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NUREG/CR-6634
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Computer-Based Procedure Systems: Technical Basis and Human Factors Review Guidance

Brookhaven National Laboratory

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

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NUREG/CR-6634
BNL-NUREG-52564

Computer-Based Procedure Systems: Technical Basis and Human Factors Review Guidance

Manuscript Completed: January 2000
Date Published: March 2000

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NRC Job Code J6012

ABSTRACT

Plant procedures are instructions to guide operators in monitoring, decision making, and controlling nuclear power plants. While plant procedures historically have been paper-based, computer-based procedures (CBPs) are being developed to support procedure use. CBPs have a range of capabilities that may support operators and reduce demands associated with paper procedures. The objective of this study was to establish human factors review guidance for CBP systems based on a technically valid methodology. While the study mainly addressed emergency operating procedures, much of the guidance developed applies to other types of procedures. First, a CBP characterization was developed for describing their key design features including both procedure representation and functionality. Then, the research on CBPs and related areas was reviewed. This information provided the technical basis on which the guidelines for design review were developed. The review guidelines address both the design process and the implementation of CBP systems. For some aspects of CBPs the technical basis was insufficient to develop guidance; these aspects were identified as issues to be addressed in future research.

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EXECUTIVE SUMMARY

The Human-System Interface Design Review Guideline, NUREG-0700, Rev. 1 (O'Hara et al., 1996), was developed to provide guidance on human factors engineering (HFE) for the U.S. Nuclear Regulatory Commission (NRC). The NRC staff uses NUREG-0700 for (1) reviewing submittals of human-system interface (HSI) designs prepared by licensees or applicants for a license or design certification of a commercial nuclear power plant (NPP), and (2) undertaking HSI reviews that could be included in an inspection or other types of regulatory review of HSI designs, or incidents involving human performance. It describes those aspects of the HSI design review process that are important to identifying and resolving human engineering discrepancies that could adversely affect plant safety. NUREG-0700 also has detailed HFE guidelines for assessing the implementation of HSI designs.

In generating NUREG-0700, Rev. 1, several topics were identified as "gaps" because there was an insufficient technical basis upon which to formulate guidance. One such topic is the integration of advanced HSI technology into conventional NPPs. The NRC is currently sponsoring research at Brookhaven National Laboratory (BNL) to (1) better define the effects of changes in HSIs brought about by incorporating digital technology on personnel performance and plant safety, and (2) develop HFE guidance to support safety reviews, should a review of plant modifications or HSIs be necessary.

Based upon the literature, interviews, and site visits, O'Hara et al. (1996) identified changes in HSI technology and their potential effects on personnel performance. The topics were then evaluated for their potential safety significance (Stubler et al., 1996); computer-based procedures (CBPs) was one HSI technology that was found to be potentially safety significant. (The safety analysis is described in more detail in Section 5.4.2.2 of this report.)

Plant procedures provide instructions to guide operators in monitoring, decision making, and controlling the plant. Historically, plant procedures have been paper-based and were not considered part of the HSI. Following the accident at Three Mile Island, the nuclear power industry recognized the importance of having technologically sound and easy-to-use procedures to handle major plant disturbances. For emergency operations, symptom-based procedures were established that enabled operating crews to restore and maintain the plant's safety functions without having to diagnose events or the specific causes of process disturbances.

Paper-based procedures (PBPs) have characteristics that limit how information can be presented to the operators. These limitations include presenting information in sequential form, requiring numerous iterations through steps, and cautions or warnings that may not be applicable for all system states (Wourms and Rankin, 1994; Mampaey et al., 1988). PBPs also impose tasks on the operator that are not directly related to controlling the plant. To make transitions between procedure steps and documents, and maintain awareness of the status of procedures that are in progress, operators must handle, arrange, scan, and read PBPs in parallel with monitoring and control tasks.

CBPs are being developed to support procedure management. CBPs have a range of capabilities that may support operators in controlling the plant and reduce the demands associated with PBPs. In their simplest form, CBPs show the same information via computer-driven video display units (VDUs). More advanced CBPs may include features to support managing procedures (e.g., making transitions between steps and documents, and maintaining awareness of procedures in progress), detecting and monitoring the plant's state and parameters, interpreting its status, and selecting actions and executing them.

The objective of this study was to develop HFE review guidance for CBP systems based on a technically valid methodology. To support this objective, the following tasks were undertaken:

- Development of a framework for characterizing key design features of CBP systems
- Development of a technical basis using research and analyses on human performance relevant to CBPs

- Development of HFE review guidelines for CBPs in a format that is consistent with NUREG-0700, Rev. 1, and NUREG-0711
- Identification of remaining CBP issues for which research was insufficient to support our development of NRC review guidance

The status of each will be briefly addressed below.

CBP System Characterization Framework

For this study, CBP systems were narrowly defined to encompass computer systems that support procedure presentation and use. The focus was on the HFE aspects of CBPs, and not the I&C or software aspects (although the latter are important as well, and are described in other NRC regulatory and research programs). CBPs were characterized along the following dimensions:

- Representation of Procedure Elements
- Procedure Functionality
- Interface Management and Support
- CBP Hardware
- Backup Systems for Procedures
- Integration of CBP System with the HSI

Development of the Technical Basis

The effects of CBPs on crew performance were determined by examining three types of research: (1) empirical studies of CBPs where data on personnel performance were collected, (2) analyses of personnel performance using models, and (3) expert opinion about their postulated effects on personnel performance.

The human performance research was organized into three categories: comparisons of CBP and PBP systems, observations of operators' use of CBPs, and comparisons of design characteristics of procedures. Several conclusions were made from comparing CBPs with PBPs:

- Operators perform tasks more quickly.
- Operators' overall cognitive workload is reduced.
- Operators may make fewer errors in transitioning through procedures.
- Operators may accept CBPs readily and find them easier to use.

However, much of the human performance research had insufficient detail to evaluate its generalizability. Studies that were sufficiently documented had potential methodological weaknesses which limited their conclusiveness and generalization.

Personnel performance was analyzed with two classes of techniques: performance models and risk models. The performance models showed no clear advantage of CBPs over PBPs. Instead, they illustrated the importance of performance tradeoffs in assessing different procedure systems. In general, complexity and attentional demands were higher, while data retrieval was easier and task completion time was less for CBPs. Similarly, mixed results were obtained from the risk analyses. They illustrated the potential for these systems to improve performance by supporting such procedure-related activities as process monitoring, logic analysis, navigation, and place keeping. However, when poorly implemented, CBPs can reduce human reliability.

Finally, the SME review of CBPs identified many positive aspects of their use on the crew's performance. However, they also identified a wide range of issues to be resolved in developing CBPs. The review highlighted the importance of considering HFE activities in CBP development, e.g., the integration of the CBP system with the other HSIs and with the overall operational philosophy of the plant. Thorough V&V programs were also emphasized. In general, these findings were consistent with the information discussed earlier.

When considering all the results, we concluded that there is evidence that CBPs can support and enhance operator performance. However, important issues remain to be addressed both in research and in the development of individual systems. Thus, we repeat the advice of researchers and developers: CBP systems should be developed in such a way that their benefits and drawbacks can be fully evaluated for each specific system. CBPs have important impacts on NPP operations, some of which extend beyond those the designers intended.

Reflecting this approach, we offer some general considerations for near-term approaches to CBP systems:

- Support cognitive functions that may be distracting and error prone, such as
  - process monitoring
  - logic analysis (cautiously so not to underspecify the analysis and undermine operator's judgement)
- Support procedure management, e.g., step completion, place keeping, transitioning between procedures
- Provide PBP backup systems and ensure similarity of CBPs and PBPs in order to (1) ensure confidence in near-term CBP applications, (2) enable operating experience to be gained, (3) minimize the impact on function allocation, (4) ease the training burdens associated with both systems, and (5) ensure successful crew performance when transitions to and from backups are necessary (minimize the potential for negative transfer or difficulties in performance)

<u>HFE Review Guidelines</u>

Guidance for the review of CBPs was developed to address the CBP design process and HFE design. Both types of guidance are needed for a design review. That is, while there was a sufficient technical basis to develop detailed guidance for design-implementation review, as is typical in NUREG-0700, several limitations in the technical basis were identified. Many issues (listed below) remain for which typical NUREG-0700 guidance could not be developed. Therefore, until the additional guidance is developed, these issues should be addressed for specific CBP systems using CBP design process guidance.

EXECUTIVE SUMMARY

<u>CBP Issues</u>

As noted above, several human performance issues associated with CBPs were identified. They represent topics for which research is necessary before developing guidance. From a regulatory review perspective, many of them can be dealt with on a case-by-case basis during the design process review. Briefly, the issues included the following:

Methodological and Criterion Requirements for Evaluating CBP Effects - Most of the studies reviewed had methodological weaknesses which limited their conclusiveness and generalizability. This issue addresses the need to evaluate CBPs and their effects on crew performance comprehensively, to better understand them under a wide range of scenarios and complex situations, using varied measures of personnel and system performance.

Role of Plant Personnel in Procedure Management - This issue addresses the need to determine how to design and review CBP systems (1) to allow operators to maintain an independent perspective and to recognize the procedure's contribution to higher-level safety goals, (2) to automate distracting and lower-level error-prone tasks, and (3) to monitor the crew's performance, especially when the crew and CBPs disagree.

Team Performance - This issue addresses the requirement to explore the effect of CBPs on crew member's roles, teamwork, and communication. How CBPs can be designed to effectively promote both is considered as well.

Situation Awareness, Response Planning, and Operator Error - This issue addresses the need to assess the effect of CBPs on situation awareness including:

- Procedure management, such as status of procedure steps, how procedures are structured, and the current location within a procedure or between a set of procedures
- The appropriateness of procedures for achieving high-level procedure goals
- The plant's status

Level of Automation of Procedure Functions – This issue addresses the need to evaluate the tradeoffs between automating procedure functions, e.g., the analysis of procedure step logic, and the operator's involvement, independence, and supervisory control.

Keyhole Effects and Use of Multiple CBP Procedures – This issue concerns the requirement to evaluate the significance of the keyhole effect in situations where operators are required to be in multiple procedures and must access information in parallel.

CBP Failure in Complex Situations – This issue involves the need to evaluate operator's management of the transition from CBPs to PBPs and back to CBPs under complex conditions, e.g., in a situation where operators are deep into the procedures, multiple procedures are open, many steps are completed, many are continuously applicable, and time and parameter steps are being monitored by the CBPs.

Hybrid Procedure Systems – This issue addresses the need to evaluate any differential effects of having all plant procedures presented in a CBP system versus a hybrid system, e.g., EOPs presented using CBPs and all other procedures are paper-based.

Specific CBP Design Features – This issue addresses the need to evaluate the relative effects of specific CBP design features on performance.

PREFACE

This report was prepared by Brookhaven National Laboratory for the Division of Systems Technology of the U.S. Nuclear Regulatory Commission's (NRC's) Office of Nuclear Regulatory Research. It is submitted as part of the requirements of the project *Human Factors Topics Associated with Hybrid Human System Interfaces* (NRC JCN J6012), specifically, as part of Task 3, "Develop Review Guidance." The NRC Project Manager is Joel Kramer and the BNL Principal Investigator is John O'Hara.

ACKNOWLEDGMENTS

The authors wish to express their sincere gratitude to our colleagues Bill Brown, Lew Hanes, Mike Fineberg and his review team at the Crew Systems Ergonomics Information Analysis Center (CSERIAC), and Bill Ruland, Greg Galletti, Jim Bongarra, Clare Goodman, Jim Stewart, and Rich Correia of the U.S. NRC for their review of the reports. These reviewers provided insightful comments and perspectives on the issues addressed in the report and their knowledge and understanding significantly contributed to the study.

We also wish to thank Barbara Roland, Mary Anne Corwin, and Avril Woodhead for their preparation and careful technical editing of the report.

ACRONYMS

ADS	Automatic depressurization system
AECB	Atomic Energy Control Board (Canada)
AECL	Atomic Energy Canada, Limited
ALWR	Advanced Light Water Reactor
ANS	American Nuclear Society
BNL	Brookhaven National Laboratory
BWR	Boiling water reactor
CALS	Continuous acquisition and life-cycle support
CANDU	Canadian Deuterium Uranium Reactor
CBP	Computer-based procedure
CFR	Code of Federal Regulations (U.S.)
COMPRO	Westinghouse Computerized Procedure
COPMA	Computerized Operation Manual
COPRO	Computerized Procedure
COSS	Computerized operator support system
CR	Control room
CSF	Critical safety function
DDD	Detection-diagnosis-decision making
DOD	Department of Defense (U.S.)
DOE	Department of Energy (U.S.)
DSIN	Nuclear Installations Safety Directorate (France)
EdF	Electricite de France
EOP	Emergency operating procedure
EOPTS	Emergency Operating Procedure Tracking System
EPRI	Electric Power Research Institute
GE	General Electric
GOMS	Goals, operators, methods, and selection
GTG	General technical guidance
HFE	Human factors engineering
HRA	Human reliability analysis
HSI	Human-system interface
I&C	Instrumentation and control
IAEA	International Atomic Energy Association
IPSN	Institute for Nuclear Safety and Protection (France)
IETM	Interactive Electronic Technical Manuals
ISLOCA	Interfacing systems loss-of-coolant accident
KBS	Knowledge-based system
LOCA	Loss-of-coolant accident
LWR	Light water reactor

ACRONYMS

M-MIS	Man-machine information system
MCOSS	Mitsubishi Computerized Operator Support System
MIDAS	Man-Machine Integrated Design and Analysis System
MMI	Man-machine interface
NAS	National Academy of Sciences
NASA-TLX	National Aeronautics and Space Administration - Task Load Index
NPP	Nuclear power plant
NRC	Nuclear Regulatory Commission (U.S.)
P&ID	Piping and instrumentation diagram
PBP	Paper-based procedures
PEAM	Portable Electronic Aid for Maintenance
PRA	Probabilistic risk assessment
PSN	Institute for Nuclear Safety and Protection (France)
PWR	Pressurized water reactor
RAI	Request for additional information
RCS	Reactor coolant system
RO	Reactor operator
SDT	Signal detection theory
SME	Subject-matter expert
SPDS	Safety parameter display system
SRO	Senior reactor operator
TMI	Three Mile Island (nuclear power plant)
URD	Utility Requirements Document
V&V	Verification and validation
VDU	Video display unit

PART 1

Guidance Development and Technical Basis

1 INTRODUCTION

1.1 Background

The Human-System Interface Design Review Guideline, NUREG-0700, Rev. 1, (O'Hara et al., 1996) was developed to provide guidance on human factors engineering (HFE) for the U.S. Nuclear Regulatory Commission (NRC). The NRC staff uses NUREG-0700 for (1) reviewing submittals of human-system interface (HSI) designs prepared by licensees or applicants for a license or design certification of a commercial nuclear power plant (NPP), and (2) undertaking HSI reviews that could be included in an inspection or other types of regulatory review of HSI designs, or incidents involving human performance. It describes those aspects of the HSI design review process that are important to identifying and resolving human engineering discrepancies that could adversely affect plant safety. NUREG-0700 also has detailed HFE guidelines for assessing the implementation of HSI designs.

In generating NUREG-0700, Rev. 1, several topics were identified as "gaps" because there was an insufficient technical basis upon which to formulate guidance. One such topic is the integration of advanced HSI technology into conventional NPPs. The NRC is currently sponsoring research at Brookhaven National Laboratory (BNL) to (1) better define the effects of changes in HSIs brought about by incorporating digital technology on personnel performance and plant safety, and (2) develop HFE guidance to support safety reviews, should a review of plant modifications or HSIs be necessary. This guidance will be integrated into NUREG-0700 and provide the NRC's staff with the technical basis to help ensure that HSI designs or plant modifications do not compromise safety.

The results of this project are expected to contribute to satisfying the NRC's goals of (1) maintaining safety, (2) increasing public confidence, (3) increasing regulatory efficiency and effectiveness, and (4) reducing unnecessary burden.

Based upon the literature, interviews, and site visits, O'Hara et al. (1996) identified changes in HSI technology and their potential effects on personnel performance. The topics were then evaluated for their potential safety significance (Stubler et al., 1996); computer-based procedures (CBPs) was one HSI technology that was found to be potentially safety significant. (The safety analysis is described in more detail in Section 5.4.2.2 of this report.)

Plant procedures provide instructions to guide operators in monitoring, decision making, and controlling the plant. Historically, plant procedures have been paper-based and were not considered part of the HSI. Following the accident at the Three Mile Island NPP, the nuclear power industry recognized the importance of having technologically sound and easy-to-use procedures to handle major plant disturbances. For emergency operations, symptom-based procedures were established that enabled operating crews to restore and maintain the plant's safety functions without having to diagnose events or the specific causes of process disturbances. The NRC and industry put a great deal of effort into the design and review of emergency operating procedures (EOPs) (American Nuclear Society, 1981; Barnes et al., 1989; Galletti and Sutthoff, 1992; NRC, 1982). More recently, studies of other operating procedures (e.g., normal and abnormal procedures) also have demonstrated the importance of these categories of procedures to plant safety (Grant et al., 1989).

Paper-based procedures (PBPs) have characteristics that limit how information can be presented to the operators. These limitations include presenting information in sequential form, requiring numerous iterations through steps, and cautions or warnings that may not be applicable for all system states (Wourms and Rankin, 1994; Mampaey et al., 1988). PBPs also impose tasks on the operator that are not directly related to controlling the plant. To make transitions between procedure steps and documents, and maintain awareness of the status of procedures that are in progress, operators must handle, arrange, scan, and read PBPs in parallel with monitoring and control tasks.

CBPs are being developed to support procedure management. CBPs have a range of capabilities that may support operators in controlling the plant and reduce the demands associated with PBPs. In their simplest form, CBPs show the same information via computer-driven video display units (VDUs). More advanced CBPs may include features to support managing procedures (e.g., making transitions between steps and documents, and maintaining awareness of procedures in progress), detecting and monitoring the plant's state and parameters, interpreting its status, and selecting actions and executing them.

CBPs are being developed for new plants, e.g., the Westinghouse AP600, and as upgrades for existing plants, e.g., the Beznau plant in Switzerland. Although CBP systems are being developed, the general consensus is that guidance for their design is lacking (Chignell and Zuberec, 1993; Converse, 1992; EPRI, 1993a).

The introduction of advanced HSI technology, such as CBP systems, is generally considered to enhance performance, but there also is the potential to lower human performance, spawn new types of human errors, and reduce human reliability (O'Hara, 1994). Therefore, it is important to consider the potential effects of these technologies on human performance. Like other advanced HSI technologies, CBPs have many characteristics that can enhance a crew's performance, but other characteristics may impair their responses. In addition, CBP failures may place special demands on operators, e.g., transitions between CBPs and PBPs may introduce problems associated with their different presentation media and requirements for operation.

1.2 Earlier NRC Work on Computer-Based Procedures

As part of their review of advanced reactors, the NRC's staff evaluated the Electric Power Research Institute's (EPRI) Advanced Light Water Reactor Utility Requirements Document, hereafter referred to as the URD (see EPRI, 1993a). EPRI specified CBPs as a requirement in the URD, but gave limited guidance for their development and implementation. The NRC (1994) concluded that CBPs were a "desirable goal" whose appropriate implementation must be demonstrated.

In 1994, the NRC staff in the Office of Nuclear Reactor Regulation published the Human Factors Engineering Program Review Model (NUREG-0711), giving an approach to reviewing the HFE aspects of advanced reactor designs (O'Hara, Higgins, Stubler, Goodman, Eckenrode, Bongarra, and Galletti, 1994). Criterion 7 of Element 8, Procedure Development, of the NUREG-0711 states the following:

> An analysis should be conducted to determine the impact of providing computer-based procedures, CBPs, (either partial or complete), and to specify where such an approach would improve procedure utilization and reduce operating crew errors related to procedure use. The justification for use of CBPs over paper procedures should be documented. An analysis of alternatives in the event of loss of CBPs should be performed and documented.

In supporting NUREG-0711, preliminary review guidance was developed for CBPs based upon the considering current issues and practices in using PBPs (Barnes et al., 1996).

From a research perspective, CBPs were identified in 1994 as a technology being developed in the nuclear power industry for which little human factors knowledge and guidance existed (O'Hara, 1994). After this identification of the CBPs issue, the literature was reviewed for the NRC (Wourms and Rankin, 1994) and a workshop for subject-matter experts (SMEs) was held in San Diego, California, to identify the state-of-the-art in CBP research and design. The workshop generated an excellent overview of the systems under development and some of the human factors challenges to their use and evaluation (see Section 5.4.3, Expert Opinion, of this report). Also in 1994, the NRC started a study of CBP systems and their potential impact on human and plant reliability (Orvis and

Spurgin, 1996). It also sponsored a comparison of operators' performance with CBPs and PBPs in a simulator study (Converse, 1995).

As noted above, the potential human performance issues and safety significance of CBPs recently were evaluated the early phases of this project (O'Hara, Stubler, and Higgins, 1996; Stubler, Higgins, and O'Hara, 1996). Also, observations were made on introducing advanced HSI technology, including CBPs, into a conventional NPP (Roth and O'Hara, 1998).

This work is discussed in greater detail in Section 5 of this report; all of it contributed to the CBP review guidance developed.

1.3 Organization of the Report

The report is divided into two parts. Part 1 describes the methodology for developing guidance and its technical basis. The objective of the study is described in Section 2, and the guidance development methodology in Section 3. Section 4 characterizes CBP systems, and Section 5 discusses the literature and information that served as the technical basis for the review guidance. The actual way we used the technical information is described in Section 6. Our CBP research is summarized in Section 7. Section 8 lists the references to the published literature.

Part 2 of the document contains the results of the guidance development, presented in two sections. Section 9 identifies the design-process considerations for CBP review, and Section 10 contains the HFE design guidelines for reviewing an implemented CBP design.

2 OBJECTIVE

The objective of this study was to develop HFE review guidance for CBP systems based on a technically valid methodology. While the primary focus of the guidance was on EOPs, many of the principles identified apply to other types of plant procedures.

To support this objective, several tasks were performed:

- Development of a framework for characterizing key design features of CBP systems
- Development of a technical basis using research and analyses on human performance relevant to CBPs
- Development of HFE review guidelines for CBPs in a format that is consistent with NUREG-0700, Rev. 1, and NUREG-0711
- Identification of remaining CBP issues for which research was insufficient to support the development of NRC review guidance

3 METHODOLOGY

3.1 Overview

Figure 3.1 shows the overall methodology used for developing NUREG-0700 guidance. The process is discussed in detail elsewhere (O'Hara, Brown, and Nasta, 1996; Stubler and O'Hara, 1996). The portion of the methodology applicable to this report and project is boxed in the figure. This section of the report describes the general rationale behind guidance development.

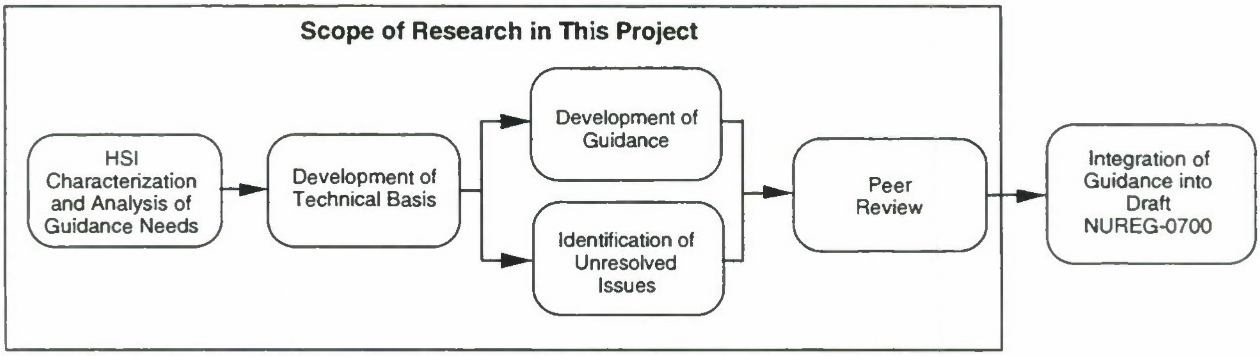

Figure 3.1 Major Steps in the Development of NUREG-0700 Guidance

The methodology was guided by the following objectives:

- Establish a process that will result in valid, technically defensible, review criteria
- Establish a generalizable process applicable to any aspect of HSI technology needing review guidance
- Establish a process that optimally uses available resources; i.e., develop a cost-effective methodology

The methodology places a high priority on establishing the validity of the guidelines. Validity is defined along two dimensions: internal and external. Internal validity is the degree to which the individual guidelines are based on an auditable technical basis. The technical basis is the information upon which the guideline is established and justified, and varies for individual guidelines. Some guidelines may be based on technical conclusions from a preponderance of empirical research evidence, some on a consensus of existing standards, while others are based on judgement that a guideline represents good practices based on the information reviewed. Maintaining an audit trail from each guideline to its technical basis serves several purposes:

- Evaluation of the technical merit of the guideline by others
- A more informed application of the guideline since its basis is available to users
- Evaluation of deviations or exceptions to the guideline

External validity is the degree to which the guidelines are subjected to independent peer review. Peer review is a good method for screening guidelines for conformance to accepted HFE practices, and for comparing guidelines to the practical operational experience of HSIs in real systems.

For individual guidelines, these forms of validity can be inherited from the source documents that form their technical basis. Some HFE standards and guidance documents, for example, already have good internal and external validity. However, if validity is not inherited, it is established as part of the process of guidance development. The NUREG-0700 methodology was established to ensure validity, both inherited from its technical basis, and through the development and evaluation of guidance.

Figure 3.2 depicts the process used to develop the technical basis and guidance; it emphasizes information sources with the highest degree of internal and external validity. Thus, primary and secondary source documents were sought for guidance first, followed by tertiary source documents, basic literature, and industry experience, and from them design principles and lessons from industry experience were identified. Using this technical basis as a foundation, the guidance was developed. For specific aspects of the topic in which there was an inadequate technical basis to develop guidance, unresolved research issues were defined. Thus, the analysis of information led to the formulation of both guidance and issues. The resulting guidance documentation includes HFE guidelines, technical basis, the development methodology, and unresolved research issues.

Each step in this research – characterizing the topics, developing the technical basis, developing and documenting guidance, identifying issues, and peer review – is discussed in greater detail in the sections that follow.

3.2 Characterization of CBP Systems

The first step in the development process was to identify the areas for which guidance was needed. Existing CBP systems were reviewed to identify the features and functions along which CBP systems can be defined. Characterization was important because it provided a structure with which to organize the design review guidance. The characterization will also provide a reviewer with a framework for requesting information about a CBP system. Section 4 describes the characterization of CBP systems.

3.3 Development of Technical Basis

The development of detailed review guidelines began by collecting technical information on which they would be based (see Figure 3.2); the process was designed to develop valid guidance cost effectively. First, primary source documents were sought. These were HFE standards and guidance documents with internal and external validity; that is, these documents generally had their own research bases, and the developers of these documents had considered the available research and operational experience, along with their own expertise, to establish HFE guidelines. These primary source documents were extensively peer reviewed. They were developed by experts who consider research in terms of its applicability and generalizability to real systems, include knowledge and expertise gained through operational experience and the application of guidance, and modify the guidance based on extensive peer review. Such documents provided a technically valuable starting place.

Since little primary source information was available, the technical basis for CBPs considered the other sources identified in Figure 3.2. Secondary sources were documents for which either internal or external validity had been established. They were preferred over tertiary source documents for which neither was established.

In addition to these sources, the results from basic literature were analyzed (articles from technical journals, reports from research organizations, and papers from technical conferences). When guidance was based on basic literature, engineering judgement was required to generalize from the individual experiments to actual applications in the workplace because individual experiments had unique constraints limiting their generality (such as their unique participants, types of tasks performed, and types of equipment used). For example, most scientific

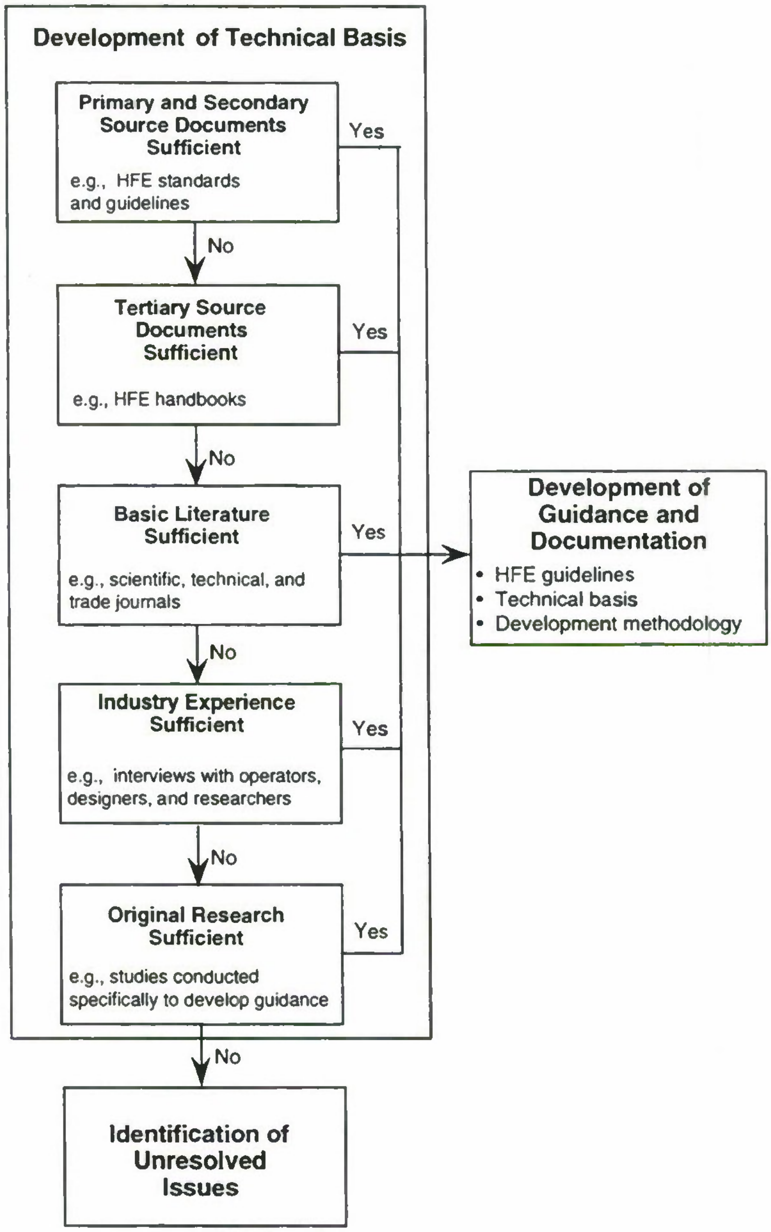

Figure 3.2 Technical Basis and Guidance Development Process

experiments do not involve tasks of the complexity of NPP operations, nor do they examine tasks under the same performance shaping factors (such as rotating shifts, stress, and fatigue) as exist in a work environment. While information from research is a valuable part of guidance development, it usually cannot be uncritically adopted. Thus, the results must be interpreted in the context of real-world tasks and systems, based on professional and operational experience.

Industry experience also was used, such as published case studies, surveys, and interviews with knowledgeable experts. Although such information may lack a rigorous experimental basis (and thus, a measure of validity), it is highly relevant.

Finally, some issues were evaluated by original research. This approach has the advantage of being focused on specific issues of interest, and has both high relevance and a sound basis from which to establish validity. The study (Roth and O'Hara, 1998) is described in Section 5.4.1, Empirical Evaluation of CBPs Based on Personnel Performance.

3.4 Development and Documentation of Guidance

Once the technical information was assembled, a draft set of guidelines was developed from it. The guidelines were organized and specified in a standard format (discussed in Section 6). They are identified in Part 2 of this document.

3.5 Identification of Issues

Where there was insufficient information to provide a technical basis upon which to develop valid design review guidance, an issue was defined; these issues are described in Section 7.

From a research standpoint, issues reflect aspects of CBP design and use that require additional investigation to resolve. From a design review standpoint, these issues will have to be addressed case-by-case. For example, an issue can be dealt with as part of design-specific tests and evaluations.

3.6 Peer Review

The resulting technical basis and guidance was submitted for review by knowledgeable experts. These included reviews by personnel from the U.S. NRC with expertise in human factors engineering and engineering fields directly related to the topic. Additional reviews were conducted by human factors specialists outside the NRC who have expertise in human performance in complex systems, such as nuclear power plants and aviation. These external reviews included evaluations of the topic characterization along the following criteria: clarity, accuracy, and completeness; and of the review guidance along the following criteria: organization, necessity, sufficiency, resolution, and technical basis. Comments from the peer reviews were incorporated into the present version of this document.

4 CHARACTERIZATION OF CBP SYSTEMS

In the nuclear power industry, a procedure has been generally defined as a written document (including both text and graphics) that presents a series of decision and action steps to be performed by plant personnel (e.g., operators, technicians) to accomplish a goal safely and efficiently. NPP personnel use procedures for a wide variety of tasks, from administration to testing, and plant operation. This project is focused on procedures that prescribe interactions between personnel and the plant systems and components. The purpose of NPP procedures is to guide human actions when performing a task to increase the likelihood that the actions will safely achieve the task's goal. In contrast to decision aids, procedures define decisions to be made and actions to be taken where the task goals are unambiguous and the correct or desired course of action is generally known.

In recent years, many efforts have been started in NPPs to assist personnel through the computerization of procedure information. Several CBP systems have been, or are being, installed in operating plants or in their training simulators. The following are examples of some of the more mature systems:

- Westinghouse Computerized Procedure (COMPRO) System at Beznau, Switzerland, and Temelin, Czech Republic

- EdF Computerized Control Room (CR) for N4 Reactors at Chooze and Civaux, France

- EPRI Boiling Water Reactor (BWR) Emergency Operating Procedure Tracking System (EOPTS) at Kuosheng, Taiwan

- Tokyo Electric's BWR Computerized EOPs, France

(For a general description of specific CBP systems, see Moieni and Spurgin, 1993a; Spurgin, Wachtel, and Moieni, 1993.)

For this document, CBPs are defined narrowly to include computer systems whose purpose is supporting the presentation and use of procedures; systems whose functions include diagnosis or disturbance analysis are not within its scope. The focus of the effort is on the HFE aspects of CBPs, not the software aspects (for a discussion of general software development, testing, and management, see NRC Regulatory Guides 1.168 through 1.173; NRC, 1997 a-f).

The characterization and guidance focuses on EOPs. However, it is recognized that normal and abnormal operating procedures have been identified as important contributors to many significant events (Trager, 1988), and play a significant role in the plant's safety (Grant et al., 1989). Much of the guidance may apply to such procedures, and to test, surveillance, troubleshooting, and maintenance procedures when they are delivered by CBP systems.

The design review of CBP systems requires two types of guidance: procedure guidance and HSI guidance. The first addresses the human factors aspects of procedure design and is intended to ensure that technically correct and usable procedures are developed. There is considerable guidance on procedure design, such as NUREG-0899, but because it was developed for PBPs, modifications may be necessitated by computerization of CBPs. Sections 9 and 10 of this report have guidance specific to CBPs.

For HSI guidance, CBPs will share many of the HSI resources and characteristics as other plant information systems. That is, information will be presented on VDUs, and operators will interact with the CBP information using the computer's dialogue and navigation facilities, accessed with input devices, such as keyboards and mice.

4 CHARACTERIZATION OF CBP SYSTEMS

Many human factors guidelines currently exist, such as NUREG-0700, Rev. 1, covering these general characteristics of HSI design. What still is needed is the specific application of HSI principles to the computerization of procedure functions, such as monitoring steps that are continuously applicable.

In this section, a characterization framework for CBP systems is discussed based on our examination of many CBP-system implementations. A system characterization is the identification of important design features and functions that can be used to describe it. The characterization provides a framework for NRC's reviewers to collect information about the system for reviewing its design. It also forms an organizational structure for the guidelines used to review the system.

The CBP characterization framework discussed includes the following:

- Representation of Procedures (Section 4.1)
- Functionality of Procedures (Section 4.2)
- Management and Support of Procedures (Section 4.3)
- CBP Hardware (Section 4.4)
- Backup System for Procedures (Section 4.5)
- Integration with Other HSI Components (Section 4.6)

4.1 Representation of Procedures

In their basic form, procedures have a number of elements for which considerable guidance already exists. These same elements must be represented in the CBP system.

Identification Information for Procedures

Procedures are identifiable to the operators and maintainers through their title, procedure number, revision number, and date. Procedures also contain statements of the high-level objective and its applicability, including their category, e.g., emergency or abnormal.

Basic Steps

Steps are the basic unit of the procedure. A basic action step is composed of a verb and a direct object. In general, the rules of English grammar are followed and the syntax reflects concise language that is simply stated, explicit, and consistent. Decision steps give instructions for evaluating conditions and for then choosing the appropriate action(s) from a predefined set. The decisions may involve conditional logic, i.e., where the actions are to be performed only if a specified set of conditions exists. Action steps identify actions to be taken, i.e., instructions to perform physical steps (e.g., "Depress") and mental ones (e.g., "Verify"); they also describe the objectives of those actions. Some procedure steps (e.g., in EOPs) have a dual nature, with an action to be accomplished in one column, and a second action if the first is not successful. Some steps may require calculations.

Implementation of procedures has a temporal flow, i.e., some steps are carried out when encountered, others are continuous (steps of continuous applicability), while time or process criteria determine when others are undertaken.

Performance of a procedure step may be supported by information, such as cautions and notes, that qualifies the required actions and decisions.

Warnings, Cautions, Notes, and Supplementary Information

Warnings alert operators to potential hazards of their actions that may cause death or injury to workers or the public; cautions alert operators to potential hazards for machinery or equipment. Notes call attention to important supplemental information that may enhance an operator's understanding and performance of the procedure.

Procedure steps may cite supporting supplementary material helping the operator implement the step; this material may be tables, figures, lists, text, or numeric information.

Lists

A list is a display containing alphanumeric strings arranged in a single column. Procedures frequently use list formats to present groups of items, such as actions, conditions, components, criteria, and systems. When lists are used in CBPs, additional considerations relate to the grouping of items, provision of checkoff capability, and operator alerts to potentially overlooked items.

Organization of Procedures

NPP procedures are not simple checklists where the operator starts at the top and linearly proceeds step-by-step to the end. Based on the plant's conditions, the operator may be required to branch from one part of a procedure to another, or from one procedure to another. Thus, the way procedures are organized is important.

Format and Screen Layout

PBPs generally present the basic steps in text or flowchart formats. The CBP systems that have been designed also follow these principles, and may use either format. Thus, the Westinghouse COMPRO CBP is text based and is consistent with the two-column format developed by the Westinghouse Owner's Group for their EOPs. The EdF N4 CBP uses a flowchart format.

Unlike PBPs, CBPs are viewed through the limited display area of one or more VDUs. Thus, whether the format is text or flowchart, the designer must decide whether the procedure will be presented in a continuous, scrollable display or be divided into discrete pages.

The overall layout of the screen for showing elements of the procedure refers to the determination on what information should be continuously presented, and the manner in which individual elements are presented.

For example, the procedure's title and identification information may be displayed continuously at the top of the CBP screen, while the steps are shown on a scrollable window. Cautions may be represented in a separate window. Supporting features, such as bookmarks, checklists, and operators' comments may also be displayed.

Presentation formats, such as text and flowcharts, can be enhanced by the coding capabilities of computer-based displays, e.g., color, flashing, animation, and auditory cuing, which enhance the salience of important information. CBPs use coding for conditions such as:

- Whether procedure step logic is satisfied or not

- Whether information is static or dynamic with the plant's state
- When a caution is in effect
- When a change occurs in the status of a continuously monitored step

CBPs can be designed to allow operators to choose the level of detail shown. For example, operators may choose to have less detail presented when a procedure step is satisfied. Alternatively, an operator may choose to see all of the individual evaluations that led to the conclusion that the step is satisfied.

4.2 Functionality of Procedures

A significant difference between PBPs and CBPs is in the functionality provided by the latter. Procedure functions can be organized into four cognitive categories: monitoring and detection, situation assessment, response planning, and response implementation (see Section 5.1 for an in-depth discussion of these cognitive functions). In monitoring and detection, operators must monitor the process parameters referenced by procedures, and also their own actions in response.

Situation assessment is frequently required by procedures. While EOPs enable operators to act without diagnosing the disturbance, operators must assess whether EOP entry conditions exist. Within the procedure, operators assess each decision step by comparing actual values to the reference values, evaluating whether cautions are applicable, assessing the completeness of each step, and tracking and remembering their path through the procedure (the procedure history); at the same time, they must evaluate steps of continuous applicability and steps that are time or parameter dependent. Operators also must assess the applicability of individual steps because PBPs are generic and not context sensitive (context sensitivity is the selection of procedural information based on the plant's state). Finally, operators must evaluate the success of the current procedure in achieving the high-level procedure goals, and the procedure's termination conditions.

Procedures were originally designed to support response planning. For example, EOPs assist operators in responding to events by setting out the steps necessary to achieve safety goals. They relieve the operator of the burden of formulating response plans in real time. Instead, the actions necessary to restore and maintain critical safety functions were analyzed in advance and developed into a set of detailed procedures. However, operators must still evaluate whether transitions to other parts of the procedure or other procedures are warranted. Rarely, they may have to modify procedures when current conditions render the existing procedure inapplicable (see Section 5.1).

With respect to response implementation, the operator's responses involve acting upon the procedures themselves, such as making the transition from one step to the next, to other parts of the procedure, or to other procedures. Responses also include controlling equipment based on procedural guidance.

While PBPs support response planning, they give little active support for monitoring, situation assessment, and responses. On the other hand, CBPs may support these cognitive functions as well; the extent to which they do so depends on their design. Examining the role of the operator is very significant in defining how cognitive functions are supported by CBP design (see Section 5).

Table 4.1 provides an overall scheme within which the level of automation of CBPs can be organized. It illustrates the wide levels of automation and functionality that CBPs may possess. The table also can be used to catalog the functionality of a particular CBP system.

In the rows, the general cognitive functions (as described above) are identified, along with the associated procedure-related activities. In the columns, four levels of automation are identified; manual, advisory, shared, and automated:

- Manual - The function is performed by the operators with no assistance from the CBP.
- Advisory - The CBP provides advice only. For example, it may advise the operator that Pump A should be started, but does not start it.
- Shared - The CBP and the operators both perform the function. For example, a CBP system may perform process monitoring but may not monitor all information about the system, such as a valve's position, because it lacks the instrumentation. When this type of information needs to be monitored, the operator provides it.

Table 4.1 Levels of Automation of Procedure Functions

Procedure Functions	Level of Automation			
	Manual	Advisory	Shared	Automatic
Monitoring and Detection				
Process parameter values		NA		
Operator actions		NA		
Situation Assessment				
Procedure entry conditions		NA		
Resolution of procedure step logic		NA		
Step status (incomplete or completed)		NA		
Procedure history		NA		
Context sensitive step presentation		NA		
Assessment of continuous, time, and parameter steps		NA		
Assessment of cautions		NA		
High-level goal attainment and procedure exit conditions		NA		
Response Planning				
Selection of next step or procedure				
Procedure modification based on current situation				
Response Implementation				
Transition from one step to the next				
Transition to other parts of procedure or to other procedures				
Control of plant equipment				

Note: NA means "not applicable." For a given CBP system, the advisory level of automation may not be applicable or an entire function may not be applicable.

- Automated - The CBP performs the function automatically without the operator's direct intervention; the operators may or may not be notified of the actions taken.

A given level of automation does not necessarily apply to all functions. For example, for process monitoring, it is not meaningful to have advisory automation. The CBP system will either have monitoring capability or not. These are indicated by NA (not applicable) in the table.

A given procedure system may not provide an entire function. For example, a particular CBP may not address the control of equipment in any capacity, not even manual; equipment would be operated from other HSIs.

Individual CBP systems differ in terms of their levels of automation (i.e., the extent to which they provide features beyond those identified above as the basic procedure elements). For example, to allow manual control of components, the CBP must include a control, e.g., a soft control, for that equipment.

4.3 Management and Support of Procedures

CBP systems have design features that support operators' interaction with the system, procedure maintenance, and configuration control. Therefore, interface management features (such navigation aids)[1] are part of the characterization of CBP systems. Procedure-specific management support includes HSIs to transition between procedure steps and between different procedures. The use of procedures can be supported by facilities to monitor and record the operator's actions and to provide help.

Maintenance of procedures and configuration control are important for CBPs, as they are for PBPs. However, their mechanisms are likely to differ, such as how procedures are entered into the computer system, how their quality is verified (e.g., no typos or omissions), how errors in the CBPs are identified, tracked and corrected, how changes are incorporated, and how configuration is controlled. Guidance on these aspects is not part of this project.

Many general interface management design features are addressed in NUREG-0700. More specific guidance to address soft controls (Stubler, O'Hara, and Kramer, 2000) and interface management (O'Hara, Stubler, and Nasta, 1997) is being developed.

4.4 CBP Hardware

CBPs utilize CR devices such as VDUs, printers, and computer input devices, such as alphanumeric keyboards, trackballs, mice, and touch screens that are part of the CBP characterization. NUREG-0700, Rev. 1 has guidance for their review.

4.5 Backup System for Procedures

CBPs can fail or malfunction. When important operations cannot be suspended or put off while the system is repaired, backup to the CBP is needed. For EOPs, a delay in operations during a failure is unacceptable; therefore, some form of procedure backup is warranted.

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[1] Guidance for interface management review is currently being developed in a separate NRC research project.

4.6 Integration with Other HSI Components

Integration of the CBP with other CR HSIs must be considered. Depending on the level of automation (see Table 4.1), CBP systems require varying types of interconnection with the remainder of the CR HSI. Their consistency and compatibility with other HSI components can affect operators' performance. Thus, important considerations in reviewing CBPs include the degree to which (1) the display of plant variables in the CBP is compatible with normal monitoring displays, (2) coding schemes are compatible, and (3) control modes of the CBP are consistent with the rest of the HSI (e.g., with the modes of automated control systems).

5 TECHNICAL BASIS FOR DEVELOPING CBP GUIDELINES

The purpose of this section is to establish a technical basis for developing CBP guidelines and to identify human performance issues. The review considers human performance research that contributes to understanding CBP design and operational use. The research included CBP use in the NPP industry and several related areas: issues associated with PBPs, computerization of tasks traditionally using paper performance aids, and computerized operator support systems (COSSs). In addition, we consider the general cognitive functions associated with the supervisory control tasks which procedures support.

5.1 Cognitive Tasks Associated with Operating the Plant

Operators contribute to the plant's defense-in-depth approach to safety, serving a vital function in ensuring its safe operation. However, they may impact safety by making errors. Basically, an error occurs when personnel do not perform a safety-related action within the time required (sometimes called an error of omission). An error also may occur because personnel have an incorrect understanding of conditions and take the wrong action (an error of commission). Many attempts were made over the past 20 years to identify the causes of error. The main conclusion is that few errors represent random events; instead, most can be explained by human cognitive mechanisms (Reason, 1988; Rasmussen, 1986). Therefore, it is important to understand how operators process information and how this relates to HSI design and human error.

The operator's role in an NPP is that of a supervisory controller, i.e., the plant's performance results from the interaction of human and automatic control. Reason (1990) called this a complex multiple-dynamic configuration, which is difficult for personnel to handle when things go wrong. In addition to process failures, automatic control systems and the HSI also can fail. Thus, personnel must respond to plant failures and to the interfaces that communicate their occurrence. One significant aspect of the HSI in responding to process failures is the procedure system. In complex systems using a defense-in-depth philosophy operations are analyzed in advance to provide procedural support for both normal and abnormal events. However, even when procedures are used, operators must still engage in higher-level cognitive functioning (Dien, Montmayeul, and Beltranda, 1991; Roth, Mumaw, and Lewis, 1994).

The operators' impact on the plant's functions, processes, systems, and components is mediated by a causal chain from their physiological and cognitive processes, to task performance, and ultimately, to the plant's performance through the operators' manipulation of the HSI (see Figure 5.1). HSI design, including its procedures, affects the plant's performance through personnel tasks that support operations. Conceptually, the role of personnel can involve two types of tasks. Primary tasks are those the operator performs as part of the functional role of supervising the plant. Operators may be required to act in support of the plant's performance of a higher-level function. Even when they are not required to take an explicit action, they must monitor the performance of automatic systems and intervene when the systems fail or perform at unacceptable levels.

Primary tasks involve several generic cognitive tasks; i.e., situation assessment, monitoring and detection, response planning, and response implementation (see Figure 5.2). For primary tasks, these generic cognitive tasks are discussed, rather than the detailed specific tasks, such as monitoring steam flow, starting pumps, and aligning valves. Secondary tasks are those the operator must perform when interacting with the HSIs or job performance aids, but which are not directed to the primary task (O'Hara, Stubler, and Nasta, 1997). They include navigating through an information system and manipulating windows on a VDU. To adequately perform both primary and secondary tasks, operators use their information processing resources, such as attention, reasoning, and memory.

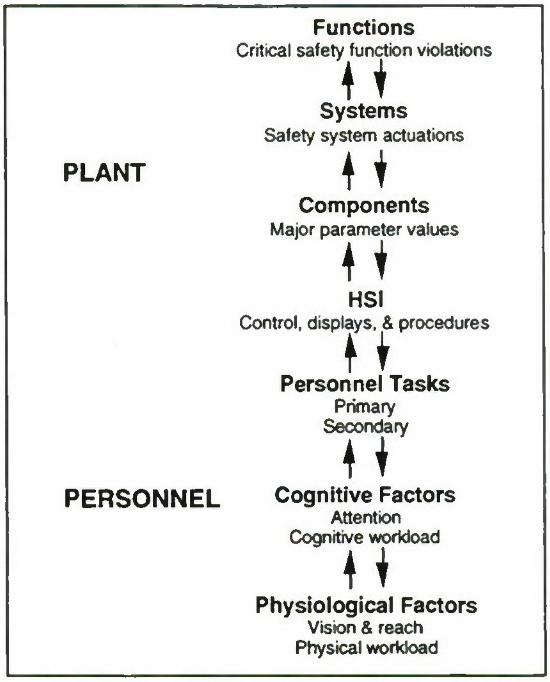

Figure 5.1 Hierarchical Influence of Human Activity on Plant Performance

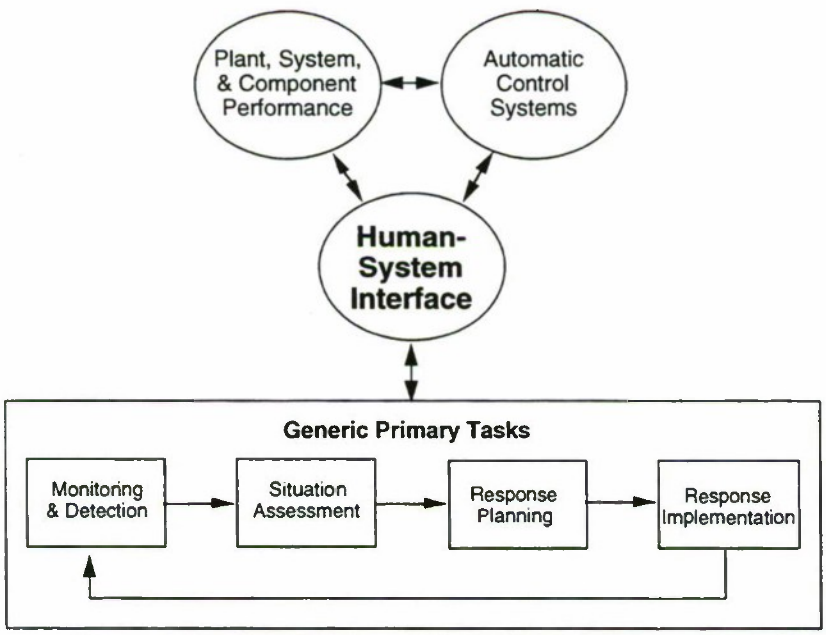

Figure 5.2 Generic Primary Tasks of a Supervisory Controller

In their traditional paper form, plant procedures mainly support response planning. On the other hand, CBPs potentially can affect all the generic cognitive primary and secondary tasks that operators undertake:

- Monitoring and detection, especially monitoring parameters used to evaluate procedure steps, monitoring steps of continuous applicability, and detecting violations of the conditions specified in these steps

- Situation assessment, especially assessing the plant's state with respect to the steps' logic, steps of continuous applicability, and cautions

- Response planning, the main function of procedures

- Response implementation, for manual or automatic control of (1) procedure flow (transitions within and between procedures), or (2) plant equipment

Situation assessment and response planning are discussed next because they are the most important and complicated cognitive functions involved in using procedures. Monitoring and response implementation are described afterwards.

<u>Situation Assessment</u>

When operators observe indications of an abnormal occurrence, they try to construct a coherent, logical explanation for them. This cognitive activity may be called situation assessment and involves two related concepts: the situation model, and the mental model. Operators develop and update a mental representation, or so-called *situation model*, of factors known or hypothesized to be affecting the plant's state at a point in time. The *situation model* is the person's understanding of the specific situation, and the model is constantly updated as new information is received. To construct a situation model, operators use their general knowledge and understanding about the plant and its operation to interpret information and understand its implications. Limitations in knowledge may result in incomplete or inaccurate situation models and response plans.

The general knowledge governing the performance of highly experienced individuals may be referred to as a *mental model* which constitutes the operator's internal representation of the physical and functional characteristics of the system and its operation. Mental models may not always be accurate or complete. The mental model is built up through formal education, system-specific training, and operational experience; it resides in the knowledge bases of long-term memory. An accurate mental model is a defining characteristic of expert performance (e.g., Wickens, 1984; Bainbridge, 1986; Moray, 1986; Rasmussen, 1983; Sheridan, 1976) and is extremely important to many aspects of information processing. It is thought to drive skill-based processing, control rule-based activity through the mediation of the operator's conscious effort in working memory, and provide the substantive capability to reason and predict future plant states required of knowledge-based processing (Rasmussen, 1983).

The distinctions between the mental and situation models reflect their cognitive basis in long-term and working memory, respectively. The mental model is relatively permanent. By contrast, an operator's situation model is the current interpretation of the plant's status and, therefore, changeable.

When the operator's situation model accurately reflects the plant's state, the operator has good *situation awareness*. Thus, the accuracy of situation awareness depends on the correlation between the operator's situation model and the actual conditions. An operator can have a good mental model (e.g., knowledge of how the plant functions) but poor situation awareness because the situation model does not match the current conditions. Endsley (1988) identified situation assessment as the single most important factor in improving a crew's effectiveness in complex systems. Endsley (1995) distinguishes three levels of situation awareness (discussed below).

An experienced, well-trained operator easily develops an accurate situation model when the HSI provides information that readily maps to knowledge in the operator's mental model. If no easy match can be made between them, then situation assessment will require more working memory and attention, and cognitive workload will be high (Endsley, 1993, 1995; Fraker, 1988). However, in addition to supporting situation assessment, working memory must support other activities, such as selecting and taking actions. Accordingly, if other tasks place high demands on working memory, situation awareness may suffer.

Situation awareness and cognitive workload may vary inversely under complex, ambiguous situations. For example, under unfamiliar or otherwise difficult conditions, a high cognitive workload may entail decreased situation awareness, possibly due to a lack of available attentional resources for analyzing the situation. However, Endsley (1993) points out that situation awareness and cognitive workload, while interrelated, may vary independently. For example, a task may be intensive, but readily recognizable. Situation awareness demands cognitive resources that contribute to workload, but is not the only cognitive activity requiring such resources.

Thus, mental models enable operators to engage in situation assessment and to establish situation models. Good situation models include a knowledge of the important elements of the current situation, and a comprehension of how they interrelate to reflect the overall situation. These two aspects of good situation models correspond to Endsley's (1995) Level 1 (Perception of Elements) and Level 2 (Comprehension of Situation) situation awareness.

Mental models enable operators to make predictions and form expectations; projection of future states corresponds to Endsley's (1995) Level 3 situation awareness. These expectations guide monitoring and affect how information is interpreted. This is a general characteristic of information processing; it is a synthesis of "bottom-up" processing (what an operator perceives from the environment) and "top-down" processing (what an operator expects) (Neisser, 1967). An example of bottom-up processing occurs during a disturbance when an operator monitors the HSI and processes data from the interface to determine what is wrong. Simultaneously, these data are used to formulate hypotheses or expectations about the plant's status that structure the perceptual process and data-gathering at lower levels. This is top-down processing. Both contribute to the operator's interpretation of the situation.

The ability to predict from a mental model based on the current situation model facilitates "open-loop" performance (Moray, 1986). "Open-loop" in this context means that behavior becomes less driven by feedback and more governed by the operator's prediction of future system behavior and the desired goal. An NPP mental model includes such knowledge as the physical interconnections among plant systems to predict flow paths (e.g., considering piping and valve interconnections to figure out how water from one system could get into another), and knowledge of mass and energy changes in one system to predict the effect on a second system (e.g., predicting the effect that changes in the secondary side steam generator levels and temperatures will have on cooldown of the primary system). While mental models provide the principles upon which predictions are made, the situation model provides the starting point and is the basis for developing expectations about events that should be happening at the same time, how they should evolve over time, and any future effects.

The operator's expectations of the near-term future of the plant guide the sampling of indicators to confirm the inference (Bainbridge, 1974). Expectations are used to search for evidence to confirm the current situation model, and to explain observed symptoms. If a new symptom is consistent with the operator's expectations, a ready explanation for it will be developed, yielding greater confidence in the situation model.

While the mental model allows prediction and expectancy to guide control responses, expectancy may confound the detection of subtle system failures (Wickens and Kessel, 1981). When a new symptom is inconsistent with an operator's expectations, it may be discounted or misinterpreted in a way to make it consistent with the expectations of the current situation model. For example, an operator may fail to detect key signals, or detect them but misinterpret or discount them, because of an inappropriate understanding of the situation and the derived expectations. Operators tend to ignore or discount symptoms that are not consistent with their situation model. However, if the new symptom is recognized as an unexpected behavior, the need to revise the situation model may become apparent. In that case, the symptom may trigger situation assessment activity to better explain current observations. In turn, situation assessment may involve developing a hypothesis for what might be occurring, and then searching for confirmatory evidence. Thus, situation assessment can result in the detection of abnormal plant behavior and of symptoms and alarms that otherwise might not have been observed or might have been missed, and the identification of problems such as sensor failures or plant malfunctions.

The situation model is constantly updated as new information is received and a person's understanding of a situation changes. In NPPs, maintaining and updating a situation model entails tracking the changing factors influencing plant processes, including faults, operators' actions, and automatic system responses.

The importance of mental and situation models, and the expectations generated, cannot be overemphasized. They not only govern situation assessment, but play an important role in guiding monitoring, using procedures and formulating response plans, and implementing responses.

Response Planning

Response planning refers to deciding upon a course of action to address an event. Response planning can be as simple as selecting an alarm response or EOP, or it may involve thoroughly developing a plan when existing procedures have proved incomplete or ineffective.

In general, response planning involves operators using their situation model to identify goal states and the transformations required to achieve them. The goal state may be varied, such as to identify the proper procedure, assess the status of back-up systems, or diagnose a problem (Rasmussen, 1981). To achieve the goals, operators generate alternative response plans, evaluate them, and select the one most appropriate to the current situation model.

This is the basic sequence of cognitive activities in response planning; one or more of these steps may be skipped or modified based on the operator's assessment in a particular situation. When available procedures are judged appropriate to the current situation, the need to generate a response plan in real-time may be largely eliminated. However, even then, some aspects of response planning will be undertaken. For example, operators still need to (1) identify goals based on their own situation assessment, (2) select the appropriate procedure, (3) evaluate whether the procedure-defined actions are sufficient to achieve those goals, and (4) adapt the procedure to the situation, if necessary.

The decision making involved in situation assessment and response planning, especially in ambiguous situations when available procedures do not suffice, can be a large cognitive burden and draw heavily upon working memory, long-term memory, and attentional resources. Information then is consciously manipulated in working memory, and the ability to do so is a direct function of attentional resources available. Working memory has very limited capacity, and without sustained attentional resources (or transfer of the information to long-term memory), information decays rapidly. Information can be lost due to (1) insufficient attentional resources to keep it active, (2) overload of the working-memory capacity, and (3) interference from other information in working memory. To increase the capacity of working memory, operators use memory heuristics, such as chunking – aggregating and organizing information into higher-level, meaningful units. A heuristic, as used here, means a shortcut for information processing developed through experience and trial-and-error, rather than systematic, formal analysis. Once this is accomplished, the higher-level units, not the individual elements, are stored in working memory.

Dien et al. (1991) discussed the importance of higher-level cognitive functions when operators use procedures. Operators must compensate for inadequacies, fill in gaps, and resolve conflicts between the control objectives specified in the procedures and those established by the operators assessing the situation. Operators sometimes must implement more practical strategies than those in the procedures. They must also consider whether operating actions should be anticipated, or whether automatic devices should be left to operate.

Roth et al. (1994) demonstrated the need to maintain a supervisory role, even when responses are largely dictated by EOPs. They investigated how operators handle cognitively demanding emergencies, their objective being to examine the role of situation assessment and response planning on guiding a crew's performance when EOPs were being utilized. NPP operators from two different utilities performed interfacing systems loss-of-coolant accident (ISLOCA) and loss-of-heat-sink scenarios on training simulators where complexities made it difficult to simply follow the appropriate procedure. The results illustrated the importance of high-level cognitive functions during use of EOPs. The operators developed an understanding of the plant's state and confirmed their situation assessment, and also attempted to understand plant performance that was unexpected based on their current situation model. These cognitive activities enabled them to evaluate the appropriateness of the EOP to achieve the high-level goal dictated by the situation assessment within the context of current conditions. Roth et al. noted the importance of the crew's interactions and communications to these high-level cognitive functions, due partly to the need to obtain information from many HSIs in different locations. In addition, communication helped operators overcome the fact that EOPs do not cover all the important information on the current plant state. When a specific procedure seemed to fail to meet the high-level goal, operators would alter the procedure path to better address the current situation.

Thus, Roth et al. (1994) demonstrated the importance of understanding the basis of the procedure and its intended higher-level goals. The need to formulate modifications to procedure pathways also means that operators may not simply proceed linearly through a procedure. They may need to consider future steps, reexamine previous ones, and refer to other procedures to verify that their current activities are correct and will meet the high-level goals.

Roth (1994) considered the implications of the Roth et al. (1994) study for designing operator support systems. First, the requirement of situation assessment and response planning independent from procedures suggests that operators must maintain awareness of abnormal plant symptoms, determine what malfunctions could produce them, and know the manual and system actions that are being undertaken and their effects. Second, since crews must anticipate the consequences of their actions, operator support systems could help in identifying their consequences and side effects. Third, operators must understand the assumptions and logic behind the procedures, i.e., their intent, their overall strategies, and the transition logic between them. Since operators may not move linearly between procedures, CBP navigation systems will be important to the success of CBPs in complex emergencies.

Monitoring and Detection

Monitoring and detection refer to the activities involved in extracting information from the environment. Monitoring is checking the state of the plant to determine whether the systems are operating correctly; it can include checking parameters indicated on the CR panels, monitoring those displayed by the process computer, obtaining verbal reports from operators in the plant areas, and sending them to other areas to check equipment.

Detection is the operator's recognition that something is operating abnormally. Procedures guide monitoring and detection by identifying the parameters to be monitored. However, operators must also monitor the crew's actions taken in response to disturbances.

Monitoring and detection are influenced by two factors: (1) the characteristics of the environment, and (2) the operator's knowledge and expectations. These factors lead to two types of monitoring: (1) data-driven, and (2) model-driven. Monitoring driven by environmental characteristics often is referred to as data-driven monitoring. Data-driven monitoring is affected by the salience of the information's presentation (e.g., size, color, and loudness). Thus, alarm systems are basically automated monitors designed to influence data-driven monitoring by using physical salience to attract attention. Auditory alerts, flashing, and color coding are physical characteristics that enable operators to quickly identify an important new alarm. Data-driven monitoring also is influenced by the behavior of the information, such as the bandwidth and rate of change of the information signal; observers more frequently monitor a rapidly changing signal.

Operators may initiate monitoring based on their knowledge and expectations (model-driven) about the most important information; this typically is called knowledge- or model-driven monitoring. Model-driven monitoring can be viewed as active monitoring, in that the operator is not merely responding to environmental characteristics that "shout out" like an alarm system does, but is deliberately directing attention to areas expected to provide specific information.

Model-driven monitoring may be initiated by several factors. First, it may be guided by operating procedures or standard practice (e.g., control panel walk-downs at shift turnovers). Second, it can be triggered by situation assessment or response planning activities and is, therefore, strongly influenced by a person's current situation model. The situation model allows the operator to direct attention and focus monitoring effectively. However, model-driven monitoring can lead operators to miss important information. For example, an incorrect situation model may focus operators' attention in the wrong place, cause them to fail to observe a critical finding, or to misinterpret or discount an indication.

An operator is faced with an information environment containing more variables than can be realistically monitored. The real challenge comes from the fact that there are many potentially relevant things to attend to at any time, and the operator must determine what information is worth pursuing within a constantly changing environment (Vicente, Mumaw, and Roth, 1997). Then, the operator must decide what to monitor and when to shift attention elsewhere. These decisions are strongly influenced by an operator's current situation model, which guides the allocation of attentional resources to sampling data from the environment based on its statistical properties; i.e., expected probability and correlation. The operator's ability to develop and effectively use knowledge to guide monitoring relies on the ability to understand the current state of the process. As cognitive workload increases, monitoring strategies become less thorough, and the capability to detect particular failures decreases (Ephrath and Young, 1981).

Under normal conditions, situation assessment is attained by mapping the information obtained from monitoring to elements in the situation model. For experienced operators, this comparison is relatively effortless. During unfamiliar conditions the process is considerably more complex. The first step in realizing that the current plant conditions are inconsistent with the situation model is detecting a discrepancy between information representing the current situation and that derived from monitoring. This process is facilitated by the alarm system, which directs the operator's attention to an off-normal situation.

When determining whether a signal is significant and warrants further investigation, operators examine it in the context of their current situation model. They must judge whether the anomaly indicates a real abnormality or an instrumentation failure. They then will assess the likely cause of the abnormality, and evaluate the importance of the signal in determining their next action.

Monitoring has been described in terms of signal detection theory (SDT) (Green and Swets, 1988). Process control operators are in a monitoring environment described in SDT terms as an alerted-monitor system (Sorkin et al., 1985; Sorkin et al., 1988). Such a system is composed of an automated monitor and a human monitor. The automated monitor in an NPP is the alarm system which detects off-normal conditions. When a parameter exceeds the criterion of the automated monitor, the human monitor is alerted and then must detect, analyze, and interpret the signal as a false alarm or a true indication of an upset. The human monitor also can assess plant parameters independently of the automated monitor (the alarm system). Both monitors have their own specific detection parameter values for sensitivity (d') and response criterion. The latter refers to the amount of evidence needed before an operator will conclude that a signaled event is actually present; this is called response bias since it describes an operator's conservatism. Sensitivity refers to the resolution of the system, i.e., the ease with which signals (represented as a statistical distribution) can be distinguished from signals plus noise (similarly represented).

SDT research has many implications for understanding how operators process information during a disturbance. First, the response criterion is affected by expectancy; i.e., the expected probability that an event will occur and the payoff structure (rewards and penalties for making correct and incorrect detections, respectively). While alarms can occur frequently, significant off-normal events in NPPs typically have a low probability. Therefore, operators have low expectancy about their actual occurrence which creates a conflict between the cost to productivity for falsely taking an action that shuts down the reactor versus the cost for failing to take a warranted action. In actuality, because disturbances have a low probability, operators rely on redundant, supplemental information to confirm the alarm. Having verified several confirmatory indicators, the operator can accept the alarm information as indicating an actual off-normal condition.

There are two types of anomalies: (1) deviations from desired system functions, called abnormal findings, and (2) deviations from the operator's situation model, or unexpected findings. The two anomalies lead to different follow-up reasoning and monitoring behavior:

- Abnormal findings lead to information processing about how to cope with the disturbance (response planning) and to monitoring behavior to see if the expected coping responses have occurred and are having the desired effect.

- Unexpected findings or process behavior lead to situation assessment activity and model-driven monitoring to explain the finding.

Failures in monitoring can include failing to observe parameters, misunderstanding the significance of parameters, or failing to obtain needed reports from plant areas. Failures in detection can include failure to recognize an abnormality despite proper monitoring. An error in monitoring or detection can cause the operator's failure to respond to the event, or at least, to respond within the required time.

<u>Response Implementation</u>

Response implementation is the performance of the actions identified in response planning. This can be as simple as an individual operator selecting and operating a control, or it can involve communications and coordination with teams of operators in different parts of the plant, who each then select and operate equipment controls in a centrally coordinated manner. The actions may be discrete (e.g., flipping a switch) or may involve continuous control (e.g., controlling steam generator level).

The results of actions are monitored through feedback loops. Two aspects of NPPs jeopardize the implementation of responses: time and indirect observation. Time and feedback delays disrupt response implementation because they make it difficult to determine whether control actions are having their intended effect. Consequently, the operator's ability to predict future states from mental models can be more important in controlling responses than feedback. Further, since plant processes cannot be directly observed, their status is inferred through indications; thus, errors in cognition can impede performance.

Failures in implementing a response can lead to the operation of the wrong equipment, or the incorrect operation or control of particular components.

Summary

The role of the operating crew in an NPP is that of a supervisory controller that must engage in situation assessment, monitoring and detection, and response planning and implementation. These cognitive functions are applied to tasks for which the crew has primary responsibility, as well as to automated systems and systems designed to support crew tasks. Procedures fall into the latter category. Historically, procedures were designed to support response planning by providing operators with strategies that were based on previous detailed analyses of normal and abnormal plant states. However, when these preplanned strategies are applied to the unique circumstances of a particular disturbance, unforseen or unanticipated situations may render an aspect of a procedure inappropriate or ineffective. Thus, confronted with the complexities of real-world process disturbances, operators must monitor the performance of the procedure to verify its conformity to the higher-level goals that it was designed to achieve. Under such circumstances, it is important for operators to assess the effectiveness of the response plan even when it is described by established procedures, evaluate the consequences of particular procedure actions, and evaluate the appropriateness of the procedure path for achieving identified goals. This assessment enables operators to detect when procedures are not achieving the goals, when they may contain errors, or when errors are made in carrying out procedure steps. Another cognitive activity is adapting the response plan. This includes filling in gaps in a procedure, modifying it to fit the specific situation, redirecting its path, and using additional or alternative procedures.

Thus, rather than assuming the role of rote, verbatim "procedure-followers," it is important that the operators maintain the role of supervisory controllers and monitor the performance of the procedures as well as the process.

With the development of CBPs, the support of procedure systems extends beyond response planning and includes aspects of situation assessment, monitoring and detection, and response implementations. This support may be applied to the operator's primary tasks as well as secondary tasks.

5.2 Issues with Paper-Based Procedures and Implications for Computerization

As we discussed, plant procedures provide instructions to guide operators in monitoring, deciding on appropriate actions, and controlling the plant. The design of procedures was identified as a major cause of human error because PBPs have characteristics limiting the manner in which information can be presented, and impose tasks upon operators that are not directly related to controlling the plant. Properly following the procedures sometimes is complicated by the necessity to track several EOPs or EOP branches simultaneously. Current symptom-based procedures appear to place significant workloads on operators.

The purpose of examining the human performance issues associated with PBPs is to (1) ensure that these design deficiencies are addressed by CBPs where possible, and (2) identify aspects of procedure use that can be supported by computerization where human performance issues are not a simple function of the paper medium.

In this section, the factors associated with difficulties with PBPs are identified, and their implications for CBP design are discussed.

Issues with PBPs

Several studies have addressed the problems associated with PBPs, and identified a broad range of deficiencies that fall into the following categories: design process, implementation, training, and maintenance. The deficiencies identified in these studies came from various sources including NRC procedure inspections, operator interviews, and literature reviews. Table 5.1 compiles the overall results. Four studies whose findings are included in the table are briefly discussed next.

For non-EOP procedures, the types of deficiencies identified include (1) an excessive number of procedures and poor classification schemes for their use, (2) technical inaccuracies, (3) lack of clearly specified goals and criteria for determining that the intent of the procedure was attained, and (4) vaguely written procedures that do not specifically describe the necessary actions (Morgenstern et al., 1987; Barnes and Radford, 1987).

These procedure limitations were associated with numerous problems in performance. Flow control and transitions between procedures can be associated with potential safety-significant errors (Chignell and Zuberec, 1993) when operators do the following:

- Skip a step in the procedure
- Follow out of sequence
- Inadvertently use the wrong step
- Follow an out-of-date, erroneous, imprecise, or ambiguous procedure
- Follow the wrong procedure due to incomplete procedure references
- Miss a procedure transition and continue in the current one
- Become lost or confused when a transition is identified in a caution rather than as an action step

Teamwork and communication are also important. Hoecker et al. (1994) and Hoecker and Roth (1996) identified errors in communication during the acquisition of procedure-specified information as problematic, including delays, suspended tasks, and difficulty identifying the correct display from other displays. These limitations increase workload and the likelihood of procedural errors.

Implications for CBPs

The deficiencies identified in PBPs are associated with implementing the procedures as well as with the procedure design process, training, and maintenance (illustrated in Table 5.1). Teigen and Ness (1994) identified the following CBP features as important in addressing these limitations:

- A structured, consistent format
- Ease of transition between procedures, and recording transitions
- Place keeping in procedures when operators are in several simultaneously or when they access support information, such as tables and charts
- Clear, consistent logic statements
- Monitoring of process control parameters
- Simplification of flowcharts by allowing operators access to varying levels of detail
- Maintenance of procedures

Similarly, Lipner and Rusnica (1996) identified some of the CBPs' features that can reduce the mental load and time demands of working with PBPs. They included monitoring plant parameters, centralizing all procedural information in one place, creating detailed record keeping on procedure implementation, and facilitating the maintenance of procedures.

CBPs can directly affect many, but not all such deficiencies. In fact, a significant consideration in evaluating CBPs may be the extent to which they solve these problems. Next, we describe each of the problems associated with the paper medium and their possible resolutions by CBPs. For those problems not directly impacted by computerization, many of the same factors that contribute to PBP problems can also undermine CBPs.

We now consider the major areas of procedure use that can be impacted by computerization. Several categories were previously identified (Barnes et al., 1996). While they mainly cover implementation of procedures, an initial category is identified which includes the more general areas of design process and support:

- Design Process and Support
- General Cognitive Workload
- Level of Detail
- Context Sensitivity
- Sequence Control and Navigation
- Management of Multiple Procedures
- Maintenance of Technical Accuracy of Procedures
- Integration of Procedure Tasks and Other Tasks

Table 5.1 Deficiencies in Paper-Based Procedures

Issue	Deficiency	Note
Design Process	• Inadequate participation of operations and training personnel in developing procedures	(1)
	• Technically incorrect EOPs	(1)
	• Address standard situations, but are less supportive in unusual situations	(1)
	• Incomplete procedures	(3)
	• Inadequate consideration of the time required to complete procedural actions	(1)
	• Insufficient verification and validation (V&V) of procedures	(1)
Imple-mentation	• Non-specific entry and exit conditions for support procedures	(1)
	• Fixed and inflexible procedures	(2)
	• Incorrect sequencing of action steps	(1)
	• Inadequate consistency across procedure	(1)
	• Inconsistencies in formatting and use of terminology	(1)
	• Incorrect identification of equipment	(1)
	• Inadequate ability to provide varying level of detail	(4)
	• Non-sequential presentation of information	(4)
	• Navigation to related information	(4)
	• Management of multiple procedures	(4)
	• Integration of procedure tasks and other tasks	(4)
	• Problems in labeling and headings	(3)
	• Notes and cautions in improper places	(3)
	• Lack of context-dependent highlighting and navigation	(3)
	• Need to use multiple procedures simultaneously and move between sections	(3)
	• Lack of flowcharts to guide use of procedure	(3)
	• Inadequate support and reference material	(1)
	• Bulkiness	(3)
	• Physical handling of procedures near control panels	(2)
	• Separation from other information sources, such as the safety parameter display system (SPDS)	(3)
	• Inconsistency with other HSIs in referring to plant equipment	(1)
Training	• Poor training of operators in use of procedures	(1)
Maintenance	• Maintaining technical accuracy of procedures	(3, 4)

Notes: (1) Lapinsky, 1989; Galletti and Sutthoff, 1992
(2) Niwa, Hollnagel, and Green, 1996
(3) Chignell and Zuberec, 1993
(4) Barnes, Desmond, Moore, and O'Hara, 1996

Design Process and Support

The NRC's analysis of EOPs (Lapinsky, 1989) concluded that deficiencies in the design of EOPs were likely to be found when any of the following were lacking:

- A multidisciplinary team
- An independent review to assure technical accuracy and usability
- A systematic process to ensure EOPs do not degrade over time
- Management's commitment to the EOP design process

These factors can also negatively impact the development and use of CBPs. A development program should address these issues and those in the non-implementation categories in Table 5.1 to ensure that the final CBP system will adequately support safe operations.

General Cognitive Workload

Many problems with PBPs result from the high demands on cognitive activities, especially monitoring (e.g., of parameters needed to use procedure logic), decision making (e.g., analyzing procedure step logic), and memory (e.g., to perform steps of continuous applicability). These problems are amplified by the stress created by complex process disturbances. Mumaw (1994) found that stress lowers human performance by (1) narrowing and shifting attentional focus, (2) reducing working memory capacity, and (3) impairing the crew's communication patterns. Reducing the demands on cognitive processes can support the operator in managing stress and maintaining performance. By supporting cognitive functions such as obtaining parameter values (monitoring), comparing them to reference values, and monitoring steps of continuous applicability (discussed further below), CBPs may reduce the demands on attentional resources and working memory, enabling operators to focus on evaluating higher-level procedure goals.

Level of Detail

Space for explanatory information is limited in PBPs and the level of detail in procedure steps is fixed. Determining the appropriate level of detail in presenting procedure steps, and deciding upon the type and level of detail in supporting information are inexact processes that may be facilitated by computerization. Substantial interaction with trainers and operators is needed to decide upon the level of detail, which increases costs and still has an uncertain outcome. Linkages between training programs and the procedures can lessen over time, and so the operators' knowledge bases can change. In addition, even though all operators have reached the expertise required for licensing, differential experience may lead to differences in familiarity with the components, systems, and processes defined in the procedures. Those more familiar with a task may become impatient if the information is too detailed and may inadvertently skip steps to avoid wading through unneeded information. Operators who are less familiar with the task may be unable to perform the procedure correctly with the amount of information provided.

An advantage of CBPs is that they can provide varying levels of detail (Fischer et al., 1991; Jenkinson et al., 1991), and computerization has been used elsewhere to resolve these problems. For example, in the early 1980s, the Navy developed computer-based troubleshooting aids for maintenance that allowed the user to choose between two different levels of detail. In the more detailed option, general steps (e.g., "start the pump") were broken up into specific substeps (e.g., "depress the start button on Pump XYZ") and more detailed graphical displays were shown.

Hypertext applications are under development within the Department of Defense (DOD) as part of the Continuous Acquisition and Life-Cycle Support (CALS) initiative that also allow the user to determine the level of detail of information. Some systems allow the user not only to set a preferred level of detail, but also to browse through supplementary information, and the information that was used to develop the technical content of the procedure steps. Access to this latter information may be particularly useful if the procedure cannot be performed under existing plant conditions and must be modified.

NPPs and vendors of nuclear steam supply systems have developed procedure-basis documents that give significant details and insights into the reasons for procedure steps and the logic for choosing parameters, operations, and step order; such information does not normally appear in procedures to avoid clutter. In CBPs this information can be made available when necessary.

Improper implementation of a variable level of detail potentially may impair operators' performance if operators do not understand the level appropriate to their use of the procedure.

Context Sensitivity

Irrelevant information about conditions that do not exist during a specific implementation of a procedure must continuously be shown for decision steps in PBPs. Because nearly all procedures involve decisions, operators may have to read several pages of irrelevancies to find the appropriate action steps. This can cause operators to lose track of their place in the procedures, to miss important information, and to delay their performance.

Several techniques are used in PBPs to present decision steps, some of which require less space than others. In text-format procedures, decision steps typically are represented by Boolean logic terminology (e.g., "if the following conditions exist, then perform these actions"). In flowchart-format procedures, the antecedent conditions are typically presented in decision diamonds, and consequent actions in rectangular symbols that are linked by flow lines to the decision diamonds. Other formats are possible, such as the two-column, "response not obtained" format used in EOPs for pressurized water reactors.

These techniques also may be used in CBP systems, but may create similar paging problems on a VDU. However, CBPs can display only the relevant action steps for existing conditions. For example, once the operator has evaluated the existing conditions and chosen an action, only the information relevant to that action would be displayed. Alternatively, a CBP system could be designed to evaluate the existing conditions and to choose the action for the user. Then, both the full listing of possible antecedent conditions and the action steps for non-existent conditions could be "hidden" from the user. Although there may be some value in having the decision criteria and the "paths not taken" continuously available for review, a system may be designed to reduce the amount of information displayed to reduce errors and improve the efficiency of task performance.

Sequence Control and Navigation

In PBPs, information is presented sequentially. However, as Roth (1994) indicated, non-sequential access to other procedure information and support materials may be necessary for operators to adequately assess the procedure. In addition, even in current procedures, some steps are not performed sequentially. Two examples may clarify these problems and show how computerization could resolve them. Steps of continuous applicability are performed at any point in a procedure at which certain conditions are met (e.g., pressurizer pressure exceeds a given level).

Therefore, because the triggering conditions may be met at any time, the steps of continuous applicability always should be immediately available to the user. However, space on paper procedure pages is at a minimum (as it is on a VDU), so that continuously repeating the steps on each page increases the amount of skimming through pages that the operator must do. Further, because the steps of continuous applicability are not part of the direct sequence of actions means that they can be easily overlooked, even if they are invariably shown in a dedicated box on the procedure page or on a facing page. If a CBP system was designed to detect the triggering conditions for these steps, it could insert the appropriate step exactly when it is needed, so that the operator could immediately attend to it. Thus, space on the VDU screen is not wasted with a continuous display.

Time-dependent steps are similarly problematic because they are only performed after some specified period (e.g., some NRC notification requirements in EOPs). Because the time taken to progress through a procedure may vary under different circumstances, it is difficult to show a time-dependent step exactly when in the sequence of steps it must be undertaken. Presenting the time-dependent step at the point in the sequence that "starts the clock" may mean that operators forget to perform it after the designated amount of time has passed. Continuously displayed reminders have the same limitations as repeating steps of continuous applicability in PBPs. However, because timekeeping is easily automated, a CBP system could have the timekeeping function (where either the operator or the system "starts the clock") and then display the action step when it must be performed.

In paper procedures, cross-referencing between steps and procedures introduces errors and delays in task performance. Navigating through such cross-linked steps and procedures is a significant problem for NPP operators with PBPs because cross-references interrupt the user's sequential performance of action steps. For example, unconditional branches instruct the user to leave the current procedure and begin again in another procedure or in another section of the same one. References direct the user to another procedure for supplementary information or for a series of action steps, after which the user is redirected to the original procedure and continues then to follow it. These non-sequential movements through PBPs cause the operators to lose track of their place in the original procedure, or to waste time trying to locate the procedure to which they are referred.

CBP systems could be designed to assist operators in following cross-references or to eliminate the need for them. A CBP system can simplify the user's search task, for example, with a menu of procedures allowing the user to choose the cross-referenced procedure, rather than having to physically locate it in a paper manual. Operators can select the step to begin performing actions in the cross-referenced procedure, rather than scanning a document to locate the desired steps. Windowing or some other technique can support the function of place keeping in the original procedure so that the user can later return to it. Checkoff and place-keeping functions can be automated, so that operators can easily determine where they have been, what steps were completed, and where they left off in various procedures.

More sophisticated systems are under development in the DOD's CALS initiative. Interactive electronic technical manuals (IETMs) for maintenance tasks are being developed in which procedure steps and other elements are stored in a database. At the beginning of a task, the user specifies the task and the circumstances under which it will be performed. The sequence of action steps and associated supplementary information (i.e., a complete procedure) then are generated by the system from the database, so that no cross-referencing is required.

Management of Multiple Procedures

Physical management of multiple procedures and place keeping when concurrently carrying them out are awkward with PBPs; the EOPs currently used in many boiling water reactors (BWRs) are an example. Operators who must use EOPs based on the General Electric (GE) Owners' Group technical guidelines, in some emergency scenarios may have to manage the concurrent performance of actions in up to 14 different procedures. The bulk of the action steps are shown in flowcharts the size of engineering drawings; finding laydown space for these procedures in a typical CR is difficult, and the reader must physically move around them to track procedure steps. In addition, operators may be required to carry out abnormal operating procedures and some system operating procedures at the same time as the actions in the EOPs. Prioritizing the performance of steps in the different procedures is left to the unit supervisor, based on the staff available and the extent of degradation of particular parameters. The opportunities are clear for the CR crew to overlook steps in the procedures and to commit other types of errors.

At a simple level, computer management of the progress and place keeping for multiple procedures may facilitate their use. At a more sophisticated level, CBP systems can be developed to prioritize and sequence the actions for each anticipated emergency scenario, and thereby substantially reduce the operators' workload. However, designing such a CBP system would seem to necessitate a significant change in the underlying mitigation strategy adopted by the GE Owners' Group. Because the Westinghouse Owners' Group's Emergency Response Guidelines already prioritize and sequence actions for pressurized water reactor (PWR) crews and involve fewer instances in which multiple procedures must be performed, EOPs for PWRs may be easier to translate into CBPs. Additionally, physical management of PBP manuals at remote locations, such as the remote shutdown panel, can be difficult. CBPs offer a simple solution to this problem, as they can provide the operators with the same interface normally used in the main CR.

Maintaining Technical Accuracy of Procedures

It can be difficult to maintain the accuracy of procedures, due to procedure modifications or to changes in other plant operations (e.g., regulatory requirements, equipment modifications). Maintaining technical accuracy is particularly difficult on paper. Thus, a design change in a single component can invalidate every procedure that refers to that component. Similarly, a procedure revision that changes the step numbers in one procedure can invalidate every step in other procedures cross-referencing the changed procedure. Some licensees already have developed elaborate configuration control software to solve this problem.

Procedure-generation systems, such as the IETMs described above, can overcome some of these difficulties. Where procedure actions and the objects of those actions are stored in a database as objects, a change in a step or a part of a step in the database will ensure that the step is correct whenever it is used in any future procedure generated by the system.

Integration of Procedures and Other Tasks

The tasks associated with handling and reading a paper procedure may be incompatible with other tasks the operator has to perform. CBP systems for tasks performed at workstations, where the control actions can be performed at the same workstation at which the user obtains procedures information, can decrease the delays and potential errors associated with PBPs. Indeed, many licensees assign the task of reading the procedure to a different person to avoid delays and potential errors; CBP systems can eliminate this requirement.

<u>Summary</u>

Numerous limitations of PBPs have been identified and associated with delayed performance and human errors. CBPs offer the opportunity to rectify these problems. The following are PBP issues and the types of CBP support that may address them:

- Design Process and Support

  - Weaknesses in the design process and management support have led to problems in PBPs and should be addressed when developing CBPs.

- General Cognitive Workload
  - CBPs may reduce the demands on attentional resources and working memory, and enable the operator to focus more on evaluating higher-level procedure goals.
  - CBPs can support cognitive functions, such as obtaining parameter values (monitoring), comparing actual values to reference values (resolution of procedure step logic), and monitoring steps of continuous applicability.

- Level of Detail
  - CBPs can allow adjustment of the level of detail for operators with varying familiarity with the tasks, components, systems, and processes defined in the procedures may enable them to use procedural guidance more efficiently.

- Context Sensitivity
  - CBPs can display only the relevant procedure steps for existing conditions, so operators are not distracted by irrelevant information.

- Sequence Control and Navigation
  - CBPs can take advantage of non-sequential access to information using computer navigation functions.
  - CBPs can automatically detect the triggers for the steps of continuous applicability and time-dependent steps and insert the action step to be performed exactly when it is needed.
  - CBPs can perform cross-referencing, place keeping, and checkoffs.

- Management of Multiple Procedures
  - CBPs can manage the progress of, and place keeping for, multiple procedures.
  - CBPs can prioritize and sequence the needed actions.
  - CBPs can eliminate some physical problems and coordinate many procedure manuals, especially when laydown space is unavailable.

- Maintaining Technical Accuracy of Procedures
  - Procedure-generation systems using procedure databases can enhance accuracy.

- Integration of Procedures and Other Tasks

- Control actions for executing the procedure can be performed at the same workstation as the CBP, and can decrease the delays and the potential for errors associated with using PBPs.

We note that some of these concepts have not yet been fully implemented or evaluated. Others may require substantial changes in the manner in which technical information is managed in NPPs.

5.3 Existing Guidance for CBP Systems

In this section, we discuss the available guidance for CBP systems. Three principal conclusions emerge. First, guidance for CBP systems is extremely limited. Wourms and Rankin (1994) noted that no comprehensive standards or guidelines are available for designing or evaluating CBPs. EPRI (1991) indicated that "... guidelines for such soft procedures are not well established and will have to be developed by the M-MIS designer."

Second, there is some uncertainty over generalizing the principles and guidelines for PBPs to CBPs. Converse (1992) stated that "... There is no evidence that guidelines for the design of traditional hard-copy procedures can be successfully applied to computerized procedures, and few guidelines specifically address the design of computerized procedures" (p. 170). Similarly, Tolbert et al. (1991) concluded while much is known about the design of PBPs, the applicability of the information to CBPs is unknown. They also believe that problems may result from combining the use of PBPs and CBPs due to the need to train operators on both systems, to changes in "allocation of function" due to the CBP, consistency differences, and issues of procedure maintenance.

Based on the generally acknowledged lack of HFE CBP guidance, the third conclusion is that the development of CBP systems for operational use should proceed in a way such that the benefits and drawbacks of CBP systems can be fully evaluated for each specific system. From reviewing the literature on CBPs, Chignell and Zuberec (1993) determined that "... a cautious approach should be taken [to computerization of procedures]. Relatively little is known about how operating procedures should be used in practice, and there is a possibility that problems with existing hard copy procedures may be compounded when they are computerized" (p. 1). Similarly, after reviewing several CBP systems, Spurgin, Wachtel, and Moieni (1993) concluded that "... more work needs to be done before the industry can make a safe transition from traditional paper and pencil procedures to computerized systems" (p. 1017).

In the remainder of this section, the existing sources for high-level CBP design principles and guidance are discussed.

EdF CBP Design Principles

Based on their experience with developing CBPs for the N4 design, EdF (Dien, Montmayeul, and Beltranda, 1991) offered the following general high-level guidance:

- The CBP should leave the operators in-the-loop. Therefore, it has no advisory role and leaves final decisions to the operators.

- The CBP display screens should associate the control objectives, the current process solution, and the required actions.

- Operators should be able to navigate freely within the procedure to make up for its insufficiencies.

- The procedures should be represented at different levels to accommodate various operator skill levels. The EdF system has an action level, which covers the detailed tasks, and an "objectives-task" level showing the chronology and links between different objectives.

It is noteworthy that several of these guidelines relate to the postulated ways in which CBPs can improve on PBP limitations discussed previously.

EPRI Utility Requirements Document

High-level CBP guidance was developed also by EPRI in the URD (EPRI, 1993b). It was based on EdF's CBP experience. EPRI required CBP systems in advanced light water reactors (paragraph 3.4.2.2). However, due to the lack of industry experience with them, the URD suggests that simulations are needed to develop detailed guidance and to validate the systems. The URD guidance is summarized below:

- Procedures shall be in the form of logic or flowcharts.

- The procedures shall normally provide, on the same display, the parameters necessary for the operator to make each decision.

- Plant parameters and status in the procedures should be continuously updated.

- The operator will be able to access the control needed to carry out the tasks directly from the procedure.

- The procedures should have software to verify the operators' decisions. The operator shall retain control and be the final authority as to whether or not to proceed. Disagreements should be automatically logged.

- Where appropriate, the procedures shall provide software which retraces certain sequences of steps to assure that proper status of systems or components is maintained. These steps shall not include actions taken by the operators to control components.

- For control stations where CBPs are impractical, and to supplement CBPs, hard-copy procedures should be available.

- The format and content of hard-copy procedures should be consistent with the CBPs. Their practices shall also consider using PBPs when the normal CBPs are not available. In their rationale for this guideline, EPRI noted that the correspondence of CBPs and PBPs is important in minimizing the training burden and the potential for errors and misunderstanding. Further, this consideration is especially important when hard-copy procedures are used as a backup.

- The M-MIS design process shall include validation of each operating procedure using the plant's simulator and performance model.

The NRC's review of the URD raised questions about the basis for the last URD requirement (see RAI 620.13, in NRC, 1991, pp. 6-7). As noted above, EPRI (1991) indicated that CBP guidance is lacking and that it will have to be developed by the designer, using simulation. The response noted that "... Since both the 'soft' and 'hard' procedures are subject to the test of active simulation, there will inherently be a direct comparison between the 'soft' and the 'hard' procedures as part of the design process. Differences in operator performance with the computer-presented procedures compared to the conventional printed procedures should be evident from these evaluations"

(p. 31). Further, EPRI indicated that "... If the soft procedures are not concluded to represent an improvement when active simulation is attempted, there is a clear fall-back to hard copy procedures" (p. 30). This is consistent with the URD requirements for an *unproven* HSI technology. The URD defines proven technology as one which has at least three years of documented satisfactory service in a light water reactor (LWR) or similar application. When these criteria cannot be met, a testing and V&V program must be conducted.

In considering the EPRI URD and the subsequent response to the RAI, the staff noted the following:

> ...the development of electronically displayed procedures is a desirable goal for the overall integration of operator information needs. The staff position is that the M-MIS designer should consider the use of electronically displayed procedures early in the design process to resolve any issues concerning their development, operability, maintainability, and reliability. If electronically displayed procedures are determined to be an improvement over hard-copy procedures and the M-MIS designer has integrated electronically displayed procedures into the overall M-MIS design, they should be provided as part of the design. (NRC, 1994, p. 10.B-17)

<u>Barnes, Desmond, Moore, and O'Hara</u>

Barnes et al. (1996) developed a set of principles representing a logical extension of PBP guidance to CBPs based on their experience with PBP design, operational experience, and with issues on computer-based systems. Recognizing concerns about generalizing PBP principles to CBP applications, it was done carefully, in a limited fashion.

The guidance was divided into two primary sections. The first, "Design Development," covered aspects of the design process in procedure development. The second section, "Implementation," addressed the detailed design of the procedures in the HSI. Each section was divided into several subsections:

- Design Development
  - Concept of Operations
  - Procedure Bases
  - Design Process Considerations
  - Maintainability of Computer-Based Procedures
  - Training Specifications
- Implementation
  - General Considerations
  - Detailed Considerations
    - Detailed Interface Design for Constructing Basic Steps
    - Steps Containing Conditional Relationships

- Warnings, Cautions, and Notes
- Level of Detail
- Organization

These guidelines were evaluated and used in the context of the current review.

Niwa, Hollnagel, and Green

Niwa, Hollnagel, and Green (1996) identified some high-level requirements for CBP systems. In general, they stated that computerization should make procedure tasks easier without imposing additional tasks, and that CBP systems should provide the following to improve the use of EOPs:

- Formatting - The CBPs can help to structure the various procedure components such as steps, conditions, comments, and advice. Graphical techniques may also help operators to understand the logical relationships (conditionals, conjunctive, and disjunctive) defined in procedure steps.
- Process linking - Integrating parameter values into procedure steps will facilitate their usage.
- Navigation Support - CBPs can assist operators in moving between procedures and support information.
- Progress monitoring - CBPs can track what steps were completed. Check boxes can be used, either manual or automatic, depending on whether the CBP has the specific criteria and information to determine whether a step was completed. Completion also can be time-stamped to facilitate post-hoc incident analysis.
- Help and explanation - Information can be provided to help operators carry out procedure steps. For example, the help facility could describe how a control action should be carried out. The rationale for procedure steps could also be explained. CBP systems could also permit variations in the level of detail based on operators' experience and input.
- Procedure adaptation - CBPs may facilitate changing a procedure to better meet the current situation.

Niwa et al. (1996) stated that their guidelines are good for general aspects of procedures, but lower-level details should be developed with operations and engineering personnel. They stressed the need for consistency between the CBPs and the rest of the HSIs in characteristics such as colors, typography, interaction methods, and input devices. Such lack of integration is a potential source of risk, and reduced reliability in performance. They noted that lack of consistency may be a problem with third-party CBP systems.

Summary

The principal conclusions of this section are, first, that while some guidance for CBP systems exists, it is limited. Second, there is uncertainty over the generalization of PBP principles and guidelines to CBPs. Finally, CBP systems for operational use should be developed in such a way that the benefits and drawbacks for each specific system can be fully evaluated.

5.4 Research on Computer-Based Procedure Systems

Human performance concerns related to CBPs have been raised. For example, Wourms and Rankin (1994) indicated that CBPs may exceed the processing and attentional limitations of operators. Chignell and Zuberec (1993) suggested that operators may become disoriented and lost, may suffer from keyhole effects, and may lose the location of information in windows displays. In this section, the effects of CBPs on performance are considered from three perspectives: empirical evaluations of performance, analytical evaluation of CBPs, and expert opinion.

5.4.1 Empirical Evaluations of CBPs Based on Personnel Performance

Empirical evaluations of CBP systems and characteristics provide the best information upon which to develop guidance for design reviews. Several empirical investigations of CBPs have been reported, but before discussing them, it is important to identify the criteria by which such studies were evaluated. A most important consideration is that the CBP studies provide a basis from which conclusions can be generalized beyond the specific individual study. Therefore, the CBP studies were evaluated within the context of validation reviews where generalization (external validity) is a primary consideration.

O'Hara, Stubler, Brown, and Higgins (1997) discussed the detailed methodological considerations for validating complex human-machine systems, and developed a conceptual approach that identified important principles and their relationships. The general concepts are concerned with (1) establishing the requirements for making a logical, defensible inference from validation tests to predicted integrated system performance under actual operating conditions, and (2) identifying aspects of validation methodology that are important to the inference process. The technical basis for inference is based upon four general forms of validity: system representation, performance representation, test design, and statistical conclusion.

Validity of system representation refers to the degree to which the tests include aspects of the integrated system that are important to real-world conditions. Specifically, this validity is based on the representativeness of the system model, human-system interface, personnel, and operational events. Inference is supported to the extent that important aspects of the integrated system are represented with high fidelity, and to the extent to which important contributors to potential variability in system performance were adequately sampled. It is especially important in evaluating CBP studies that they were conducted in situations - test scenarios - that reveal the complexity of procedure use, and that the procedures were used by professional operators trained in their use.

Validity of performance representation refers to the completeness and representativeness of the performance measures. A comprehensive, hierarchal approach to evaluation guided by supervisory control theory may be used to specify important aspects of performance, ranging from the operators' cognitive processes to system functions. The effects of CBPs on performance can stem from both the technology itself, and its interaction with the other CR technologies. In general, the effects can be related to (1) *personnel role* - a change in functions and responsibilities of personnel, (2) *primary tasks* - a change in the way that personnel perform their primary tasks, such as process monitoring, situation assessment, response planning, and response implementation and control, (3) *secondary tasks* - a change in the tasks the operator must perform when interacting with the CBP, such as navigating through displays and searching for data, (4) *cognitive factors* - e.g., a change in cognitive workload, and (5) *personnel factors* - a change in the required qualifications or training of plant personnel. The performance measures used must address these effects. Failure to include measures of all important performance variables, poor measurement properties, and poorly specified criteria weaken this validity and the ability to generalize the results.

Validity of test design addresses the procedures used for conducting the tests. Inappropriate test procedures can bias the relationship between the observations of performance and the integrated system, and thus undermine their causal linkage. When factors introduced by the test methodology weaken the ability to interpret this correlation, validity is compromised.

Finally, validity of statistical conclusions addresses the relationship between the observed data and established performance criteria.

While these types of validity and their associated methodologies were evaluated in the studies reviewed in this section, the analysis was severely limited by the extent to which the studies are documented. With this caveat in mind, the studies are discussed below.

The research is organized into three sections: (1) Comparisons of CBP and PBP Systems, (2) Observations of Operators' CBP Use, and (3) Comparisons of CBP Design Characteristics.

Comparisons of CBP and PBP Systems

Spurgin et al. (1990) compared the BWR Emergency Operating Procedure Tracking System (EOPTS) with PBPs in flowchart format. The study was conducted with professional operators at the training simulator of the Kuosheng plant in Taiwan. The operators did not have much experience with either form of EOPs. EOPTS is used by the shift supervisor. It automatically engages when an entry condition is specified; otherwise, the EOPTS display screens are blank. The plant is controlled through the normal HSI.
The study was conducted in two phases. In phase 1, six crews performed four scenarios; three crews used the CBPs, and three used the PBPs. The study was undertaken as the crews were being trained on EOPTS. In phase 2, there were 12 crews, six for each condition. The performance measures included:

- Time - specific waypoints were defined for each scenario, measured from first cue to when the appropriate response was made.

- Errors - the number of deviations from EOPTS-specified actions (this measure also was applied to the PBP groups because, the EOPTS was running although the crews could not use it).

- System measures - specific measures of system performance were defined for each scenario.

The results showed that the CBP compared favorably to paper flowcharts. The time measures for human interactions were not completely reported. For those that were, the median response times for the CBP crews were faster in 16 of the 18 HSIs analyzed (an overall time reduction of about 75 percent). In addition, the response times of CBP crews were less variable than those of the PBP crews. There were scenario effects, as well. For two of the six scenarios, the response time was slightly increased in the CBP group.

Overall, the operators made about twice as many errors with the flowchart procedures; unrecovered errors were 65 percent with flowcharts, and 27 percent using EOPTS. When using flowcharts, the most likely source of error was misinterpretation of a procedure statement. With EOPTS, it was communication with the control board operators.

Several possible flaws in this study make interpretation of the findings difficult. First, since it was a between-groups design and a small number of crews was used, their differences may have been confounded with differences in the presentation of procedures.

Measurement was another issue. Errors were identified as the number of deviations from the specified path through the procedure, as defined by the CBP. However, as discussed earlier, such a strategy of following procedures by rote may not be desirable (Barnes et al., 1996; Roth et al., 1994) and may reflect a blind, unverifiable approach. Further, the instruction given to the CBP group was to follow the CBP *verbatim*, but, no equivalent instructions were given to the PBP group. Thus, a confound was created favoring the CBP group who were given the criterion for performance while the PBP group was not. This also affects the interpretation of the "error" recovery measure. Another issue was that since the crew's responses differed across crews, the appropriate procedural response differed within the same scenarios.

System measures were not reported in any organized detail. In fact, they were only reported for the "LOCA with Dry Well H2 Control" scenario. The maximum drywell hydrogen concentration averaged 5.9 percent for the CBP group, and 8.8 percent for the PBP group. Further, the cumulative time below "top of active fuel" was 92.5 and 325 seconds for the CBP and PBP groups, respectively.

Without system measures for other scenarios, it is difficult to assess whether the differences between the crews' performance on the two procedure systems are meaningful.

Several interesting observations were reported on situation awareness and crew communication and coordination. Spurgin et al. noted that SROs using EOPTS were likely to use it as their primary way of following a transient (i.e., not using other HSIs), which may have hampered their awareness of the overall condition of the plant. Crew members in the EOPTS condition who were not using the CBPs expressed concern about being aware of the EOP's status.

Time differences also were important. One SRO called for ADS initiation twice because he did not think it had occurred after his first request. The misunderstanding was due to the delay in the CBP's updating of ADS status.

It is interesting to examine the establishment of EOPTS at Kuosheng. The system was gradually introduced so that all plant personnel could become familiar with it. It was first introduced into the training simulator (1) as an aid to instructors to track the operators' responses to accidents, (2) as a training tool for the crews to examine accident response strategies, and (3) as a tool to be used by the crews during accident response. During this time, in addition to training, the correctness of EOPTS was examined. Spurgin et al. (1990) point out that several errors in the PBPs then were discovered as well. They noted that crews in the CBP conditions operated much more in the skill- and rule-based mode, while crews in the PBP conditions operated more in the knowledge-based mode. This could certainly be another artifact of the instructions to follow the procedures verbatim. However, it is not necessarily a positive outcome (see discussion in Section 5.1 on the need for crews to maintain an independent perspective on the procedures). Spurgin et al. considered that the major benefit of EOPTS was that it helped operators to follow the procedures correctly, and to interpret the logical statements that are a part of the procedure steps.

Another factor that may have affected the results was the crews' inexperience with either form of procedure. A comparison of performance with the flowcharts between the first and second phases of the study indicated that there was a considerable improvement. In fact, Spurgin et al. noted that one crew studied the flowcharts before the scenarios. They used the process computer to display important variables referenced in the EOPs, and their response time was comparable to that of the EOPTS crews. Since the CBP group was following the CBP verbatim, their task may have been easier only because they did not have to know how to use the flowchart. If so, performance differences between the two groups may be considerably less if they received additional training, or if they gained more experience with the PBPs.

The observations of differences between crews and scenarios led Orvis and Spurgin (1996) to recommend that CBPs should be thoroughly validated using several crews and scenarios. CBP systems should be validated by operator-in-the-loop evaluations to ensure that they achieve their objectives, and that a smooth transition between CBPs and PBPs can occur when necessary.

In general, while this study illustrates some potential benefits of CBPs, the results are limited by (1) methodological confounds and procedural limitations, (2) incomplete reporting of data, (3) questionable measures of performance, and (4) underspecification of performance measures, i.e., important aspects of performance were not measured, such as situation awareness and workload.

Nelson et al. (1990) compared another procedure system, Halden's Computerized Operation Manual (COPMA), to performance using PBPs. COPMA was an earlier version of COPMA II. Fourteen Halden reactor operators participated in the study during simulated process disturbances. The dependent variables included time to access and complete the procedure, number of errors, and process parameters reflecting the operator's effectiveness in handling the disturbance. In general, it took longer to access the correct procedure with COPMA than with PBPs, a difference attributed to processing time. Further, COPMA did not reduce the time needed to perform procedure activities, and sometimes the PBP condition was significantly faster. The COPMA group made slightly more errors than the PBP group; however, the differences were not significant. No significant differences were observed for the process variables.

On a methodological note, Follesø, Meyer, and Volden (1993) and Hallbert and Meyer (1995a, 1995b) indicated that there were large differences between the COPMA and PBP groups as measured in a pretest, and concluded that the results were confounded by them. When the pretest measures were used to adjust the performance measures, the differences between the two groups lessened (the CBP group performed a little better than the PBP group). However, the assumption of confounding based on pretest differences may not be warranted when participants are randomly assigned to conditions. Thus, such an approach for correcting the data may not be justified in a randomized design, and is more appropriately used in a quasi-experimental design where non-equivalent groups exist prior to the study. Thus, the results for the unadjusted data are reported above.

Based on the evaluation of COPMA, the CBP was revised to produce COPMA-II. Some of the changes were increased functionality, including support for procedure search, improved instructions on procedure steps, and more explicit references to procedure branches.

Crews' performance using COPMA-II was compared to PBPs in another study (Converse, 1994, 1995). Sixteen licensed operators managed a change in power, small-break LOCA, and a steam generator tube rupture on the Scaled Pressurized Water Reactor Facility at North Carolina State University. The operators worked in teams of two, with an SRO managing the procedure, and a reactor operator (RO) assisting in data collection and control. The dependent measures were procedure initiation time, completion time, subjective estimate of workload using the National Aeronautics and Space Administration Task Load Index (NASA-TLX), and number of errors (defined as deviations from the "optimal" sequence of procedure actions).

The operators responded faster in accident scenarios with PBPs, but their response-completion time showed no significant differences. Measurements of the operators' accuracy revealed an interaction between the type of procedure and the accident scenario. The error rate for PBPs was four times higher than COPMA-II for the LOCA emergency event, while there was no significant difference for the tube rupture. As with the Spurgin et al. study, the meaning of the error data may be open to alternative interpretation. Defining error as a deviation from an optimal sequence may be overly restrictive. If an operator looks ahead at upcoming steps, an error is recorded, but these types of activities are not necessarily undesirable (Roth et al., 1994). There were no differences in workload between the two procedures.

Converse concluded that future evaluations of CBPs should systematically vary the type of scenario because of the different CBP effects on the two types.

Like the EOPTS study, the results of this study are difficult to interpret. The most significant result was related to error data and, like the EOPTS study, the definition of error is questionable. No differences in completion time nor workload were found. Again, performance measures were underspecified, i.e., situation awareness and plant performance were not measured.

Collier (1996) developed the following lessons learned from Halden's CBP evaluations:

- Operators must maintain an appropriate degree of control. The CBP system should not overly structure the operator's movement through the procedure, but should offer flexibility to skip steps or skim over them quickly when appropriate.

- New HSI systems must offer an advantage over other HSI resources to be used.

- To be effective, automation needs the operator's trust. One reason offered for the slower performance with COPMA compared with PBPs was that operators spent time double-checking COPMA information because they may not have developed confidence in it.

Three other studies comparing CBP and PBPs were reviewed; however, they did not provide sufficient information to analyze them in detail. Kang (1997) described an intelligent HSI being developed in Korea by the Korea Power Engineering Company, Inc., that included a CBP for EOPs. Each step is composed of an observation, judgement, and control. Observations are performed automatically. The system makes two types of judgements. Quantitative judgements are easily made. Qualitative judgements, for example, "If RCS average temperature is greater than 292°C and increasing, then..." are evaluated by fuzzy logic.[2] The level of automation is varied depending on the complexity of the required decisions. For simple skill- and rule-based tasks, the system is automated. For knowledge-based tasks, control is manual. The related piping and instrumentation diagram (P&ID) and summary information are automatically presented. The system was tested in a steam generator tube rupture scenario with a full-scope simulator. The response time for completing the required actions were compared with hard-copy EOP performance. The operators took 37 percent more time with the PBP system than with the CBP.

The Emergency Operator Support System was developed in Japan to support the transition from event- to function-based emergency procedures, and for using of the EOPs (Yamamoto and Ito, 1993). The system automatically displays the highest priority procedure in a flowchart form consistent with that of the PBPs. The system extends beyond procedures and includes supporting displays for diagnosing event and plant status. The system was validated in tests involving ten crews; errors were reduced approximately 50 percent with the CBP.

Mavko et al. (1995) state that classical paper-based EOPs are not suitable for use in CRs with digital process information systems. They developed the Computerized Procedure (COPRO) system. COPRO is function oriented and enables operators to restore and maintain critical safety functions. It includes the same information as the symptom-based PBPs, to provide operators with necessary information, record their actions, and perform tasks

[2] This type of step is qualitative because its specification is imprecise in that judgement is used to determine the rate of increase that is minimally necessary for operators to conclude the rate is actually increasing.

automatically - such as monitoring of critical safety function (CSF) status trees and comparing referenced and actual values. The procedure continued automatically until stopped. The system was tested using a small-break LOCA event. An operator completed the procedure more quickly with the CBP than with the PBP and believed that fewer errors would be made.

Observations of Operators' Use of CBPs

The N4 CBP system includes all the N4 procedures, not only the EOPs. However, while EdF spent significant effort on designing and evaluating the CBPs, we are not aware of any papers with detailed results of the evaluations. Therefore, we reviewed the results of several papers that discussed various lessons learned from the evaluation.

Bozec et al. (1990) investigated an early version of the N4 CBP system. Six crews of operators participated in the tests with the N4 simulator. Their evaluation was mainly qualitative, but from the deficiencies revealed, they made recommendations for improving the system. They found that the objectives of the procedure needed to be better emphasized to increase the operators' awareness of the high-level goals. They suggested that providing too much detail should be avoided, except when there is a problem. The operators did not want the procedure to automatically reset or return to a previous step when the status of the process changed. However, they wanted automatic monitoring of previous steps and indications of a change in their status. The operator should be able to override a course of action that is recommended by a CBP system, as when the operator has access to information that is not available to the CBP, the CBP's guidance is too strict, or the CBP is using old information.

Pirus and Chambon (1997) offered additional lessons learned from EdF's CBP evaluations. Handling multiple procedures is easier when the relevant information in each is highlighted, so that when operators transition from one to another, the highlighted information directs them to the appropriate location. Also, automatic monitoring of process parameters helps the operators. Finally, the quality of operations is improved when operators are alerted to deviations from the specified procedure path, because they then can decide if that is what they want to do.

Jeffroy and Charron (1997) discussed the safety assessment of the EdF CBP system performed by France's Institute for Nuclear Safety and Protection (French acronym IPSN) for the Nuclear Installations Safety Directorate (DSIN). The evaluation was a simulator exercise which revealed several problems. While these have been resolved in the N4 system, they are important considerations for other CBP systems:

Overall View of the Process - Early in the design, operators worked through the flowchart and responded yes or no to each step. Their responses were monitored by a "path monitoring function" and deviations from the computer were highlighted. This enabled operators to catch "local" errors, but made it easy to lose the overall view because of the step-by-step attentional demands. By presenting procedures as a series of pages, computerization makes it more difficult to view the path taken, to apply hindsight, and to anticipate the consequences of an answer.

Conflicts - While a high degree of guidance can be delivered, not all steps can be specified in equal detail. While the CBP is designed with steps in a certain sequence, operators sometimes need to alter it. Also, sometimes operators may disagree with the CBP's recommendations. In both situations, operators may find it hard to disagree with the procedures, especially when the level of detail is high. CBPs also make it difficult to view the path taken, and this can hamper independence from the procedure. Operators would sometimes reset the procedure to get a better sense of how they got to a particular place.

Limited view - While the CBP monitors the plant through instrumentation and control (I&C), the operators must supply some information; thus, the CBP may consider specific components to be available when they are not. If such communications fail, the CBP may make incorrect assessments and give incorrect guidance.

These findings illustrate the importance of operators being aware of the CBP's constraints. However, some situations made it particularly difficult to recognize them. For example, after the crew negates a procedure decision, their awareness of the basis for the procedure decisions becomes less clear, and the operators' and CBP's "situation awareness" begins to diverge. Operators then may not understand the information provided nor the effects of their actions on the computer's interpretation of steps.

Jeffroy and Charron (1997) concluded that operation of procedures is a dynamic process involving interpretation of plant data, actions to be carried out by the plant, and interactions between crew members. Knowledge-based understanding is needed to properly follow procedures and to evaluate the correctness of recommendations. Procedure steps often require the operators' input and cannot be resolved independently.

Roth and O'Hara (1998) studied the integration of advanced HSIs into an NPP. During computer replacement, the plant's CR was upgraded to include a CBP system, an advanced alarm system, and a graphic-based plant display system. The authors observed crews during their initial training with the new systems on a full-scope simulator, and interviewed operators and other utility and vendor personnel. The training included full-scope simulations of plant disturbances.

This study was one of the first to evaluate a text-based CBP system (previous studies were of flowchart CBPs) and one of the first to look at the transition to PBP upon a CBP failure. It also was one of the first to examine performance with a combination of computerized HSIs. The results are summarized below.

(1) The general effect of the CBP on performance was good. The SROs could go through procedures more quickly, and felt that their cognitive workload was reduced because information on plant parameters was immediately available (the SROs did not have to ask for it, and operators did not have to run around to get it), and the SROs did not have to resolve step logic. In general, procedures were followed more efficiently because the operator was less likely to miss a transition step and did not have to track location within the procedure, steps of continuous applicability, applicable cautions, or applicable foldout page criteria. The CBP was easy to learn, and the operators' acceptance was high.

(2) The CBP had an important effect on the crew's roles and communication; the extent of the change was greater than anticipated for board operators. Since the SRO could handle the procedure mainly alone, the need for communication between the SRO and ROs was reduced. The operators identified the importance of communication in maintaining effective teamwork. The ROs expressed a need to be aware of status of EOPs. Because the ROs no longer needed to support the SROs in following the EOPs (by providing parameter values called out in the EOPs), they had more time and attentional resources available to monitor the plant, giving them an additional independent overview of its state. The ROs felt they became more independent and, thus, had more responsibility. Therefore, their individual skills become more important.

(3) The operators' trust in the CBP was high. They generally assumed that the software logic was correct and did not feel a need to double-check it by reading every substep. Instead, they double-checked the system's conclusions from independent sources (e.g., the alarms and the board indicators). Because they generally trusted the CBP, they sometimes felt there was too much information, preferring detailed information only when a procedure step was not satisfied.

(4) Operators occasionally wound up in the wrong place when using the CBPs, such as when step-logic resolution was oversimplified, but usually recovered quickly. Determining whether a step was satisfied was sometimes more complicated than at first it appeared (e.g., interpreting apparently simple statements such as "If pressure is decreasing..." can involve judgement that is difficult to reduce to a simple calculation). Mostly, crews could detect when CBP information was inappropriate. The operators were generally tolerant of these situations, and felt that similar ones occur with PBPs.

One question was whether the ability to identify such errors would be the same with crews that were not initially trained with PBPs. Walking through paper-based EOPs enabled operators to identify the goals and logic behind them which they could transfer in using the CBPs. CBPs may exacerbate the tendency to follow EOPs verbatim, without sufficiently reflecting on the appropriateness of procedure steps to high-level goals.

(5) Operators expressed initial concern over lowered situation awareness with CBPs, but it diminished with practice.

(6) Operators did not have a problem when transitioning to PBPs upon CBP failure, although such failures were simple ones and happened early in the EOP.

The results should be interpreted within the context of the study's constraints: (1) the observations were made during the first training period using the new CBP systems, (2) the CBP systems were not completely debugged, and (3) the scenarios were limited to relatively simple events.

During an evaluation of CBPs for a low-pressure injection system, Blackman and Nelson (1988) noted the following:

(1) Operators tended to believe the computerized procedure even if it was wrong; they should be trained to question it.

(2) If selecting procedures is automated, the operators' involvement was reduced, and they reported that they thought less, and acted as switch-turners. Operators should be trained on the decision process used by the procedure system and to verify its recommendations.

(3) Operators continued attempts to implement a computer's recommendation even when failures prevented it. Operators need to be trained to take over if the computer fails or is in error.

(4) Computers do not have common sense functions employed by operators. The computer cannot consider what operators are doing nor other important information.

The major conclusion was that operators need to understand the overall purpose of the procedures and stay cognitively involved in their progress. They should be trained to question any recommended steps that appear inconsistent with the overall goals. Similarly, CBPs should be designed to maintain information on anything the crew is doing that is relevant to implementing the procedure.

<u>Comparisons of CBP Design Characteristics</u>

In this section, we discuss research on three characteristics of procedure design: presentation format, salience coding, and integration of indicators.

Presentation Format

PBPs generally present procedural information in text or as flowcharts. A concern associated with CBPs is the appropriateness of the presentation format, given the operator's task requirements and the characteristics of the display system.

Wourms and Rankin (1994) commented that text is a sequential format that often requires users to read information that is not relevant to existing conditions. Sorting through this information to identify the correct course of action is time-consuming and confusing. An important consideration in using text is to establish the appropriate level of detail. Operators rely more on their memories than on the actual procedures because the narrative style uses too many conditional statements, which slows their response time. Some systems overcome this problem by providing information at more than one level of detail for each step. For example, an extended text version of a particular step may be used by less experienced operators, while an abbreviated version may be used for familiar procedures and steps.

In general, a flowchart format is useful because of its ability to specify the sequence of, and relationships between, procedures (Krohn, 1983; Wourms and Rankin, 1994). Desaulniers, Gillian, and Rudisill (1988) compared flowchart formats to text and extended text formats. Each was displayed in a six-line window. Participants were asked to diagnosis a malfunction in a Space Shuttle system. Performance was most accurate with the flowchart format. Overall completion times did not differ between formats, but individual steps were completed faster with the flowchart format.

In a second experiment, an interaction was revealed between format and window size (6- vs. 12-line). As the window's size increased, performance degraded with the flowchart format, but improved with the text formats. An examination of the errors that occurred suggested that participants lost their place on the flowchart with the larger display. For text procedures, the increased window size helped users to better understand the context of procedure steps. The effect of screen size upon accuracy may have important consequences when converting PBPs featuring flowcharts to a computer-based medium. Currently, paper-based EOPs based on the GE Owners' Group technical guidelines have flowcharts that are the size of engineering drawings (Barnes et al., 1996).

Salience Coding

CBPs are intended to guide the operators' performance during plant upsets that may be associated with time pressure and stress. Also, multiple procedures may be simultaneously in use. Salience coding can visually enhance presentation formats, such as text and flowcharts. Color, flashing, and animation may be used to enhance the salience of important information. These techniques can lower workload by helping to organize information and guide the operators' attention to that which is most important.

However, because salience coding can affect the operators' behavior, care must be given to avoiding coding schemes that are distracting, confusing or misleading. For example, Mosier, Palmer, and Degani (1992) state:

> The logical conclusion from the results of research on salience effects on decision making has been that, in a diagnostic situation, the brightest flashing light, or the gauge that is largest or most focally located will bias the operator toward processing its diagnostic information content over that of other stimuli. Time pressure, stress, or information overload can cause a "perceptual tunneling" and exacerbate this tendency to focus on central or salient cues. (p. 10)

Integration of Indicators

Incorporating plant indications into CBPs poses both potential benefits and obstacles to human performance. Errors associated with monitoring the wrong display can be avoided by providing the operator with specific indications; Galletti (1996, event 4) describes the actuation of an engineered safety feature because the operator was monitoring a wide-range instrument rather than a narrow-range one. However, while PBPs force the operator to monitor plant indications, incorporating them into CBPs may increase errors by becoming a substitute for good monitoring practices, or by competing with other information sources in the CR for the operator's attention. For example, an assessment of electronic checklists (Mosier, Palmer, and Degani, 1992) concluded that those encouraging crews to rely on the system's state, as indicated by the checklist, rather than as indicated by the system itself, can discourage information gathering, and may lead to dangerous errors. In this aircraft simulation, the mean number of informational items discussed among crew members decreased as the checklist became more automated. Pilots who used paper-based procedures were less likely to shut down one of the aircraft's engines unnecessarily.

Thus, while using CBPs, operators may not feel the need to look at other sources of information in the CR and, thus, may miss important indications that are not present in the CBP system. This need for other information is particularly important where the system's designer did not fully understand the plant's behavior, or where the CBP system fails in a manner that is not immediately obvious to the operator. For example, in events 2 and 3 described by Galletti (1996), lockups of the plant's alarm systems were only discovered after other information sources were compared to the data provided by the failed alarm systems.

<u>Summary</u>

In the beginning of this section, we discussed criteria for assessing studies. However, only two studies were described in sufficient detail to evaluate their generalizability (Spurgin et al., 1990; Converse, 1994, 1995). Both had potential methodological weaknesses which limit the conclusiveness and generalizability of their results. Most other studies were not reported in sufficient detail to make this evaluation, or contained only qualitative observations.

Even considering the weaknesses in the design or in the reporting of methodology and results, some tentative conclusions can be drawn based on human performance data, observations, and interviews. On the positive side, when using CBPs

- operators can perform procedures more quickly,
- operators' cognitive workload seems to be reduced, and
- operators may make fewer errors in transitioning through procedures.

In addition, the CBP systems seem to be relatively easy to use and are accepted by operators.

However, there remain several important, unresolved questions needing additional empirical research:

- What is the effect of CBPs on team performance and reliability?
- What is the effect of CBPs on the operators' high-level situation awareness of the status of the overall procedure goal and the plant?

- Do operators become over reliant on, and unquestioning of CBPs, or can they maintain the independence and objectivity to evaluate the adequacy of the procedure to achieve high-level goals?
- What is the overall effect on operators' errors of CBP systems (especially where errors are not defined in terms of verbatim compliance)?
- What is the effect of CBPs on performance in complex disturbances involving many procedures or branches?
- How well do operators manage complex CBP failures, such as when multiple procedures are being used, many steps have been completed, and many steps of continuous applicability are being monitored?
- What are the relative effects of specific design features on performance (most studies were overall system comparisons, e.g., CBP vs. PBP, not systematic evaluations of individual characteristics, such as the appropriate level of automation)?

5.4.2 Analytical Evaluations of CBPs

In this section, two classes of analytical techniques, performance models and risk models, are described that were used to evaluate CBP design.

5.4.2.1 Performance-Model Analyses

CBPs were evaluated using a variety of performance-analysis models including the Goals, Operators, Methods, and Selection (GOMS) model, MicroSaint Task Network Modeling, the Man-Machine Integrated Design and Analysis System (MIDAS) model, and classical task analysis.

GOMS

Endestad and Meyer (1993) compared COPMA and COPMA-II using the GOMS model of HSI developed by Card, Moran, and Newel (1983). As noted earlier, changes in the CBP included increased functionality for searching procedures; improvement in instructions for procedure steps, and more explicit references to procedure branches. Their results indicated that the modifications resulting in COPMA-II require additional learning and make the system more complex; however, COPMA-II can be used more rapidly. They did not identify the net effect of this tradeoff on human performance.

MicroSaint Task Network Modeling

COMPA-II was evaluated using MicroSaint Task Network Modeling (Laughery and Persensky, 1994). The operator's performance was compared with experimental data collected on a simulator (Converse, 1995). The comparisons were described as encouraging; the model's predictions of performance differences were consistent with the data in five out of six conditions.

MIDAS

Hoecker et al. (1994) and Hoecker and Roth (1996) used the MIDAS to evaluate CBPs (Westinghouse's COMPRO) against PBPs. We note that the primary objective of the study was to demonstrate the application of MIDAS to HSI evaluation. This comparison provided a test case.

The results indicated that the effect of CBPs on workload depends on the situation. For example, the demands of using procedures can fall when the delays associated with waiting for a response from a board operator are eliminated. However, when the operators need to access information in parallel, the CBP system can increase load.

Task Analysis

Niwa, Hollnagel, and Green (1996) evaluated CBP systems as part of a CBP development study for the Institute of Nuclear Safety Systems in Japan. They identified several reasons for their slow development. First, there has been a tendency to keep procedures separate from the HSI so they constitute a "fallback for when all else fails." Second, procedures are not easily automated because they contain imprecise elements and depend on information about conditions that are not easily instrumented.

Niwa et al. (1996) made a subjective comparison of the attentional demands of PBPs and CBPs based on task analysis. The basic tasks for using EOPs involve identifying which EOP to use, proceeding step-by-step through the procedure, carrying out actions specified in steps, checking-off completed steps, and retrieving additional information (from other documentation). The results are summarized in Table 5.2 (adapted from Table 1 of Niwa et al., 1996). CBP ratings were based on a "well human-factored solution" although this was not clearly defined. In general, they determined that interactions with a CBP are more complicated than interactions with a PBP. CBPs may increase attentional demands in selecting the required display (turning procedure pages) and check-marking step completions. However, other aspects of procedure use are easier with CBPs, such as retrieving data.

Table 5.2 Attentional Demands of PBP and CBP Systems[1]

Activity	PBP	CBP
Go through steps	medium	medium or high
Turn pages (select display)	very small	small or medium
Check-mark completion	very small	small or medium
Retrieve additional information	very high	small or medium
Access required source	medium or small	small
Find information	medium	small or medium

[1]Information is based on the findings of Niwa et al. (1996)

In summary, these evaluations show no clear advantage of CBPs over PBPs. Instead, they illustrate the importance of performance tradeoffs in assessing different procedure systems. In general, cognitive load, complexity, and attentional demands were higher for CBPs, while data retrieval was easier and task-completion time was less.

5.4.2.2 Risk-Informed Analyses

There have been several risk-informed analyses of CBPs. In one qualitative study of the anticipated impacts on human performance introducing digital technology in NPP designs, Wilhelmsen et al. (1992) identified several concerns. By impacts, the study referred to potential changes in generic failure rates associated with a crew's performance in traditional systems. One of the "most pressing issues" identified was the availability of on-line procedures. The study also indicated that these systems might improve performance if they list procedure steps, logic flow, and allow simultaneous access to multiple procedures.

Two other studies examined different aspects of performance: one evaluated whether CBPs represent a potential safety-significant issue (Stubler et al. 1996), and the second examined their potential effects on components of human error (Orvis and Spurgin, 1996).

Stubler et al. based their safety evaluation methodology on an adaptation of EPRI's approach in *Guideline on Licensing Digital Upgrades* (EPRI, 1993b), which was endorsed by the NRC in Generic Letter 95-02 (NRC, 1995). The following aspects of CBPs were associated with potentially negative effects on human performance:

- Level of automation - The appropriate level of automation of CBP systems for managing information is not well understood.
- Design errors - CBPs that assess plant conditions and then present corresponding procedure steps may have design errors that stem from the system designer's incomplete understanding of the plant's behavior. These errors may result in inappropriate analysis of information or incorrect guidance to the operator.
- Situation awareness - Because only a portion of the procedure can be observed at one time, operators may lose a sense of where they are within the total set of active procedures. The display space may be inadequate to allow simultaneous viewing of multiple procedures and associated plant data.
- Overreliance on CBP information - PBPs require operators to monitor plant indications. If these are present in the CBP, the operator may not feel the need to look at other sources of information in the CR and, thus, may miss important indications that are lacking in the CBP.
- Navigation - Navigation within one procedure, or among multiple ones and related supporting information, can be time consuming and error prone.
- Computer-based text characteristics - In general, comparisons of task performance for information presented via VDUs and hard copy indicate that there are significant differences between them. Reading is generally slower and more fatiguing using VDUs, and they have been associated with poorer performance and lower usability ratings.
- Salience coding - Presentation formats, such as text, flowcharts, and hypertext, can be visually enhanced by the graphical capabilities of computer-based displays. For example, color, flashing, and animation can enhance the salience of important information. However, improper coding can have negative effects on operators' behavior by de-emphasizing or drawing attention away from important information. Thus, the design of coding schemes is critical for successfully implementing CBPs.
- Consistency with the HSI - Any inconsistency of the CBP with the rest of the HSI can lower performance and increase the likelihood of errors. Some important aspects include the degree to which the display of plant variables and units of measurement used in the CBP are the same as in the normal monitoring displays, the same coding schemes are used, and navigation mechanisms are compatible with those of other display devices in the HSI.
- Transfer between CBPs and PBPs - Under some circumstances, the operators may be required to switch between PBPs and CBPs. For example, if the normal operating procedures are given in paper-based form and

the EOPs in computer-based form, then the operator must switch to CBPs when the EOPs are to be used. If the CBP system fails, then the operators may be required to use PBPs. Transfers between them may be difficult, especially if their formats (e.g., flowchart versus text format) and mechanisms for managing the use of multiple procedures (e.g., "place holders" and navigation features) differ. The operator's burden is likely to increase with such switching when other demands are high (e.g., as a result of the condition that required using EOPs).

Orvis and Spurgin (1996) evaluated CBPs from a perspective of a cognitive reliability model. We note the analysis assumed that CBPs had positive effects on performance and, therefore, it was aimed at where improvements in crew reliability can be expected. For example, Moieni and Spurgin (1993b) have noted that

> ...computers can make up for some of the human limitations, such as short term memory and limited working memory capacity, and together with the human operator can be more effective and reliable than either acting separately. Thus, computers can help the user find his way through the procedures and help ensure that steps in the procedures are taken in the correct sequence. More importantly, they can support the crew in taking into account the correct set of symptoms, and help ensure that key elements are not ignored. In some systems, the computer can take control if the crew fails to follow the procedures as prescribed.

The cognitive model had two separate phases: the detection-diagnosis-decision making (DDD) phase, and the implementation phase. There are three pathways to failure to provide the correct response within the required time. First, the crew may fail to detect the need to take action, or may make a misdiagnosis (P_1). Second is the failure to complete the DDD phase within the required time (P_2). The third path is the crew's failure to complete all required actions (P_3). The total probability of human error for a given human interaction is

$$P_{Hum,Tot} = P_1 + P_2 + P_3$$

Orvis and Spurgin felt that the CBP should reduce the probability of all failure pathways. Since the CBP automatically detects parameters and matches them to EOP conditions, P_1 could be essentially eliminated. When CBPs monitor whether an action was taken and notify the crew if it is still needed, P_3 can be essentially eliminated as well. Thus,

$$P_{Hum,Tot}(CBP) < P_{Hum,Tot}(PBP)$$

Orvis and Spurgin (1996) have determined that the following features of CBPs will affect crew reliability:

- Quality of display
- Number of windows concurrently open
- Coupling with plant parameters
- Coupling with alarms
- Display of control status
- Display of plant mimics with component status

- Automatic EOP selection
- Easy navigation
- Similarity of operation for normal and abnormal procedure use
- Automatic place keeping in EOPs
- Limited amount of user configuration
- No lockup on erroneous use

The analysis by Orvis and Spurgin was to be an assessment of the potential benefits of CBPs. Potentially negative factors, such as those examined by Stubler, Higgins, and O'Hara (1996), were not examined. They are careful to point out that improvements in reliability have to be made using the results from simulations.

While the evaluations of performance models showed no clear advantage of CBPs over PBPs, the risk-oriented analyses show that while CBPs have the potential to increase the reliability of human performance, when poorly implemented, they can reduce it.

5.4.3 Expert Opinion

This section reviews literature that discusses CBPs where the findings are based on the opinion of subject-matter experts (SMEs), rather than *specific* data collection or analyses. It includes the NRC-sponsored review of CBP systems by Spurgin et al., the NRC CBP workshop, and an IAEA working group on computerization of CRs that covered CBPs.

NRC-Sponsored Review of CBP Systems

Spurgin, Wachtel, and Moieni (1993) reviewed several CBP systems based on a literature review, a questionnaire, and interviews. Their findings indicated that CBPs have important impacts on NPP operations, some of which extend beyond those intended by the designers. The change from PBPs to CBPs may affect the crew's structure, human reliability, training, and selection criteria. They identified the following general findings:

- CBPs can perform many tasks typically undertaken by multiple crew members; these include monitoring functions, selecting a procedure, selecting procedure steps based on the plant's state, and providing the rationale for the choices. Thus, CBP use will require a single crew member.
- EOPs are used differently in different countries; therefore, their design will reflect these differences.
- Recovery from human error is faster with CBPs than with PBPs.
- CBPs appear to be beneficial during multiple failures.
- CBPs may introduce new types of errors related to software errors and those due to the designer's incomplete understanding of the plant.
- Thorough V&V is a crucial requirement.

- The extent of system automation and allocation of functions between the CBP and crew are important, but may not be sufficiently considered by designers.
- CBPs will significantly affect the administrative control and configuration control of plant procedures.
- The way in which CBPs are introduced into plants and the training that operators receive are very important. For example, it is unknown whether CBPs should be introduced into training simulators first, or whether they should be given to novice crews only.

It was concluded that "... more work needs to be done before the industry can make a safe transition from traditional paper and pencil procedures to computerized systems" (p. 1017).

Spurgin (1995) discussed the effect of computerizing EOPs on the operator's role. Two classes of CBPs were identified. The first presents EOP information to the operators, and they decide on the subsequent actions. The second class recommends how to proceed, and the operator confirms. The latter minimizes the operator's role and, according to Spurgin, may be a deterrent to taking action.

NRC CBP Workshop[3]

The NRC conducted a major workshop on CBPs in 1994 to identify the key issues that need to be resolved to support HFE guidance for reviewing CBPs. Fifteen participants were identified as SMEs by an international selection process. Individual presentations on the current status of CBP systems development and research were discussed. The SMEs were divided into two working groups to identify the issues. The results are summarized below.

CBP Taxonomy

A taxonomy to describe CBP features and functions is needed to support regulatory evaluations and regulators in exploring differences in systems.

Automation and Task Allocation

While it is important for operators to be in control of the CBP, they may become more complacent or dependent on the CBP and fail to consider whether it is malfunctioning. The extent of the crew's monitoring should be considered. The CBP should inform operators of disagreements, but should allow them to take actions if they want to override. The crew's actions should be logged.

The degree to which specific CBP features should by automated is unknown and should be assessed.

Crew Performance and Coordination

The impact of CBPs on task performance of crew members needs careful assessment; CBPs should support cooperation, interaction, and decision making. Beyond these generalities, several specific issues were identified:

[3]The findings from the NRC CBP Workshop are being documented in a report that is currently in draft form (Kancler, D., Schopper, A., and Wachtel, J. *Findings of a workshop on computer-based procedures in nuclear power plant control rooms.* Washington, D.C.: U.S. Nuclear Regulatory Commission.) For the purposes of our research, any findings from the workshop that contributed to CBP design review guidance development are included in the summary provided in this section.

- An operator's situation awareness should not be adversely affected by CBPs. Two aspects are important: awareness of the plant's status (information should be available, and interacting with CBPs should not interfere with situation assessment), and procedural awareness (awareness of procedure goals, how they are structured, and knowledge of the location within a procedure or between a set). Situation awareness should be measured in evaluating the systems.

- High workload may be a concern.

- Use of CBPs should be consistent with normal, daily operations to be effective.

- CBPs should support cross-checking.

Training

The SMEs noted that training was critical to the success of CBPs, but that significant changes may be required. VDUs may introduce effects such as glare and eyestrain. They also offer features not found in PBPs. Training should address the procedures' structure, conventions, and rules of use.

Training also should focus on limitations of the system and establishing the operators' trust. However, operators should be trained to minimize overdependence or reliance on CBPs, and also on the proper means of handling disagreements between the crew and the CBP system about appropriate actions. In addition, operators need to be trained to detect failures and on both CBPs and their backup systems. The evaluation of training should ensure that any effects of negative transfer are minimized.

Human-System Interface

Several aspects of HSI design were discussed. CBPs should represent procedure attributes, such as steps of continuous applicability and transitions, and should provide navigational means to access different parts of the procedure, different procedures, and additional information. Another issue identified was the appropriate application of the computer's capabilities (color coding, animated graphics, and video) to procedures.

Desirable characteristics of CBPs included the capability to adjust the level of detail and to annotate the CBP. The degree of flexibility in the CBP HSI was identified as a concern; such flexibility should not affect procedure information. Consistency with other HSIs also was identified as an important requirement.

An issue was raised as to whether the computer medium may affect how operators interpret procedures. For example, some procedural details intentionally are left abstract. While computerization may allow an increase in detail, the result could be an inadvertent change in the procedure's context and its interpretation.

CBPs should be able to support improvements in procedures. Gaps occur in procedures because they do not cover all possible situations and actions; CBPs allow operators to log their occurrence in an on-line database. The database could be accessed to identify aspects of the procedure that need improvement.

System Reliability

Failure modes (bugs, logic failures, and bad input) need careful evaluation along with how operators can detect those that were not corrected during design.

Verification and Validation

CBP V&V evaluations should provide evidence that operators can perform their tasks in real time. They should involve procedure guidance (such as NUREG-0899), usability testing, findings of prior research, and realistic scenarios. V&V should address CBP failure, the transition between PBPs and CBPs, the introduction of CBPs into a PBP CR, and using PBPs if the CBP fails. Finally, V&V for software should be clarified.

IAEA Working Group on CR Computerization

Similar to Spurgin (1995), the IAEA working group on CR computerization concluded that CBPs potentially can minimize the operator's role but may deter people from taking action (IAEA, 1995). They considered CBPs to be a future trend. Some of the advantages noted were that (1) information will be integrated, (2) events will be confirmed (e.g., CBP can indicate if a procedure step is satisfied), and (3) information will be context sensitive (procedures can inform operators based on the current state, e.g., they will not display the step, "turn on Pump A," if Pump A is on already). CBPs should guide systematic, rapid implementation of procedures. However, the IAEA believed that current usage of CBPs is "minimal and in its infancy" and, therefore, recommended that CBPs "should be developed as research projects and prototypes, and feasibility tested on suitable full-scale application where these may be possible" (p. 62).

Summary

The SME examination of CBPs identified many positive aspects of CBPs' use on crew performance. However, SMEs also identified a wide range of unresolved issues which partly have led to the conclusion that CBPs should be introduced carefully into operational plants. The issues identified should be considered in developing CBPs. A noteworthy observation is that CBP development must consider related HFE activities, such as training, and integrating the CBP system with the other HSIs and the overall operational philosophy of the plant. V&V programs are again emphasized. In general, these findings are fully consistent with the other sources of information discussed earlier.

5.5 Other Related Research on Computerization of Task Aids

Two areas of research will be discussed that provide insights generalizable to procedures, while not specifically addressing their computerization. The first research includes general comparisons of task performance using computerized versions of what historically were hard-copy support materials. The second area is the topic of computerized operator support systems (COSSs).

5.5.1 General Comparisons of Hard-Copy and Computer-Based Task Performance

In this section, we briefly review the general research literature comparing hard-copy and computer-based presentations of the same information. While there have been many such comparisons for reading, there have been few studies of the effects on job performance (of which reading is only a component), such as maintaining equipment.

Reading is an important part of any task in which information is presented to users on a computer, and an important aspect of procedure use. Therefore, a great deal of research was devoted to comparing reading performance on computers vs. typical hard copies. Generally, reading is slower and more fatiguing with VDUs than with a hard copy of the same material (Gould et al.,1987).

Examining the computerization of technical manuals, Shneiderman (1987) identified several potential disadvantages:

- Computer screens are not as readable as printed material.
- Computer screens provide less information than paper, and also the rate of paging is slower.
- The need to use a computer interaction technique, such as command language, and navigation, requires more mental effort and may interfere with the primary tasks.
- If the display screen is used for other work, users may have to switch back and forth between the computerized manual and other information.

To examine these potential issues, Shneiderman reviewed several studies of computerized manuals; he concluded that performance may not improve and may actually degrade. Thus, Shneiderman concluded that "At this stage of technology, paper manuals are still preferred" (p. 382). However, this conclusion was based on 1980's data.

We reviewed several more recent studies which compared task performance using computer-based and hard-copy aids. Consistent with Shneiderman's conclusions, they generally found that computer-based presentations are associated with slower, poorer task performance (e.g., Reaux and Williges, 1988; Fox, 1992) and the use of different task strategies (e.g., Ogawa and Yonemura, 1992).

Nelson and Smith (1990) set up repair manuals, including text and graphics for mining equipment, in HyperCard on an Apple Macintosh computer. Subjects performed tasks using either the computer-based or the hard-copy manuals. The first task required subjects to complete written statements by searching the manual and filling in the exact information that was found in it. The second task required subjects to answer multiple choice or true-false questions on nine realistic maintenance situations. They then were asked about their personal preferences to assess their acceptance of the modes of information presentation, and how it compared to other manuals they had used. Subjects using the computer-based manuals were significantly slower and finished fewer of the tasks, but performed much more accurately on the parts they completed. While those using the on-line manual considered it harder to use, subjective evaluations were positive ("quick response, good illustrations, compact, fun to use, finding general subjects area and Word Find are very helpful, and no greasy, dirty, torn pages"). The problems identified included annoyance due to its brightness, eyestrain, and headaches.

Federico (1991) tested Navy subjects' identification of Soviet and U.S. planes using either computer-based or hard-copy presentations. The two modes did not differ in accuracy or internal consistency; however, the subjects' confidence in their recognition was greater when using the hard-copy presentation. As the experimenters hypothesized, "...the longer exposures intrinsic to the paper-based method seemed to have facilitated subjects' recognition scores. They performed significantly better on the paper-based test than the computer-based test."

Krauss, Middendorf, and Willits (1991) compared one group of subjects who learned to use a software product through an on-line tutorial with another group learning the same tasks using a hard-copy tutorial. Subjects were given a sample application task and a main application task. In the first, they were led explicitly through the actions necessary to complete the task in a cookbook fashion. Immediately afterwards, they began the main task, which required them to develop an application that allowed entry of information about employees (such as names, social security numbers, and job classifications). To accomplish this task, they had to specify tables, define records, and create screens, and were expected to refer back to their respective tutorials. Subjects working on-line were slower and found it more difficult than did those with the hard copy. This was due to navigational problems associated with their confusion with manipulating windows and finding information on hidden screens; they reported a "lost" feeling. The authors hypothesized that providing an outline of the entire document (e.g., in the corner of the screen) and highlighting the user's location in it might mitigate this problem.

Weldon, Koved, and Shneiderman (1985) compared two types of information structure: linear (usually found in books) and tree (browsing through specific titles and finding details elsewhere). Subjects read from four different versions (one for each of the experimental conditions: online-linear, online-tree, hard copy-linear, and hard copy-tree) of a simulated electronic intercom-maintenance manual, written for the experiment. Each version was identical in content, but organized differently. The subjects were asked to determine the correct settings for two sets of eight dip-switches soldered to a prototyping card. The problems required different combinations of on and off switch settings. The dependent variables were the time to solve the problems, the number of errors, the number of pages viewed, and the subjective evaluations. It was found that the information's structure did not affect performance. Instead, the important variable was whether the subject had read from the on-line manual or from the hard-copy manual; subjects using hard copies were faster. Within the online condition itself, there was a significant difference in the number of pages viewed; subjects given tree-structured information looked at more pages than people given linear information. There were no significant differences in the number of errors in switch-setting combinations among the experimental conditions. In the subjective evaluations, subjects preferred the on-line mode over the paper mode, but there were no significant differences in type of information structure preferred. The experimenters hypothesized that structure may be more important in studies which used larger manuals, but this suggestion was not tested.

Kincaid, Schurman, and Hays (1990) compared a paper maintenance manual with a computer-based manual, the Portable Electronic Aid for Maintenance (PEAM), observing technicians in a tank-maintenance task. The results indicated that use of the electronic system resulted in only about 1/3 of the errors of the paper manuals; however, the time to perform the task was slightly longer, which was attributed to computer delays in presenting information. Based on the PEAM results, Inaba (1990) identified several lessons learned:

- HFE principles for paper presentations also apply to electronic presentations.

- The major advantage of the electronic manual was its ability to display, store, and retrieve large amounts of data.

- The major hardware limitation of a restricted screen area can be overcome by applying HFE principles.

One study found a positive effect of computerization. Andre and Pouraghabagher (1995) compared computer checklists to paper checklists for missile Launch Control Center tasks. The computer-based formats reduced the response time of expert operators by 10 percent, and substantially reduced their error rates (by 58 percent) compared to the paper-based system. The effects were not as marked with non-experts.

<u>Summary</u>

It can be concluded from the general literature that task performance differs when information is computer based versus when it is presented as hard copy. Reading from a VDU is generally slower and more fatiguing. VDU-based complex task performance also was associated with poorer performance and problems in usability. Contributing to these differences are difficulties in maintaining a sense of location (knowing where you are in a document), navigation (moving from one place in a document to another), and fatigue. Chignell and Zuberec (1993) noted similar potential difficulties with use of CBPs: visual fatigue, glare, and resolution.

5.5.2 Computerized Operator Support Systems (COSSs)

Numerous COSSs based upon knowledge-based systems (KBSs), such as expert systems, assist in cognitive tasks such as evaluating plant conditions, diagnosing faults, and selecting response strategies. Intelligent aids may include (1) automatic checks which track operators' actions and compare them to actions expected from plant procedures or other models, (2) automatic warnings based on current conditions, predicted consequences or side effects, and (3) smart interlocks that block control actions that conflict with the plant's current configuration.

The nuclear industry has developed a wide range of KBS applications for off-line analysis and on-line cognitive support to plant personnel (IAEA, 1993, 1995):

- Fault detection and diagnosis
- Safety function monitoring (e.g., severity of challenges to critical safety functions)
- Plant-performance monitoring (e.g., efficiency of main pumps, turbine, and generator)
- Core monitoring
- Advising on unforeseen maintenance problems
- Interpretation of complex procedures or regulations
- Support for controlling the plant

Several off-line systems have been applied to areas related to safety. The overall trend in the nuclear power industry appears to be a move from conventional off-line applications toward on-line systems. The principal area of application appears to be fault diagnosis, which requires a monitoring capability. A variety of computer-based aids that analyze plant conditions and then make recommendations to personnel (e.g., for improving plant performance, diagnosing failures, and identifying success paths) are discussed in the literature; many of them are research prototype systems. For example, expert systems, based on artificial neural network technology, were developed for the following NPP applications: diagnosing faults, analyzing core vibrations, monitoring loose parts, modeling thermodynamics, estimating thermal margins, and identifying transients (Uhrig, 1994). The commercial uses of computer-based aids include:

- Emergency response projection code - Software for projecting doses that would be received by the areas surrounding a nuclear generating station in an accident involving airborne release of radioactive materials. [The Pickering Emergency Response Projection computer code is described in AECB (1994).]
- Fuel loading expert system - A computer-assisted system for fuel reloading while at power was designed for CANDU NPPs (Gertman et al., 1994).

AECL has several aids under development (O'Hara, Stubler, and Higgins, 1996):

- Advanced Process and Analysis Control System - This is a rule-based computer system that assists operators and maintenance personnel with on-line diagnosis of process and equipment faults. The prototype system was applied to the CANDU Bruce B feedwater system.

- Feedwater Corrosion-Monitoring and Prediction Analysis System - This system supports the detection, monitoring, diagnosis, and prediction of corrosion problems in the secondary side of a CANDU plant, based on chemical analyses. Neural nets are used in the diagnosis portion of the system.

- A signal-analysis system for calibrating trip channel signals.

- A virtual-reality-based system for visualizing the interior of a reactor fuel channel to support the removal of stuck fuel bundles. This system is envisioned as a training aid.

AECB described an operator decision aid currently under development in Canada that simulates plant performance using an ideal model. It continuously compares actual plant values to simulated values to identify plant systems that may be degrading or failing.

Japan Atomic Power Company's Tsurugan NPP (Unit 2) includes a Mitsubishi Computerized Operator Support System (MCOSS). Its objective is to aid operator's decision making by detecting abnormal operating conditions before they become serious and to advise the operator of appropriate actions. If its early warning capability does not prevent a plant trip, the MCOSS assists the operator in reaching safe shutdown. The utility was concerned that measurement noise would impair the system's diagnostic capability; however, this was not the case. The system's response time is approximately 6 to 7 seconds, which was judged acceptable, although shorter times were preferred.

This system will be further developed in the Mitsubishi Advanced PWR. Mitsubishi is developing a KBS for use during accident conditions and when operators are under high stress. The system develops hypotheses about plant conditions based upon the available symptoms, and then tests each one. It uses a windows interface with dialogue control at the bottom of the screen. The operator can request an explanation of the system's hypothesis, procedural guidance, and evaluation of alternative solutions before actions are taken. It is anticipated that use of the system in a real CR would be a full-time job, probably for a senior operator.

Despite the development of many COSSs, there is not much experience with operational aspects of their use. Several experimental evaluations of the value of expert systems to operators were inconclusive (Bernard and Washio, 1989). Furthermore, there is a trend for expert systems to be abandoned after prototype testing and brief, in-plant trials. The transition from a prototype system to a production-grade product requires a significantly greater effort than initial prototyping (Cain and David, 1989).

As discussed, the predominant role of COSSs has been as decision aids. In this role, perhaps the most significant factors are intelligibility and communication (IAEA, 1995; Malin et al., 1991a, 1991b; Land et al., 1995; Rook and Donnell, 1993). It is essential to the operators' acceptance and use of COSSs that the reasoning process is fully understood by those using them. Personnel must be able to communicate both ways with the KBS COSSs, i.e., the degree to which the bases for its results are given and to which operators can query the system when its results are not understood is important.

Rook and Donnell (1993) experimentally manipulated the interface of an expert system which was designed to support fault diagnosis during simulated space station problem-solving situations to make its reasoning more or less intelligible to the subjects. They found that users of the system had to have a good mental model of its reasoning process to use it effectively. Since understanding the system was critical to its use, they predicted that the design of the display would be a significant factor in using the system.

Malin et al. (1991a) discussed case studies of the design of 15 intelligent systems developed for a variety of aerospace projects. The systems mainly were real-time fault management systems. The interfaces between the human operator and intelligent systems were found to be problematic. Some specific concerns identified were quite similar to those identified above: providing visibility into the system's reasoning, understanding its reasoning, the system's response in the context in which a question is asked, distinguishing hypotheses from facts, determining the credibility and validity of information, handling interruptions, handling changes in planned activity sequences, distinguishing between modes of operation, gaining control over the system's actions, and identifying system errors. The systems also had many problems related to their general HFE design. Operators often did not get the information they needed; it was presented in confusing formats not well suited to their task requirements, and excessive detail was given. This made it difficult for operators to "visualize the intelligent system's situation assessment and recommendations in relation to the flow of events in the monitored process."

Similar results were obtained by Dien and Montmayeul (1995), who surveyed operating experience with COSSs placed into existing CRs. They concluded that while much effort went into their design, the focus was on technology, and feedback showed that operations were not improved by their implementation. In many cases, the approach led to failure. COSSs often provide guidance for situations that operators already are equipped to handle. That is, they are designed for situations which were previously analyzed with which designers are familiar. Such aids are of little help to operators, except for confirmation. These systems poorly address unforseen circumstances and may not then provide appropriate guidance.

Another problem observed was that aids were "acontextual." That is, their guidance had little reference to the current situation. Also, guidance was given without appropriately communicating what led to its issuance, what parameters were analyzed, or what sequence of reasoning was followed. When the reasoning process is shown, it may conflict with that of the operators, i.e., it may be based on the designer's theoretical understanding and not on the operator's practical experience.

The new aids are often poorly integrated with other HSI systems, and their design characteristics, such as dialog principles and coding, are often different. Reed, Hogg, and Hallbert (1995) found that concerns about the interface design and system implementation limited the usefulness of a KBS system, the Process Operations and Management System, which was installed in a conventional British Nuclear Fuels plant to provide on-line early warning and fault diagnosis. These limitations led operators to prefer the conventional systems.

Roth, Bennet, and Woods (1987) indicated that the interface provided to a KBS must enable a cooperative dialogue so the operator can better understand and utilize the system. In general, these aids tend to be technology driven and do not address the needs of the operator; that is, they are developed by finding an application for a given technology, rather than being designed to meet users' needs. An inadequate analysis of users' requirements usually leads to problems with information content. The system should provide accurate information that is needed, and not force extraneous material on the user. Expert systems should support the operators' cognitive processes and reinforce their existing approach to plant operation developed through training and experience. The KBS should not require operators to conform to the machine's method of analysis (Bernard and Washio, 1989).

KBSs also have inherent limitations (Terry, 1989). They cannot reason broadly over a field of expertise, and are limited to narrow tasks. They cannot reason from axioms, analogies, or general theories. In addition, they lack common sense and often do not make simplifying assumptions. They are limited by their programming and cannot learn. Their performance deteriorates rapidly when applied to large problems. Such limitations of the expert system should be made obvious, so operators are not required to decide between their own judgment and the machine-generated advice (Bernard and Washio, 1989). The system's security should be controlled so that inappropriate changes cannot be made.

The IAEA (1994) identified several criteria that should be considered when licensing authorities evaluate COSSs:

(1) *Compatibility with the operations* - To work effectively, operators may require more than occasional simulator training to become familiar enough with COSSs to use them. They may need day-to-day experience.

The operator's effectiveness in using the COSS requires that the system is used not only in very specific conditions for which it was designed, but also in normal operation. For maximum compatibility with the global MMI, the data produced by the COSS must be integrated into the procedures used by the operators for normal operations, as well as in the specific abnormal or emergency conditions for which the COSS was designed. This may be an issue for CBP systems that are designed for emergency systems only. (p. 31).

(2) *Consistency with the HSI design* - The detailed design of the COSS, e.g., labeling and dialog conventions, should be fully consistent with the rest of the HSI. This may be a particular problem for off-the-shelf systems.

(3) *Cognitive support* - The COSS must enhance performance, or, at a minimum, not degrade it.

(4) *Team performance* - The user of the COSS must be clearly specified. However, NPP control is a team operation. COSSs may change task allocation and the type and quantity of information to be communicated between crew members. These effects must be evaluated and it should be demonstrated that the team's performance is not degraded.

Summary

The following human performance concerns are associated with COSSs:

(1) The design of computer-based systems commonly fails to account for user needs. This includes the need for information in the context of current tasks, goals, and objectives for operations, maintenance, crew configuration, and feedback from control actions.

(2) COSSs and other computer-based systems add to the plant's complexity. Operators must have a good mental model or understanding of the computer-based system for monitoring, supervision, and maintenance of the plant. Failure to account for this leads to poor situation awareness and a sense of being out-of-the-loop.

(3) COSSs often are not designed so that their logic is sufficiently observable. That is, they do not make clear their reasoning basis or enable operators to adequately query or otherwise verify system performance.

(4) Compatibility with day-to-day operations needs to be considered. Systems with very limited use in normal operations that are only used in infrequent special circumstances may have little success.

(5) Integration of a COSS with other CR HSIs is important.

(6) Training and team performance are significant considerations when introducing new technology.

5.6 Summary and Discussion

This section summarizes and discusses the implications for CBPs of the material reviewed in Section 5.

5.6.1 Supervisory Control and Procedure Use

The role of the operating crew in an NPP is that of a supervisory controller that must engage in situation assessment, monitoring and detection, and response planning and implementation. These cognitive functions are applied to tasks for which the crew has primary manual responsibility as well as to automated systems, and systems which support the tasks. Procedures fall into the latter category.

Historically, procedures were designed to support response planning by providing operators with strategies based on "off-line" detailed analyses of both normal and abnormal states. However, when these preplanned strategies are applied to the unique circumstances of a particular process disturbance, unforseen or unanticipated situations may render parts of a procedure inappropriate or ineffective. Thus, confronted with complex, real-world process disturbances, operators must monitor the performance of the procedure to verify its correspondence to the higher-level goals that it was designed to achieve. It is important for operators then to assess the effectiveness of the response plan even when described by established procedures, the consequences of particular actions, and the appropriateness of the path for achieving identified goals. This enables operators to detect when procedures are not achieving the goals, when procedures are erroneous, or when errors are made in carrying out procedure steps.

Another cognitive activity is adapting response plans. Adapting plans to the current situation is necessary because steps may be vague and have to be interpreted by the operators, or their judgement is necessary to evaluate the procedure. In addition, procedures do not have all the information about the plant that the operators do. Operators must fill in the gaps in a procedure, modify it to fit the specific situation, and direct the procedure path. Thus, rather than assuming the role of rote, verbatim procedure followers, it is important that operators maintain the role of supervisory controllers and monitor the performance of the procedures as well as the process. They need to stay cognitively involved in the procedure's progress. Operators need to understand the intent of procedures, their overall strategies, assumptions and underlying principles, and the transition logic between procedures. They should question procedure steps that appear inconsistent with the overall goals of the procedure for the situation at hand.

With the development of CBPs, procedure systems have the potential to support not only response planning, but also aspects of situation assessment, monitoring and detection, and response implementation. This support may be applied to the operators' primary tasks, such as monitoring parameters, and to secondary tasks, such as navigating from one portion of a procedure to another.

5.6.2 The Effects of CBPs on Crew Performance

There are limitations to PBPs that CBPs potentially can address: cognitive workload associated with process monitoring and analysis of the logic in procedure steps; attention required for assessment of procedure steps that are continuously applicable, time dependent, and process dependent; the need for varying levels of detail in procedure information; the lack of context sensitivity; management and place keeping in multiple procedures; and, sequence control and navigation. The limitations of PBPs have been associated with delayed task performance and human errors in existing plants.

CBPs may address these issues; however, they must maintain acceptable performance on the main tasks for which procedures are used while not introducing unintended negative effects. The latter is an important consideration. Our general review of the literature indicated that comparisons of task performance for information presented either on a VDU or in hard copy revealed significant differences between them. Reading on a VDU is generally slower and more fatiguing. VDU-based task performance also is associated with slower and poorer performance and concerns about usability. In addition, different task strategies are used. Contributing to these differences are keyhole effects, difficulties associated with maintaining a sense of location (knowing where you are in a document), navigation (moving from one place in a document to another), and fatigue. Some of these same concerns were raised regarding computerization of NPP procedures (Chignell and Zuberec, 1993).

In general, the computerization of other types of support systems, e.g., COSSs, has had limited success (Dien and Montmayeul, 1995; IAEA, 1994; Malin et al., 1991a; Roth, Bennet, and Woods, 1987). The problems included the failure to account for users' needs and therefore, incompatibility with day-to-day operations; added complexity of the HSI; obscurity of the reasoning basis; inadequate communication facilities preventing operators from asking questions; poor integration with other HSIs; and personnel concerns, such as training and team performance.

Thus, while there are PBP deficiencies that may be resolved by computerization, it is essential to carefully examine the effects on personnel performance. We did this by reviewing three types of research: (1) empirical studies of CBPs where performance data were collected, (2) analyses of personnel performance using models, and (3) expert opinion on postulated effects on performance. Each is briefly summarized below.

The human performance research was organized into three categories: comparisons of CBP and PBP systems, observations of operators' CBP use, and comparisons of design characteristics of procedures. Several conclusions were drawn about using CBPs compared to PBPs:

- Operators may perform procedure tasks more quickly.
- Operators' cognitive workload may be reduced.
- Operators may make fewer errors in transitioning through procedures.
- Operators may accept CBPs more readily and find them easier to use.

However, there remain several important unresolved questions including (but not limited to) the following ones:

- What is the effect of CBPs on team performance and reliability?
- What is the effect of CBPs on operators' high-level situation awareness of the status of the overall procedure goal and the plant?
- Do operators become overreliant and unquestioning of CBPs, or can they maintain independence and objectivity to evaluate the adequacy of the procedure to achieve its goals?
- What is the effect of CBPs on performance in complex disturbances that may involve many procedures or branches?
- How well do operators manage complex CBP failures, such as when multiple procedures are being used, many steps have been completed, and many steps of continuous applicability are being monitored?

- What are the relative effects of specific design features on performance?

These and other CBP issues are discussed in Section 5.6.3.

Another problem with the human performance research reviewed was that many studies were not discussed in sufficient detail to evaluate their generalizability. Those studies that were sufficiently documented had potential methodological weaknesses which limited their conclusions and generalizability.

Personnel performance also was analyzed using two classes of analytical techniques: performance models and risk models. CBPs were evaluated by a variety of performance analysis models including the GOMS model, MicroSaint Task Network Modeling, the MIDAS model, and classical task analysis. The performance models showed CBPs had no clear advantage over PBPs. Instead, they illustrated the importance of performance tradeoffs in assessing different procedure systems. In general, complexity and attentional demands were higher for CBPs while data retrieval was easier and task completion time was less.

It is interesting that the use of performance models for evaluating procedures has had some success. Their continued development may focus the testing of specific design issues that must be addressed in CBP design; this view is consistent with the conclusions of a National Academy of Science (NAS) assessment of applying quantitative models of human performance to complex systems. The NAS (Baron et al., 1990) concluded that "In all, there are compelling reasons to believe that systematic human performance modeling efforts should be regularly advocated and used along with expert judgement and manned part- and full-task simulation, as a regular part of the design process for large-scale human-machine systems" (p. 86).

Several risk-informed analyses of CBPs have been made, each looking at risk somewhat differently: examining the potential to change generic failure rates, the potential effects of CBPs on components of human error probabilities, and whether CBPs may represent a potentially safety significant issue.

Like the studies with performance model analyses, the findings were mixed. They illustrated the potential for these systems to improve performance by supporting such procedure-related work as process monitoring, logic analysis, navigation, and place keeping. However, they indicated that poorly implemented CBPs can reduce human reliability.

Finally, SME opinion on the postulated effects on personnel performance was reviewed, including an NRC-sponsored review of CBP systems, an NRC CBP workshop, and an IAEA working group on computerization of CRs that addressed CBPs. The SME review of CBPs identified many positive effects of their use on the crew's performance; however, a wide range of issues was identified to be resolved in developing CBPs. Also noteworthy was the observation that CBP development must consider related HFE activities, such as training, and integrating the CBP system with the other HSIs and with the plant's overall operational philosophy. V&V programs were emphasized. In general, these findings were consistent with those from other sources discussed earlier.

Considering all the results, we concluded that CBPs have the potential to support operators' performance and there is evidence to support this claim. As the NRC indicated in its review of the URD, "...the development of electronically displayed procedures is a desirable goal for the overall integration of operator information needs" (NRC, 1994).

However, there are also important issues to be considered both in research and in the development of individual systems. Thus, the advice of several researchers and developers of CBP systems is repeated: the development of

CBP systems for operational use should proceed in a way that the benefits and drawbacks of CBP systems can be fully evaluated for each specific system. CBPs have important impacts on NPP operations, some of which extend beyond those intended by the designers (Spurgin, Wachtel, and Moieni, 1993).

The following are some general considerations for near-term approaches to CBP systems:

- Support cognitive functions which may be distracting and error prone, such as
    - process monitoring
    - logic analysis (cautiously, so as not to underspecify the analysis and undermine the operator's judgement)
- Support procedure management, e.g., step completion, place keeping, transitioning between procedures
- Provide PBP backup systems and ensure the similarity of CBPs and PBPs to (1) ensure confidence in near-term CBP applications, (2) enable operating experience to be gained, (3) minimize impacts on function allocation, (4) reduce burdens in training operators to use both systems, and (5) ensure successful crew performance when using backups (minimize the potential for negative transfer or difficulties in performance arising from disuse).

5.6.3 CBP Issues

This section summarizes the human performance issues associated with CBPs identified from the literature review. These issues represent topics for which research is needed before developing additional guidance. From a regulatory review perspective, these issues may be addressed on a case-by-case basis, as part of the design process review discussed in Part 2 of this document.

The issues are not mutually exclusive; they overlap and some are more general than others; some may be considered secondary to others. Interdependencies are unavoidable, as they all pertain to the interactions within an integrated human-machine system.

Methodological and Criterion Requirements for Evaluating CBP Effects

A more definitive conclusion about the value of CBP systems was hampered by the lack of operational experience with their use, and lack of quality experimental evaluations. The detailed methodological considerations validating complex human-machine systems and a conceptual approach to it were discussed. The methodology focused on (1) establishing the requirements for making a logical, defensible inference from validation tests to predicted integrated system performance under actual operating conditions, and (2) identifying aspects of validation methodology that are important to the inference process. The technical basis for inference in validation is based upon four general forms of validity: system representation, performance representation, test design, and statistical conclusion.

The studies examined generally had not undertaken well-controlled, comprehensive evaluations that would supply valuable data to better understand the impact of CBP effects under a wide range of scenarios and complex situations, using varied personnel and system measures. Most of them had methodological weaknesses which limited their conclusiveness and generalizability. Thus, important questions remain (many are discussed in more detail below). A good comprehensive evaluation of CBPs and their effects on crew performance has yet to be made.

One question that needs to be addressed from both research and regulatory review perspectives is, "What are the criteria for CBP acceptance?" While some authors specified that such systems should improve performance, others indicated that performance should not be degraded (implying that equivalent performance with PBPs and CBPs is acceptable). This is an extremely important distinction because of the impact on performance that would be necessary if CBPs were required to improve it.

Role of Plant Personnel in Managing Procedures

Procedures are guidance to operators for achieving high-level objectives. While they are correct most of the time, for analyzed situations, adaptation sometimes may be necessary. Thus, operators must remain as independent supervisors who manage procedure implementation and independently assess its appropriateness. Operators must understand the overall purpose of the procedures, stay cognitively involved with their progress, and question any steps inconsistent with the overall high-level safety goals. However, CBPs potentially might work against this independence, minimizing the operator's role. They may increase the tendency to follow procedures without a critical independent perspective, and may even deter the operator's action. Resolving these concerns affects both design and training.

Thus, one pressing issue is how to design and review CBP systems that enable the operators to maintain this independent perspective, but at the same time, reduce the operator's workload, automate distracting and lower-level error-prone tasks, and monitor the crew's performance, especially when the crew and CBPs disagree. Equally important is how to train operators in handling this role while using CBPs. The knowledge required to manage a CBP system may differ from that required to handle PBPs. For example, the CBP system may use different analyses to resolve procedure logic steps than operators do.

Team Performance

Research showed that CBPs may significantly affect crew member's roles, teamwork, and communication. Teamwork is an important element of defense-in-depth. Operators work as a team to support situation assessment, error detection and recovery. These roles and communication may be changed more than anticipated. Since SROs using CBPs can handle a procedure almost completely on their own, communication between the SRO and ROs may be reduced (Roth and O'Hara, 1998). While this is not, in itself, good or bad, its impact on team performance needs assessment. Board operators identified the importance of communication in maintaining effective teamwork when the SRO is using a CBP and expressed a need to be aware of the status of EOPs. Thus, the potential for isolating the CBP user from the other operators, and changing operators' roles and responsibilities may undermine team performance in emergencies. Such effects on team performance were noted for many aspects of computer-based HSI technology (Stubler and O'Hara, 1996).

The function of supporting coordination of the crew's work centers on the need for operators to be aware of the activities of other crew members. The CR is the context within which personnel convey, directly and indirectly, their intentions and actions to others. Advanced CRs, especially those with individual workstations, may isolate operators, making an individual's information and control actions less visible to others, thus reducing team effectiveness.

Salas et al. (1992) define a team as "...a distinguished set of two or more people who interact, dynamically, interdependently, and adaptively toward a common and valued goal/objective/mission, who have each been assigned specific roles or functions to perform" (p. 4). In a CR setting, operators must share information and coordinate their tasks to satisfy specific goals or mission requirements. This requires a common understanding of the status of the system and of each others' actions and intentions. Identification and resolution of errors, coordinated information exchange, and team reinforcement were identified as important to team performance (Oser et al., 1989). Successful teams actively located errors, questioned improper procedures, and monitored the status of others. In a study of ship navigation, Hutchins (1990) discussed team performance in terms of facilitating error checking by others, allowing others to assist, and supporting training in the work setting.

Hutchins found that longstanding work environments with traditional technologies have characteristics that contribute to team performance: horizon of observation, openness of tools, and openness of interaction. However, when computer-based technologies are introduced, these positive characteristics may be compromised.

- *Horizon of Observation* - This refers to the portion of the team task that can be seen or heard by each individual. It results from the arrangement of the work environment (e.g., proximity of team members) and is influenced by the openness of tools and interactions. By making portions of a task more observable, team members can monitor errors of intent and implementation, and determine when assistance might be helpful.

- *Openness of Tools* - This is the degree to which an observer is able to infer information about another's ongoing tasks through observation of a tool's use. Open tools show characteristics of the problem that give an observer the context for understanding what has been done and the possible implications.

- *Openness of Interaction* - This is the degree to which the interactions between team members provide an opportunity for others with relevant information to contribute. Openness of interaction depends on the type of communication (e.g., discussing actions or decisions in the presence of others) and the style of interaction (e.g., the extent to which unsolicited input is accepted). Openness of interaction is also influenced by characteristics of the work environment (e.g., openness of tools, horizon of observation) that allow other team members to see and hear the interaction.

Conventional CR designs typically have a broad horizon of observation facilitating the observation of team activities. In addition, they may be "open tools" in the sense that an observer can infer information about control actions (e.g., which plant system was involved, which control was operated, and what action was taken) by observing the operator's location at a control panel and the action performed. Interactions may be considered "open" because most involve speech that can be heard from across the CR.

Advanced HSI technologies, such as CBPs, may impair these good characteristics. For example, using an individual computer-based workstation with an individual view of the plant may reduce the horizon of observation because that view cannot be readily seen by others and may lead to less open styles of communication. Also, the openness of tools may be impaired by having methods of user-system interaction that convey less task-related information to observers.

Situation Assessment, Response Planning, and Operator Error

The effect of CBPs on the operator's situation awareness has not been carefully evaluated. Operators need to maintain several levels of situation awareness when using procedures, including assessment of:

- procedure steps, how procedures are structured, one's location within a procedure or between a set of procedures,

- the appropriateness of procedures to achieve high-level procedure goals, and

- the overall situation in the plant

Some concern over lowered situation awareness with CBPs was noted (Roth and O'Hara, 1998). PBPs require operators to monitor plant indications. However, if CBPs are present, the operator may not feel the need to look at other sources of information and may miss important indications that are not present in the CBP. The situation awareness of other operators is affected as well. Spurgin et al. (1990) noted that SROs use CBPs as their primary way of following the overall plant condition rather than relying on information from crew members. Consequently, the other crew members expressed concern about being aware of the EOP status.

Jeffroy and Charron (1997) described another aspect of situation awareness - the joint awareness of the operators and the CBP. Such combined awareness may be separated when operators depart from the recommendations of the CBP, creating a situation that makes it difficult for them to recognize the CBP's constraints. They may not understand how their actions affect the procedure's ability to analyze individual steps.

Research is needed to clarify the effects of CBPs on these different levels of situation awareness, the crew's ability to detect errors, and adaptation of the response plan in the face of procedure failures. In addition, knowledge is needed on the effect of CBPs on the number and types of operator errors (especially where errors are not defined in terms of verbatim compliance).

Two related issues affect situation awareness: complexity and level of abstraction. Research on COSSs emphasized that computerized support systems add to complexity. Operators need a good mental model or understanding of the computer-based system to properly monitor and supervise the CBP. Failure to account for this leads to poor situation awareness and a sense of being out-of-the-loop.

Roth and O'Hara (1998) observed that too little information presented at each procedure step can cause operators to lose a sense of where they are, while too much may distract them. The level of abstraction at which the results of procedure steps are presented will affect the operators' situation assessment.

Level of Automation of Procedure Functions

The human performance issues associated with automation have been well documented; see O'Hara, Stubler, and Higgins (1996) for a discussion of general automation. Table 4.1 listed procedure-related functions in terms of several levels of automation. The choices of levels of automation and their implementation will impact operator's performance, situation awareness, workload, and errors. Blackman and Nelson (1988) found that when the procedures were selected automatically, operators' involvement was reduced; they reported that they thought less and acted as switch-turners. A better understanding is needed of the tradeoffs between automatic procedure functions and operators' involvement, independence, and supervisory control.

One area of procedure automation is especially noteworthy. An important capability of CBP systems is the analysis of procedure step logic; that is, comparing actual parameter values to the reference value in procedures using the logical relationships described in the step. When the step logic or the data analysis required to evaluate the step logic is underspecified, both the procedure and the operator can misjudge the situation. Therefore, procedures, especially EOPs, must be carefully designed and evaluated to guard against such underspecification. Where the operator's judgement is involved, such analyses are better kept manual.

Keyhole Effects and Use of Multiple CBPs

Viewing information through the limited area provided by VDUs is referred to as the "keyhole effect" (Woods et al., 1990); its consequence is that, at any time, most information is hidden. Therefore, operators must know what information and controls are available in the computer system, where they are, and how to navigate and retrieve them.

The keyhole effect was identified as a root cause of many challenges to performance (O'Hara, Stubler, and Nasta, 1997). If the viewing area is insufficient for operators to perform their tasks, they may have to navigate repeatedly. A problem with the keyhole effect is that access to controls and displays tends to be serial, e.g., only a few controls can be accessed at once, in contrast to the parallel presentation of controls and displays in conventional CRs. The sheer burden of navigating and retrieving many displays can interfere with the operators' ability to obtain an overview of the plant's situation. If workload is already high, operators decide not to retrieve all the information they need so they can invest their mental resources in their current task.

The issues may become significant for CBPs when operators are required to be in multiple procedures. Hoecker et al. (1994) and Hoecker and Roth (1996) noted that when the operators are required to obtain information in parallel, the CBP system can increase workload. This lack of parallel access is a limitation of the keyhole effect. Because only a portion of the procedure can be observed in the display's space at one time, operators may lose a sense of where they are within the total set of active procedures.

CBP Failure in Complex Situations

Ensuring the transfer from CBPs to PBPs was recognized as an important consideration in designing and evaluating CBPs. This transition may be easy when the procedure context is simple, such as when operators are in its first few steps. However, the transition may be quite complex if operators are deep into the procedures, or when there are multiple procedures open, many steps completed, many steps of continuously applicability, time-dependent steps, and parameter-dependent steps being monitored by the CBPs. How operators will manage failures in such complex situations is unknown.

Hybrid Procedure Systems

Some CBP systems computerize all plant procedures (e.g., in EdF N4 CBP) while others contain only the EOPs (e.g., EOPTS). The ability to use CBPs effectively when they are designed only for emergencies may be problematic.

Several studies recommended that for COSSs to be effective, they must be well integrated into everyday operations. Further, operators may require more than occasional simulator training to become familiar enough with COSSs to use them, as the IAEA (1994) stated:

> Operator effectiveness in using the COSS requires that the system be used not only in very specific conditions for which it was designed but also in normal operation. For maximum compatibility with the global MMI, it is necessary to integrate the data produced by the COSS into the procedures used by the operators for normal operations, as well as in the specific abnormal or emergency conditions for which the COSS may have been designed. Note that this may be an issue for CBP systems that are designed for emergency systems only. (p. 31)

Others commented on the need for CBPs to be consistent with normal, daily operations (NRC CBP Workshop). While EOPs are not used in daily operations, their computerization and the use and functionality of the system may raise difficulties if the operators' interactions with them are unlike those with other systems in the CR.

Specific CBP Design Features

Most studies we reviewed did not discuss the relative effects of specific CBP design features on performance. They were overall system comparisons, e.g., CBP vs. PBP, not systematic evaluations of individual characteristics. In addition, concern over the generalization of PBP guidance to CBPs was expressed.

Thus, traditional procedure formats may require modifications when implemented on a computer. Two primary formats are used for procedures: text and flowcharts (Section 4). While both are successful in paper form, Chignell and Zuberec (1993) questioned whether flowchart presentations are acceptable in computer media where the limited screen and need for scrolling may make them less effective. Similarly, reading extended text from VDUs was found to be visually fatiguing. The proper implementation of CBPs in text and flowchart formats may require more guidance than that available for the paper forms. The effects of HSI techniques (such as outline views, navigational aids, and highlighting) on text and flowchart use, requires exploration.

6 DEVELOPMENT OF GUIDANCE

Section 5.6.2 identified an approach to near-term CBPs, based on a consideration of lessons learned and of the remaining CBP issues. General considerations for near-term approaches to CBP systems include (1) supporting cognitive functions, such as process monitoring and logic analysis; (2) supporting procedure management, such as step completion, place keeping, and transitioning between procedures; and (3) providing PBP backup systems and ensuring similarity of CBPs to them. The review reflects these considerations.

As an emerging technology, the technical basis for CBP guidance is limited, and there remain unresolved issues that cannot currently be reviewed with HFE guidelines. Thus, CBP reviews will require review of the CBP design processes as well as the design implementation. The latter conclusion is fully consistent with the NUREG-0700 approach to reviewing HSI technology for which HFE design review guidance is limited, and also with the URD approach to an unproven technology. The development of guidance, therefore, took two forms: HFE design review guidance (typically found in NUREG-0700), and design process guidance. Guidance for products and processes is described in Part 2 of this report.

As part of the design process, CBP systems will have to be evaluated using simulations and comparisons to reference systems, i.e., PBPs. This will confirm their acceptability and will support the development of more detailed guidance for specific systems. In the staff's URD review, the NRC (1994) stated that the:

> ... designer should consider the use of electronically displayed procedures early in the design process to resolve any issues concerning their development, operability, maintainability, and reliability. If electronically displayed procedures are determined to be an improvement over hard-copy procedures and the M-MIS designer has integrated electronically displayed procedures into the overall M-MIS design, they should be provided as part of the design. (p. 10.B-17)

NUREG-0711 gives the NRC's high-level design process criteria for reviewing overall HFE programmatic goals and objectives but not for detailed reviews of final HSI designs, such as displays, control, or procedures. Rather it cites NUREG-0700 for guidance on detailed reviews of plant HSIs. In Part 1 of NUREG-0700, Rev. 1, the design process is covered under the review of plant HSIs for which the general framework of NUREG-0711 was used. However, Part 1 also addresses general aspects of reviewing HSI designs, i.e., it does not identify the specific considerations that may be important for an individual technology, such as CBPs. The only detailed HSI technology-specific guidelines are in Part 2 of NUREG-0700; they cover the detailed form and functional characteristics for HSI implementations, but not design process considerations.

Both types of guidance are necessary for a design review of CBPs. That is, while there is sufficient technical basis to develop detailed design-implementation guidance for many characteristics of CBPs, as is typical in NUREG-0700, several limitations in the technical basis have been identified, and so issues remain for which typical NUREG-0700 guidelines could not be developed. However, until more guidance becomes available, these issues can be resolved for specific CBP systems. To support resolution of issues for specific systems, guidance for the CBP design process review was established.

6.1 CBP Design Process Review Guidance

Guidelines were formulated for the design process review to address important points raised in the literature, and to provide a place where CBP human performance issues could be explored during a design review on a case-by-case basis. The format of the guidelines corresponds to the NRC's general guidance in NUREG-0711. They are organized into the following sections:

- HFE Program Management
- Operating Experience Review
- Functional and Task Analysis
- Staffing
- Human Reliability Analysis
- Human-System Interface Design
- Procedure Development
    - Scope
    - Bases
    - Technical Information
    - Maintenance
- Training Program Development
- Human Factors Verification and Validation

These guidelines are discussed in Section 9, Part 2 of this report.

6.2 CBP HFE Design Review Guidelines

A draft set of guidelines was developed from the findings and source materials that we surveyed, along with the high-level design review principles from NUREG-0700, Rev. 1. These principles were developed from research and industrial experience on integrating personnel into complex systems. They reflect the important design goals of (1) maximizing primary task performance (i.e., process monitoring, decision making, and control), (2) minimizing secondary task demands unrelated to the primary task (e.g., the distraction of tasks such as configuring a workstation), and (3) minimizing human errors and making systems more tolerant of them. These principles are also set out in Appendix B.

An example of these guidelines written in the standard format of NUREG-0700, Rev. 1 is presented below:

10.2.2-2 Automatic Monitoring of Plant Parameters and Equipment Status
The CBP should automatically provide accurate and valid information on the values of parameters and status of equipment, when they are available to the system.
ADDITIONAL INFORMATION: It should be clear to operators what specific information is used as the source of these actual values and states.
Discussion: Supporting cognitive functions, such as obtaining parameter values (monitoring) may reduce the demands on attentional resources and working memory and enable the operator to focus more on evaluating higher-level procedure goals. It may also help solve PBP issues. This capability was identified

as being beneficial to the crew's reliability (Orvis and Spurgin, 1996; Pirus and Chambon, 1997; Niwa et al., 1996). Further, presenting plant parameters and status in procedure steps is a URD requirement (EPRI, 1993a). This guideline is an application of the High-Level Design Review Principles of Situation Awareness and Cognitive Workload (see Appendix B).

Each guideline has the following components:

- *Guideline Number* - Within each section, individual guidelines are numbered consecutively. The number includes its section and subsection location, followed by a dash and its unique number.
- *Guideline Title* - Each guideline has a brief, unique, descriptive title.
- *Review Criterion* - Each guideline contains a statement of an HSI characteristic so that the reviewer may judge the HSI's acceptability. The criterion is not a requirement, and discrepant characteristics may be judged acceptable based on the procedures in the review process.
- *Additional Information* - For many guidelines, there is additional information including clarifications, examples, exceptions, details on measurement, figures, and tables to support the reviewer's interpretation or application of the guideline.
- *Discussion* - The discussion summarizes the technical basis of the guideline. It may identify the primary source documents, the technical literature, such as journal articles, or the general principles from which the guideline was derived. This section will be removed when the guidance is integrated into NUREG-0700, Rev. 2.

In place of the Discussion will be a Source field:

- *Source* - The source field identifies the NUREG or NUREG/CR (or other document) containing the technical basis and development methodology for the guideline. As is the standard practice for NUREG-0700, the source field will give a reference to this document.

The guidelines, contained in Section 10, are organized into the following sections:

- Procedure Representation
  - Identification
  - Basic Steps
  - Warnings, Cautions, Notes, and Reference Materials
  - Lists
  - Organization
  - Formatting and Screen Layout

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- Procedure Functionality
  - Procedure Supervision and Control
  - Procedure Monitoring and Assessment
  - Monitoring Operator Actions
  - Planning and Implementation
- Procedure Management and Support
  - Path Monitoring
  - Navigation
  - Communication and Help
- CBP Hardware
- CBP Procedure Backup
- CBP Integration with Other HSI Components.

7 SUMMARY

The objective of this study was to develop HFE review guidance for CBP systems based on a technically valid methodology. To support this objective, the following tasks were undertaken:

- Development of a framework for characterizing key design features of CBP systems
- Development of a technical basis using research and analyses on human performance relevant to CBPs
- Development of HFE review guidelines for CBPs in a format that is consistent with NUREG-0700, Rev. 1, and NUREG-0711
- Identification of remaining CBP issues for which research was insufficient to support our development of NRC review guidance

The status of each will be briefly addressed below.

CBP System Characterization Framework

For this study, CBP systems were narrowly defined to encompass computer systems that support procedure presentation and use. The focus was on the HFE aspects of CBPs, and not the I&C or software aspects (although the latter are important as well, and are described in other NRC regulatory and research programs). CBPs were characterized along the following the dimensions:

- Representation of Procedure Elements
- Procedure Functionality
- Interface Management and Support
- CBP Hardware
- Backup Systems for Procedures
- Integration of CBP System with the HSI

Development of the Technical Basis

The effects of CBPs on crew performance were determined by examining three types of research: (1) empirical studies of CBPs where data on personnel performance were collected, (2) analyses of personnel performance using models, and (3) expert opinion about their postulated effects on personnel performance.

The human performance research was organized into three categories: comparisons of CBP and PBP systems, observations of operators' use of CBPs, and comparisons of design characteristics of procedures. Several conclusions were made from comparing CBPs with PBPs:

- Operators perform tasks more quickly.

7 SUMMARY

- Operators' overall cognitive workload is reduced.
- Operators may make fewer errors in transitioning through procedures.
- Operators may accept CBPs readily and find them easier to use.

However, much of the human performance research had insufficient detail to evaluate its generalizability. Studies that were sufficiently documented had potential methodological weaknesses which limited their conclusiveness and generalization.

Personnel performance was analyzed with two classes of techniques: performance models and risk models. The performance models showed no clear advantage of CBPs over PBPs. Instead, they illustrated the importance of performance tradeoffs in assessing different procedure systems. In general, complexity and attentional demands were higher, while data retrieval was easier and task completion time was less for CBPs. Similarly, mixed results were obtained from the risk analyses. They illustrated the potential for these systems to improve performance by supporting such procedure-related activities as process monitoring, logic analysis, navigation, and place keeping. However, when poorly implemented, CBPs can reduce human reliability.

Finally, the SME review of CBPs identified many positive aspects of their use on the crew's performance. However, they also identified a wide range of issues to be resolved in developing CBPs. The review highlighted the importance of considering HFE activities in CBP development, e.g., the integration of the CBP system with the other HSIs and with the overall operational philosophy of the plant. Thorough V&V programs were also emphasized. In general, these findings were consistent with the information discussed earlier.

When considering all the results, we concluded that there is evidence that CBPs can support and enhance operator performance. However, important issues remain to be addressed both in research and in the development of individual systems. Thus, we repeat the advice of researchers and developers: CBP systems should be developed in such a way that their benefits and drawbacks can be fully evaluated for each specific system. CBPs have important impacts on NPP operations, some of which extend beyond those the designers intended.

Reflecting this approach, we offer some general considerations for near-term approaches to CBP systems:

- Support cognitive functions that may be distracting and error prone, such as
  - process monitoring
  - logic analysis (cautiously so not to underspecify the analysis and undermine operator's judgement)
- Support procedure management, e.g., step completion, place keeping, transitioning between procedures
- Provide PBP backup systems and ensure similarity of CBPs and PBPs in order to (1) ensure confidence in near-term CBP applications, (2) enable operating experience to be gained, (3) minimize the impact on function allocation, (4) ease the training burdens associated with both systems, and (5) ensure successful crew performance when transitions to and from backups are necessary (minimize the potential for negative transfer or difficulties in performance).

HFE Review Guidelines

Guidance for the review of CBPs was developed to address the CBP design process and HFE design. Both types of guidance are needed for a design review. That is, while there was a sufficient technical basis to develop detailed guidance for design-implementation review, as is typical in NUREG-0700, several limitations in the technical basis were identified. Many issues (listed below) remain for which typical NUREG-0700 guidance could not be developed. Therefore, until the additional guidance is developed, these issues should be addressed for specific CBP systems using CBP design process guidance.

CBP Issues

As noted above, several human performance issues associated with CBPs were identified. They represent topics for which research is necessary before developing guidance. From a regulatory review perspective, many of them can be dealt with on a case-by-case basis during the design process review. Briefly, the issues included the following:

Methodological and Criterion Requirements for Evaluating CBP Effects - Most of the studies reviewed had methodological weaknesses which limited their conclusiveness and generalizability. This issue addresses the need to evaluate CBPs and their effects on crew performance comprehensively, to better understand them under a wide range of scenarios and complex situations, using varied measures of personnel and system performance.

Role of Plant Personnel in Procedure Management - This issue addresses the need to determine how to design and review CBP systems (1) to allow operators to maintain an independent perspective and to recognize the procedure's contribution to higher-level safety goals, (2) to automate distracting and lower-level error-prone tasks, and (3) to monitor the crew's performance, especially when the crew and CBPs disagree.

Team Performance - This issue addresses the requirement to explore the effect of CBPs on crew member's roles, teamwork, and communication. How CBPs can be designed to effectively promote both is considered as well.

Situation Awareness, Response Planning, and Operator Error - This issue addresses the need to assess the effect of CBPs on situation awareness including:

- procedure management, such as status of procedure steps, how procedures are structured, and the current location within a procedure or between a set of procedures,
- the appropriateness of procedures for achieving high-level procedure goals, and
- the plant's status.

Level of Automation of Procedure Functions - This issue addresses the need to evaluate the tradeoffs between automating procedure functions, e.g., the analysis of procedure step logic, and the operator's involvement, independence, and supervisory control.

Keyhole Effects and Use of Multiple CBP Procedures - This issue concerns the requirement to evaluate the significance of the keyhole effect in situations where operators are required to be in multiple procedures and must access information in parallel.

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CBP Failure in Complex Situations - This issue involves the need to evaluate operator's management of the transition from CBPs to PBPs and back to CBPs under complex conditions, e.g., in a situation where operators are deep into the procedures, multiple procedures are open, many steps are completed, many are continuously applicable, and time and parameter steps are being monitored by the CBPs.

Hybrid Procedure Systems - This issue addresses the need to evaluate any differential effects of having all plant procedures presented in a CBP system versus a hybrid system, e.g., EOPs presented using CBPs and all other procedures are paper-based.

Specific CBP Design Features - This issue addresses the need to evaluate the relative effects of specific CBP design features on performance.

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PART 2

CBP Guidelines for Design Review

9 GUIDANCE FOR CBP DESIGN PROCESS REVIEW

As discussed in Section 6.1, the design process guidelines were developed to address important aspects of the process and to provide a means whereby human performance issues may be assessed during a design review. The guidelines were formatted to correspond to the NRC's general guidance for design process review in NUREG-0711. They are organized into the following sections:

- HFE Program Management
- Operating Experience Review
- Functional Analysis
- Task Analysis
- Staffing
- Human Reliability Analysis
- Human-System Interface Design
- Procedure Development
- Training Program Development
- Human Factors Verification and Validation

Guidelines may specify that some identified aspect of CBPs needs to be "evaluated." NUREG-0700 defines general methods for evaluation and for identifying criteria. Since the guidance in this section will eventually be incorporated into NUREG-0700, those methods and criteria are not repeated below.

9.1 HFE Program Management

(1) CBP design and evaluation should be performed with a multidisciplinary team.
Discussion: The NRC's analysis of EOPs (Lapinsky 1989) noted that the lack of a multidisciplinary team was associated with procedure deficiencies which can negatively impact the development and use of CBPs; therefore, a CBP development program should address this issue. The exact skills needed on the multidisciplinary team will vary, depending on the scope of the CBP systems. Appendix A, NUREG-0711 gives a range of the broadest possible skills required; typical ones would be those described in Subsections 2, 4, 6, 7, 9, and 10; namely, Systems Engineering, I&C Engineering, Human Factors Engineering, Plant Operations, Plant Procedure Development, and Personnel Training.

(2) An implementation plan should be developed to deal with CBP design, maintenance, training and evaluation.
Discussion: The NRC's analysis of EOPs (Lapinsky, 1989) noted that the lack of a systematic process was associated with procedure deficiencies, and can negatively impact the development and use of CBPs; therefore, a CBP development program should include this issue.

(3) The CBP's design constraints or assumptions should be documented and their implications for safety should be evaluated to ensure they do not compromise the CBP system's goals.
Discussion: Identifying design constraints and assumptions is important to HFE design in general (O'Hara et al., 1994), and for procedures systems in particular (Barnes et al., 1996). Reviewers should evaluate the constraints and assumptions applied by the designers of the system and specify their implications for safety. These might include limitations in the capabilities of the hardware or software, assumptions about operators' knowledge and skills, uncertainties about particular content areas that are not fully developed, or decisions to leave the design of some system aspects of the CBP to other individuals. The reviewer should evaluate the acceptability of the designers' assumptions and assure that any constraints do not compromise the system's goals.

(4) The CBP development program should be fully documented, including design goals and assumptions, use of operating experience, design analyses, establishment of system requirements, tests and evaluations, detailed description of the design, and verification and validation.
Discussion: Reviewers should be able to follow the designers' development process from the analysis of requirements to the final design and testing. In addition, reviewers should ascertain that the information used to develop the procedures will be retained in a form accessible to the licensees who will implement the CBPs at a new or existing plant. Such records are essential for assuring that the procedures can be kept current (Barnes et al., 1996; Lapinsky, 1989).

9.2 Operating Experience Review

(1) The CBP design should eliminate or minimize PBP problems where practical. Experience with paper procedures should be reviewed to take advantage of lessons learned in their operational use, maintenance, and configuration control as well as to help ensure that problems in implementing PBPs are resolved. Table 9.1 is a partial list of identified PBP problems.
Discussion: Studies of PBPs at NPPs, the experiences of assisting licensees in developing procedures, and lessons learned through inspections suggest that some problematic aspects of PBPs may be rectified by computerization (Barnes et al., 1996).

(2) Operating experience with CBP systems should be reviewed to take advantage of lessons learned in using the systems, as well as to ensure that any problems in implementing CBPs are dealt with.
Discussion: The review should consider the use of CBPs in the nuclear industry and related industries.

(3) Human performance issues, such as visual fatigue, arising from the computerization of documents and manuals should be addressed.
Discussion: Many HFE issues were identified that limited personnel performance when support aids are transferred from paper to computers. Familiarity with this literature may help to minimize these issues.

9.3 Functional Analysis

An overall concept should be developed of the operators' role in managing and supervising plant procedures.
Discussion: Operators must be able to supervise the conduct of procedure operations, evaluate their success at achieving safety goals, and formulate response plans when those goals are not being met. Research shows that CBPs can lessen operator independence. A clear statement of the operators' roles and responsibilities will help the design and training aspects of CBP development. The design decisions (e.g., scope and content, integration, and function allocation) should flow clearly from the designers' overall concept of the operators' role in managing plant

systems. Design documents should clearly articulate this concept and its rationale, and describe how the design carries out the concept (Barnes et al., 1996).

9.4 Task Analysis

(1) The effect of the CBP on the tasks of individual members of the crew should be analyzed, considering any potential changes that may result from the combined use of CBPs and PBPs, and also the effect on communications.

Table 9.1 Examples of Deficiencies in Paper-Based Procedures

Issue	Deficiency
Design Process	• Inadequate participation of operations and training personnel in developing procedures • Technically incorrect EOPs • Suitable under standard situations, but less support in unusual situations • Incomplete procedures • Inadequate consideration of the time required to complete procedural actions • Insufficient verification and validation (V&V) of procedures
Implementation	• Nonspecific entry and exit conditions for support procedures • Procedures are fixed and inflexible • Incorrect sequencing of action steps • Inadequate consistency across procedures • Inconsistencies in formatting and use of terminology • Incorrect identification of plant equipment • Inadequate provision for varying level of detail • Non-sequential presentation of information • Difficulties in navigating to related information • Inadequate management of multiple procedures • Unsatisfactory integration of procedure tasks and other tasks • Problems in labeling and headings • Notes and cautions in improper places • Lack of context-dependent highlighting and navigation • Requirements to use multiple procedures simultaneously and move between sections • Lack of flowcharts to guide procedure use • Inadequate support and reference material • Bulkiness • Physical handling of procedures near control panels • Separation from other information sources, such as SPDS • Inconsistency with other HSIs in terms of references to plant equipment
Training	• Operators poorly trained in using procedures

Maintenance	•	Maintaining technical accuracy of procedures lacking

Discussion: CBP may have an important effect on crew member's roles and communication. The extent to which they are changed relative to PBP use may impact the crew's situation awareness and plant safety (Roth and O'Hara, 1998).

(2) CBP tasks should be analyzed and used as an input to its design.
Discussion: To ensure that the design of CBPs is acceptable and usable, the results of task analyses should be incorporated. Following the decisions on function allocation, the operators' tasks should be defined at increasing levels of detail to specify their actions and information requirements.

(3) Tasks associated with CBP failure and back-up should be identified to define the requirement for indicating malfunctions. The task of smoothly transitioning from CBPs to a back-up method (such as PBPs) also should be addressed.
Discussion: By identifying this capability as a task, the designer will then include it in the HSI, procedures, and training. A failure of the CBP System may be total or a more insidious partial one that is not obvious to the operators. Besides designing-in indicators of failure, a means should be identified to smoothly move to the back-up system; the content of the CBP and PBP (or other back-up) should be compatible.

9.5 Staffing

(1) The demands of operating and maintaining the CBP should be assessed for their implications for personnel skills and qualifications.
Discussion: CBPs may impose demands on plant personnel that are unlike other systems, for example, maintaining a large database. Human error in that particular task was identified as a major cause of events involving these systems (O'Hara, Stubler, and Higgins, 1996).

9.6 Human Reliability Analysis

(1) Any effects on performance caused by computerization of procedures should be analyzed for their implications for those human actions modeled in a PRA.
Discussion: PRAs may reflect analyses of human actions based on paper procedures. CBPs have broad effects on performance, both from team and individual perspectives. Accessing EOPs through a computer system may create keyhole effects and may increase interface management demands. Some tasks may be eliminated, such as monitoring procedure-specified parameters, or analyzing procedure logic. Also, human errors in maintaining digital systems is a major cause of events (O'Hara, Stubler, and Higgins, 1996). All of these potential effects should be considered in evaluating impacts on reliability assumptions and analyses. Further, since operating experience with CBPs is limited, assessing the impact of CBPs on human performance and reliability should utilize, in part, the results of tests obtained during CBP design, evaluation, verification, and validation (Converse, 1995; EPRI, 1993a; Orvis and Spurgin, 1996).

(2) The analysis should consider the effects on human reliability of loss of CBPs and transfer to PBPs.
Discussion: Using PBPs places different demands on the crew and can change their interaction and roles; risk analyses should consider the implications of these changes.

9.7 Human-System Interface Design

(1) The HSI design should consider methods by which procedure elements are represented in the CBP and the extent to which usability principles for PBPs generalize to CBP systems.
Discussion: There are many guidelines for designing PBPs. However, how far they are applicable for implementing a CBP system must be assessed. For example, representing procedure format, e.g., in a flowchart or text, may not reflect a simple application of the PBP guidance.

(2) The procedure functions to be provided by the CBP system should be carefully analyzed to ensure that the system is consistent with the utilities' general approach to procedure-based operations, and that the operator's inputs and judgements are included, where appropriate.
Discussion: The CBP system should provide operators with capabilities and functions to support their roles as system supervisors and their performance of tasks.

(3) The following aspects of CBP design should be carefully evaluated to ensure that the use of procedures is not jeopardized and that task requirements are adequately supported:

- Number of VDUs
- Interface management and navigation functions
- Flexibility of CBP display and operations

Discussion: The keyhole effect that results from the limited view of plant information afforded by VDUs, interface management tasks, and computer system flexibility can significantly degrade performance. These aspects of the design should be evaluated as part of the design review.

(4) The potential interactive effects between procedure use and the hardware and software used to implement them should be evaluated.
Discussion: NUREG-0700, Rev. 1 has guidance on hardware aspects of interacting with CBPs, such as VDUs and input devices. However, there may be other such interactions, including those with software, that are not addressed. Since there is no technical basis for guidance, these interactions should be examined during the design process.

(5) The means by which CBPs can support crew cooperation, communication, and decision making should be evaluated.
Discussion: The NRC CBP workshop and several investigations (e.g., Roth and O'Hara, 1998) highlighted the need to address crew interactions during the design and implementation of CBPs.

(6) Operators should be involved in developing and evaluating prototypes to ensure that their final design is usable.
Discussion: Lacking guidance, CBP designers should have access to system prototypes, control room mockups or simulations, and representatives of the users to refine the design of the CBPs. Having users carry out procedure steps at the worksite (or a simulation) provides important information about step-sequencing, implementation times, access to the displays and controls, and other physical characteristics of the work environment, and an opportunity to collect their feedback on initial designs (Barnes et al., 1996).

9.8 Procedure Development

9.8.1 Scope of Procedures

(1) The purpose and scope of the CBP system should be clearly defined.
Discussion: If CBPs encompass only some operator tasks, justification should be given for excluding others. The implications for operator performance of using CBPs and PBPs for different tasks should be considered.

9.8.2 Bases of Procedures

Procedure bases refer to the background information used to develop the CBPs. Procedures are critical management tools because they are among the more important means of guiding human interactions with the plant systems. The procedures must not only prescribe technically correct actions, but must also implement licensee's and the NRC's expectations for the conduct of operations. Consequently, their content should be consistent with the technical, regulatory, and management bases of plant operations, no matter what medium is used to present them.

(1) The technical bases for procedures should be documented. Where the documented bases for paper procedures are unchanged by computerization, the existing document may be used. This should include the sources of technical information, as well as the process by which the information was used to define the desired operator actions and supplemental information, such as cautions and warnings, figures, and tables.
Discussion: The technical bases for procedures are the information used to define the plant's operational characteristics and may be beyond the scope of a human factors review. However, an HFE reviewer should evaluate whether and how the CBP designers used this information to define the operators' actions and supplemental information, such as cautions and warnings, figures, and tables. Technical bases for procedures should include the following:

- Results of operational "lessons learned"
- Technical guidelines from owners' group
- Plant-specific technical guidelines
- Deviation documentation
- Results of safety analyses and accident analyses
- Probabilistic risk assessments (PRAs)
- Engineering documents
- Engineering standards applied to the design of the plant
- Design criteria for the plant's components and systems

- Drawings and the specifications applied to designing and constructing the plant
- Records of the basis for, and development of, methods and calculations
- Results of design verification, qualification tests and functional tests
- Operational safety limits and technical specifications
- Expected configuration of plant systems when the procedure (or specific action step) is performed
- Other anticipated conditions of performance
- Documentation of setpoints
- Information on equipment and component labeling
- Information on location of equipment and components

(2) The regulatory bases for procedures should be specified, and the manner in which they were applied in developing the CBPs should be documented.
Discussion: The regulatory bases for the procedures are the requirements and guidelines that affect, constrain or are implemented by the CBPs, including:

- NRC Rules, such as 10 CFR 50.54(m) pertaining to shift-staffing requirements, and 10 CFR 50.47(b) pertaining to emergency plans
- NRC Regulatory Guides and Standards, such as ANS/ANSI 18.7 (ANS, 1981) endorsed in Reg. Guide 1.33, on plant procedures
- NRC guidance documents, e.g., NUREG-0800 (NRC, 1984); NUREG-0711 (O'Hara, Higgins, Stubler, Goodman, Eckenrode, Bongarra, and Galletti, 1994); NUREG-0899 (NRC, 1982), NUREG-1358 and Supplement 1 to NUREG-1358 (Galletti and Sutthoff, 1992); generic communications; and NUREG/CRs
- Any commitments made by the licensee to the NRC that affect the procedures

(3) The management bases for procedures should be documented.
Discussion: The management bases for procedures are plant or site specific:

- The licensee's operational philosophy
- Roles, responsibilities, and authorities assigned to procedure users
- Policies, programs, and plans for managing plant operations that may affect the content or performance of the procedures, such as quality assurance or emergency response
- Requirements for adhering to procedures

- Requirements for independent verification of step completion and accuracy

(4) If the CBPs are to be implemented in an operating plant using PBPs, their impact on existing management bases should be evaluated.
Discussion: If the CBPs are to be installed in an existing plant, designers should obtain information on the management bases from plant personnel. Introducing the CBP system may impact existing licensee programs and procedures, such as operator-licensing training programs, emergency response plans, or the role of senior operations personnel in managing outages. The licensee's management, rather than the CBP designers, should be responsible for determining the impact of CBP design and whether the changes introduced by the CBPs are acceptable or should be revised to conform with existing practices. Those policies, practices, programs, and procedures affected should be revised before implementing the system.

(5) If the CBPs are developed for a generic plant design or for new designs, plans and methods should be specified for incorporating the licensee-specific management bases. Since the specific characteristics of the intended users and their work environments may not be known, the methods by which the CBPs can be tailored for them should be identified.
Discussion: For CBP designs for advanced control rooms, complete bases for the procedures may be unavailable. For example, the plant's Technical Specifications and plant-specific design information may not exist until an advanced reactor is built in the United States or a current licensee decides to install CBPs in an existing control room. A final review of the incorporation of the bases in the CBPs cannot occur until plant- or site-specific information is available.

The management bases for CBPs for a new plant will not be available in a generic design. Therefore, plans and methods for incorporating the management bases for CBPs should be developed by their designers. In addition, when CBPs are being developed for generic designs, the specific characteristics of the intended users and their work environments may not be known; accordingly, designers should include the following provisions for tailoring a CBP design for site-specific applications:

- Any unique aspects of a plant's design (such as characteristics of heat sinks)
- The attributes of the worksite (e.g., ambient noise levels, physical location of required displays and controls)
- The intended users (e.g., operator language, experience levels and types, training, crew size, and roles)

9.8.3 Technical Information

(1) The selection of parameters and indicators of plant state to be monitored at each procedure step should be reviewed.
Discussion: How the CBPs use parameters and plant states will affect the evaluation of procedure steps and use by operators, as well as the system's design. Parameters and indicators of equipment states should be appropriate.

(2) The means by which any the CBPs make the following types of assessments should be completely documented and reviewed by a multidisciplinary team, including plant operators:

- Conditions for entering procedures

- Analysis of step logic
- Assessment of cautions and notes
- Performance of calculations
- Assessment of exit conditions from procedures
- Assessment of high-level procedural goals

Discussion: Underspecifying procedure logic can cause misunderstandings and potential errors in their use. The appropriateness of the analyses must be assured, and the role of operators' judgement accounted for. The exact skills needed on the multidisciplinary team will vary with the scope of the CBP systems. Appendix A of NUREG-0711 lists the range of the broadest skills required; typical ones are those in Subsections 2, 4, 6, 7, 9, and 10; namely, Systems Engineering, I&C Engineering, Human Factors Engineering, Plant Operations, Plant Procedure Development, and Personnel Training.

(3) Procedures should be specifically tailored to the intended users, their physical work environment, and the organization in which the tasks are performed.
Discussion: Some of the information necessary to prepare a procedure can be developed generically by a design organization (e.g., Owners' Group Technical Guidelines for EOPs in current plants). However, lessons learned in the nuclear power and other industries showed that procedures must be specially tailored to fulfill their functions of supporting users' accurate performance, their physical work environment, and the organization in which the tasks are performed. If there is a mismatch, procedures may not be followed, or they may be used in unintended ways. Because procedures also are management tools, mismatches between licensees' management philosophies and the processes defined in procedures can introduce unintended organizational changes or break down existing structures and processes (Barnes et al., 1996).

9.8.4 Maintenance of Procedures

(1) Methods should be specified for assuring that procedure revisions do not introduce technical inaccuracies, or inconsistencies in how the CBPs are presented.
Discussion: CBP designers should provide for maintaining the integrity of the CBPs and their supporting documentation. Because characteristics of users, systems, regulatory requirements, and operational and management practices change over time, methods must be devised to control revisions to the CBPs and any documentation and databases on which they depend. Methods should be specified for assuring that revisions do not lead to technical inaccuracies, or to inconsistencies in how the CBPs are presented. For example, a CBP system may depend upon a database to maintain a list of required setpoints for different conditions and automatically generate setpoint information included in procedure steps. To maintain the integrity of the CBPs if the database is revised, it is critical that the implications of changing any value can be traced and controlled whenever that value appears in procedure steps (Barnes et al., 1996).

(2) Provisions should be made for temporarily changing procedures. Administrative procedures for introducing and handling procedure changes should identify how to properly implement the changes in the CBP system. These changes should be clearly identified in the CBP's interface.

Discussion: It should be very clear to personnel what temporary changes were made and whether an aspect of the procedure being used is a temporary one. Thus, the HSI should support such discriminations (Barnes et al., 1996).

9.9 Training Program Development

(1) The training program should address the role of the operators to assure that they remain in control of the CBP system and independently supervise it.
Discussion: Operators need to understand the overall purpose of a procedure, and should stay cognitively involved with its progress. They should be trained to be in control and to question recommended steps apparently inconsistent with the overall procedure goals (Blackman and Nelson, 1988). While operators need to trust the CBP (Collier, 1996), overreliance on its information can be a concern. For example, while operators using PBPs monitor a variety of plant indications, operators using CBPs may not feel the need to look at other sources of information in the CR and, thus, may miss important indications that are not present in the CBP (O'Hara, Stubler, and Higgins, 1996).

(2) The knowledge, skills, and abilities that users will require to interact successfully with the CBP should be specified by the designers.
Discussion: The demands of CBPs on personnel may be different than those of PBPs (Barnes et al., 1996); designers need to fully analyze personnel requirements so training can address them.

(3) The training requirements for using CBPs should be specified and incorporated into a training program which should cover both initial and ongoing training. Training should consider the design features, functions, and limitations of CBPs (such as the potential for incorrect assessments).
Discussion: Training was identified as critical to CBP use and may require significant changes (NRC CBP Workshop).

(4) The training program should inform operators about limited and complete failures of the CBP. Operators should be trained to determine when to override CBP evaluations and advice. They should be able to manage the transition to PBPs when CBPs are lost and move back to them when system function is restored.
Discussion: Research showed that operators may be reluctant to override the CBP's advice, and may believe the computerized procedure even when it is wrong (Blackman and Nelson, 1988). Operators should be trained on making such judgements, and on what to do when they disagree with the CBP (Jeffroy and Charron, 1997).

(5) The training program should address the importance of teamwork and communication when the CBP is being used.
Discussion: The NRC CBP Workshop and several investigations of CBPs (e.g., Roth and O'Hara, 1998) correlated the importance of the crew's communications and interactions to their reliability; this should be addressed in CBP training.

(6) For CBP systems used for EOPs only, the compatibility with day-to-day operations needs to be evaluated to ensure that the system can be easily understood and used.
Discussion: IAEA (1994) noted that the CBP's compatibility with day-to-day operations needs to be considered. Systems that have very limited use in normal operations and are only used under infrequent special circumstances may have limited success. Thus, they noted that "...this may be an issue for CBP systems that are designed for emergency systems only" (p. 31).

(7) The means by which the CBP will be introduced and implemented in an operating plant should be specified.
Discussion: Spurgin et al. (1990) discussed the gradual introduction of EOPTS at Kuosheng. It was first introduced into the training simulator (1) as an aid to instructors to track the operators' responses to accidents, (2) as a training tool for crews to examine accident-response strategies, and (3) as a tool to be used by crews in responding to accidents. During this time, the correctness of EOPTS was examined, and several errors in the PBPs were discovered. Roth and O'Hara (1998) indicated the importance of the method of implementing the system to the operators' subsequent confidence in it.

9.10 Human Factors Verification and Validation

(1) A verification and validation (V&V) plan should be established.
Discussion: The complexity and formalization of the plan will depend on the scope of the CBP systems. In some cases, it may be part of the overall CBP implementation plan discussed in Section 9.1 (2) above. In others, it should be more formal and extensive. NUREG-0700 and NUREG-0711 give more detailed guidance on V&V plans.

(2) V&V of procedures should ensure that the CBPs are technically correct and usable. Three types of design considerations must be addressed when evaluating their usability: (1) HFE design standards and guidelines for human-computer interaction, (2) HFE design guidelines for the format of text instructions and graphics used in presenting procedural information, and (3) the unique influence of site-specific characteristics and users. The acceptability of a CBP system cannot be determined without documentation that all three types of considerations were acceptably addressed.
Discussion: V&V refers to methods of ensuring that the CBPs are technically correct and usable. The scope, methods, timing, and composition of the V&V team are important to the success of the system. For CBP systems that select the task instructions to be displayed, V&V will be a more complex process than for paper procedures or CBPs that are not integrated with the plant's information display and control systems.

(3) An independent review team should conduct V&V.
Discussion: The NRC's analysis of EOPs (Lapinsky, 1989) noted that the lack of an independent review to assure technical accuracy and usability was associated with procedure deficiencies that may negatively impact the development and use of CBPs; therefore, a CBP development program should provide for independent review. The exact skills needed on the review team will depend on the scope of the CBP systems. Appendix A of NUREG-0711 gives the broadest range of skills likely to be required; typical ones are those in Subsections 2, 4, 6, 7, 9, and 10 – namely, Systems Engineering, I&C Engineering, Human Factors Engineering, Plant Operations, Plant Procedure Development, and Personnel Training.

(4) CBP evaluations should use several crews and scenarios. They also should use operator-in-the-loop evaluations to ensure that the system's objectives are achieved and that any transitions between CBP and PBP are accomplished.
Discussion: For details, see Converse, 1995; EPRI, 1993a; Orvis and Spurgin, 1996.

(5) Each CBP EOP procedure should be evaluated in the plant's simulator.
Discussion: Use of simulation to evaluate CBP systems was identified as an important component of determining their acceptability (EPRI, 1993a).

(6) Operators should be able to detect CBP errors and failures.

Discussion: The NRC CBP Workshop and several investigations of CBPs (e.g., Roth and O'Hara, 1998) identified the importance of crews being able to detect errors and failures of the CBP system.

(7) The V&V should establish that crew performance is not degraded as compared with that reached using PBPs.
Discussion: Teamwork is essential to a defense-in-depth approach to safely operating the plant and any failings can compromise it.

(8) The criteria for accepting the CBP should be specified.
Discussion: The specific criteria by which the CBP will be accepted should reflect considerations of task-performance criteria, such as task time and error rate, determined by analysis, and of criteria based on a comparison to performance with PBP systems.

10 GUIDELINES FOR CBP HFE DESIGN REVIEW

The guidelines in this section follow the characterization of CBP systems discussed in Section 4. They also reflect the findings from our literature review of the effects of CBPs on crew performance, specifically the identification of functions discussed in Section 5.6.2 as reflecting near-term approaches to implementing CBPs. According to the HSI design review procedure described in Part 1 of NUREG-0700, Rev. 1, the first step in a design review is to select a subset of guidelines relevant to the unique aspects of the particular design. There is a wide range of CBP designs, and some may not include all of the characteristics and functions in these guidelines; the reviewer will have to determine, case-by-case, the importance of CBP features that are included in the guidelines but not part of the system being reviewed. This determination should be based on considerations of the specific purposes and goals of that CBP system.

As described in Section 6.2, guidelines were developed from the findings and source materials reviewed in Section 5. These guidelines were constructed in the standard format adopted in NUREG-0700, Rev. 1 (see Section 6.2 of this report), and organized into the following sections:

- Representation of Procedures
- Functionality of Procedures
- Management and Support of Procedures
- CBP Hardware
- CBP Procedure Backup
- Integration of CBPs with Other HSI Components

These new guidelines will be integrated into NUREG-0700, Rev. 1.

Guidelines may specify that some identified aspect of CBPs needs to be "evaluated." NUREG-0700 defines general approaches to methods of evaluation and for identifying criteria. Since the guidance in this section will be incorporated into NUREG-0700, those methods and criteria are not repeated below.

10.1 Representation of Procedures

10.1.1 Identification of Procedures

10.1.1-1 Procedure Title and Identification Information
Each procedure should contain identifying information including title, procedure number, revision number, date, and organizational approval.
ADDITIONAL INFORMATION: This information helps the user establish the appropriate context for using the procedure.
Discussion: This guideline was developed for application to CBPs as an extension of HFE guidance for paper-based procedures, e.g., NUREG-0899 (NRC, 1982), and from lessons learned discussed in Barnes, Desmond, Moore, and O'Hara (1996).

10.1.1-2 High-Level Goals
Each procedure should state its high-level goals and applicability, including its procedure category, e.g., emergency or abnormal.
ADDITIONAL INFORMATION: Information should be given allowing the user to understand the purpose or goal of a series of steps and supporting the user's assessment of the success of the procedure in achieving its safety goal.
Discussion: Procedure objectives need to be emphasized to increase operator's awareness of the high-level goals (Bozec et al., 1990; Wieringa, Moore, and Barnes, 1992). This guideline is an application of the High-Level Design Review Principle of Situation Awareness (see Appendix B).

10.1.2 Basic Steps

10.1.2-1 Concise Steps
Procedure steps should be concise.
ADDITIONAL INFORMATION: Steps should be designed to communicate information clearly and unambiguously so that they can be easily understood and interpreted without error.
Discussion: This guideline was developed for application to CBPs as an extension of HFE guidance for paper-based procedures, e.g., NUREG-0899 (NRC, 1982), and from lessons learned discussed in Barnes, Desmond, Moore, and O'Hara (1996). This guideline is an application of the High-Level Design Review Principle of Simplicity of Design (see Appendix B).

10.1.2-2 Short Sentences
Procedure steps should be written as short sentences.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps.

10.1.2-3 Active Voice
Procedure steps should be written in active voice.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps.

10.1.2-4 Positive Commands
Procedure steps should be written as positive commands.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps.

10.1.2-5 Simple Wording
Short, simple words from standard American English should be used.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps.

10.1.2-6 Standard Punctuation
Punctuation should conform to standard American English usage.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps.

10.1.2-7 Consistent Word References
Words, phrases, and equipment names and numbers should be used consistently within and among procedures, drawings, other HSIs, and equipment labels.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principle of Consistency (see Appendix B).

10.1.2-8 Abbreviations and Acronyms
Abbreviations and acronyms should be used consistently and limited to those well known to the users.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principles of User Model Compatibility and Consistency (see Appendix B).

10.1.2-9 Units of Measures
Numerical information should include units of measure.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps.

10.1.2-10 Numerical Precision
Numbers should be specified at the appropriate precision.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principle of Task Compatibility (see Appendix B).

10.1.2-11 Number Ranges
Ranges of numbers should be specified, rather than error bands.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principles of Situation Awareness, Task Compatibility, and Cognitive Workload (see Appendix B).

10.1.2-12 Use Arabic Numerals
Arabic numerals should be used.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps.

10.1.2-13 Spelled Numbers
Numbers that are spelled out should be consistently spelled under the same conditions.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps.

10.1.2-14 Presentation of Conditional Steps
Conditional steps should be shown in traditional text formats following the guidance in Appendix B of NUREG-0899.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps.

10.1.2-15 Specification of Preconditions for Steps
The procedure should specify any conditions that must be met before an action can be undertaken.
ADDITIONAL INFORMATION: Information about preconditions in the procedure should be located so that users read the information before acting. Information given in other locations may be overlooked, or require additional actions to retrieve it, which may be distracting and time consuming. Further, if conditions are implied, users may easily miss or misinterpret them.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principles of Situation Awareness, Task Compatibility, Timeliness, Feedback, and Response Workload (see Appendix B).

10.1.3 Warnings, Cautions, Notes, and Supplementary Information

10.1.3-1 Parallel Display with Procedure Step
The warnings and cautions applicable to a single step (or to a series of steps) should be displayed when the step(s) is on the screen.
ADDITIONAL INFORMATION: Displaying warnings and cautions at the same time as their associated procedure steps will help ensure that users read the information when they evaluate the step. Information provided elsewhere may be overlooked, or may require retrieval by distracting and time-consuming actions.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principles of Situation Awareness, Timeliness, and Response Workload (see Appendix B).

10.1.3-2 Position Before Action Steps
Warnings, cautions, and notes should be presented so that they will be read before the applicable action steps.
ADDITIONAL INFORMATION: Displaying warnings, cautions, and notes before action steps will help ensure that users will read the information before taking action. Information provided in other places may be overlooked or may be distracting and time consuming to retrieve.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principles of Situation Awareness, Task Compatibility, Feedback, and Timeliness (see Appendix B).

10.1.3-3 Action References
Warnings, cautions, and notes should not include implied or actual action steps.
ADDITIONAL INFORMATION: Actions should be specified in procedure steps only.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principle of Task Compatibility (see Appendix B).

10.1.3-4 Distinction from Other Procedure Elements
Warnings, cautions, and notes should be uniquely presented, so that they are easily distinguished from each other and from other display elements.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principles of Task Compatibility and Organization of HSI Elements (see Appendix B).

10.1.3-5 Supplementary Information
All supplementary information (such as tables and figures) required for a procedure step and available to the CBP should be shown on the screen concurrently with the step, or on another easily viewed display.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principles of Situation Awareness, Task Compatibility, and Response Workload (see Appendix B).

10.1.4 Lists

10.1.4-1 Appropriate Application of Lists
Groups of three or more related items (e.g., actions, conditions, components, criteria, systems) should be presented as a list.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principle of Organization of HSI Elements (see Appendix B).

10.1.4-2 Distinction from Other Procedure Elements
Formatting should be used to differentiate items in a list from other procedure elements.
ADDITIONAL INFORMATION: See additional information in Guideline 10.1.2-1, Concise Steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps.

10.1.4-3 Identification of Precedence
The presence or absence of precedence among items in lists should be indicated.
ADDITIONAL INFORMATION: It should be clear to users whether some items take precedence over others.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principle of Situation Awareness (see Appendix B).

10.1.4-4 List Overviews
Overviews should introduce each list.
ADDITIONAL INFORMATION: An example of an overview is "Ensure that all of the following tests were completed:"
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principle of Situation Awareness (see Appendix B).

10.1.4-5 Assuring Users' Attention
The method for assuring that each item in a list has received the users' attention should be consistent.
ADDITIONAL INFORMATION: For example, an electronic checklist may be provided so that operators can check off items they have attended to. If operators proceed before all items are checked off, the CBP may alert them to the unchecked items.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principle of Task Compatibility (see Appendix B).

10.1.5 Organization of Procedures

10.1.5-1 Hierarchical, Logical Organization
The procedures should be organized in a hierarchical, logical, consistent manner.

ADDITIONAL INFORMATION: Organization will make it easier for users to see the relationships among procedures.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principles of Logical/Explicit Structure and Consistency (see Appendix B).

10.1.5-2 Organization of Procedure Steps
Each procedure should be organized into sections of related steps.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principles of Logical/Explicit Structure and Consistency (see Appendix B).

10.1.6 Formatting and Screen Layout

10.1.6-1 Organization Format of Procedures
The procedure's format should reflect its organization.
ADDITIONAL INFORMATION: Formatting methods to indicate the organization of a procedure may include the use of headings or colors to distinguish parts of the procedure.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principles of Logical/Explicit Structure and Consistency (see Appendix B).

10.1.6-2 Format of Procedures
A consistent format should be used to display procedures.
ADDITIONAL INFORMATION: Whether procedures are presented in text, flowchart, or otherwise, a consistent approach across procedures will facilitate using and moving between multiple procedures.
Discussion: There is insufficient research to specify one format over another for presenting CBPs. Further, it is important that CBPs are consistent with paper procedures. However, whatever format is used, consistency supports the rapid use of information when moving within and between procedures, and enables operators to form expectancies which can reduce the workload of finding information. This will also speed procedure use and reduce errors. This guideline is an application of the High-Level Design Review Principles of Logical/Explicit Structure and Consistency (see Appendix B).

10.1.6-3 Partitioning Procedures
A consistent approach to partitioning procedures should be used.
ADDITIONAL INFORMATION: Partitioning refers to how a procedure is organized to be displayed on the VDU screen. For example, it may be divided into distinct pages, and users would navigate from one to the next. Alternatively, it may be presented as one continuous display that the user scrolls.
Discussion: Unlike PBPs, CBPs are viewed through the limited display area of one or more VDUs. Thus, regardless of format, the designer must decide whether the procedure will appear as a continuous scrollable display or be divided into discrete pages. This guideline is an application of the High-Level Design Review Principles of Task Compatibility, Logical/Explicit Structure, and Consistency (see Appendix B).

10.1.6-4 Organization of Display Screen
Each display screen should locate information and HSI features consistently.
ADDITIONAL INFORMATION: When the information and features, such as procedure steps, controls, and navigation aids are consistently located, users' performance improves because expectations can guide the search for information, and reduce the time and workload associated with finding it.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principles of Logical/Explicit Structure and Consistency (see Appendix B).

10.1.6-5 Continuously Presented Procedure Information
The procedure's title and identification should be continuously presented.
ADDITIONAL INFORMATION: This information helps set the context for the overall procedure within which its steps are interpreted. It is especially important when more than one procedure can be open at one time.
Discussion: One concern identified with CBP systems is the loss of awareness of the context in which procedures are used, e.g., high-level safety goals and plant status (NRC CBP Workshop; Roth and O'Hara, 1998; Spurgin et al., 1990). The identifying information maintains focus on the way in which individual steps are interpreted, especially when multiple procedures are in use. This guideline is an application of the High-Level Design Review Principle of Situation Awareness (see Appendix B).

10.1.6-6 Continuously Presented Status of High-Level Goals
The status of high-level procedure goals should be continuously presented.
ADDITIONAL INFORMATION: This information helps set the overall context in which procedure steps are interpreted. Continuous presentation of high-level goal status, such as status of critical safety functions, will facilitate users' awareness of them, particularly when more than one procedure is open simultaneously.
Discussion: The loss of awareness of the context in which procedures are used, e.g., high-level safety goals and plant status is a concern with CBPs (NRC CBP Workshop; Roth and O'Hara, 1998; Spurgin, et al. 1990). Awareness of high-level goals is important to interpreting individual steps and for determining which procedure is appropriate. Roth and O'Hara (1998) also observed that the most significant series of information needed by operators on loss of the CBP was critical safety function status. This guideline is an application of the High-Level Design Review Principles of Situation Awareness and Timeliness (see Appendix B).

10.2 Functionality of Procedures

10.2.1 Supervision and Control of Procedures

10.2.1-1 Users' Control of Procedure Path
Users should be in control of the sequence of steps that are followed.
ADDITIONAL INFORMATION: Most procedures have specifically defined steps that have to be performed sequentially, and others that can be varied at the operator's discretion; CBPs should identify which one is applicable. However, operators should have the flexibility to move around within the procedure, so that they can check and make verifications.
Discussion: The CBP guidance level should leave the operators in the loop so they retain control and are the final authority (EPRI, 1993a; Dien et al., 1991). This guideline is an application of the High-Level Design Review Principles of Cognitive Compatibility and Situation Awareness (see Appendix B).

10.2.1-2 Users' Control of Pace of Procedures
Users should be in control of the pace at which procedure steps are followed.
ADDITIONAL INFORMATION: Operators need to maintain situation awareness of procedure-related decisions. To accomplish this, they must be in control of the pace at which steps are followed.
Discussion: The operator should retain control and should be the final authority (EPRI, 1993a; Dien et al., 1991). This guideline is an application of the High-Level Design Review Principles of Cognitive Compatibility and Situation Awareness (see Appendix B).

10.2.1-3 Understandability of Analysis of Procedure Steps
The methods by which CBPs analyze procedure steps should be consistent with the methods by which users analyze steps in procedure logic steps, so that the results are understandable.
ADDITIONAL INFORMATION: Users must be able to judge the acceptability of the CBP's advice and recommendations.
Discussion: To maintain their role of system supervisors, operators need to be able to understand and evaluate the appropriateness of procedure analyses. The CBP should not require the operator to conform to its method of analysis (Bernard, 1989). This guideline is an application of the High-Level Design Review Principles of Task Compatibility and Situation Awareness (see Appendix B).

10.2.1-4 Users' Verification of CBP Information
The users should be able to verify the system's assessment of plant status.
ADDITIONAL INFORMATION: This verification includes process parameters, equipment status, analysis of procedure step logic, and evaluation of cautions. Any analysis done by the CBP should be accessible to users for review.
Discussion: To maintain their role of system supervisors, operators need to be able to access information enabling them to determine the appropriateness of procedure information. This guideline is an application of the High-Level Design Review Principles of Task Compatibility and Situation Awareness (see Appendix B).

10.2.1-5 Users' Override of CBP
Users should be able to override any CBP information, calculation, evaluation, or assessment.
Discussion: Operators should be able to override a course of action suggested or recommended by a CBP system. This is necessary for situations in which the operator has access to information that is not available to the CBP, the CBP's guidance is too strict, or when the CBP uses out-of-date in formation (Bozec et al., 1990). This guideline is an application of the High-Level Design Review Principles of Cognitive Compatibility and Situation Awareness (see Appendix B).

10.2.2 Monitoring and Assessment of Procedures

10.2.2-1 Automatic Identification of Procedures
The CBP should alert users when entry conditions to a procedure are satisfied.
ADDITIONAL INFORMATION: This capability will help users determine the appropriate procedures for the existing plant situation.
Discussion: This capability was identified as being beneficial to crew reliability (Orvis and Spurgin, 1996). This guideline is an application of the High-Level Design Review Principles of Situation Awareness and Cognitive Workload (see Appendix B).

10.2.2-2 Automatic Monitoring of Plant Parameters and Equipment Status
The CBP should automatically provide accurate and valid information on the values of parameters and status of equipment, when they are available to the system.
ADDITIONAL INFORMATION: It should be clear to operators what specific information is used as the source of these actual values and states.
Discussion: Supporting cognitive functions, such as obtaining parameter values (monitoring) may reduce the demands on attentional resources and working memory and enable the operator to focus more on evaluating higher-level procedure goals. It may also help solve PBP issues. This capability was identified as being beneficial to the crew's reliability (Orvis and Spurgin, 1996; Pirus and Chambon, 1997; Niwa et al., 1996). Further, presenting plant parameters and status in procedure steps is a URD requirement

(EPRI, 1993a). This guideline is an application of the High-Level Design Review Principles of Situation Awareness and Cognitive Workload (see Appendix B).

10.2.2-3 Frequent Monitoring
The CBP should frequently monitor procedure-defined parameters.
ADDITIONAL INFORMATION: Frequent monitoring, such as twice a second, promptly notifies users of status changes.
Discussion: The continuous updating of plant parameters and status is identified as a URD requirement (EPRI, 1993a). This guideline is an application of the High-Level Design Review Principles of Situation Awareness, Cognitive Workload, and Timeliness (see Appendix B).

10.2.2-4 Automatic Calculation of Procedure-Referenced Values
The system should undertake calculations, such as subcooling margin, that are required when using procedures.
Discussion: The capability to perform calculations was identified as an important feature of CBPs (Roth and O'Hara, 1998; Barnes et al., 1996). This guideline is an application of the High-Level Design Review Principle of Cognitive Workload (see Appendix B).

10.2.2-5 Analysis of Step Logic
The CBP should evaluate the logic of each procedure step and show the results to the user.
ADDITIONAL INFORMATION: Procedure steps often contain logical relationships; for example, actions are to be performed if an identified set of conditions exists. The analysis of these logical relationships must be carefully verified to avoid underspecification. This occurs when the logic used to resolve a procedure step is too simplified, and does not address all of the considerations that operators do when evaluating the step.
Discussion: Supporting cognitive functions, such as comparing actual parameter values to reference values (resolution of procedure step logic) may reduce the demands on attentional resources and working memory, and enable the operator to focus on evaluating high-level procedure goals. This CBP capability was identified as a major benefit and one which helped operators to follow the procedures correctly, and to interpret the logical statements that are a part of the procedure steps (Spurgin et al., 1990). It also was thought to improve the crew's reliability (Orvis and Spurgin, 1996; Moieni and Spurgin, 1993b). This guideline is an application of the High-Level Design Review Principles of Situation Awareness and Cognitive Workload (see Appendix B). However, while this is a potentially powerful feature, it must be used cautiously. Some procedural details are intentionally left relatively abstract because they require the operator's judgement on the basis of local knowledge; e.g., knowledge of equipment availability and status at the current time. While computerization can increase the detail, this could inadvertently change the procedure's context and the operator's interpretation of it. Thus, underspecification of the logic can be an issue (O'Hara, Stubler, and Higgins, 1996; Roth and O'Hara, 1998). Further, the CBP is not fully aware of what operators are doing nor of their intentions (Blackman and Nelson, 1988).

10.2.2-6 Continuous Analysis of Non-Current Step Logic
Steps of continuous applicability, time-dependent steps, and process-dependent steps should be monitored by the CBP and the user should be alerted when conditions in those steps become effective.
ADDITIONAL INFORMATION: The analysis must be carefully verified to avoid underspecifying its logic. The alert should not automatically remove the user's current display. Instead, it should be presented as a supplemental display or as an alert.
Discussion: See discussion of the previous guideline. In addition, operators prefer that procedures not automatically reset or return to a previous step when there is a change in process status; instead automatic

monitoring of previous steps and indications of a change in their status is preferred (Bozec et al., 1990). This guideline is an application of the High-Level Design Review Principles of Situation Awareness and Cognitive Workload (see Appendix B).

10.2.2-7 Coding of Logical Analysis
When procedure's step logic indicates a violation of the step, the information should be coded to make that step more salient to users.
Discussion: Handling of multiple procedures is easier when the relevant information in each is highlighted. When operators transition from one to another, the highlighted information directs them to the appropriate location (Pirus and Chambon, 1997). This guideline is an application of the High-Level Design Review Principle of Situation Awareness (see Appendix B).

10.2.2-8 Analysis of Cautions
The conditions described in cautions should be automatically monitored by the CBP system, and the user should be alerted when the caution is in effect.
ADDITIONAL INFORMATION: Evaluating cautions and alerting users to their applicability will ensure that users will read the information at the appropriate time, and reduce the chance that it may be overlooked. The conditions for cautions must be established with care such that the logic is not underspecified.
Discussion: Supporting cognitive functions, such as monitoring caution conditions and comparing their reference values, may reduce the demands on attentional resources and working memory and enable the operator to attend more to the higher-level procedure goals. Alerting operators to applicable cautions will help ensure that they are not overlooked. This guideline is an application of the High-Level Design Review Principles of Situation Awareness and Cognitive Workload (see Appendix B).

10.2.2-9 Coding Applicable Cautions
CBPs should use coding to indicate when a caution is in effect.
ADDITIONAL INFORMATION: Coding techniques, such as color coding, may be used to enhance the salience of important information.
Discussion: This guideline is an application of the High-Level Design Review Principle of Situation Awareness (see Appendix B).

10.2.2-10 Users' Acknowledgment of Procedure Analyses
Users should make some form of acknowledgment of procedure steps and recommendations for terminations and transitions.
ADDITIONAL INFORMATION: As an example, operators may acknowledge that a step is satisfied by depressing the "Return" key, or clicking on an onscreen acceptance button. Such acknowledgment helps the operators to maintain awareness of the procedure's status.
Discussion: The CBP guidance level should leave the operator in the loop, so they retain control and are the final authority (EPRI, 1993a; Dien et al., 1991). This guideline is an application of the High-Level Design Review Principles of Cognitive Compatibility and Situation Awareness (see Appendix B).

10.2.2-11 Identification of User Input Requirements
The CBP should provide users with clear, timely indications when they need to input any information not available to it.
ADDITIONAL INFORMATION: CBPs may rely on users to for process parameter values, equipment status (such as whether a valve is open or closed), analyses of logic steps where users' judgement is involved, or to assess any conditions not within the capability of the CBP.

Discussion: While the CBP monitors the system through the I&C, operators must provide some information. Failures to do so can lead to incorrect assessments and guidance from the CBP (Jeffroy and Charron, 1997). This guideline is an application of the High-Level Design Review Principles of Logical/Explicit Structure and Timeliness (see Appendix B).

10.2.2-12 Adjustable Level of Detail
Users should be able to choose the level of detail with which procedures are presented.
ADDITIONAL INFORMATION: While plant practices on using procedures may be specified by management, there may be flexibility in the level of detail that can be provided. For example, users may want less detail when a procedure step is satisfied. Alternatively, a user may choose to see all of the individual evaluations leading to the conclusion that the step was satisfied. This must be done with care so that it does not affect the interpretation of procedure information. Also, users should be trained as to how and when to vary levels of detail.
Discussion: Procedural guidance can be used more efficiently when CBPs can adjust the level of detail for operators with varying familiarity with the tasks, components, systems, and processes defined in the procedures. This may also help address a deficiency of PBPs. It was identified as a desirable feature of CBPs by many studies (NRC CBP Workshop; Dien et al., 1991). However, providing too much detail should be avoided (Bozec et al., 1990; Roth and O'Hara, 1998), especially for experienced operators (Niwa et al., 1996). This guideline is an application of the High-Level Design Review Principles of Flexibility (see Appendix B).

10.2.2-13 Context-Specific Guidance
Procedure guidance should be context sensitive where possible.
ADDITIONAL INFORMATION: For example, the CBP system should not indicate an action to start a pump when it can determine that the pump is already running.
Discussion: A general problem observed with COSSs is that the information is "acontextual," i.e., their guidance had little reference to the current situation (Dien and Montmayeul, 1995). For CBPs, this problem can be corrected by supporting procedure sensitivity to the current situation (Niwa et al., 1996). Removing information inappropriate to the current situation and which is, therefore, potentially distracting and uses up valuable time, will help operators to concentrate on important information. This guideline is an application of the High-Level Design Review Principles of Cognitive Compatibility and Situation Awareness (see Appendix B).

10.2.2-14 Assessment of High-Level Goal Status
The CBP should continuously assess and present the status of higher-level safety goals, such as critical safety functions, and alert the user to any challenges.
Discussion: Supporting cognitive functions, such as comparing parameter values to goal-reference values, may reduce the demands on attentional resources and working memory and enable the operator to better attend to determining the success of the procedure in achieving the higher-level goals. Alerting operators to possible challenges will help ensure that they will not be overlooked. The availability of safety-goal status is important to operators' overall assessment of the procedure (Roth and O'Hara, 1998). This guideline is an application of the High-Level Design Review Principles of Situation Awareness and Cognitive Workload (see Appendix B).

10.2.2-15 Assessment of Conditions Terminating a Procedure
The CBP should automatically identify when conditions are met for transitioning or exiting from a procedure.

ADDITIONAL INFORMATION: This capability will help users determine when procedures they are using are no longer appropriate for the existing situation.
Discussion: By helping users determine when procedures become inappropriate for the existing situation, the chances of operators delaying actions identified in the appropriate procedure are reduced. This guideline is an application of the High-Level Design Review Principles of Situation Awareness and Cognitive Workload (see Appendix B).

10.2.3 Monitoring Users' Actions

10.2.3-1 Monitoring Users
User responses to procedures should be monitored and recorded by the CBP.
ADDITIONAL INFORMATION: Monitoring information on users' input to information requested by the procedure and their subsequent actions is necessary if the CBP is to properly assess appropriate procedural pathways.
Discussion: CBPs should be designed to maintain information on what the crew is doing that is relevant to implementing the procedure (Blackman and Nelson, 1988). To evaluate procedure steps the operators must be aware of the information being analyzed by the CBP. To the extent that the CBP system has information on users' actions, it can perform this task more effectively.

10.2.3-2 Alert Users to Deviations in Procedure
Users should be alerted if their input is incorrect, or when their actions are not consistent with CBP evaluations.
ADDITIONAL INFORMATION: The alert should be advisory and not discourage the user's actions. This feature must be supported with training, so users are not reluctant to go against the CBP's evaluations.
Discussion: EPRI suggested that CBPs should have software to verify the operators' decisions. While the operator should retain control and authority as to how to proceed, disagreements should be logged automatically (EPRI, 1993a). Alerting crews to possible unintentional deviations from the procedure was identified as a potential improvement to the crew's reliability by enabling them to recover from mistakes (Orvis and Spurgin ,1996; Moieni and Spurgin, 1993b) and to catch "local" errors (Jeffroy and Charron, 1997). Other studies also identified this as a desirable CBP feature (NRC CBP Workshop). By alerting operators, they can decide if that is what they want to do (Pirus and Chambon, 1997). This guideline is an application of the High-Level Design Review Principles of Error Tolerance in Control, Feedback, and Situation Awareness (see Appendix B). However, care must be taken to assure that operators are not reluctant to deviate from the CBP. As Jeffroy and Charron (1997) noted, there are situations where operators may disagree with the CBP's recommendations and may find it hard to disagree with the procedures, especially when the level of detail in the CBP is high.

10.2.4 Planning and Implementation

10.2.4-1 Display of Action Status
The status of procedure-related actions should be displayed by the CBP.
Discussion: This feature is a potential improvement to crew reliability (Orvis and Spurgin, 1996). This guideline is an application of the High-Level Design Review Principles of Situation Awareness and Feedback (see Appendix B).

10.2.4-2 Timing of Procedures
The CBP's timing, such as status update rates, screen changes, and navigation features, should be consistent with the time demands of the task.
Discussion: The timing of CBP responses affects operators' performance. Spurgin et al. (1990) indicated that an SRO requested ADS initiation twice thinking it had not been presented after the first request; the misunderstanding was due to the delay in the CBPs update of ADS status (Spurgin et al., 1990). This guideline is an application of the High-Level Design Review Principles of Timeliness and Feedback (see Appendix B).

10.3 Management and Support of Procedures

10.3.1 Path Monitoring

10.3.1-1 Monitoring Step Status
There should be an indication of whether or not a step was completed.
ADDITIONAL INFORMATION: The indication can be manual or automatic, depending on whether the CBP has the specific criteria and information to determine this.
Discussion: CBPs can keep track of what steps have been completed, using check boxes. This can be manual or automatic, depending on whether the CBP has the specific criteria and information to determine whether a step was completed. Completion also can be time stamped to facilitate post-hoc incident analysis (Niwa, Hollnagel, and Green, 1996). This guideline is an application of the High-Level Design Review Principles of Cognitive Workload and Situation Awareness (see Appendix B).

10.3.1-2 Alert User to Incomplete Procedure Steps
Users should be alerted to incomplete procedure steps.
ADDITIONAL INFORMATION: The alert should be advisory and not discourage the crew's actions.
Discussion: CBPs should monitor whether procedure steps were not fully completed and notify the crew if further action is needed (Orvis and Spurgin, 1996; Moieni and Spurgin, 1993b). This guideline is an application of the High-Level Design Review Principles of Error Tolerance in Control, Feedback, and Situation Awareness (see Appendix B).

10.3.1-3 Coding Current Location
The current procedure step(s) should be indicated.
Discussion: Automatic place keeping is a CBP feature that can improve the crew's reliability (Orvis and Spurgin, 1996), especially when using multiple procedures. This guideline is an application of the High-Level Design Review Principle of Cognitive Workload (see Appendix B).

10.3.1-4 Automatic Path Monitoring
The pathway taken through procedures should be stored and made available to users.
ADDITIONAL INFORMATION: A history should be maintained and available for display on request. Step completion can be time stamped to facilitate post-hoc incident analysis (Niwa, Hollnagel, and Green, 1996).
Discussion: CBPs can keep track of what steps have been completed; this can be manual or automatic depending on whether the CBP has the specific criteria and information to make this determination (Niwa, Hollnagel, and Green, 1996). This guideline is an application of the High-Level Design Review Principle of Cognitive Workload (see Appendix B).

10.3.1-5 Indication of Multiple Active Procedures
The user should be informed when multiple procedures or multiple procedure steps are to be followed concurrently. A list of all currently active procedures should be available.
ADDITIONAL INFORMATION: It may be helpful for the list of active procedures to include start and stop times for the procedures in use.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps. This guideline is an application of the High-Level Design Review Principle of Cognitive Workload (see Appendix B).

10.3.2 Navigation

10.3.2-1 Flexible Navigation
Navigation support should allow users to freely and easily move between procedure steps, to other parts of the same procedure, and to other procedures.
ADDITIONAL INFORMATION: Users should not be forced to access procedures in a fixed sequence of the procedure nor should their access to supporting information be limited. (See also the additional information on Guideline 10.2.1-1.)
Discussion: Navigation within one procedure, or among multiple procedures and related supporting information, can be time consuming and error prone (O'Hara, Stubler, and Higgins, 1996). Collier (1996) noted that the CBP system should not overly structure the operator's movement through the procedure but should offer flexibility for operators to skip steps or skim over them quickly. Operators need to move easily between procedures and support information (Niwa, Hollnagel, and Green, 1996), in part to make up for the insufficiencies of procedures (Dien et al., 1991). In addition, flexibility improves the crew's reliability (Orvis and Spurgin, 1996). This guideline is an application of the High-Level Design Review Principles of Response Workload and Flexibility (see Appendix B).

10.3.2-2 Support Parallel Access to Information
The CBP should have the ability to access more than one piece of information at once.
Discussion: Hoecker et al. (1994) and Hoecker and Roth (1996) found that the workload associated with CBPs can increase when the operators cannot access needed information in parallel. Similarly, CBPs can significantly improve the crew's performance in comparison with PBPs if they allow simultaneous access to multiple procedures (Wilhelmsen et al., 1992). This guideline is an application of the High-Level Design Review Principles of Cognitive Workload and Response Workload (see Appendix B).

10.3.2-3 Navigational Links to Related Information
Navigational links to cross-referenced information and to notes, cautions, warnings, reference material, and communication and help facilities should be provided.
ADDITIONAL INFORMATION: Techniques such as hyperlinks can expedite navigation to information material cross-referenced in a procedure or its supporting material.
Discussion: Navigation to and from cross-referenced material can be time consuming, distracting, and error prone. Computer support for these transitions can reduce the workload associated with these tasks. This guideline is an application of the High-Level Design Review Principles of Response Workload and Flexibility (see Appendix B).

10.3.2-4 Access to Contingency Actions
Users should be able to easily access appropriate contingency actions.
Discussion: See discussion for Guideline 10.1.2-1, Concise Steps.

10.3.3 Help

10.3.3-1 Explanation Facilities
CBPs should have facilities to enable the user to determine how CBP functions are performed.
ADDITIONAL INFORMATION: When CBPs support users' decision making, such as offering advice on how to select procedures, analyze step logic or follow procedure paths, users should be able to query the basis for the advice. Cooperative dialogue enables the user to better understand and utilize the system.
Discussion: In general, COSSs often are not designed to be sufficiently observable. That is, they do not clarify their reasoning basis, nor have adequate communication facilities to enable operators to question and verify system performance. Guidance may be given without sufficient communication about what led to its issuance, what parameters were analyzed, and what sequence of reasoning was followed. When the reasoning process is shown, it may conflict with that of the operators, i.e., it may be based on the designer's theoretical understanding and not the operators' practical experience (Dien and Montmayeul, 1995; IAEA, 1994; Malin et al., 1991a; Roth, Bennett, and Woods, 1987). Explanations of the rationale for procedure steps have been identified as a necessary CBP feature (Niwa et al., 1996). This guideline is an application of the High-Level Design Review Principle of User Guidance and Support (see Appendix B).

10.3.3-2 Help Facilities
Help for performing procedure specified activities should be provided.
Discussion: Information should be given to help operators carry out procedure steps. For example, a help facility could provide information as to how a control action should be carried out (Niwa, Hollnagel, and Green, 1996). This guideline is an application of the High-Level Design Review Principle of User Guidance and Support (see Appendix B).

10.3.3-3 Note Taking
There should be a way for users to record their notes and comments in the CBP.
Discussion: Procedures have gaps because they do not cover all possible situations and actions. CBPs can help eliminate them by allowing operators to log omissions in an on-line database which then could be accessed to identify improvements to the procedure (NRC CBP Workshop). This guideline is an application of the High-Level Design Review Principle of Response Workload (see Appendix B).

10.4 CBP Hardware

Guidance for CBP hardware, including VDUs, printers, computer input devices, is part of the CBP review, and is available in NUREG-0700. An additional consideration is discussed below.

10.4-1 Number of VDUs
The number of VDUs on which CBP information is displayed should be sufficient to provide all the procedure-related information needed for a procedure step, including cautions and reference material.
Discussion: VDUs can create a keyhole effect and the requirement for potentially distracting interface management tasks. This guideline is an application of the High-Level Design Review Principles of Situation Awareness and Task Compatibility (see Appendix B).

10.5 Backup for CBP Procedures

10.5-1 Paper-Based Procedure Availability
PBPs should be available in the event of CBP failure.
Discussion: PBPs will enable operators to perform safety-related tasks in situations where the CBP system is malfunctioning or has failed. This guideline is an application of the High-Level Design Review Principle of Error Tolerance and Control (see Appendix B).

10.5-2 Consistency of PBPs and CBPs
The content and presentation of procedure information in PBPs and CBPs should be consistent.
ADDITIONAL INFORMATION: Smooth transfer between CBPs and PBPs and vice versa will be facilitated by the degree to which their formatting is consistent; this also will facilitate training in procedure use.
Discussion: The hard-copy procedures should be consistent in format and content with the CBPs. EPRI noted that their consistency will minimize the training burden and lower the potential for errors and misunderstandings. This consideration is especially important when the hard-copy procedures have to be used as a backup (EPRI, 1993a). This guideline is an application of the High-Level Design Review Principles of Consistency and Error Tolerance and Control (see Appendix B).

10.5-3 Support for Transfer to PBPs
Upon transfer to PBPs, a means should be provided to support the user's determination of currently open procedures, location in the procedures, completed and not completed steps, and currently monitored steps.
ADDITIONAL INFORMATION: When the CBP is lost, it may be difficult for operators to reconstruct this information from memory. Therefore, the operator should be supported in making a safe, easy transition. For example, a CBP system might automatically print out a status sheet with this information once every minute so that if it fails, the operator can retrieve the latest sheet and use it to establish the crew's tasks for using PBPs.
Discussion: Operators may be in multiple procedures when the CBP fails. For each, the CBP may have been monitoring progress, monitoring and evaluating steps of continuous applicability and other steps in the background. Providing these supports is one of the CBP benefits that reduce the operators' cognitive workload in remembering this information. When the CBP is lost, it may be difficult for operators to reconstruct this information from memory. Therefore, some means should be provided to support this transfer. This guideline is an application of the High-Level Design Review Principles of Cognitive Workload and Error Tolerance and Control (see Appendix B).

10.6 Integration of CBPs with Other HSI Components

10.6-1 Consistency with Other HSI Conventions
The detailed CBP design should be fully consistent with the rest of the HSI.
ADDITIONAL INFORMATION: HSI features for format and functionality (such as labeling, acronyms, dialog conventions, use of colors, and input devices) should be consistent between the CBP and other HSI components. Consistency may be a special consideration when reviewing "off-the-shelf" systems.
Discussion: Lack of consistency between CBPs and the other HSI resources was identified as an important consideration (NRC CBP Workshop). Any such inconsistency can degrade the operator's performance and increase the likelihood of errors. Thus, inconsistency was identified as a potential source of risk and reduced performance reliability (Niwa et al., 1996). This guideline is an application of the High-Level Design Review Principle of Consistency (see Appendix B).

APPENDIX A

Human Factors Engineering Program Review Model (NUREG-0711) Element 8: Procedure Development

(This appendix reflects the Element 8 changes that will be made in Revision 1 to NUREG-0711)

ELEMENT 8: PROCEDURE DEVELOPMENT

A.1 Background

In the nuclear industry, the development of procedures historically was considered the responsibility of individual utilities, but the rationale for including a procedure development element in NUREG-0711 is that procedures are an essential component of the HSI design, and should be derived from the same design processes and analyses as other HSIs (e.g., displays, controls, operator aids) and evaluated in the same way. Technically detailed, emergency operating procedures (EOPs) were an improvement instituted after the accident at Three Mile Island (TMI) to support safe operations. First, the NPP owners groups developed generic technical guidance (GTG) and utilities then produced EOPs based on the GTG. Thus, procedure development programs were conducted by the individual utilities and were not part of HSI design activities. However, since procedures were developed after the design of the plant HSI (e.g., control room), they were essentially retrofitted to suit the existing interface. Further, since they were established by individual utilities, their development and final implementation varied greatly. As a result, human factors problems existed, and the identification, access, interpretation, and validation of procedures remained troublesome for years in several plants, as shown by the NRC EOP inspection series (Lapinsky, 1989; Galletti and Sutthoff, 1992). In addition, inconsistencies between procedures and the HSI have been a source of difficulty for operators.

For new plant designs and advanced reactors, these problems should clearly be addressed and solved during the design process. To accomplish this objective, GTG and, if possible, procedures should be developed as part of the same design process as that for other components of the HSI to ensure their full integration into the HSI. The same human factors analyses, such as task analysis, should be used to guide the design of the control panel, as well as procedure development. The same human factors principles should be applied to both aspects of the interface to ensure complete integration and consistency. Further, procedures should be evaluated in conjunction with the HSI; procedures are a significant aspect of system verification and validation (Element 10).

A.2 Objective

The objective of this review is to ensure that the applicant's procedure development program will result in procedures that guide human interactions with plant systems and control plant-related events. Human engineering principles and criteria should be applied, along with all other design requirements, to develop technically accurate, comprehensive, explicit, easy to utilize, and validated procedures.

A.3 Applicant Submittals

The applicant should provide the following documents for staff review: implementation plan, analysis-results report, and HFE design team evaluation report. Section 1.4.4 (of NUREG-0711) describes these submittals.

In addition, GTG and draft procedures should be available for review.

A.4 Review Criteria

(1) The following procedures are within the scope of the element:

- GTG for EOPs

- Plant and system operations (including startup, power, and shutdown operations)
- Abnormal and emergency operations
- Preoperational, startup, and surveillance tests
- Alarm response

(2) The basis for procedure development should include:

- Plant design bases
- System-based technical requirements and specifications
- Results of task analyses
- Risk-important human actions identified in the HRA/PRA
- Initiating events to be considered in the EOPs, including those events in the design bases
- GTG for EOPs

(3) A writer's guide should be developed to establish the process for developing technical procedures that are complete, accurate, consistent, and easy to understand and follow. The guide should contain sufficiently objective criteria so that resulting procedures are consistent in their organization, style, and content. The guide should be used for all procedures within the scope of this element. It should provide instructions on the procedures' content and format, including writing action steps and specifying acceptable acronym lists and terms.

(4) The content of the procedures should incorporate the following elements:

- Title
- Statement of applicability
- References
- Prerequisites
- Precautions (including warnings, cautions, and notes)
- Limitations and actions
- Required human actions
- Acceptance criteria
- Checkoff lists

(5) In addition to the general procedure elements identified in Criterion 4 above, GTG should be symptom based with clearly specified entry conditions.

(6) All procedures should be verified and validated; a review should ensure they are correct and can be carried out. They should be finally validated in a simulation of the integrated system, as part of the verification and validation activities described in Element 10.

(7) An analysis should determine the impact of providing computer-based procedures, CBPs, (either partial or complete) and specify where such an approach would improve the use of procedures and reduce related errors by the operating crew. Justification for using CBPs rather than paper procedures should be given. An analysis should be made and documented of alternatives in the event of loss of CBPs.

(8) A plan for maintaining procedures and controlling updates should be developed.

(9) The physical means by which operators access and use procedures, especially during operational events, should be evaluated as part of the HFE design process. This criterion generally applies to both hard-copy and computer-based procedures, although the types of issues differ somewhat for them. For example, the process should address the storage of procedures, ease of operator access to the correct procedures, and laydown of hard-copy procedures for use in the control room, remote shutdown facility, and local control stations.

(10) The following documents may be used as guidance (per Section 1.4.4):

NUREG-0800, Rev. 1: *Standard Review Plan*, 1984 (NRC).

NUREG-0899: *Guidelines for the Preparation of Emergency Operating Procedures*, 1982 (NRC).

NUREG-1358: *Lessons Learned From the Special Inspection Program for Emergency Operating Procedures*, 1989 (NRC).

NUREG-1358: *Lessons Learned From the Special Inspection Program for Emergency Operating Procedures*, Supplement 1, 1989 (NRC).

NUREG/CR-5228: *Techniques for Preparing Flowchart Format Emergency Operating Procedures*, Volumes 1 and 2, 1989 (NRC - Barnes et al.).

NRC Regulatory Guide 1.33, Rev. 2: *Quality Assurance Program Requirements*, 1978 (NRC).

ANS 3.2-1994: *Administrative Controls and Quality Assurance for the Operational Phase of NPPs*, 1994 (American Nuclear Society).

BNL TR E2090-T4-2-9/96: *Preliminary Review Criteria for Evaluating Computer-Based Procedures*, 1996 (Barnes et al.)

APPENDIX B

High-Level Design Review Principles from NUREG-0700, Rev. 1

HIGH-LEVEL DESIGN REVIEW PRINCIPLES FROM NUREG-0700

The design of human-system interfaces (HSIs) should support the operating personnel's primary task of monitoring and controlling the plant, without imposing an excessive workload associated with using the HSI (manipulating windows, selecting displays, and navigating, for example). The HSI also should support the recognition, tolerance, and recovery from any human errors. Guidelines for reviewing human factors engineering designs help to ensure that these goals are achieved. As part of the guidance development for NUREG-0700, Rev. 1, a set of "high-level" design review principles was developed representing the generic HSI characteristics necessary to support personnel performance. They were used to develop many detailed review guidelines in Part 2 NUREG-0700 (O'Hara, Brown, and Nasta, 1996 discuss their use). The high-level principles also were used in formulating guidelines for computer-based procedures.

The 18 principles are divided into four categories: general principles, primary task design, secondary task control, and task support. The categories and the principles that underlie them are described below.

B.1 General Principles

These principles ensure that the HSI design supports personnel safety, and is compatible with their general cognitive and physiological capabilities.

- *Personnel Safety* – The design should minimize the potential for injury and exposure to harmful materials.

- *Cognitive Compatibility* – The operators' roles should consist of purposeful, meaningful tasks that enable them to maintain familiarity with the plant and maintain a level of workload that is not so high as to lower performance, but sufficient to maintain vigilance.

- *Physiological Compatibility* – The design of the interface should reflect consideration of human physiological characteristics, including visual/auditory perception, biomechanics (reach and motion), characteristics of motor control, and anthropometry.

- *Simplicity of Design* – The HSI should represent the simplest design consistent with function and task requirements.

- *Consistency* – There should be a high degree of consistency between the HSI, the procedures, and the training systems. At the HSI, the way the system functions and appears to the operating crew always should be consistent, reflect a high degree of standardization, and be fully consistent with procedures and training.

B.2 Primary Task Design

These principles support the operator's primary tasks of monitoring and detection, situation assessment, response planning, and response implementation.

- *Situation Awareness* – The information presented to the users by the HSI should be correct, rapidly recognized, and easily understood (e.g., "direct perception" or "status at a glance" displays) and support the higher-level goal of their awareness of the system's status.

- *Task Compatibility* – The system should meet the requirements of users in performing their tasks (including operation, safe shutdown, inspection, maintenance, and repair). Data should be presented in forms and formats appropriate to the task (including the need to access confirmatory data or raw data in the case of higher-level displays), and control options should encompass the range of potential actions. There should be no unnecessary information or control options.

- *User Model Compatibility* – All aspects of the system should be consistent with the users' mental models (understanding and expectations about how the system behaves from training, use of procedures, and experience). All aspects of the system also should be consistent with established conventions (i.e., expressed in customary, commonplace, useful and functional terms, rather than abstract, unusual or arbitrary forms, or in forms requiring interpretation).

- *Organization of HSI Elements* – The organization of all aspects of the HSI (from the elements in individual displays, to individual workstations, to the entire control room) should be based on the users' requirements and should reflect the general principles of organization by importance, frequency, and order of use. Critical safety function information should be available to the entire operating crew in dedicated locations to ensure its recognition, and to minimize data search and response.

- *Logical/Explicit Structure* – All aspects of the system (formats, terminology, sequencing, grouping, and operator's decision-support aids) should reflect an obvious logic based on task requirements or some other non-arbitrary rationale. The relationship of each display, control, and data-processing aid to the overall task and function should be clear. The structure of the interface and its associated navigation aids should make it easy for users to recognize where they are in the data space, and should enable them to rapidly access data not currently visible (e.g., on other display pages). The way the system works, and is structured, should be clear to the user.

- *Timeliness* – The system's design should take into account users' cognitive processing capabilities as well as process-related time constraints to ensure that tasks can be performed within the required time. Information flow rates and control performance requirements that are too fast or too slow could diminish performance.

- *Controls/Displays Compatibility* – Displays should be compatible with the requirements for data entry and control.

- *Feedback* – The system should provide useful information on its status, permissible operations, errors and error recovery, dangerous operations, and validity of data.

B.3 Secondary Task Control

These principles minimize secondary tasks, i.e., tasks personnel must perform when interfacing with the system that are not directed to the primary one. Examples include managing the interface, such as navigation through displays, manipulating windows, and accessing data. Performing secondary tasks detracts from the crew's primary tasks, so the demands of secondary tasks must be controlled.

- *Cognitive Workload* – The information presented by the system should be rapidly recognized and understood; therefore, the system should minimize requirements for making mental calculations or transformations and using recall memory (recalling lengthy lists of codes, complex command strings, information from one display to another, or lengthy action sequences). Raw data should be processed and presented in directly usable form (although raw data should be accessible for confirmation).

- *Response Workload* – The system should require a minimum number of steps to accomplish an action; e.g., single versus command keying, menu selection versus multiple command entry, single input mode (keyboard, mouse) versus mixed mode. In addition, the system should not require redundant data to be entered, nor the re-entry of information already in the system, or information the system can generate from already resident data.

B.4 Task Support

These principles address the characteristics of the HSI that support its use by personnel, such as providing (1) HSI flexibility so tasks can be accomplished in more than one way, (2) guidance for users, and (3) mitigation of errors.

- *Flexibility* – The system should give the user multiple means to carry out actions (and verify automatic actions) and permit displays and controls to be formatted in a configuration most convenient for the task. However, flexibility should be limited to situations where it is advantageous for task performance (such as to accommodate different levels of experience of the users); it should not be provided for its own sake because there is a tradeoff between flexibility and the increase in interface management workload (which detracts from monitoring and operations).

- *User Guidance and Support* – The system should provide an effective "help" function. Informative, easy-to-use, and relevant guidance should be given on-line and off-line to help the user understand and operate the system.

- *Error Tolerance and Control* – A fail-safe design should be provided wherever failure can damage equipment, injure personnel, or inadvertently operate critical equipment. Therefore, the system should generally be designed such that a user's error will not have serious consequences. The negative effects of errors should be controlled and minimized. The system should offer simple, comprehensible notification of the error, and simple, effective methods for recovery.

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-6634
BNL-NUREG-52564

2. TITLE AND SUBTITLE

Computer-Based Procedure Systems: Technical Basis and Human Factors Review Guidance

3. DATE REPORT PUBLISHED

MONTH	YEAR
March	2000

4. FIN OR GRANT NUMBER

J-6012

5. AUTHOR(S)

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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.)*

Department of Advanced Technology
Brookhaven National Laboratory
Upton, NY 11973-5000

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

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11. ABSTRACT *(200 words or less)*

Plant procedures are instructions to guide operators in monitoring, decision making, and controlling nuclear power plants. While plant procedures historically have been paper-based, computer-based procedures (CBPs) are being developed to support procedure use. CBPs have a range of capabilities that may support operators and reduce demands associated with paper procedures. The objective of this study was to establish human factors review guidance for CBP systems based on a technically valid methodology. While the study mainly addressed emergency operating procedures, much of the guidance developed applies to other types of procedures. First, a CBP characterization was developed for describing their key design features including both procedure representation and functionality. Then, the research on CBPs and related areas was reviewed. This information provided the technical basis on which the guidelines for design review were developed. The review guidelines address both the design process and the implementation of CBP systems. For some aspects of CBPs the technical basis was insufficient to develop guidance; these aspects were identified as issues to be addressed in future research.

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

Control rooms, human factors engineering, human-system interface, man-machine systems, reactor safety, reactor operators, test and evaluation, human-factors review criteria

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page) *Unclassified*

(This Report) *Unclassified*

15. NUMBER OF PAGES

16. PRICE