

COMPUTERIZATION OF NUCLEAR POWER PLANT EMERGENCY OPERATING PROCEDURES*

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ABSTRACT

Emergency operating procedures (EOPs) in nuclear plants guide operators in handling significant process disturbances. Historically these procedures have been paper-based. More recently, computer-based procedure (CBP) systems have been developed to improve the usability of EOPs. The objective of this study was to establish human factors review guidance for CBP systems based on a technically valid methodology. First, a characterization of CBPs 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 were developed. 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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BACKGROUND

Nuclear power plant emergency operating procedures (EOPs) provide instructions to guide operators in monitoring, decision making, and controlling the plant during process disturbances that could potentially impact safety. Following the accident at the Three Mile Island plant, 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 the specific causes of process disturbances.

Nuclear plant EOPs are typically paper based and are necessarily somewhat complex. Paper-based procedures (PBP) 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. PBPs can be difficult to manage, e.g., physically handling the transition between procedure steps and other procedures. To 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.

Computer-based procedure (CBP) systems are being developed to support procedure use and management. 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.

OBJECTIVES AND METHOD

The objective of this study was to develop human factors engineering (HFE) review guidance for CBP systems based on a technically valid methodology. To support this objective, the following tasks were undertaken: (1) development of a frame-

work for characterizing key design features of CBP systems, (2) development of HFE review guidelines for CBPs, and (3) identification of remaining CBP issues for which research was insufficient to support our development of NRC review guidance. These tasks were accomplished using our guidance development methodology reported in O'Hara et al. (1999). This paper provides a brief summary of this research. For details see O'Hara et al. (1999).

RESULTS

CBP System Characterization Framework

Characterization of a system consists of the identification of important design features and functions that can be used to describe it. It also forms an organizational structure for the guidelines used to review the system. We developed a characterization framework based on our examination of several CBP systems in operating plants or in their training simulators. The CBP characterization framework discussed includes the following six dimensions:

Representation of Procedures – Procedures have a number of elements, including (1) identifying information such as title, procedure number, revision number, and date; (2) basic action steps composed of a verb and a direct object; and (3) warnings, cautions, notes, and supplementary information. The information is presented in a specific format, such as text or flowchart format.

Functionality of Procedures – Procedure functions can be organized into four categories related to the operators' cognitive use of the information: monitoring and detection, situation assessment, response planning, and response implementation. Table 1 provides an overall scheme within which the level of automation of CBPs can be organized. It illustrates the wide levels of function automation that CBPs may possess. In the rows, the general cognitive functions are identified, along with the associated procedure-related activities. Procedure functions can be implemented in four levels of automation, identified in the columns of Table 1 – 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.
- Automated – The CBP performs the function automatically without the operator's direct intervention.

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.

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) are part of the characterization of CBP systems. These include features to transition between procedure steps and between different procedures. The use of procedures can be supported by facilities for monitoring and recording the operator's actions and for providing help.

CBP Hardware – CBPs utilize devices such as VDUs, printers, and computer input devices, such as alphanumeric keyboards, trackballs, mice, and touch screens.

Backup System for Procedures – CBPs can fail or malfunction. When important operations cannot be suspended or put off while the system is repaired, a backup, such as PBPs, is needed.

Integration with Other Interface Components – Integration of the CBP with other human-system interfaces (HSIs) must be considered. Their consistency and compatibility with other HSI components can affect operators' performance.

Guidance Development

The first step in guidance development is to develop a technical basis from research literature and operational experience. From that technical basis, scientifically defensible guidance can be developed. 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) subject matter expert opinion about the postulated effects of CBPs 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. Generally, in comparison to PBPs, operators using CBPs performed tasks more quickly and made fewer errors in transitioning through procedures. In addition, their overall cognitive workload was reduced; they accepted CBPs readily and found them easier to use. However, much of the

Table 1. Levels of Automation of Procedure Functions

PROCEDURE FUNCTIONS	LEVEL OF AUTOMATION			
	M	Ad	S	Au
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 procedures				
Control of plant equipment				

Note: M=Manual; Ad=Advisory; S=Shared; Au=Automated

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.

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 and increase risk.

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 verification and validation 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 as will be discussed in the next section.

Once the technical information was assembled, a draft set of guidelines was developed. In general, guidelines were only developed for those aspects of CBPs that, in our interpretation, were supported by the technical basis. The guidelines were developed in the standard format adopted in NUREG-0700, Rev 1 (O'Hara et al., 1996) and were organized into sections corresponding to the CBP characterization described above. The guidance was then peer reviewed and revised accordingly (O'Hara et al., 1999).

RESEARCH ISSUE IDENTIFICATION

Human performance issues were topics for which research is necessary before developing guidance. Briefly, the issues included the following:

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

Team Performance – The introduction of CBPs has been found to effect crew members' roles, teamwork, and communication. This effect needs to be studied to determine how CBPs can be designed to effectively support team performance.

Situation Awareness – A better understanding is needed of the effect of CBPs on situation awareness of (1) procedure management, such as status of procedure steps, overall procedure structure, and the current location within a procedure or between a set of procedures; (2) the appropriateness of procedures for achieving high-level procedure goals; and (3) overall plant status.

Level of Automation of Procedure Functions – Additional research is needed 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 – The characteristic of limited viewing area has sometimes been referred to as the "keyhole effect," an analogy to the limited view of a room that is provided by a physical keyhole (Woods et al., 1990). For CBPs, the keyhole effect is that at any given time most of the information is hidden from view. Further research is needed 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 – Additional research is needed to evaluate the operator's management of the transition from CBPs to backup systems, such as 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 – Additional research is needed 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 while all other procedures are paper based.

CONCLUSIONS

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. Based on our study, 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 and logic analysis (cautiously so not to underspecify the analysis and undermine operator's judgement)
- Support procedure management, e.g., step completion, place keeping, and 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 (i.e., minimize the potential for negative transfer or difficulties in performance)

Guidance for the review of CBPs was developed to address the CBP design process and their implementation (O'Hara et al., 1999). However, as noted above, human performance issues remain. Therefore, until the additional guidance is developed, these issues should be addressed for each specific CBP system during the CBP design process. The new CBP guidance will be integrated into the existing human factors guidance in NUREG-0700, Rev. 1.

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