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Computer-Based Procedures for Field Workers in Nuclear Power Plants: Development of a Model of Procedure Usage and Identification of Requirements

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April 2012



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# Computer-Based Procedures for Field Workers in Nuclear Power Plants: Development of a Model of Procedure Usage and Identification of Requirements

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### **EXECUTIVE SUMMARY**

This research effort is a part of the Light Water Reactor Sustainability (LWRS) Program, which is a research and development (R&D) program sponsored by the Department of Energy, performed in close collaboration with industry research and developments programs, to provide the technical foundations for licensing and managing the long-term, safe and economical operation of current nuclear power plants. Most currently operating nuclear power plants will soon begin reaching the end of their 60-year operating licenses granted by the United States (US) Nuclear Regulatory Commission. If these plants do not operate beyond 60 years, the total fraction of generated electrical energy from nuclear power will begin to decline - even with the modest addition of new nuclear generating capacity. The LWRS Program serves to help the US nuclear industry adopt new technologies and engineering solutions that facilitate the continued safe operation of the plants and extension of the current operating licenses.

With advances in nuclear power plant (NPP) design, the current fleet of nuclear plants will be soon competing with new reactors both in terms of efficiency and attracting the available workforce. While the current fleet is installing technological upgrades to their systems, the fact remains that they will remain less technologically advanced as the newly built plants. However, by introducing new technical solutions in the current fleet the gap between the old and new plants can be reduced. The effort to bridge this gap between the current fleet and new plants is an important step in the mitigation of workforce loss to new plants. One step in this process is to phase out the paper-based procedures (PBPs) that are currently used at most nuclear power plants and to replace them with computer-based procedures (CBPs). Before such an extensive replacement effort is conducted, there are many underlying research issues that need to be investigated and resolved, especially in the fields of human factors and humanmachine interaction. Most of the existing research focuses on CBPs for new and highly integrated systems. This research can be difficult to adapt to the current fleet since there are different challenges involved when CBPs are to be incorporated into existing systems. The goal for this research effort is to define requirements for CBPs that will ensure that the CBPs will be an improvement compared to current PBPs. The research effort does not focus on how to display PBPs on an electronic device. Instead, the focus is to evaluate how to streamline and distill the information in the paper-based procedure in order to increase efficiency, improve the ease of use, and reduce opportunities for errors.

Most existing research in the area of CBPs primarily focuses on CBP systems for operations in the main control room. There has been very little research conducted that focus on CBPs for field workers and how research can help these field organizations to increase their efficiency and improve human performance. Therefore, this specific research effort has a strong focus on field workers. In a long term perspective all organizations that conduct proceduredriven tasks that affect the plant will be covered, including main control room operations.

During the course of the research effort's first year a series of activities will be conducted. These include a literature review, a qualitative study; a user needs survey, and an evaluation study. The main objectives for the first year of the present research effort are to:

- 1. Determine the challenges utilities are having with current PBP systems,
- 2. Identify requirements for CBPs for field procedures,
- 3. Develop a prototype CBPs system based on the requirements identified,
- 4. Evaluate the CBP prototype, and
- 5. Define an industry-wide vision and path forward for CBP deployment.

The researchers reviewed existing CBP research and guidelines and procedure use and writer's guides. Based on the insights from the literature review, the team concluded that the existing research does not sufficiently address areas such as design guidelines for CBPs. Nor does the literature sufficiently address CBPs for field workers. There is a gap between the existing literature and what is needed to address the nuclear industry's needs. The current research effort aims to minimize this gap.

The qualitative study consisted of three information gathering efforts: Observations, Interviews, and Focus Groups. The primary goal of the qualitative study was to develop a model of procedure use; secondary goals were to validate and refine the problem statement, develop an information flow diagram, determine the feasibility of some of the potential CBP solutions, and to identify requirements for CBPs. The observations focused on two main types of information: 1) Activities involved in the execution of a task and 2) Information related to communication and information flow while a task is executed. The researchers conducted fifteen semi-structured interviews with field operators and maintenance technicians. The questions asked in the interviews aimed to address procedure use as well as procedure adherence. The goal was to gain a deeper understanding of what would cause the operator to deviate from the procedure, what would cause the operator to stop work and contact the supervisor, and what physical and cognitive functions are involved in the execution of a procedure step. The purpose of the focus groups was to discuss how technology can support field workers as well as what functions are needed in order to make a computerbased procedure system useful for the field worker. Insights from the focus qualitative study included the need for a set of requirements and standards for CBPs, and the need to design CBPs in a manner that will to enhance human performance compared to PBPs. A CBP system that simply mimics PBPs and displays them on an electronic device would not be enough of an improvement to justify a migration to CBPs. Another important insight gained is utilities are reluctant to be the first one to implement CBPs. The risk that regulators will not accept a CBP system makes the cost associated with developing and implementing CBPs difficult to justify However, utilities' would be mitigated or at least more manageable if the industry as a whole moved forward with CBPs.

One of the purposes of the observations, interviews, and focus groups was to map the task flow and the information flow related to procedure use in the plant. The task flow aimed to identify work processes and mental processes involved in carry out procedure-driven tasks in the field. The goal of the information flow mapping exercise was to identify how information is transferred during the execution of a procedure-driven task. The research team 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 implement CBPs systems. The focus groups discussions were the initial part of this analysis. To follow up on the information gathered in these discussions, a utility survey was conducted. One hundred percent of the participating utilities reported that CBPs for field operators were part of their long-term vision and sixty-six percent reported that CBPs for control room operators were in the long-term vision, indicating that utilities are indeed interested in moving forward with implementing CBPs

The research team could not identify an existing model of procedure usage in any of the research reviewed in during the literature review effort. This was identified as one potential explanation to why the nuclear industry has found it difficult to apply the research to the real environment in the plant. Therefore, a model of procedure usage was developed based in the insights from the studies conducted. The purpose of the model is to identify the physical and cognitive actions involved in the execution of one procedure step as well as potential error traps and what factors affect the risk of these human errors. The model of procedure usage contains the following elements:

- 1. Detailed task flow
- 2. Description of the techniques used to make decisions
- 3. Description of the conditions that must be satisfied to ensure task success
- 4. Description of the cognitive factors that influence the error likelihood

The model of procedure usage is used by the research team both in the process of identifying requirements for CBPs and in the prototype development process. It is important that the error traps identified in the model are adequately addressed and that the cognitive load on the operator is reduced.

The research team developed a general set of requirements for CBPs for field operators; the identification, definition, and selection process was based on an analysis of the model of procedure usage and a review of basic psychological and human factors literature. The research team complemented the set of general requirements with a list of specific CBP requirements for field operators. This list of requirements was developed based on review of existing CBP guidance. The general requirements state that CBPs should:

- 1. *Guide operators through the logical sequence of the procedure*. The CBPs should be designed so that they automatically take the operators through the specified procedure path based on initial conditions and operator input.
- 2. *Ease the burden of place-keeping for the operator*. CBPs should keep track of where the operator is in the procedure, should mark steps as completed, and should highlight the current step.
- 3. *Make the action steps distinguishable from information gathering* steps. CBPs should use some method to differentiate steps for which an operator must actually manipulate the plant versus when he must simply check a condition or value.
- 4. *Alert operator to dependencies between steps.* Typically, the operator has to rely on previous experience or on a caution or warning in order to identify

the situations in which he needs to read ahead in the steps. CBPs should alert the operator when he reaches a step with dependencies, rather than relying on him to read ahead (or remember from previous experience) to detect the dependency. Additionally, if a CBP system has access to real-time plant data the system should alert the operator when plant status changes in a manner that affects the operator's task.

- 5. *Ease the burden of correct component verification for the operator*. CBPs should employ some method to automate correct component verification (e.g., include barcode scanning or text recognition functionality).
- 6. *Ease the identification and support assessment of the expected initial conditions.* Some method of illustrating the expected initial conditions in a simple and easy to understand manner should be available to the operator through the CBPs. For example a schematic or piping and instrument diagram of the relevant equipment could be available on-demand.
- 7. *Ease the identification and support assessment of the expected plant and equipment response.* Some method of illustrating the expected equipment and plant response in a simple and easy to understand manner should be available to the operator through the CBPs. For example a schematic or Piping and Instrument diagram of the relevant equipment could be available on-demand.
- 8. *Include functionality that improves communication.* In the event that an operator encounters a situation that he needs to contact a supervisor to resolve, he needs to be able to efficiently and accurately describe the problem. Tools such as texting, capturing photographs and streaming video have all been identified as highly desirable to have built into any device that display CBPs.

Examples of items on the list of requirements specific for field CBPs are that they should:

- 1. Be designed so that the operator controls the procedure pace.
- 2. Make calculations when the necessary information is available.
- 3. Alert users when procedure steps or conditions have been violated.
- 4. Alert users when conditions require transitioning to another procedure.
- 5. Evaluate step logic when the necessary information is available.
- 6. Be designed so that it is easy for the user to "undo" an unintended or incorrect action (an error of commission).
- 7. Allow the operator to look ahead and back in the procedure.

In the next phase of this research effort (starting April 1<sup>st</sup>, 2012), the research team will develop prototypes of CBP user interfaces based on the results from the literature review and the qualitative study, which includes the model of procedure use and the identified requirements for CBPs. The results from the previous studies will help inform the selection of design concepts to implement and what specific issues related to procedure use and adherence to address. The prototypes will also be designed to test different functionalities that are of interest to investigate and evaluate. In the fall of 2012 an evaluation study will be conducted at a nuclear power utility. The study will focus on the use of the CBP

and the current PBP version of the selected plant procedure, and the comparison of the two. Field workers at the plant will be observed using both versions of the procedure. The purpose of the evaluation study is to compare the use and execution of the CBP to the current use and execution of the PBP version. The CBP's user interface design will also be evaluated in terms of usability, acceptability, and potential increased process efficiency.

This report describes the literature review, qualitative study, and the utility study in detail; and contains a brief summary of the planned evaluation study. The data and gathered and insights gained from first three activities were used to develop a model of procedure usage and requirements for CBPs. The model of procedure usage proved to be an essential tool to understand the actual physical and cognitive activities involved when executing a procedure step. The requirements were developed to address the specific challenges identified in the qualitative study and in the model.

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# ACRONYMS

CBP **Computer-Based Procedures** DOE Department of Energy EPRI **Electrical Power Research Institute** IAEA International Atomic Energy Agency 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 Nuclear Regulatory Commission NRC PBP Paper-Based Procedures PPA Procedure Professionals Association R&D Research and Development

#### 1. INTRODUCTION

Most currently operating nuclear power plants will soon begin reaching the end of their 60-year operating licenses granted by the United States (U.S.) Nuclear Regulatory Commission. If these plants do not operate beyond 60 years, the total fraction of generated electrical energy from nuclear power will begin to decline—even with the modest addition of new nuclear generating capacity. This research effort is a part of the Light-Water Reactor Sustainability (LWRS) Program, which is a research and development (R&D) program sponsored by Department of Energy (DOE), performed in close collaboration with industry R&D programs, to provide the technical foundations for licensing and managing the long-term, safe, and economical operation of current nuclear power plants. The LWRS program serves 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.

With advances in nuclear power plant (NPP) design, the current fleet of nuclear plants will be soon competing with new reactors both in terms of efficiency and in attracting the future workforce. While the current fleet is installing technological upgrades to their systems, the fact remains that they will remain less technologically advanced than newly built plants. However, by introducing new technical solutions into the current fleet, the gap between existing and advanced plants can be reduced. The effort to bridge this gap between the current fleet and new plants is an important step in the mitigation of workforce loss to new plants. One step in this process is to phase out the paper-based procedures (PBPs) that are currently used at most NPPs and replace them with computer-based procedures (CBPs).

Even though PBPs have successfully ensured safe plant operation for decades, they have also been identified as a potential contributor to human error. One of the main issues with PBPs is that they are static while the environment on which they should apply is dynamic (i.e. constantly changing). Due to the static nature of PBPs and the dynamic systems, most of the PBPs are written to accommodate many different scenarios. Hence, the procedure layout forces the operator to search through a large amount of irrelevant information to locate the pieces of information relevant for the task and situation at hand, which has potential consequences of taking up valuable time when operators must be responding to the situation, and potentially leading operators down an incorrect response path. Other recognized challenges related to PBPs are the management of multiple procedures, place-keeping, and finding the correct procedure for the task at hand (Fink et al. 2009). The static nature of the PBPs also forces the operator to rely on other sources of additional information to ensure a functional and accurate understanding of the current plant status. These sources can be things such as drawings, manuals, operational experience, and the operator's own knowledge and expertise. The operator typically has to carry additional papers and/or maintain a lot of information active in his or her memory to have the additional information available when needed.

Much of the existing research in the area of CBPs focuses on procedures for new designs and highly integrated systems. This research can be difficult to adapt to the current NPP fleet because there are different challenges involved when CBPs are to be incorporated into existing systems. In the new system designs, the CBPs are designed as an integral part of the highly coupled system from the beginning of the design process. However, this is not feasible in an existing plant, as it would require a redesign of most systems. The challenge for the existing NPP fleet is to find ways to incorporate the use of CBPs with the existing systems. Therefore, the requirements of CBPs use, design, and implementation will be different for the current fleet than for new-builds. Despite a 30-year history of research on CBPs for main control rooms, almost no NPPs are currently using them, in part because of the difficulty in adapting them to existing plants.

Additionally, existing research in the area of CBPs has primarily focused on CBP systems for operations in the main control room, and more specifically on emergency operating procedures. There has been very little research conducted that focuses on CBPs for field workers and how research can help these field organizations to increase their efficiency and improve human performance. The term *field workers* is used to describe field operations, chemistry operations, maintenance, and any other

organization that might exist in the NPP that conducts procedure-driven tasks out in the plant. Utilities have expressed a need for research tailored to the specific needs of field workers, because the limitations of PBPs are particularly relevant for field work.

The design of field procedures is different than those in the main control room. Procedures in the control room are mostly designed to handle events or changes (e.g., transitions or mode changes) executed by the use of a control device such as a handle, button, or mouse. The procedures used in the field are mostly designed for execution of specific tasks (e.g., to isolate a system or start a pump) where the field worker manually operates the physical component. The environment in the control room is also quite different compared to the field. The control room is a smaller space with stable environmental conditions. However, the plant is a much larger environment, and the conditions in the plant vary depending on location and plant status. Throughout the work day the field worker may execute tasks in locations with varying temperatures and radiological levels. The field worker also travels much more during the day than the control room operator. For example, the field worker may climb ladders or crawl in tight spaces to get to a component, and while doing such the field worker also needs to physically carry all of the materials they need to perform the task at hand. This could be a paper print-out of the procedure, manuals, blueprints, and other information needed. As a result, utilities see limitations in adapting the current CBP research to field worker organizations. However, a dedicated research effort on CBPs for field workers may demonstrate the value of CBPs and gain the momentum for their use. In the long-term, a successful demonstration of the value of CBPs in the field might help the implementation of CBPs in the main control room as well.

The goal of the present research effort is to define requirements for CBPs used in the field that will ensure that the CBPs are an improvement over current PBPs. The focus of the research is on CBPs for field workers, but the research may be extended to cover CBPs for the main control room in the future. The research team's long-term vision is to cover all organizations that conduct procedure-driven tasks that affect the plant. This research effort does not simply focus on how to display existing PBPs on an electronic device. Instead, the research team is investigating how to streamline and distill the information in the PBP to increase efficiency, improve the ease of use, and reduce opportunities for errors.

### 1.1 Overview of the Report

The report contains three distinctly separate parts: the main body of the research report, appended publications based on this research, and additional information related to the research. Table 1 provides an overview of the three parts as well as a guide to where to find them within the report. The publications on which the summary is based consist of three research papers that the research team has submitted to conferences and are currently in press.

	Part of Report	Description	Pages
1	Summary	A summary of the research performed.	1–26
2	Publications (the three first appendixes)	Research papers based on the performed research. Provide detailed descriptions of conducted studies and results.	27–64
3	Other Appendixes	Additional information related to the conducted research.	65–79

### 2. VISION AND PROBLEM STATEMENT

To ensure a clear research focus, the research team defined a vision, a problem statement, and a hypothesis. The focus of this research is to enhance field workers' procedural performance with CBPs. Therefore, it is important to ensure that the commercial nuclear industry's needs related to procedures are accurately addressed. To do such, the research team involved utility partners in the identification and development process of the vision, problem statement, and hypothesis. These three statements will be used as a qualitative measure to make sure the research progresses in a successful manner. This section describes the process of formulating the statements as well as the final definitions of the vision, problem statement, and hypothesis.

#### 2.1 Vision

The vision statement can be summarized as follows: operator performance—and ultimately plant performance—may be improved by significant advancements in how procedure usage is achieved with new technologies. Plans to upgrade existing plants with digital equipment and wireless technology present an opportunity to enhance procedures by transforming the existing PBPs to CBPs. These CBPs have the potential to integrate plant information (including plant mode, equipment status, and procedure relevant plant parameters) and make it readily available to plant personnel in real time. CBPs with this enhanced functionality will be dynamic and context-sensitive, affording the opportunity to mitigate many of the issues associated with static PBPs.





Figure 1. Illustration of current state and future vision

Currently, the field operator typically has to carry procedures, drawings, turnover sheet (information shared and captured during the shift turnover), and a handheld device (used to capture values checked throughout the round) out to the field. Along with these things (which the field operator must physically carry), he also needs to keep things such as operational experience, human performance tools, information shared during shift turnover, etc., in his memory. The field operator also needs to maintain an accurate and updated awareness and understanding of the current plant status and other ongoing work activities. When executing the task, the operator has to incorporate the physical tools with the information stored in his memory, which may pose a great load on his working memory capacity.

The research team envisions that in the not-so-far future, the field operator will be using one device that seamlessly integrates plant information (plant mode, equipment status, etc.), other work in progress, operational experience, just-in-time training, and CBPs. The procedures will be dynamic and context-sensitive in the sense that they will automatically update the information and steps displayed to the operator based on current plant status and other work in progress. Figure 1 depicts the current state and the future vision.

#### 2.2 Problem Statement and Hypothesis

The research team formulated an initial problem statement and hypothesis based on information gained from interviews with personnel at two different NPPs as well as on results from the conducted literature review. The literature review is described in Section 3.2, "Literature Review." The research team involved the utility collaboration partners in the formulation of the problem statement and hypothesis. The initial versions of the problem statement and hypothesis were later revised based on the deeper understanding of the problem, which was mainly gained as a result of the qualitative study. The description of the qualitative study is presented in Section 3.3, "Qualitative Study."

The process of formulating the problem statement began with the researchers identifying the general purpose of written procedures and identifying potential gaps in the ability of procedures to serve their main function. Written procedures are intended to guide operators through the complex tasks they must perform; however, there are two main gaps in the ability of written procedures to address all of the situations an operator may encounter. Those gaps are illustrated in Figure 2. The first gap (Gap A) between the real world and what the intended use of procedures (i.e., what they are intended to cover). Gap A exists due to the facts that procedures can only be written for events that humans can anticipate. This gap may be reduced by increased procedure quality and the manner procedures are written. However, even with the highest quality procedure, this gap is unlikely to ever be fully eliminated. Thus, the computer-based procedure research effort will not attempt to address this. The second gap (Gap B) is between procedure's intended use and the actual use of the procedures. The gap between procedures intended use and the actual use of the procedures. The gap between procedures intended use and the actual use of the procedures. The gap between procedures intended use and actual use (Gap B) is usually nonexistent. However, occasionally the operator may intentionally deviate from a procedure (i.e., a workaround) or make an unintentional error. This gap can be reduced by a greater focus of human factors and human system interaction in the design of procedures and procedures and procedure research effort will focus on Gap B.



Figure 2. Identified gaps related to procedure use.

Initially, there was an emphasis on lack of procedure adherence due to the operators intentionally deciding to deviate from a procedure. In early conversations with collaboration partners, the research team captured statements such as "We must force the operator to follow the procedure at all times," and "Operators should not make decisions while being out in the field." The initial problem statement and hypothesis were formulated to address Gap B, and specifically non-adherence due to intentional deviations from procedures. These initial statements are described in the research paper, Model of Procedure Usage - Results from a Qualitative Study to Inform Design of Computer-Based Procedures (Appendix A). However, the results from the qualitative study revealed that the lack of procedure adherence is not mainly due to intentional deviations. It was found that operators will stop work as soon as they encounter something that makes them question the situation instead of making the decision to deviate from the procedure. The operator will call a supervisor or other coworker qualified to decide how to resolve the situation. Hence, lack of procedure adherence is unlikely due to intentional deviations in most cases. Instead, procedure non-adherence and human errors related to procedure use are more likely to be caused by unintentional operator errors. Even though research on CBPs has been conducted already (as described in the literature review section) the question of what is really wrong with PBPs for field workers has not yet been investigated in great detail. There is not a well-documented theory of why unintentional errors occur when using PBPs or how to best reduce the risk of them. However, there are a lot of assumptions of the deficiencies of PBPs. These deficiencies include the ease of unintentionally skip a step, the static nature of the procedure, and the cumbersome task of keeping track of current plant status and other work in progress. To understand how to best and most efficiently address the risk of unintentional operator errors with CBPs it is necessary to gain an detailed understanding of how PBPs are currently used as well as the underlying causes of operator error when executing a procedure-driven task. These findings resulted in a shift of the research focus from addressing intentional deviations from procedures to the reduction of the risk of unintentional errors during the execution of a procedure driven task. The final definition of the problem statement is as follows:

Numerous events and subsequent corrective actions are attributed to procedural usage issues in NPPs. The PBPs currently utilized pose challenges in that they are static while actual plant conditions are dynamic. Therefore, the procedures may include sections or steps not applicable to the current situation as well as cautions or warnings that are misleading or confusing given the current plant status. These issues are all known to lead to unintended or erroneous actions.

Based on the problem statement a research hypothesis was defined. The hypothesis will be tested multiple times throughout the span of the research effort. The identified hypothesis is:

The risk of unintentional operator errors or erroneous actions conducted by plant personnel can be greatly reduced with the development of procedures that are both dynamic and context sensitive.

### 3. METHOD DESCRIPTION AND RESULTS

The general approach to this research includes a mix of qualitative and quantitative data collection activities. All the activities are designed so that their results inform the next activity. This section describes the activities that are to be conducted during the first year of the research effort. These activities are (1) Literature review, (2) Qualitative study, (3) Prototype development, and (4) Evaluation Study. These four activities will help inform the path forward for the second year of the research effort. A description of the methods used in the studies, the purposes and goals, and a summary of the results are presented below. The main focus will be on the literature review and the qualitative study; however, a brief description of the other tasks will be provided as well.

## 3.1 Research Overview

The main objectives for the first year of the present research effort are to:

- 1. Determine the challenges utilities are having with current PBP systems
- 2. Identify requirements for CBPs for field procedures
- 3. Develop a prototype CBPs system based on the requirements identified
- 4. Evaluate the CBP prototype
- 5. Define an industry-wide vision and path forward for CBP deployment.

To address these objectives the research effort was divided into four main parts. Figure 3 shows the four parts and how they relate to each other. The first part is a literature review of current and existing research related to CBPs and human factors. As a part of this review the researchers also benchmarked existing and proposed CBP systems. The literature review informs the qualitative study by identifying the gaps in the existing literature on CBPs. The qualitative study (represented as the second part in Figure 3) aims to develop a model of procedure use. This study included a data gathering effort at a NPP. The results from the study including the model of procedure use were used to define requirements for CBPs. Those requirements will be used to inform the third part—the development of CBP prototypes. Based on the model of procedure use and the identified requirements, prototypes will be developed to demonstrate different design concepts. The research team will conduct usability tests and gather feedback from field workers throughout the iterative development phase to ensure the validity and acceptance of the concepts.



Figure 3. Research activities to be conducted the first year

When the prototypes are developed an Evaluation study will be conducted at a utility, which is the fourth part in Figure 3. The study will be designed to include user tests and data collection. All the activities conducted during first year of the research effort will inform the decision of the path forward for the next year. This decision will be made based on all results from the first year and in tight collaboration with the utility partners. In the process of making the decision topics such as what field worker organization to focus on next, which specific issues or problems this specific organization struggles with, and which CBP concepts should be explored to address these issues should be considered.

### 3.2 Literature Review

The literature review focused on three main literature categories:

- 1. Evaluation of CBPs
- 2. Nuclear industry documents focusing on procedure use and adherence
- 3. Design, development, and review guidelines for CBPs

The review of these three areas was aimed to inform the qualitative study, the development of a model of procedure use, and the identification of requirements for CBPs. A summary of the review is presented below. The summary in this section does not represent all the literature reviewed, but instead provides a brief discussion of the findings and results of existing CBP research, as well as a brief description of issues related to procedure use and adherence. For the complete list of literature reviewed, please see Appendix D.

#### 3.2.1 Evaluation of Computer-Based Procedures

In order to better understand the specific impacts that CBPs might have on performance, the researchers reviewed literature that described empirical evaluations of existing CBP systems and prototypes. Table 2 below presents a summary of experimental evaluations of CBPs in the nuclear industry. The table includes the specific aspects or factors related to CBPs that investigators studied as well as their methodologies and their important findings.

Reference	Aspects of CBPs Investigated	Evaluation Methods/Measures	Key Findings
Xu, Song, Li, Zhao, Luo, He, & Salvendy (2008)	- Crew - Training/skill level - Presentation style	- Error rate - Operation time	<ul> <li>Presentation style had an effect on error rate, but not operation time</li> <li>Skill level had an effect on both error rate and operation time</li> </ul>
Roth & O'Hara (2002)	<ul> <li>Ability to use</li> <li>CPBs</li> <li>Ability to switch</li> <li>from PBPs to</li> <li>CBPs</li> <li>Crew</li> <li>communication</li> </ul>	<ul> <li>Expert observation</li> <li>Operator interviews</li> </ul>	<ul> <li>Crews were able to use CBPs</li> <li>Crews were able to switch CBPs to PBPs without difficulty</li> <li>Communication was generally good with CBPs, but a significant communication breakdown was identified</li> </ul>
Huang & Hwang (2009)	<ul> <li>CBPs versus</li> <li>PBPs</li> <li>Team</li> <li>performance</li> </ul>	<ul> <li>Error rates</li> <li>Operation time</li> <li>Workload</li> <li>(subjective self report)</li> <li>Situation Awareness</li> <li>(subjective self report)</li> </ul>	<ul> <li>CBPs enhanced performance as measured by error rate and operation time when compared with PBPs</li> <li>There was no significant difference between PBPs versus CBPs on self- report measures of Situation Awareness and Workload</li> <li>There are no significant difference between a team of 1, 2, or 3 operators for errors, but 1 operator took significantly longer than 2 or 3</li> </ul>
Chung, Daihwan & Kim (2002)	- CBPs versus PBPs in conventional and advanced main control rooms	- Expert Observation	- Crew communications are different with CBPs than with PBPs
Jeffroy & Charron (1997)	- CBPs versus PBPs	- Guided expert observation of videos	- This is a preliminary report, so no findings are reported
Lee, Hwang & Wang (2005)	- Embedded versus separate procedures	- Performance time	- Embedded procedures led to faster performance times than separate procedures
Converse (1995)	- CBPs versus PBPs	<ul> <li>Time to initiate procedure</li> <li>Time to complete procedure</li> <li>Errors (deviation from optimal sequence of events)</li> <li>NASA TLX</li> </ul>	<ul> <li>Errors were lower with CBPs than with PBPs</li> <li>Crews were slower with CBPs than with PBPs</li> </ul>

Table 2. Experimental evaluation of computer-based procedures in the nuclear industry

By reviewing the studies presented above in Table 2, the researchers hoped to gain a better understanding of the specific factors that make CBPs successful or unsuccessful. However, the research reviewed did not provide enough depth to fully illustrate what aspects of CBPs are desirable or undesirable. The results of most of the studies mentioned above were mostly aimed at determining whether operators could use the CBPs systems as well as the paper based system. The aim of this research project is to determine how to design a CBP system so that it is a significant improvement over PBPs in terms of human performance.

Although the existing research on CBPs is insufficient to draw broad conclusions as to what factors of CBPs are important to ensure successful implementation, some research has investigated specific factors that may be important to CBP design. For example, one study of suitable screen size for presenting procedures on a mobile device has been reviewed. Byrd and Caldwell (2009, 2011) conducted a research study where they compared procedure-based task performance using three mobile devices with different screen sizes (7in, 3.5in, and 2.8in). In the study a computer maintenance procedure was viewed and executed using a graphical user interface that simulated the different screen sizes. The results from 65 student participants indicated a significant difference in completion times between the different screen sizes. However, the subjective assessment in the study did not detect any significant in cognitive workload, errors of performance, or performance time between the uses of different screen sizes. The main conclusion drawn by Byrd and Caldwell is that when using the larger screen the user read more of the procedure before execution. When using a smaller screen the user sampled the procedure in longer intervals during execution. Thus, CPBs displayed on mobile devices may inevitably increase workload. Special care should be taken to ensure that the overall design of CBPs decreases workload when compared to PBPs.

Other studies, did not identify important aspects of CBPs, but did describe shortfalls of PBPs. In their study of CBPs and team size, Huang and Hwang (2009) identified the primary weaknesses of PBPs, which are currently used by most nuclear power plants. These aspects included:

- 1. Difficulty navigating within and between procedures
- 2. Missing steps, especially when returning to a partially completed procedure after an interruption
- 3. Experiencing difficulties in conceptually associating information with the corresponding control mechanism.

Jung et al. (2000) argue that the main reasons the operator's mental burden is high when using PBPs are place-keeping, concurrent execution of multiple procedures, continuously applicable steps, as well as the interpretation of procedures and intervention while continuing to monitor and control other systems. PBPs are static and therefore not integrated with plant information systems or control systems, which means that the operator has to rely on his memory or other cues for this information.

Park and Jung (2007) have developed a method for measuring the complexity of procedure driven tasks. They identified four main sources of complexity in procedural tasks including:

- The step information complexity (SIC) represents a complexity due to the amount of information to be processed by operators.
- The step logic complexity (SLC) denotes a complexity due to the logical sequence of the required actions to be accomplished by operators.
- The step size complexity (SSC) implies a complexity due to the amount of required actions to be accomplished by operators.
- The abstraction hierarchy complexity (AHC) indicates a complexity due to the amount of system knowledge that is indispensable for identifying the problem space of the required actions.
- The engineering decision complexity (EDC) connotes a complexity due to the amount of cognitive resources that are necessary to establish the proper decision criteria for the required actions. (p. 671)

The measure that Park and Jung (2007) developed to quantify these sources of complexity is well correlated with measures of operator performance indicating that it is a valid measure of task complexity. Computer-based procedure systems should be designed to minimize these sources of complexity where they can.

### 3.2.2 Nuclear Industry Documents Focusing on Procedure Use and Adherence

An important step in identifying how operators actually use PBPs for building the model of procedure usage was identifying how operators are expected to use procedures. To understand the organizational expectations of procedure use and how to improve the process of procedure use, the research team reviewed the guidance documents most commonly used by the nuclear industry related to procedure use and adherence. The Institute for Nuclear Power Operations (INPO) defines procedure adherence as the understanding of a procedure's purpose, scope, and intent and following its direction (INPO, 2009). There are four procedure adherence principles that apply to every person who conducts procedure-driven tasks:

- 1. The user performs all actions as written in the sequence specified by the procedure. However, if the procedure cannot be used as written, then the activity is stopped and the issue is resolved before the user continues.
- 2. Procedures are followed as written, and users do not deviate from procedures except when specifically allowed by the procedure or by approved processes.
- 3. Procedures are reviewed prior to use to ensure that potential adherence problems are resolved.
- 4. Personnel are trained/qualified or are under the direct control of a trained/qualified individual when performing procedure steps.

The research team also reviewed six guidance documents for how to write procedures and how to ensure procedure adherence from three separate organizations. These organizations are Procedure Professionals Association (PPA), Institute for Nuclear Power Operations (INPO), and Duke Energy Corporation. Table 3 below provides a brief summary of the documents reviewed.

Document Title	Organization	Brief Description
Procedure Writer's Manual (PPA AP-907-005, 2011)	PPA	The PPA developed this manual to provide a nuclear industry consensus standard for writing human factored procedures.
Procedure Process Description (PPA AP-907-001, 2011)	PPA	This is a PPA document that provides a standard process for creating and altering procedures. The document is intended to be used by nuclear facility owners and operators to assess their organization's management of the procedure process, as well as to be used as a tool for performing effective self-assessments and benchmarking.

Table 3. Summary of reviewed procedure writing and adherence documents.

Document Title	Organization	Brief Description
Procedure Use & Adherence (INPO 09-004, 2009)	INPO	This INPO document aims to provide an industry guideline based on the experience and knowledge of nuclear industry peers, factoring in the best available human performance strategies, as well as provide procedure use guidance based on the types of procedures. It also provides guidance for adherence to procedures by establishing principles, guidelines, and rules.
Administrative Instructions for Technical Procedures (NSD 703, 2011)	Duke Energy Corporation	This directive defines the processes that will be used in the development and maintenance of technical procedures within a nuclear power utility.
Technical Procedure Use and Adherence (NSD 704, 2011)	Duke Energy Corporation	This utility directive provides guidance in the proper use of and adherence to procedures and provides guidance in the completion and approval of completed procedures.
Procedure Writing Guide (OSG, 2011)	Duke Energy Corporation	The purpose of this utility procedure is to establish guidelines for development, review, approval, and changing of procedures for the operations group.

### 3.2.3 Design, Development, and Review Guidelines for CBPS

Researchers reviewed documents and standards that provide guidance on how to design CBP systems. The main documents reviewed were section 8 of NUREG-0700 (O'Hara et al., 2000) and the IEEE 1786 standard (IEEE, 2012). The review of these documents revealed that this guidance is tailored more toward control room procedures and may not be entirely applicable to field procedures. In many cases the guidance is on a high level and may not be adequate for someone seeking specific design guidance (which is a need that the researchers identified).

Based on the review of existing CBP research the team conducting this current effort concluded that the existing research do not sufficiently address areas such as design guidelines for automation and CBPs. Nor does the literature sufficiently address CBPs for field workers. There is a big gap between the existing literature and what is needed to address the nuclear industry's needs. The current research effort aims to minimize this gap.

### 3.3 Qualitative Study

The research team used the information gathered from the literature and the discussions (informal interviews) held with NPP personnel early in the research effort as a basis for designing the qualitative study to be conducted at a NPP. The qualitative study was conducted over 4 days and involved participants from four nuclear power utilities and five research institutes. The study consisted of three information gathering efforts: Observations, Interviews, and Focus Groups. The primary goal of the qualitative study was to develop a model of procedure use; secondary goals were to validate and refine the problem statement, develop an information flow diagram, determine the feasibility of some of the potential CBP solutions, and to identify requirements for CBPs. Section 3.5 discusses the development of the model of procedure usage and presents a description of the model. Figure 4 shows how the three efforts in the qualitative study supported the development of the model of procedure use. The study also

aimed to identify requirements for CBPs and the mobile devices used by the field workers when using the CBPs.



Figure 4. Activities conducted in the qualitative study.

#### 3.3.1 Field Worker Observations, Interviews and Focus Groups

#### Observations

The research team observed individual turnovers, a shift brief, and pre-job brief. The researchers observed two field operators performing rounds. One operator performed his round in the turbine building and the other field operator made his round at the service building and the outside areas, including the cooling towers. The main types of information captured during the observations were 1) activities involved in the execution of a task, and 2) information related to communication and information flow while a task is executed. Appendix E provides a complete list of questions asked in the interviews and specific activities that were observed during this portion of the qualitative study.

#### Interviews

The researchers conducted 15 semi-structured interviews with field operators and maintenance technicians. Ten interviews were with field operators and five with maintenance technicians. One-half of the interviews with field operators were conducted in direct relation to the observations. All the remaining interviews were conducted throughout the 4-day study. The questions asked in the interviews aimed to address procedure use as well as procedure adherence. The researchers' goal was to gain a deeper understanding of what would cause the operator to deviate from the procedure, what would cause the operator to stop work and contact the supervisor, and what physical and cognitive functions are involved in the execution of a procedure steps.

#### **Focus Groups**

Focus group discussions were held throughout the course of the qualitative study. The purpose of the focus groups was to discuss how technology can support field workers as well as what functions are needed to make a CBP system useful for the field worker. The groups also discussed what type of mobile device would be most effective when executing a CBP in the field. Thirty-four people participated in the focus groups. Table 4 shows the distribution of organizations represented in the focus groups. The label "Other" includes people working with human performance, radiation protection, managers, and one representative from a technology vendor. As stated above, four nuclear power utilities and five research institutes participated in the study.

Insights from the focus group discussions included the need for a set of requirements and standards for CBPs, and the need to design CBPs in a manner that will to enhance human performance compared to PBPs. A CBP system that simply mimics PBPs and displays them on an electronic device would not be enough of an improvement to justify a migration to CBPs. Another important insight gained is utilities are

reluctant to be the first one implementing CBPs. Utilities perceive the migration to CBPs to be risky because of a potential lack of regulatory buy-in for CBPs. However, this risk would be mitigated or at least more manageable if the industry as a whole moved forward with CBPs.

<b>Field Operations</b>	Maintenance	IT Department	Research	Other
5	5	4	10	10

Table 4. Distribution of focus groups participants.

### 3.3.2 Mapping Task and Information Flow

The purpose of the observations, interviews, and focus groups was to map the task flow and the information flow related to procedure use in the plant. The task flow aimed to identify work processes and mental processes involved in carry out procedure-driven tasks in the field. The goal of the information flow mapping exercise was to identify how information is transferred during the execution of a procedure-driven task. The questions asked were:

- Who receives information?
- Who is communicating the information?
- When is the information shared or received?
- Why is the information shared?
- Is the information communicated in written or verbal form?

Table 5 depicts both the initial map of information flow that the researchers had made based on early discussions with the collaborating utilities and the map of information flow developed based on the information gathered during the qualitative study. When the two maps are compared, it is apparent that the qualitative study provided a more detailed understanding of both work processes and information flow.

The initial map describes the process and information flow that occurs between the assignment of a task to a field operator and the execution of the task. The operator performs a job walk-down, he has a pre-job brief with his supervisor, and he checks with the control room to let them know that he is leaving to execute the task as well as to find out if there is any other work in progress. All of this must be conducted before he walks out to execute the task.

The researchers expected that this map was very simplified compared to reality; this expectation was confirmed during the observations and interviews at the NPP work site. A large amount of information is transferred between the different players involved in the work task, as shown in the second part of Figure 6. The research team endeavored to identify this flow of information as accurately as possible to understand how to best improve the process and reduce the risk of error prone situations within the process itself.



Figure 5. Initial and enhanced maps of information flow.

### 3.4 User Needs Assessment

The research team 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 implement CBPs systems. The focus groups discussions were the initial part of this analysis. To follow up on the information gathered in these discussions, a utility survey was conducted. The survey was distributed to 15 individuals representing six nuclear power utilities. The 10 questions in the survey (listed in Appendix F) 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 utility 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.

The main finding was that there is substantial utility interest in implementing CBPs. All of the participating utilities reported that CBPs for field operators were part of their long-term vision. Sixty-six percent reported that CBPs for control room operators were in the long-term vision. The survey and its results are discussed in greater detail in the paper, *Requirements for Computer Based-Procedures for Nuclear Power Plant Field Operators - Results from a Qualitative Study* (Appendix C).

### 3.5 Model of Procedure Usage

The research team could not identify an existing model of procedure usage in any of the research reviewed in during the literature review effort. The research team identified the lack of a detailed description of how the operator interacts with a procedure as one potential reason why the nuclear industry has found it difficult to apply the research to the real environment in the plant. As stated earlier, it is very important to understand the problem space, the real issues that must be resolved, and the research that must be done to make it applicable to the industry. One way of ensuring this is to investigate the potential problem in detail. Since the research hypothesis is that procedure use and adherence can be improved by phasing out PBPs in the favor of CBPs, it is important to gain a detail understanding of the current use of PBPs. The model of procedure usage is one major piece in gaining this understanding. A detailed understanding of the use of PBPs is needed to identify potential process improvements and reductions of the risk for human errors. One of the main goals of the qualitative study was to gather data needed to construct this model. The research team focused on work processes and procedures currently used at the utilities. Hence, the model of procedure usage reflects the use of PBPs and current work processes.

The purpose of the model is to identify the physical and cognitive actions involved in the execution of one procedure step as well as potential error traps and what factors affect the risk of these human errors. The paper *Model of Procedure Usage - Results from a Qualitative Study to Inform Design of Computer-Based Procedures* (Appendix A) presents the initial version of the model. This version contains a task flow and a set of factors that may contribute to errors. Based on result from continuous research and feedback from peer-reviews the model of procedure usage was revised. The development of the enhanced model is described in paper *A Model of Operator Interaction with Field Procedures: Insights for Computer-Based Procedures* (Appendix B). The enhanced model of procedure usage is also presented in Figure 6 on page 18. The enhanced model contains the following elements:

- 1. Detailed task flow in the execution of a single procedure step
- 2. Description of the techniques used to make decisions
- 3. Description of the conditions that must be satisfied to ensure task success
- 4. Description of the cognitive factors that influence the error likelihood.

The detailed task flow was constructed based on field operators' detailed descriptions of what actions they take when attempting to execute a procedure step. In the model of procedure usage, the detailed task flow illustrates the individual elements involved in the process of executing a single procedure step. This includes physical action steps such as locating the component and manipulation of it according to the procedure, as well as cognitive tasks such as the operator checks that he fully understands the step as written and that the plant's response to the action match the operators' mental model of the expected response.

The second part of the model of procedure usage is a description of the techniques used to make decisions outlined in the task flow. The techniques were identified based on the field operators' descriptions of exactly how they decide whether they can execute a procedure step as written. Examples of techniques are the comparison of actions to be taken according to the operator's mental model and the actual description in the procedure step, the comparison of expected conditions with actual conditions, and the comparison of component label and description in the procedure with the actual component in the plant.

The conditions that must be satisfied to ensure task success for each element in the task flow were identified by taking the operators' descriptions of situations in which they have made errors (or could have made errors) into consideration as well as evaluating decision techniques from a psychological and human factors perspective. Examples of conditions that must be satisfied are the need to have an accurate

mental model that dictates expected conditions and the ability to correctly read procedure and equipment information.

The last part of the model of procedure usage is a description of the cognitive factors that influence the error likelihood for each element. This part was constructed by reviewing the current psychological literature for research that is relevant to the errors. Some of the cognitive factors identified are working memory, long-term memory, the salience of cues, and text comprehension.

The model of procedure usage is used by the research team both in the process of identifying requirements for CBPs and in the prototype development process. It is important that the error traps identified in the model are adequately addressed and that the cognitive load on the operator is reduced. The model will be continuously revised based on operator feedback and results from studies gathered throughout the span of the research effort.