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Requirements for Control Room Computer-Based Procedures for use in Hybrid Control Rooms

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ABSTRACT

Many plants in the U.S. are currently undergoing control room modernization. The main drivers for modernization are the aging and obsolescence of existing equipment, which typically results in a like-for-like replacement of analogue equipment with digital systems. However, the modernization efforts present an opportunity to employ advanced technology that would not only extend the life, but enhance the efficiency and cost competitiveness of nuclear power. Computer-based procedures (CBPs) are one example of near-term advanced technology that may provide enhanced efficiencies above and beyond like-for-like replacements of analog systems. Researchers in the LWRS program are investigating the benefits of advanced technologies such as CBPs, with the goal of assisting utilities in decision making during modernization projects. This report describes the existing research on CBPs, discuss the unique issues related to using CBPs in hybrid control rooms (i.e., partially modernized analog control rooms), and define the requirements of CBPs for hybrid control rooms.

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ACRONYMS

CBP	Computer-Based Procedure
CCV	Correct Component Verification
COMPRO	Computerized Operating Procedures
COP	Computerized Operating Procedure
COPMA	Computerised OPerating MAnuals
COPS	Computerized Operating Procedure System
CPS	Computerized Procedures System
CR	Control Room
CSF	Critical Safety Function
DOE	Department of Energy
EDF	Électricité de France
EOP	Emergency Operating Procedure
EPRI	Electric Power Research Institute
gPWR	Generic Pressurized Water Reactor
HIS	Human System Interface
IEEE	Institute of Electrical and Electronics Engineers
INL	Idaho National Laboratory
INPO	Institute of Nuclear Power Operations
LWRS	Light Water Reactor Sustainability
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NUREG	Nuclear Regulatory Commission Regulation
PBP	Paper-Based Procedure

R&D	Research and Development
RNO	Response Not Obtained
U.S.	United States

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1. INTRODUCTION

This research is a part of the United States (U.S.) Department of Energy (DOE) sponsored Light Water Reactor Sustainability (LWRS) Program conducted at Idaho National Laboratory (INL). The LWRS program is performed in close collaboration with industry research and development (R&D) programs, and provides the technical foundations for licensing and managing the long-term, safe, and economical operation of current nuclear power plants (NPPs). One of the primary missions of the LWRS program is to help the U.S. nuclear industry adopt new technologies and engineering solutions that facilitate the continued safe operation of the plants and extension of the current operating licenses.

Many plants in the U.S. are currently undergoing control room modernization. The main drivers for modernization are the aging and obsolescence of existing equipment, which typically results in a like-for-like replacement of analogue equipment with digital systems. However, the modernization efforts present an opportunity to employ advanced technology that would not only extend the life, but enhance the efficiency and cost competitiveness of nuclear power. Computer-based procedures (CBPs) are one example of near-term advanced technology that may provide enhanced efficiencies above and beyond like-for-like replacements of analog systems.

Researchers in the LWRS program are investigating the benefits of advanced technologies such as CBPs, with the goal of assisting utilities in decision making during modernization projects. This report will describe the existing research on CBPs, discuss the unique issues related to using CBPs in hybrid control rooms (i.e., partially modernized analog control rooms), and define the requirements of CBPs for hybrid control rooms.

1.1 Procedures in the Nuclear Industry

The vast majority of tasks conducted in the nuclear power industry are guided by some form of procedure. This can be anything from a high level administrative procedure, a checklist, or a very detailed step-by-step procedure. The strong culture of procedure use and adherence has ensured safe energy production in the nuclear power industry.

Although the paper-based procedure (PBP) process has a history of keeping the industry safe there are major limitations to the paper process. As identified by Huang and Hwang (2009), examples of the primary weaknesses of PBPs are the difficulty in navigating within and between procedures, the risk of unintentionally omitting steps (especially when returning to a partially completed section after an interruption), and difficulty in conceptually associating information with the corresponding control.
The static nature of paper affects how the procedures are written as well as other administrative processes put in place to ensure the required levels of procedure use and adherence. The paper procedures are also commonly written to cover a wide range of plant configurations and conditions, which makes some procedures very lengthy documents, of which only small portions are relevant for the current task. When executing a task, the operator usually only needs a couple of sections from one or multiple procedures. The multiple printouts and/or lengthy procedures have a tendency to create the need to flip back and forth between sections during the duration of the task. This is not only time consuming, but also introduces a risk that the operator inadvertently misses steps, conducts steps out of order, or marks too many steps as not applicable.

Administrative processes such as placekeeping methods (e.g., circle-slash) have been implemented to mitigate these types of risks. Administrative processes are also implemented to mitigate the risk of conducting an action on a piece of equipment other than what was intended in the procedure. Processes such as Take a Minute and Correct Component Verification (CCV) are commonly used in the nuclear industry to ensure that the operator takes sufficient time to make sure he/she is on the right unit and on the correct component before executing the task at hand.

Over the years the nuclear industry has added a large number of administrative processes to help ensure adequate procedure use and adherence. The unfortunate result is that the processes take time and focus away from the actual task, which in turn can cause inefficiencies, may decrease human performance, and may contribute to unsafe operation of the plant.

1.2 Computer-Based Procedures

Computer-based procedures have been proposed as a way to enhance performance when using procedures since the 1990s (reference). CBPs are intended to address many of the limitations associated with static paper procedures, and in some cases to provide enhanced decision support to aid operators. CBP systems are typically categorized based on the amount of automated support they offer with the least advanced being electronic versions of the PBP displayed on an electronic device, and the most advanced providing soft controls and the capability to execute pre-defined sequences of control actions through the CBP system (referred to as procedure-based automation).

The main advantage of CBPs is that the procedure can be presented dynamically. That means that the information and instructions can be tailored to the specific conditions encountered during procedure execution including:

Task — The task to be carried out by the operator. A task can require one or multiple procedures to complete. A task can also be shared between the control room operator and the workers in the field. An example of a task to be conducted during normal operation is to swap feed water pumps. Determining the reason for a safety shutdown of the reactor is an example of a task which will be conducted during emergency operations. The capability to dynamically present the procedure in a CBP system can be used to seamlessly transfer the operator between the sections and multiple procedures needed to complete the task. The system can facilitate the coordination of different organizations involved (control room operators and workers in the field) by sending notifications and status updates. The dynamic nature of the procedure also ensures that the operator stays on the correct path through the procedure. The system can automatically placekeep the procedure and take the operator to the next relevant step based on decisions made and/or input in previous steps and current plant information.

Equipment Status — Current status of equipment in the plant can be accessed by a CBP system. This provides information useful for valve line-ups and determination of the path through the procedure in order to successfully complete a task. For example, if a valve already is open there is no need to instruct the operator to open it.

Plant Operation Mode — Certain tasks are dependent on the current plant operation mode. A static procedure (i.e., PBP) has no means of determining the operation mode of the plant. A CBP system, however, can access this type of information. If the current mode does not allow for the task at hand, the CBP system should notify the operator and disallow the task unless overridden.

Concurrent — A CBP system will be able to keep track of all procedures currently being conducted as

Procedures	well as those about to be initiated. The system will therefore be able to notify the operators of potential conflicts. For example, if the control room isolates a specific part of a system the CBP system will notify the workers in the field tasked to carry out a procedure involving equipment now isolated that there is a conflict.

As described above, the dynamic capabilities of a CBP system allow for presenting only those steps relevant for the current conditions as well as reduced step logic complexity (e.g., automated decisions and calculations based on input from the operator). The system can also be designed to provide visual cues for dependency, time sensitive steps, continuously applicable steps, etc. Additionally, a CBP system can provide additional information to the operator, such as visual illustrations of expected initial conditions, just-in-time-training, relevant operational experience, and piping and instrumentation diagrams.

2. IDENTIFICATION OF REQUIREMENTS FOR CONTROL ROOM CBPS

The purpose of this research is to enable enhanced efficiency through the use of advanced technology. Specifically, this work will demonstrate how CBPs can enhance control room operator performance and efficiency. This section describes the methodology used to develop control room (CR) CBP requirements for hybrid CRs.

2.1 Method

The identification of requirements for CR CBPs began with reviewing the existing standards and guidance on computer-based procedures. The second step was to review scientific literature investigating computer based procedures. The third and final step was to summarize the practical issues associated with implementation of CBPs in hybrid control rooms of existing plants.

2.1.1 Standards and Regulatory Guides

There are several documents that provide guidance regarding the design of CBPs to support human performance; this section provides a brief overview of the most commonly cited guidance documents on CBPs.

2.1.1.1 NUREG 6634

The U.S. Nuclear Regulatory Commission (U.S. NRC) provides a technical basis and review guidance for license review of CBP systems in *Computer-Based Procedure Systems: Technical Basis and Human Factors Review Guidance* (NUREG 6634, O'Hara et al., 2000). NUREG 6634 defines CBPs as "computer systems whose purpose is supporting the presentation and use of procedures" (page 4-1). The procedures targeted in NUREG 6634 are procedures that guide operator interaction with plant systems (as opposed to administrative procedures), and the focus of the guidance is on emergency operating procedures (EOPs) O'Hara et al. (2000) developed a framework for characterizing CBPs based on:

- Representation of Procedures. This defines the basic elements of procedures such as basic steps and warning cautions and notes.
- Functionality of Procedures. This describes what the CBPs systems can do, such as aid in situation assessment.
- Management and Support of Procedures. This describes how procedures are maintained and controlled.
- CBP Hardware. This describes the hardware used to display the CBPs such as computer monitors.
- Backup System for Procedures. This describes the backup system for procedures in case of a failure of the CBP system.
- Integration with Other HSI Components. This describes how the CBPs system is integrated with other plant systems.

The guidance targets two main aspects of the design of CBPs: the technical accuracy of the procedure and the design of the human system interface (HSI). The technical basis for the guidelines is derived from documentation of challenges associated with PBPs, general issues related to human system interaction and human cognition, research investigating performing using CBPs, and limited operating experience with CBPs. The design review guidelines are organized based on the characterization of CBPs presented above.

2.1.1.2 IEEE 1786

The Institute of Electrical and Electronics Engineers (IEEE) developed a standard providing guidance on design of CBPs or computerized operating procedures (COPs). The scope of the guidance focuses on CBPs for operations in the main control room including normal operating procedures, surveillance procedures, abnormal operating procedures, alarm response procedures, and emergency operating procedures. IEEE defined three types of computer-based procedures (or Computerized Operating Procedure System [COPS]) where each type is tied to a defined amount of automation integrated into the procedure. Table 1 below describes the capabilities linked to each type of COPS. A type 3 procedure has the capability to automatically carry out sequences in the procedure and allows for soft controls, i.e., the ability to manipulate the plant directly from within the procedure system. An example of a type 1 procedure is an electronic version of a paper procedure with added hyperlinks to provide easy navigation within the system (IEEE Std 1789-2011).

Table 1. COPS capability taxonomy (adapted from IEEE Std)

Capability	COPS		
	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
Process 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
Provide embedded soft controls.	No	No	Yes
On operator command, initiate procedure-based automation.	No	No	Yes

The standard defines guidance for CBPs based on the type of CBP (type 1, 2 or 3). The first part provides guidance on human factors engineering principles when developing a CBP system. The second part of the standard provides general guidance applicable to all CBP types. Some examples of the topics that the guidelines cover are:

- Ensuring the operator controls which procedures are used, which steps are conducted, and how they are conducted (consistent with the administrative protocols of the plant).
- Ensuring the CBP presents all of the information needed to determine if the procedure used is appropriate (e.g., revision number), and ensuring the actions are appropriate for the given conditions (e.g., logic used for decisions).
- Ensuring the procedure contains the necessary functional elements (such as placekeeping) for procedure execution.

The standard also provides guidelines specific to type 2 and 3 CBPs addressing issues such as the quality of embedded data and hold points in automatic sequences.

2.1.1.3 Electric Power Research Institute

As part of the Human Factors Guidance for Control Room and Digital Human-System Interface Design and Modification (EPRI, 2005), the Electric Power Research Institute (EPRI) provides a section of guidance on CBPs. The guidance is organized into high level categories including:

- Display of procedures
- Interaction with CBPs
- CBP functions
- Degraded conditions and CBP failure

The specific guidelines presented are similar to those in the NUREG 6634 (O'Hara et al., 2000) and IEEE 1786 (IEEE, 2009). In addition to providing guidance on the design of CBPs systems, the guide provides advice on issues related to implementing and maintaining CBPs.

2.1.2 Requirements Based on Standards and Regulatory Guides

The guidance on CBPs provides many specific recommendations for the design of CBP systems and interfaces. In some cases, the recommendations define the specific elements to be found in procedures and how to display the information in the procedure. Rather than reiterating the specific guidelines, the guidance reviewed can be distilled into several high level recommendations regarding the functionality and design of CBPs.

CBPs should be technically accurate

A large portion of NUREG 6634 is dedicated to guidance for reviewing the process by which procedures, including CBPs, are developed. In order for a CBP to support performance, it must at a minimum, be technically accurate. For CBPs that provide automated support, it is especially important that the logic used in the procedure be technically sound, as well as understandable and transparent to the operators.

CBPS should address the limitations of CBPs

CBP systems should not merely mimic the existing paper-based process, but should be designed to address the documented limitations of PBPs. The CBP should reduce operator workload by eliminating the burden of placekeeping, navigating within and between procedures, and provide support for certain tasks such as calculations. Further, CBPs that have the capability should monitor process parameters that are relevant to procedure execution.

CBPs should be compatible with the plant systems and other documents

Because CBPs are a tool used to monitor conditions, diagnose problems and, operate the plant, the CBP interface should be compatible with plant systems. There should be consistency in labels, references and displays between the systems.

Procedure execution should always be controlled by the operator

All of the guidance reviewed indicated that the procedure should not force the operator into a particular procedure or path. The operator should be able to control which procedure he executes and should be able to make decisions about his path through the procedure.

There should be a backup procedure system in case the CBP fails

There should be a backup system (usually paper) in place in case the CBP fails. The CBP system should be designed so that the transition to the backup system is smooth and timely, and the operator has all of the information he needs to safely transition from the CBP to the backup.

CBP should be consistent with human factors and information display principles

CBPs should be designed according to accepted human factors and information display principles. Any display issues unique to CBP presentation should be fully evaluated in the CBP system before implementation.

2.2 Research on CBPs

Many studies have investigated the effect of CBPs on operator performance. The majority of the studies have been focused on whether CBPs can be used in the control room as effectively as PBPs and whether they enhance performance.

2.2.1 Experimental Studies on Control Room CBPs

Several studies have sought to compare performance using CBPs to performance using PBPs, and have yielded mixed results. Converse (1995) compared error-rate, workload, and completion times between CBPs and PBPs in a simulated control room task and found that CBPs led to fewer errors but longer completions times. It is important to note that in this study, Converse defined looking ahead and back in the paper procedure (looking ahead was not possible with the CBP) as an error. Looking ahead in procedures is a desirable behavior; therefore, defining it as an error may have artificially inflated the PBP error rate and challenged the validity of these results. Chung, Daiwan, and Kim (2002) compared crew performance using CBPs and PBPs in both traditional and advanced control rooms and found that CBPs changed crew communications compared to PBPs, but did not find any other tangible performance differences. Roth and O'Hara (2002) assessed a crew's ability to use CBPs and transition to paper-based backups. They also investigated crew communication. They found that crews were able to use the CBPs and were able to transition effectively to the back-ups. They also identified a significant breakdown in crew communication using the CBP, indicating that CBPs may have a negative effect on crew communication. Lee, Hwang, and Wang (2005) compared CBPs that were either embedded into the HSI or presented as separate systems. They found that embedded procedures led to faster performance times than separate procedures, indicating that it might be important to integrate CBPs into the HSI to realize the full benefits of CBPs. Huang and Hwang (2009) compared CBPs to PBPs and measured error rates, performance time, workload, team performance, and situation awareness. They discovered that CBPs enhance performance based on error rate, but situation awareness and workload did not differ between CBPs and PBPs. They also found that smaller crews (i.e., 1 person) were slower with CBPs than larger crews (i.e., 2-3 people).

There is some evidence that CBPs may enhance control room operation (Converse, 1995; Huang & Hwang, 2009), but many of the proposed benefits such as reduced workload and increased efficiency have not been demonstrated empirically. In fact, studies have indicated that CBPs may reduce efficiency by increasing completion times (Converse, 1995). Although the potential benefits of CBPs are compelling, research has failed to provide sufficient evidence that those benefits would be realized in an operational setting. Further, existing research has typically compared CBPs with PBPs, but few have explored the impact of design choices on performance using CBPs.

2.2.2 Research on Field CBPs: Implications for Control Room CBPs

Previous research conducted by INL researchers on computer-based procedures for nuclear workers in the field has proved the feasibility of computer-based procedures and indicated that human performance can be improved by transferring to such procedure process (Oxstrand et al.2014; Oxstrand et al., *in press*; Le Blanc et al.*in press*). As previously discussed, the amount of administrative processes implemented in the nuclear industry may inadvertently shift the focus to the administrative processes rather than to the task at hand. When transferring from the paper process to a computer-based process many of these administrative processes can either be seamlessly integrated with the work flow of the computer-based procedure, or removed completely.

The previous research focused on how to streamline and distill the information in the procedure and how to present it to the field worker in a manner that allows the worker to focus on the task at hand rather than on how to decipher the procedure content. The design concepts developed and the findings from the multiple evaluation studies in the research effort provide a valuable platform for the current research for control room CBPs.

The research targeted procedures for field workers using a type that can best be described as in between type 1 and 2. The computer-based procedure system developed by the researchers is more advanced than an electronic version of the paper procedure and it does process step logic and displays results depending on previous decisions and inputs. However, it does not connect to any systems at the nuclear power plant and therefore does not have the capability to connect to process displays of soft controls.

In a highly proceduralized work environment where tasks are conducted on complex systems there is a great risk of conducting steps out of order or omitting steps. To mitigate this risk a placekeeping process is used to help operators track the performance of steps within a procedure by physically marking steps that have been completed or are not applicable. However, the current placekeeping process (along with all other administrative processes in place at the utilities) tends to take focus away from the actual performance of the task at hand. Therefore, when transferring from paper to a computer-based procedure system it is important to ensure the same level of procedure adherence but to leverage the inherent capabilities of the technology to better integrate the administrative processes into the procedure system. The researchers in the computer-based procedures for field workers successfully evaluated the use of automatic placekeeping. Their version of automatic placekeeping only allowed actions to be taken on the current relevant step while all past and future steps were visible to the operator. This built-in procedural adherence made it easy for the operator to stay on the specified path and was proven to reduce the amount and severity of human errors.

In addition to the automatic placekeeping, the researchers successfully evaluated the benefits of simplified step logic and the use of digital correct component verification. Traditionally, conditional statements are written as If/Then, While/Then, and so on. These statements have a tendency to be nested and sometimes hard to decipher. The researchers explored the option to simplify the logic by restating the conditional statements as questions (e.g., "What pump do you want to start; Pump A or Pump B?"). Based on the answer the system would automatically take the operator down the relevant path while automatically marking the other path as not applicable. This simplified step logic was very well received by the plant staff participating in the research.

There are multiple events every year caused by incorrect equipment being manipulated. To mitigate this risk operators are required to verify they are on the correct component before they take any action on it. The current administrative procedures have reduced the amount of events due to action on wrong component, but there is still room for improvement. Moving to computer-based systems provides digital solutions such as barcode and optical character recognition software that can help ensure correct component identification with a quick database search.

2.2.3 Requirements Based on Research on CBPs

Much of the research on CBPs simply demonstrates that CBPs can be used to conduct the same tasks that PBPs are used for. There is very little research that reveals how design of CBPs can enhance or degrade performance compared to PBPs. Nonetheless, there are a few general requirements that can be gleaned from the experimental research on CBPs.

CBPs should be designed so that the positive aspects of paper procedures are maintained

Paper procedures have some strengths, such as a continuously presented overview of past and future steps, and parallel access to information. To the extent possible, CBPs should provide these capabilities while also providing the advantages of digital technology.

CBPs should support the way the operator does the task

The CBP should not prevent the operator from doing his task the way he was trained to do. CBPs should allow the operator to look ahead at future steps and review previously conducted steps.

2.3 Other Factors

The majority of guidance focuses on designing CBP systems that are a suitable alternative to existing paper-based systems, meaning that they can replace PBPs without causing new errors. In order for most plants to include CBPs as part of their control room modernization efforts, it will also need to be clear that CBPs provide an advantage above and beyond simply replacing PBPs. In order for a plant to invest the cost in upgrading their procedures, it needs to be clear that the investment will be worth the cost and effort.

2.3.1 Industry Perspectives

In 2012, Le Blanc, Oxstrand, and Waicosky (2012) conducted a user needs analysis to gain a better understanding of the nuclear utilities' current plans for implementing CBPs, the current infrastructure in place to support CBPs, as well as the perceived or real barriers to implementing CBPs systems. The researchers distributed a survey to fifteen individuals representing six nuclear power utilities. The questions in the survey addressed areas such as:

- Are CBPs in the utility's long term vision?
- Is the utility considering CBPs for main control room operations, field operations, or both?
- What type of infrastructure does the plant have in place currently?
- What perceived barriers exist to implementing CBPs and what support do the utilities need to overcome those barriers?

The survey included three different types of questions: 1) Forced-choice yes/no questions, 2) Multiple choice questions, and 3) Free-form questions. The first two types provided an opportunity to quantify the answers while the third type provided the necessary context.

Le Blanc, Oxstrand, and Waicosky (2012) calculated the proportion of "yes" responses to forced-choice yes/no survey questions. 100% of the utilities surveyed reported that CBPs for field operators were part of their long-term vision. 66% reported that CBPs for control room operators were in the long-term vision. The researchers coded responses to open ended survey questions according to a list of categories developed after the data was collected. The categories that were developed for these questions are presented below in Table 2 along with the proportion of responses that fit into that category.

Table 2. Proportion of responses to needs assessment survey questions organized by category.

Question	Categories and Proportion of Responses
What are your reasons for considering CBPs?	Configuration and control of procedures – 30% Context sensitivity of procedures – 20% Procedure tracking – 20 % Human performance improvement – 20%
What functionality would you like to see in CBPs?	Context Sensitivity – 55% Specific interface issues – 28% Ability to update plant status based on procedural actions – 17%
What would your utility/plant need in order to move forward with a CBP project?	Successful implementation at another utility – 25% Infrastructure improvements – 25% Proof of concept – 16% Requirements and standards across industry – 16% Other – 18%

Based on the responses to the first question, human performance improvement is a secondary concern when utilities consider CBPs. The primary reasons are related to maintaining procedures and tracking the procedures. This indicates that human performance improvements alone are probably not sufficient to persuade plants to adopt CBPs.

Another important insight from the needs analysis is that utilities are concerned about the NRC's acceptance of CBPs, and the extra cost and risk associated with licensing CBPs systems. Factors that might influence the regulatory acceptance of CBPs are whether the CBP system employs soft controls and automated sequences of procedural action through the CBPs interface. For hybrid control rooms type 2 procedures provide the right level of advanced support without employing technology that hasn't been fully accepted by the regulators.

Finally, utilities would prefer to implement proven technology, meaning that they want to use a CBP system that has been successful at another plant. An ideal CBP system for hybrid control rooms would have been used successfully at least one plant.

2.3.2 Requirements Based on Industry Perspectives

Considering the industry perspective on CBPs highlights, there is a need for any CBP system to provide advanced support to operators without significantly changing the way the plant is operated, and without adding additional risk. The following requirements are derived from consideration of the industry needs.

CBPs need to be capable of fully functioning in a hybrid control room

The CBPs system should be designed so that it can be used effectively with both digital and analog components. CBP systems that utilize soft controls, and embedded graphical displays will not work well in a hybrid environment because the operator will need to interact with hard control panels and will not be able to interact with plant systems through the CBPs system. Similarly, embedded displays aren't likely to provide a benefit in hybrid control rooms.

CBPs should enhance configuration and control of procedures

It should be easy to track the latest revision of procedures, track necessary changes to procedures, and update procedures using the CBP system.

CBPs should provide the capability to track progress through procedures and track history of completed procedures

A key feature of CBPs that is of interest to plants is the capability to track progress though the CBP in real time. Additionally, CBPs should aid records keeping and tracking of procedures.

3. Existing CBP Systems

In order to assess which existing CBP systems are good candidates for use in hybrid control rooms, the researchers reviewed the most prominent systems currently available. Although the concept of CBPs has been around for decades, there are relatively few systems deployed for use in the nuclear industry. This section describes three existing CBPs systems based on publicly available information. The Westinghouse CPs (formerly COMPRO), the CBPs associated with Électricité De France (EdF) N4 Design, and Halden's COPMA.

3.1 Westinghouse

Researchers at Westinghouse Electric Corporation (Lipner & Kerch, 1994) were the first to develop CBPs for commercial NPP applications. Westinghouse created their early CBP system, called COMPRO, using then-current graphical user interface and relational database technologies. COMPRO was designed to be more than just a digital equivalent of a static paper-based procedure in that the operator interacted with the procedure steps dynamically. In addition, continuously updated values of safety critical functions and other plant parameters relevant to the procedure were shown on the computer screen to aid the operator's understanding of the plant's overall state, and the condition of systems being affected by the proceduralized operator actions. COMPRO essentially presented the procedures using the standard 2-column format, but to present the procedure steps dynamically, COMPRO utilized a "fisheye" design philosophy (Hoecker, Corker, Roth, Lipner, & Bunzo, 1994). With this design, the current procedure step to be performed, along with more detailed pertinent supporting information, was in the main portion of the screen, and the previous and next procedure steps were in smaller boxes on the screen just above and below (respectively) the current step. More specifically, the current procedure step was in the standard 2-column format in that the main procedure path (i.e., when the plant responds as expected to operator actions) was in the left column, and the right hand column was reserved for when the plant does not respond as expected (i.e., Response Not Obtained or RNO), while the next and previous steps were in a single column summary form.

Westinghouse researchers have continued to build on their initial CBP work, as indicated by a few reports, including the Electric Power Research Institute's report TR-1010042 (2005), Wen (2011), and other information found on Westinghouse's website (http://www.westinghousenuclear.com/Operating-Plants/Automation/Human-System-Interface, retrieved 23 April 2015). According to this information, Westinghouse changed the name of their CBP system from COMPRO to the Computerized Procedure System (CPS). Like COMPRO, CPS displays procedure steps and other relevant information interactively on a computer screen to operators to enable them to safely and efficiently operate the NPP. This dynamic interaction between operator, CBP, and NPP has a number of advantages over static paper based procedures that are intuitively apparent in principle, but may not materialize in practice unless the CBP is designed and implemented well.

Westinghouse's patent application for their CPS (Lipner, Mundy, & Franusich, 2007) provides additional details on its capabilities and features. Notable changes to the CPS include an update to the graphical user interface and enhanced capabilities to communicate to auxiliary operators and staff remotely through a secure connection, in multiple languages, and across multiple operating systems. With respect to updates to the graphical user interface, Lipner, Mundy, and Franusich (2007) note that for the procedure presentation, the CPS display has three primary windows: 1) an overview flowchart of the procedure steps, 2) a text summary of the procedure step (which the operator can hover over to obtain additional information), and 3) the underlying logic (e.g., technical specifications) for the procedure step. These three main windows are labeled as 60, 62, and 64 in Figure 1 below.

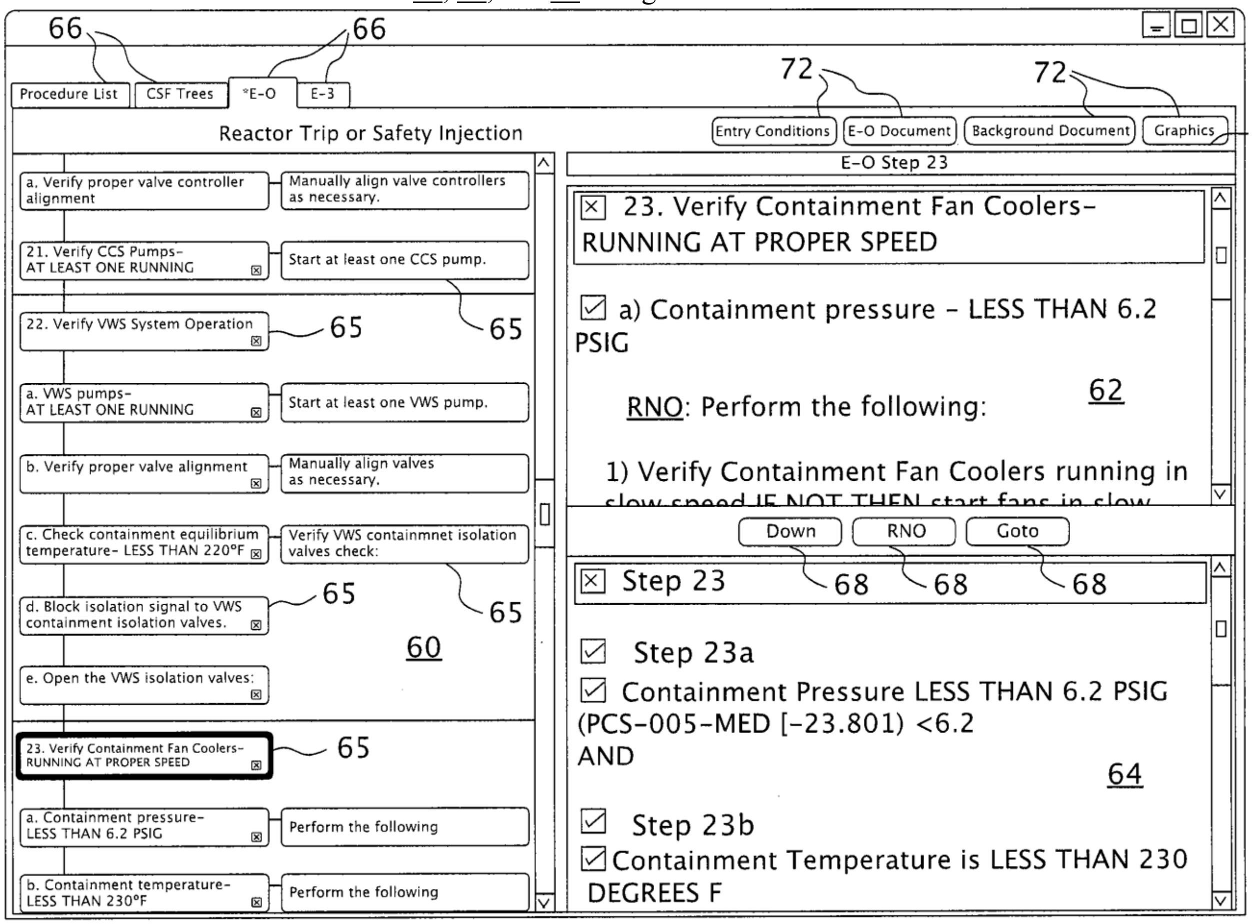

Figure 1. Drawing of the Westinghouse CPS (from Lipner, Mundy, & Franusich, 2007)

Above the text summary window (62), in the upper right header, are four buttons (72 in Figure 1) that are always visible on the screen. As their labels indicate, when clicked they will display additional information on the procedure's entry conditions, a digital copy of the procedure, and additional background documents and graphics that provide relevant contextual information to the operator. Below the text summary window (62) are context-sensitive buttons (68 in Figure 1), which allow the operator to navigate through the procedure steps. By clicking on the tabs in the upper left corner of the screen (66 in Figure 1), operators can also navigate to: 1) other procedures (e.g., transfer from E-0 to E-3), 2) a screen with a master list of procedures (i.e., Procedure List), and to 3) Critical Safety Function Trees (i.e., CSF Trees). There are six CSF Trees that present continuously updated information on six different safety critical functions or parameters (sub-criticality, core cooling, heat sink, reactor coolant system pressure, containment condition, and coolant inventory). Thus, these CSF Trees provide the operator with an overall understanding of the plant's state relative to the control actions they are performing in the procedure they are stepping through.

Interestingly, while COMPRO used the traditional 2-column format for procedures (Hoecker, Corker, Roth, Lipner, & Bunzo, 1994), CPS does not. The □ on the screen in windows 62 and 64 means the response was obtained as expected, and the □ means RNO (Wen, 2011). Additionally, according to the patent application (Lipner, Mundy, & Franusich, 2007), RNO "is indented instead of being set out in a separate column" (pg. 5). One final design feature worth noting is that CPS uses multiple displays, thereby allowing the operator to have the main window displaying the procedure always visible along with additional windows showing supplementary information (e.g., graphs, trends, P&IDs, and related procedures). In fact, one additional capability highlighted in the patent application was the ability for the operator to open two different procedures and have them displayed simultaneously on the screen.

The information regarding operating experience with COMPRO or CPS in industry is limited. According to Lipner and Kerch (1994), at least one coal-fired power plant was using COMPRO to replace their paper-based startup procedure, a Swiss NPP was using COMPRO for their emergency operating procedures, and a Czech NPP is scheduled to use COMPRO for all plant operating procedures. More recently, Wen (2011) reports that the CPS is being used in the Sanmen AP1000 NPP in China. As of the writing of this report, however, there are no publicly available reports documenting any operational experience using these Westinghouse CBP systems. In fact, a search of the Institute of Nuclear Power Operations (INPO) operational experience website returned only one limited distribution significant event report which tangentially involved issues with a CBP system (INPO SER 1-00).

The Westinghouse CPs have focused on EOPs and Abnormal Operating Procedures (AOPs) with the only plants planning to use Normal operating procedures (or general operating procedures) being in China.

3.2 EDF N4 CBPs

As part of their N4 Plants, Électricité De France (EdF) has computer-based procedures. The CBPs are fully integrated into the plant's advanced HSI. The content and instructions are based on the existing paper procedures for other French plants, and the structure of the CBPs is the same. The CBP continuously monitors parameters, and informs the operator when a key parameter is abnormal. The CBP also guides the operator to the instructions containing actions to correct the problem (Chatry, & Poizat, 1999).

The CBP system consists of two screens; one contains what is called the "Mother Image" which consists of the operating instructions, the parameters that need to be monitored and information about the procedure that should be used. The other screens contain what is called a logogram which shows the operation sequence and logic in graphical form. EDF conducted many validations of the system and one of the main findings was that the guidance level may not be flexible enough for experiences operators. They also found that operators would occasionally input incorrect information into the procedure system, and then believe that the system was faulty because it diagnosed problems differently than they had. The design team recommended that the operators be trained to be careful when they input information, and to recognize when they had input incorrect information. The issue the operators had with the CBP system highlights the importance of both allowing the operator to take action based on his understanding of the problem (this is what he is licensed to do, after all) and to make sure that CBP systems are transparent when they make recommendations so that discrepancies between the operator and the CBO system can be easily resolved (Chatry, & Poizat, 1999).

3.3 COPMA (Halden)

The Halden Reactor Project developed a computer based procedure system called COPMA in the 1980s (Converse, 1995). COPMA has been updated several times, and the current version is COPMA III. The COPMA system contains two parts, the procedure writing tool, and the procedure presentation tool. The procedure presentation tool can be used online (connected to the simulator and provides real time data), or offline (simply presenting the procedures without any real-time data or information). The online version of COPMA allows the operator to execute control commands directly from the CBP system, and provides automatic monitoring of plant functions (Converse, 1995). The procedure display contains the instruction pane (presents the procedure steps), and a flowchart that provides an overview of the entire procedure. In online mode, COPMA allows the operator to execute action through the system. COPMA also automatically monitors relevant parameters. It is important to note that COPMA was developed for research, and is not a commercial product.

4. CONCLUSIONS

The requirements developed as the first stage of this research are summarized in this section. At a minimum, any CBP system should utilize the capabilities of digital technology to address the limitations of static paper-based procedures.

4.1 Requirements

In general, a control room CBP should provide the following functionality:

1. CBPs should be technically accurate
2. CBPS should address the limitations of CBPs
    a. Provide an easily used placekeeping function
    b. Provide support for evaluating step logic
    c. Embed relevant process data in CBP
    d. Support evaluating step logic and condition where appropriate
    e. Seamless navigation between branching and other procedures
3. CBPs should be compatible with the plant systems and other documents
4. Procedure execution should always be controlled by the operator
5. There should be a backup procedure system in case the CBP fails
6. CBP should be consistent with human factors and information display principles
7. CBPs should be designed so that the positive aspects of paper procedures are maintained
8. CBPs should support the way the operator does the task
9. CBPs need to be capable of fully functioning in a hybrid control room
    a. Not require the use of soft controls
    b. Be modified for use in an existing plant with minimal effort
10. CBPs should enhance configuration and control of procedures
    CBPs should provide the capability to track progress through procedures and track history of completed procedure
11. The CBPs system should be a commercial product
12. The CBP system should be previously accepted by the Nuclear Regulatory Commission to ease licensing and regulatory acceptance

5. FUTURE WORK

The majority of the CBP systems that are currently in use are designed for use in advanced control rooms, where the procedure system can be fully integrated into the plant HSIs. All of the commercially CBP systems are designed to be specifically used with a particular plant (or type of plant, such as the Westinghouse AP100), and there is currently no generic CBP system available for plants to use. However, some systems can be modified for use in other plants, such as the Westinghouse CPS (used in the AP100 design). The Westinghouse CBP is also a commercially available Type 2 CBP system. Therefore, the Westinghouse CPS is a good candidate for research investigating the benefits of advanced technologies in hybrid control rooms.

The first phase of research investigating benefits of CBPs will utilize Westinghouse CPS. We will obtain a set of procedures for use in GSE's Generic Pressurized Water Reactor (gPWR). These procedures will be converted to be used in the Westinghouse CPS. The Westinghouse CPS will be fully evaluated against the requirements developed in this report. Researchers at INL will then conduct a series of studies investigating the effects of using the CBPs compared to traditional PBPs. The studies will be conducted in the Human System Simulation laboratory at Idaho National Laboratory. The researchers will compare performance using the CPs to performance using the traditional paper-based procedures. Other CBP systems (including emerging systems that are not yet ready for market) may be evaluated and tested in future phases of this research.

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