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REVIEW Of COMPUTERIZED PROCEDURE GUIDELINES FOR NUCLEAR POWER PLANT CONTROL ROOMS

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Computerized procedures (CPs) are recognized as an emerging alternative to paper-based procedures for supporting control room operators in nuclear power plants undergoing life extension and in the concept of operations for advanced reactor designs. CPs potentially reduce operator workload, yield increases in efficiency, and provide for greater resilience. Yet, CPs may also adversely impact human and plant performance if not designed and implemented properly. Therefore, it is important to ensure that existing guidance is sufficient to provide for proper implementation and monitoring of CPs. In this paper, human performance issues were identified based on a review of the behavioral science literature, research on computerized procedures in nuclear and other industries, and a review of industry experience with CPs. The review of human performance issues led to the identification of a number of technical gaps in available guidance sources. To address some of the gaps, we developed 13 supplemental guidelines to support design and safety. This paper presents these guidelines and the case for further research.

INTRODUCTION AND DEFINITIONS

The nuclear industry relies upon paper-based operating procedures to guide operator performance during normal, abnormal, and emergency operating conditions. Many if not all high technology, safety critical industries also rely on written operating procedures. The general perception by regulators, operators, and licensees is that operating procedures play a crucial role in ensuring crew and plant performance.

The introduction of digital systems in existing light water reactor plants and advanced plant designs provides an opportunity to implement advanced procedure systems such as computerized procedures (CPs). The role of CPs can be to facilitate automated place keeping, provide navigational support, cue operators when procedural steps are not correctly performed, assess and present parameter information used to satisfy entry conditions for branching within and between procedures, and monitor plant functions. As described later in this paper, highly automated CPs may also be responsible for taking control actions. Although the use of CPs represents a specialized version of automation, their implementation in the nuclear domain has a safety significance that warrants close human factors consideration.

Existing Guidance for Computerized Procedures

Existing regulatory guidance for CPs addresses operator monitoring, workload, vigilance, procedure navigation, decision making, and important aspects of human-system interaction (HSI) at commercial nuclear facilities. The US Nuclear Regulatory Commission (US NRC) has developed guidance for its staff to review and assess the design and implementation of CPs in nuclear power plants. For example, NUREG/CR-6634 (O'Hara et al., 2000) presents the technical basis and review guidance associated with CPs and determines a number of differences that are present when comparing paper-based and computerized procedures.

The NRC's guidance for paper-based procedures (PBPs) was made available in NUREG-0899 (NRC, 1982). As early as 1994, NUREG-0711, Revision 1, *Human Factors Engineering Program Review Model*, contained preliminary information on reviewing CPs. In NUREG 0711, Revision 2 (O'Hara et al., 2004), guidance for CP review appeared under the "Functional Allocation" section. Under this section, the human factors approach outlined in the licensee's plan should specify the roles and responsibilities of operations personnel as they apply to monitoring and interacting with CPs.

NUREG-0700, Revision 2, *Human System Interface Review Guidelines*, (O'Hara et al., 2002) provides further detail regarding CPs. Section 8, "Computer-Based Procedures System," emphasizes the application of CPs to emergency operating procedures (EOPs) and notes that these guidelines may also apply to CPs for testing, surveillance, and troubleshooting classes of procedures. NUREG-0700 guidance focuses on aspects of procedure design including technical accuracy and HSI guidance on the design characteristics associated with CPs. Much of this guidance is more general than other sections of NUREG-0700, whereby many of the guidelines from other sections are meant to be applied to CPs.

In September 2007, the NRC produced Interim Staff Guidance (ISG) that addressed instrumentation and control (I&C) including CPs in DI&C-ISG-05 (NRC, 2008). This document clarifies the human factors criteria to be used by staff when reviewing digital I&C, including CP implementations for emergency operations, safe shutdown, and emergency response. That guidance also requires regulatory review focuses upon the level of automation and interaction of the CP system with control and process systems. The ISG is not intended to be a comprehensive, final collection of guidance that represents industry experience and regulatory expectations. Rather, it is meant as a starting point.

The Institute of Electrical and Electronics Engineers (IEEE) Standards Association has developed the *Human Factors Guide for Applications of Computerized Operating Procedure Systems at Nuclear Power Generating Stations and other Nuclear Facilities*, known as IEEE STD 1786 (IEEE, 2009). The standard classifies CPs into three categories (see Table 1). IEEE STD 1786 also provides guidance on requirements for effective CP systems.

Table 1. Definition of differences between types of CPs.

Capability	Computerized Procedures		
	Type 1	Type 2	Type 3
Select and display procedure on computer screen	Yes	Yes	Yes
Provide navigation links within or between procedures	Yes	Yes	Yes
Display process data in the body of procedure steps	No	Yes	Yes
Evaluate procedure step logic and display results	No	Yes	Yes
Provide access links to process displays and soft controls that reside on a separate system	No	Yes	Yes
Issue control commands to equipment from embedded soft controls	No	No	Yes
On operator command, evaluate a sequence of steps that is predefined by the procedure	No	No	Yes

Computerized Procedures in Nuclear Power Plants

As far back as 1992, CPs were studied for their ability to allow reactor operators to track progress through several sets of parallel procedures, as well as provide varying degrees of automatic monitoring and feedback (Converse et al., 1992). One of the first design specifications for the French N4 reactor's CP system was developed during the mid-1980s (Pirus and Chambon, 1997). Currently, potential CP applications include non-safety grade systems. Ultimately, CP implementations could include aspects of automation support associated with the performance of essential safety functions.

Procedure-based automation has been proposed as a possible advance when implementing CPs, however, it is unclear what degree of automation is acceptable in nuclear power plants. Based on research in other domains, several researchers have noted that decision support should generally not be as highly automated as information acquisition or information analysis, because failures in decision support may result in degraded performance including loss of situational awareness. For example, unreliable automation has been determined to negatively

impact operator performance (Crocoll & Coury 1990; Sarter & Schroeder 2001; Rovira, McGarry, & Parasuraman, 2002). Guidance should address which aspects of decision and action selection may be automated and whether the procedure system should provide the capability to alert users when entry conditions for a procedure are satisfied, procedure steps or conditions have been violated, when something unexpected occurs, or when conditions require transitioning to another procedure.

REVIEW OF GUIDANCE

We conducted an analysis of potential CP issues relative to the human performance categories listed below:

- *Operator-in-Control* – refers to the operators' ability to control a procedure's execution, including intervening and taking manual control.
- *Use of Automation* – the level of automation and issues related to its use including the transparency of automatic processes, the use of soft controls, and the automation of information acquisition and decision support.
- *HSI* – the main HSI issues this review addressed are:
 - *Navigation* – refers to the users' ability to find their way through and between procedures.
 - *Information Presentation* – refers to both information content and the way that the information is presented.
- *Transition to Paper-Based Procedures* – refers to the extent to which operators will be able to switch back and forth from PBPs to CPs during normal as well as abnormal or emergency situations.
- *Failure Modes* – refers to human and human system failure modes and the operators' and crews' ability to recover from problems with the CPs, control of CPs, or recovery from loss of CPs.

Next, we reviewed existing guidance, and mapped that guidance to the underlying human performance issues. This revealed a number of gaps, where the guidance available for the human performance issue was too general to be implemented or used by a reviewer. Afterward we developed, based upon our reading of the literature and discussions with experts, a number of supplemental guidelines.

INITIAL FINDINGS AND INSIGHTS

Advantages of Computerized Procedures

Our review confirmed that CPs have the potential to enhance human-system effectiveness by addressing some of the limitations of traditional PBPs in the following ways:

- *Automatically track plant status and system parameters in real time.* CPs are sensitive to the context in which they are currently being implemented and can display

contextually relevant plant status information. In contrast, PBPs are static documents and, as such, require the operating crew to manually determine the status of individual plant parameters and to compare this information to procedural requirements.

- *Automatically track progress through the procedure and indicate to the operator the status of steps being performed.* With PBPs, this must be done manually through crew callbacks and sign-off of completed procedural steps.
- *Activate procedures on the fly.* Although this particular feature is not initially expected with implementation of CPs in US commercial nuclear plants, French operating experience includes successful experience with automatic procedure selection as part of the N4 reactor's control room design.
- *Introduce the use of embedded displays and integrated soft controls.* These digital HSI features can allow the operator to view plant parameters and actually control the plant from within the procedure workstation.

Challenges with Computerized Procedures

Even with the important advantages associated with the use of CPs, it is vital to carefully consider how CPs may affect human-system performance in unintended or unanticipated ways. For example:

- *Reliance on automation.* Increases in automation can introduce issues such as under reliance and overreliance on automation, out-of-the-loop issues for human operators, complacency, and failure of trust in the automation (Sheridan & Parasuraman, 2006; Wickens 2002).
- *Flexibility and interface management.* CPs have the potential to be partially configurable by the operator (e.g., screen configuration, level of detail presented, etc.). While flexibility is generally considered desirable, too much flexibility can increase interface management tasks, which could in turn increase operator workload, especially when switching between operators who must familiarize themselves with the plant status through the customized interface (O'Hara, 2002).
- *Procedure tracking.* The shift supervisor's oversight of multiple procedures presented at varying levels of detail (daisy chained from individual operator workstations) may lead toward confusion.
- *Failure of CPs.* CPs can fail in ways that PBPs cannot. For example, CPs may experience a catastrophic crash, or may freeze during execution, making the procedure system unavailable. The failure modes and dependencies associated with degraded CPs may not be clearly understood by operators.
- *Crew dynamics.* With PBPs, the procedure status and the necessary control actions are communicated through callouts between crew members. With CPs, individual operators may be able to determine these directly from the procedure interface, resulting in a

breakdown in the required three-way crew communication. This breakdown may, in turn, eliminate the benefit of second checking found in current control rooms.

- *Procedure annotation.* With PBPs, operators typically annotate the system conditions on the procedures during procedure execution. CPs may not have similar facilities for operators to make these indications, or if available, these data may not be easily accessed should a systems malfunction occur. Advances in recent technology may allow for swiping on touch screens as a means of notation, but migration of this technology from handheld devices to control room environments is probably not a near-term implementation for nuclear power plant control rooms.
- *Procedure look-ahead.* With PBPs, operators intuitively page forward to support review of how they are to respond during the evolution of the situation. CPs may not afford the same functionality.
- *Procedure override.* Identifying the boundary conditions for operator override of CPs may be difficult. Should a procedure override require concurrence by the supervisor?

RESULTS: SUPPLEMENTAL GUIDANCE

Based upon our review, a number of areas lacking sufficient CP guidance were identified. Review of additional sources including discussion with industry experts, review of guidelines for CPs in other industries (such as medicine and aviation), and discussion with US NRC staff helped identify appropriate guidance. The result of this analysis is summarized below. The rationale underlying these suggested guidelines will be presented in a future paper:

1. Information regarding the impact of sequence override should be presented to the operator.
2. Override of data or calculations should be conspicuously labeled as such.
3. For an automated task, the procedure system's decision and execution reliability should be available upon demand.
4. The CP system should request verification when an operator chooses to interrupt an automatic sequence (i.e., to prevent inadvertent override).
5. Detailed logic or calculations should be available to the operator on demand.
6. The goal of active automated sequences and their status in achieving the goal should be available.
7. If a soft control is in use, it should be locked out to preclude another operator from inadvertently reversing a control action.
8. A method should be available for switching control from one operator to another.
9. The CP system should provide an overview list of all active procedures with navigational links to each.

10. Procedure content should be protected from accidental keyed entry. Keyed entry relates to the context to the actual procedures, the parameters used by the procedures, and any annotations by the operators.
11. Characteristics of embedded process data displays should be consistent with other displays in the control room.
12. When a procedure branches, the selected branch should be clearly indicated to ensure the operators' ability to track procedural progress and to look ahead.
13. Operators should be able to log the conditions under which software malfunctions or where there are suspected errors in procedures.

For example, during a shift change, one operator may need to shift procedure control to the oncoming operator from the next shift. This could be critical if operator override of procedures is necessary. In at least one application that we know of, the operator has a unique identifier that allows her/him to have control of the procedure system. This is done either by a unique code or biometric data. There should be a mechanism for reassigning the identifier to the next operator (e.g., a procedure during shutdown might take 14-18 hours to complete, exceeding a single work shift). If this is not done, then intervention, i.e., override, during the next shift may not be possible. There is no guidance currently available that deals directly with this situation and potential ramifications.

CONCLUSIONS AND DISCUSSION

More widespread implementation of computerized procedures in support of nuclear power plant control room activities is widely anticipated, and a number of industry efforts are currently underway. A difficulty for designers of these systems and the operating crews responsible for safe plant performance is the unanticipated interactions of automated systems. Thus, the issues of transparency and highlighting of dependencies may be an important aspect of system requirements that are not yet established in existing guidelines.

Generally speaking, there were a number of gaps in terms of guidelines for CP implementation. The guidance sources we reviewed did not cover all of the potential issues that arise with the incorporation of CPs into the control room. We developed supplemental guidance in the form of additional guidelines for many of the issues that were identified as gaps. However, we only developed additional guidance for issues for which we could find an underlying rationale in the scientific literature or from our interviews with industry experts. Therefore, many of the issues remain in need of guidance. Those issues include:

- access to soft controls,
- potential lock out of soft controls,
- acceptable use of automation,
- integration of the procedure system into the other control room HSI,
- flexibility of the information display,
- navigational efficiency,
- compatibility of CPs with backup procedures,
- configuration and control,
- crew communication, and
- the impact of CPs on situation awareness.

Future research efforts should focus on these issues with respect to their impact on operator performance when using CPs in the control room.

Underlying scientific rationale does not always accompany the guidance on CPs. The guidelines contained in NUREG-0700 were developed according to an existing technical basis including empirical research, the findings from operational experience, and consensus judgment from industry working group representatives. Thus, all of the guidelines in NUREG-0700 were judged to have sufficient underlying rationale (the detailed presentation of this rationale can be found in NUREG-6634). However, the guidelines in NUREG-0700 don't cover all of the emerging issues related to anticipated CP systems with enhanced functionality and increased automation. While other guidance sources such as industry standards may fill many of the gaps in addressing these emerging issues, they often do not include rationale as part of the guidance. Providing rationale is beneficial, because it gives reviewers and licensees alike an impression of why a particular guideline is important and what the potential consequences of not adhering to a guideline might be. Currently, the research necessary to develop the underlying rationale for many of the issues related to the use of CPs is insufficient or does not exist. Thus, in order to fully address all of the important issues related to the use of CPs, additional research is necessary to investigate the specific issues that emerge with CPs.

Much of the technical basis used for developing the existing guidance on CPs and the new guidance the authors present in this paper was derived from experience in conventional control rooms (i.e., analog), or from insights from other industries using advanced technology (e.g., aviation and fossil fuel). The degree to which specific insights can be used to develop guidance on advanced technology such as CPs based on old technology may be limited. Similarly, insights gained from surrogate technologies in other industries may not necessarily apply to the nuclear industry, especially in the case of CPs, because other industries may use procedures in a different way. Efforts to fill the gaps in the guidance should also focus on developing an empirical basis for guidelines based on research that is designed using the advanced technology in the nuclear industry.

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