
- From a designer's standpoint, what were/are the significant challenges in this type of program?
  - Were there any surprises?
- From a designer's standpoint, what are some of the "lessons learned" from the project?

3 Design Evaluation

- What was the verification and validation process employed?
  - What types of evaluations were performed of the new system?
  - How was the acceptability of new technology demonstrated (e.g., computer-based procedure system)?
  - How was software V&V performed?
- From an evaluator's standpoint, what were/are the significant challenges in this type of program?
  - Were there any surprises?
- From an evaluator's standpoint, what are some of the "lessons learned" from the project?

4 Implementation and Transition

- How was/is the upgrade implemented?
  - Were all HSI components changed at once or were they changed in phases?
  - Will the old system be left in place during the transition?

- What activities were/will be performed to facilitate use of the upgrade by operations, maintenance, and engineering personnel?

5 Operator Training

- How will operators be trained to use the new system?
  - Are there any differences in the "philosophy of use" or training requirements for using this system in comparison to the existing control room systems?

- How will their regular training be changed in the long term?

- If the upgrade is phased, how will operators be trained for interim control room configurations between the current control room and the final one after the new system is completely installed?

- Is operator acceptance an issue?

- From a trainer's standpoint, what were/are the major benefits?
  - Are the potential benefits fully realized (and if not, what is needed to fully realize the benefits of the new system)?

- From a trainer's standpoint, what were/are the significant challenges in this type of program?
  - Were there any surprises?

- From a trainer's standpoint, what are some of the "lessons learned" from the project?

6 Impact on Crew Operations, Staffing, Qualifications, Communication, and Coordination

- How do the new systems impact what tasks operators must perform and in the way events are handled as a team?
- In general, what are the effects of the new systems on task performance, situation assessment, and workload?
- Are there any differences in the overall decision-making process? Are there any changes in the way individual operators contribute to the decision-making process?
- What is the impact on crew communication and coordination from the way operations were handled before?
- Were there any differences in the way you kept track of the progress on the event and understood the situation?
- Do the new systems introduce new possibilities for errors to occur?
- Are there any changes in staffing envisioned due to the upgrade?
- Do the new systems require any modifications to operator qualifications?
- From an operations standpoint, what were/are the major benefits?
  - Are the potential benefits fully realized (and if not, what is needed to fully realize the benefits of the new system)
- From an operations standpoint, what were/are the significant challenges in this type of program?
  - Were there any surprises?
- From an operations standpoint, what are some of the "lessons learned" from the project?

7 Configuration, Maintenance, and Upgrade

- Are there configuration modes for the new system and how are they accomplished and controlled?

- How is the system maintained?
  - Who is responsible for software maintenance?
  - How is it different from current maintenance activities?
  - Are the qualifications for maintenance personnel affected by the new systems?
- How are upgrades, such as software revisions, accomplished and controlled?

8 Regulatory Review Considerations

- Is the new system being addressed by the regulatory authorities?
  - Which technical areas are involved (e.g., I&C, HFE)?
  - Has the system received regulatory approval?
  - Are there further activities required before final approval is obtained?
- If a regulatory review has been performed, what has been the technical approach?

9 Follow-up Evaluations

- Is there a plan to conduct follow-up evaluations or to collect lessons-learned as the systems are implemented and operational experience is gained over the next year or so?

II DESIGN-SPECIFIC QUESTIONS

1 Computer-Based Procedure (CBP) System

- What do you see as its major impact on operator performance in comparison to paper procedures?
  - Response times, situation awareness, workload, communication, error opportunity
  - Has the system had differential impact on the shift supervisor vs. board operator?
- How is situation assessment impacted by CBPs as compared with paper procedures?
  - Ability to view multiple procedures and associated plant data simultaneously
- Was the viewing area provided by VDUs sufficient?
  - How does reading procedural text from the VDU compare with paper procedures?

- How is navigation (within one procedure, or among multiple procedures and related information) within the CBP system handled?
- How do operators compare information provided by the CBP system with other sources of information in the control room?
- Is the CBP system and its HSI consistent with the rest of the HSI?
- How will the transfer between paper procedures and CBPs that are used only in emergency conditions be handled?
- How will the transfer from CBPs to paper procedures upon loss of CBPs be handled?
- What would you like to see in the next generation of this system?

2 Alarm System

- What do you see as its major impact on operator performance?
  - Response times, situation awareness, workload, communication, error opportunity
  - Has the system had differential impact on the shift supervisor vs. board operator?
- Are definitions as to what constitutes an alarm clear and reasonable?
- Are the methods used for alarm reduction appropriate?
- What is the basis for alarm priority and can important alarms be easily found?
  - Since the system does not display all alarms at one time, are hidden alarms a concern?
- How are alarm management functions handled?
  - The new alarm system provides for greater interaction with the alarm system
- Was the viewing area provided by VDUs sufficient?
  - How is navigation accomplished?
- How are the different alarm systems used?
- How is the transition between the different types of alarm displays handled?

- How is the transition between the alarm displays and other plant information systems handled?

- What would you like to see in the next generation of this system?

3 Display System

- What is the role of the new display system and how does it relate to the existing displays?

- What is the scope of the display system?

  - Types of displays included
  - Number of displays

- When do operators use the VDU displays and who uses them?

  - Overview displays
  - Physical displays
  - Functional displays

- What do you see as its major impact on operator performance?

  - Response times, situation awareness, workload, communication, error opportunity
  - Has the system had differential impact on the shift supervisor vs. board operator?

- Are the display formats and page arrangements to operator tasks?

- Was the viewing area provided by VDUs sufficient?

  - How is navigation accomplished?

- What would you like to see in the next generation of this system?

4 Systems-Integration

- How well are the CBP, alarm, and display systems integrated?

  - Is it easy to transition between them?

- How well are the existing control room HSIs and the new system integrated?

  - Is it easy to transition between them?

- Was it possible to compare information provided by the new systems (CBP, AAS, and the Graphic Display System) with the conventional instrumentation (such as indicators, instruments, and pen recorders) on the main boards in order to check for any discrepancies?

APPENDIX B

Question Used in Operator Interviews

Opinions on the New Control Room Systems

- Now that you have experienced all three new systems [CBP, AAS, Graphic Display System], overall what features do you think will make a difference in how you do your job?

  - Are there any specific features that especially caught your attention?

- CBP

  - What do you see as the major impact of the computer-based procedure system on operator performance (in comparison to paper procedures)?
  - How does procedure use compare with use of paper?

- AAS

  - What do you see as the major impact of the new alarm system on operator performance?
  - You will now have three separate alarm systems in the control room, what do you see as the role for each?

- Graphic Display System

  - What do you see as the major impact of the new display system on operator performance?
  - When do operators use the VDU displays and who uses them?

- How well are the CBP, alarm, and display systems integrated with each other and the existing controls and displays?

- Much of the information provided by the new systems was presented on VDUs. Was the viewing area provided by VDUs sufficient?

- Information presented by the new systems involves software processing. Is it easy to understand how the software processes data and what the displayed information means? How confident are you in the accuracy of the information provided by the new systems?

APPENDIX B

- Was it possible to compare information provided by the new systems (CBP, AAS and the Graphic Display System) with the conventional instrumentation (such as indicators, instruments, and pen recorders) on the main boards in order to check for any discrepancies?

- If you were designing the next version of this system, what improvements would you recommend?

- In what situations do you think this system is most useful (e.g., normal plant conditions, minor abnormalities, plant faults that result in a trip, complex multiple fault situations)?

- Do you have any concerns about using this new system? Things that you worry about?

Impact on Operations/Crew Performance

- Do you think that CBP, AAS and the Graphic Display System change how you work as a team to respond to incidents? In what ways? Do you think these changes make you better able to handle an incident? Do you have any concerns?

- You ran one simulated scenario where none of the computerized systems were available (simulating a computer system failure). The following questions relate to the differences between the handling the event with and without the new systems.

  - Did you notice any differences in the way you handled the event as a team?
  - Was there an impact on the coordination of individual crew members and on communication between the group members?
  - Were there any differences in the way you kept track of the progress of the event and understood the situation?
  - Was there any difference in the overall decision making process? Were there any changes in the way individual operators contribute to the decision-making process?

- We are interested in how operators work as a crew to detect and correct errors. In the scenarios that you ran this week can you think of any cases where you felt confused or led astray by the new computerized systems? In those cases how did you get back on track?

Training

- Do you think based on the training you have gotten so far, that you would feel confident using these new systems in an actual incident?

- What additional activities or training do you think is needed before you will feel confident in using these new systems in an actual incident?

Operator Input to Design and Transition

- We are trying to study how control rooms are being updated (how operator input is obtained and used, the transition process for introducing the new systems) in order to provide recommendations for future upgrades to insure that operator concerns are taken into account. What are some things you think have been good about the upgrade process for your control room that you would recommend to other plants? Are there things you would recommend be done differently?

NRC FORM 335 (2-89) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1 REPORT NUMBER (Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any)

NUREG/CR-6749
BNL-NUREG-52638

2 TITLE AND SUBTITLE

Integrating Digital and Conventional Human-System Interfaces: Lessons Learned from a Control Room Modernization Program

3 DATE REPORT PUBLISHED

MONTH	YEAR
September	2002

4 FIN OR GRANT NUMBER

JCN W6546

5 AUTHOR(S)

Emilie Roth (Roth Cognitive Engineering) and John O'Hara (Brookhaven National Laboratory)

6 TYPE OF REPORT

Technical

7. PERIOD COVERED *(Inclusive Dates)*

8 PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U S Nuclear Regulatory Commission, and mailing address, if contractor, provide name and mailing address.)*

Brookhaven National Laboratory
Energy Sciences and Technology Dept.
Upton, NY 11973-5000
(Principal Contractor)

Roth Cognitive Engineering
89 Rawson Road
Brookline, MA 02445-4509
(Subcontractor)

9 SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U S Nuclear Regulatory Commission, and mailing address.)*

Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10 SUPPLEMENTARY NOTES

Paul M. Lewis, NRC Project Manager

11. ABSTRACT *(200 words or less)*

This study examined the impact of introducing advanced human-system interfaces (HSI) into a conventional nuclear power plant control room. The advanced HSIs include a computer-based procedure system, an advanced alarm system, and a graphic-based plant information display system. The impact of the new systems on the cognitive functioning of individual crew members and on the functioning of the crew as a team was examined. Information on crew performance was obtained by observing crews during full-scope training simulations of plant disturbances. In addition, interviews were conducted with operators and other utility and vendor personnel. The general findings were that the new HSIs provided positive support for crew performance, reduced workload, and were well accepted by the crews. One of the more interesting and significant effects introduced by the advanced HSI systems was on crew structure and communication. The computer-based procedure system enabled the shift supervisor to access plant state information directly, reducing the need to ask board operators for plant parameter values. In turn, the board operators had access to a richer source of plant state information via the advanced alarm system and graphic-based plant information system than previously was available, enabling them to better monitor plant state. These changes have potential implications for human performance and reliability. The fact that crews use multiple independent sources of information and multiple independent perspectives may increase the crew reliability by increasing the probability of detecting and correcting errors in situation assessment, thus reducing the potential for errors of intention. However, the improvement in human performance and reliability depends on the crew's ability to effectively communicate and maintain a shared situation awareness. The study provides illustrative cases where successful performance is dependent on effective communication among crew members. While this study began exploring these issues, further research is required to establish how new HSIs affect crew structure, commu nication, decision-making and reliability. The lessons learned from this investigation will be used to support human factors guidance development addressing these topics.

12 KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

Human factors engineering, human-system interface, control room, alarm systems, procedures, plant modernization, digital systems

13 AVAILABILITY STATEMENT

unlimited

14 SECURITY CLASSIFICATION

(This Page) unclassified

(This Report) unclassified

15 NUMBER OF PAGES

16 PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300