Current Situation Analysis and Research of Computer-Based Procedure System for Nuclear Power Plant

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Abstract. Traditional paper-based procedure play an indispensable and important role in guiding the operation and management of nuclear power plants. However, with the development and application of full digital instrument control technology and advanced main control room, its shortcomings such as low execution efficiency and mismatch with advanced technologies are beginning to emerge. In order to take full advantage of computers, most nuclear power country has developed the computer-based procedures (CBP) system itself. This paper analyzes the requirements of regulations and standards in domestic and foreign country, compares and explains the technical points of typical nuclear power units in terms of functional level, computerized range, procedure interface, automation level, upgrade maintenance, etc., summarizes the advantages and disadvantages of current CBP system, and puts forward the optimization and improvement technical scheme for future CBP application.

Keywords: Nuclear power plant · Operating procedures · CBP system · Optimization and improvement

1 Introduction

The operation procedures of nuclear power plants are used to provide necessary basis and guidance for operators to safely, reliably and efficiently control units under all operation conditions such as normal, abnormal or accident status of nuclear power plants. Operation procedures usually consist of two categories: normal operation procedures and emergency operation procedures. Normal operation procedures (including system and unit operation procedures) deal with normal start-up and shutdown, inspection and adjustment, loading and unloading of nuclear power plants, while emergency operation procedures deal with abnormal and accident conditions of nuclear power plants [1].

Traditional paper-based procedures require operators to accurately remember, retrieve and judge in real time. In actual operation, operators have a heavy burden and may misoperate and ignore the operation steps. Especially under abnormal or accident conditions, due to tight time and heavy tasks, it is very important to ensure the safe

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operation of nuclear power plants how to better use procedures to reduce the risk of human errors.

With the more and more extensive application of digital instrument control technology and advanced main control room in nuclear power plants, the operator's man-machine interface basically adopts display screen as the man-machine interaction carrier, and the computer configured by digital instrument control system can process a large amount of complex information in a short time, which provides a technical basis for the application and realization of CBP system. If the paper-based procedures are still used in the digital main control room, the operator needs to switch frequently between the procedures and the human machine interface, resulting in low efficiency of procedures execution and unable to reflect the digital advantages. CBP system can effectively solve the problem of paper-based procedures, improve the response speed of operators and reduce human errors.

2 Regulations and Standards Requirement

2.1 Regulations and Standards

With the development and application of CBP system, relevant regulations and standards have been gradually established. At present, the existing regulations and standards on CBP system are mostly shown in Table 1.

Table 1. Relevant regulations and standards for CBP system of nuclear power plant

Standard document number	Standard name
HAD 103/01-2004	Operating Limits and Conditions of Nuclear Power Plant and Operating Regulations
IEC 62646-2016	Nuclear Power Plant-Control Room-Computer-Based Program
NB/T 20267 2014	Criteria for system design of computerized operating procedures for nuclear power plants
NUREG 0800-2006	Review Outline of Nuclear Power Plant Safety Analysis Report Standards
NUREG 0711-2012	Human Factors Engineering Program Review Model
NUREG 0700-2002	Guide for review of man-machine interface design
NUREG-CR 6634-2000	Computerized Procedures System: Guidelines for Technical Basis and Human Factors Engineering Review
IEEE-1786-2011	Guide for the Application of Human Factors Engineering in Computerized Operating Procedure Systems for Nuclear Power Plants and Other Nuclear Facilities
NB/T 20270-2014	Application Criteria of Human Factors Engineering in Computerized Operation Procedure System of Nuclear Power Plant

Chapters 7, 8 and 9 of HAD 103/01 "Operating Limits and Conditions of Nuclear Power Plants and Operating Regulations" give the relevant requirements of the operating regulations, mainly including the safety standards, approval process, operating restriction requirements, qualification of compilers, etc. to be followed in the contents of the procedures, but do not involve the detailed requirements of CBP system [2].

The Nuclear Safety Administration mainly refers to NUREG 0800 (Standard Review Plan-18) to review the relevant contents of CBP. Chapter 13.5.2. 1 in NUREG 0800 gives a principle and general description of the classification, compilation content and review criteria of the procedures [3], and refers to Chapter 9 of NUREG-0711 as the specific requirements and acceptable methods for the development of the procedures [4].

Chapter 8 of NUREG 0700 gives the characteristic elements of CBP, detailed CBP design and guidelines for human factors engineering (HFE) review of human-computer interface [5]. NUREG 6634 further expands and gives the technical basis of CBP compilation guidelines and human factors engineering design guidelines, and suggests methods for carrying out procedure design according to HFE design process [6].

NB/T20270 standard is compiled with reference to IEEE-1786 and provides human factors engineering criteria for various CBP system designs [7].

IEC 62646 specifies the requirements for the whole life cycle of CBP, including the computerized principle of procedures, type classification, use environment, system function requirements, detailed design requirements, operation and maintenance, etc. [8].

On the basis of IEC 62646, NB/T20267 integrates the domestic experience of nuclear power project regulation design and operation and maintenance, and puts forward the display format and content requirements of CBP, procedure types, CBP classification methods and functional requirements of three types of CBP.

2.2 CBP System Type

In NB/T 20267, CBP systems consist of three categories based on functional level. The typical functions of different types of CBP systems are shown in Table 2 [9].

Type I CBP system only provides the text of the procedure on the computer, does not provide any real-time data display, logical processing or process equipment operation functions, but can provide navigation links within the procedure.

Type II CBP system is characterized by embedding dynamic process data into the regulations, and being able to evaluate the execution conditions or logic of the regulations according to the dynamic process data. It can support operators to make decisions, but it does not have control or automatic control functions.

Type III CBP system includes embedded soft controller, which can be used to issue control instructions to power plant process equipment. Operators can complete the control actions required by regulations without leaving CBP system. In addition, Type III CBP may also have certain automation functions, i.e. automatic execution of sequences can be initiated by the operator.

Table 2. Types and typical functions of CBP system

Functions	CBP system		
	Type I	Type II	Type III
Select and display procedures on your computer	Yes	Yes	Yes
Provides navigation links within or between disciplines	Yes	Yes	Yes
Display process parameters in procedure steps	No	Yes	Yes
Processes the procedure logic and displays the evaluation results	No	Yes	Yes
Provide operation links to call process display and soft operation functions implemented by other systems besides CBP system	No	Yes	Yes
Provide embedded soft operation and issue operation instructions	No	No	Yes
Procedures-based automation is initiated in accordance with operator instructions	No	No	Yes

3 Current Situation Analysis of CBP System

At present, typical nuclear power plants in the world adopting CBP system include French N4, EPR, AP1000 and CPR1000 units represented by Ling'ao Nuclear Power Station Phase II. In view of certain limitations in the application of CBP in N4 power station, this paper mainly compares and analyzes the CBP systems of CPR1000 unit represented by Ling'ao Nuclear Power Station Phase II, EPR unit and AP1000 unit.

3.1 CBP System of CPR1000

In China, it is a typical application for the CBP system of CPR1000 unit represented by Ling'ao Nuclear Power Station Phase II. Its computerized range includes normal operation system procedures, general procedures and accident operation procedures. But it does not establish direct connection between CBP and process parameters in the design, only some operation procedures can be modified online under various working conditions of the nuclear power plant.

The system regulations and the general regulations break the boundary between the "procedure main body" and the "computerized operation list (also MOP, Operating Mode Sheet)" and combine them into a "window structure". The sequential structure mode of chapter navigation is as shown in Fig. 1.

The accident operation procedure adopts the structure of paper-based procedure main body + MOP, MOP is a flow chart structure, and navigation links to relevant operation pictures and operation procedures are set. In order for the operator to obtain the maximum information within the limited screen range, MOP restricts scrolling. In order to make full use of the advantages of computers and improve the execution efficiency of procedures, some automatic judgment and comprehensive information are

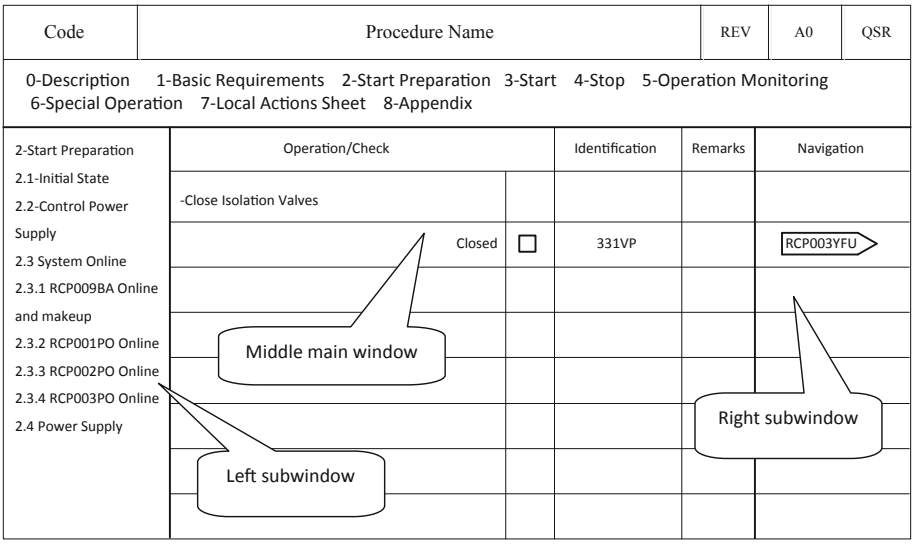

Fig. 1. Computerized system procedures combined window

designed for computerized accident operation procedures, which are arranged in the matching state monitoring display (Fig. 2).

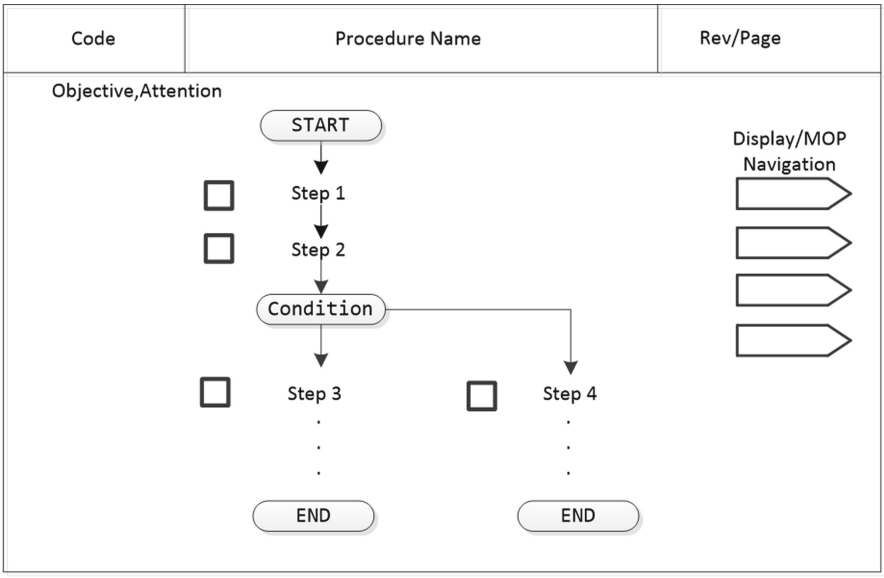

Fig. 2. Schematic structure of accident protocol MOP

For normal operation procedures (general and system operation procedures), operators are required to click on the corresponding interface to start the corresponding procedures as required; For accident conditions, the corresponding preliminary diagnosis and guidance procedures can be entered through the relevant alarm card link, and then the operator can manually diagnose according to the procedures and then enter the corresponding accident procedures.

3.2 CBP System of EPR

The EPR unit CBP system of France's third generation nuclear power technology adopts the form of paper-based procedures plus MOP. The CBP is designed according to Type I. There are no dynamic process parameters in MOP and it is compiled in units of functional tasks. During the execution of normal operation procedures and emergency operation procedures, the MOP can be called, and then the control displays can be called up through the navigation on MOP to complete the corresponding operation tasks.

In terms of accident procedures, the EPR unit adopts a state-oriented method similar to Ling'ao Nuclear Power Station Phase II, and designs an automatic diagnosis (AD) function for accident conditions as an accident treatment entrance. When an accident occurs, automatic diagnosis will be triggered, and the procedure to be adopted will be automatically calculated according to the status of the unit. The operator will deal with the accident according to the diagnosed procedure.

3.3 CBP System of AP1000

The AP1000 reactor CBP of the third generation nuclear power technology in the United States includes abnormal operation procedures and emergency operation procedures, while the normal operation procedures adopt paper-based procedures [10].

The main features of the AP1000 CBP system are:

- The server/client structure is adopted: the server has primary/standby servers, while the number of clients is not limited;
- The server collects process parameters and information from the process control system, can evaluate the status of the power station, and provides procedures selection suggestions (the operator can choose not to accept the suggestions);
- The server will track the procedure steps and notify the operator when the process state changes.
- According to the request of the operator's workstation, the server transmits the rules and parameter information to the operator through HTTP protocol.
- The instructions are textual, and the server can translate the instructions online into the user's language and transmit them to the user according to the user's request at the client.

The AP1000 CBP system interface adopts a sequential structure and has a pull-down bar. On the left is a procedure display in the form of a flow chart, on the upper right is a text display of the current step, and on the lower right is a logical display of the current step. See Fig. 3 for the schematic diagram.

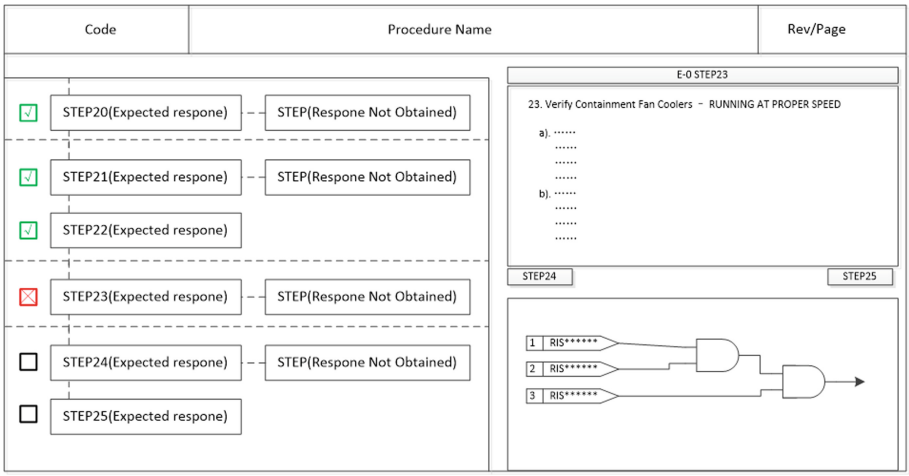

Fig. 3. Schematic diagram of AP1000 CBP [11]

The procedure part is divided into a two-column structure of expected response and expected response not reached. The current execution steps will be highlighted. Each step will set the corresponding diagnostic logic. Detailed operation instructions and diagnostic logic can be called through the steps. According to abnormal and emergency operation procedures, an critical safety function status trees is designed to automatically monitor and evaluate the critical safety function parameters in real time. Once the entry conditions of the procedures are met, the corresponding recovery procedures will be started immediately.

3.4 Comparative Analysis

Taking CPR1000 unit, EPR unit and AP1000 unit of three types of nuclear power units as examples, comparative analysis is made from the aspects of function level, computerized range, procedure interface, automation level, upgrade maintenance, etc.

See Table 3 for comparative analysis of functional levels. According to the analysis results, they all belong to Type I CBP system. There is no process parameter display in the procedure step and the process equipment cannot be directly controlled.

See Table 4 for comparative analysis of the computerized scope, procedure interface, automation level, upgrade maintenance and other aspects of CBP system.

Through the comparative analysis of three typical CBP systems, it means that the current functional level of CBP systems in the world mostly belongs to Type I. No real-time dynamic process parameters are provided in the procedures. The process system equipment cannot be controlled in the procedures, and only links are provided to call other systems to realize process display and soft operation functions. There is no automatic execution of sequences and the level of automation is relatively low.

Table 3. Comparative analysis of functional levels

Functions	Typical units		
	CPR1000	EPR	AP1000
Select and display procedures on your computer	√	√	√
Provides navigation links within or between disciplines	√	√	√
Display process parameters in procedure steps			
Processes the procedure logic and displays the evaluation results			√
Provide operation links to call process display and soft operation functions implemented by other systems besides CBP system	√	√	√
Provide embedded soft operation and issue operation instructions			
Procedures-based automation is initiated in accordance with operator instructions			

Table 4. Comparative analysis of CBP system of typical units

Contrast items	CPR1000	EPR	AP1000
Computerized Range	System/General Procedures: CBP + paper backup Emergency Procedures: paper strategy + MOP	System/General/Emergency Procedures: paper strategy + MOP	System regulations: paper-based procedures Abnormal/Emergency Procedures: CBP + paper backup
System interface	System/General Procedures: • Sequential structure with pull-down strips • Section Navigation Emergency Procedures: • Flow chart structure • Multi-page navigation • Single screen display, no pull-down bar There is no dynamic information display in CBP	System/General Procedures: Sequential Structure; MOP: • Flow chart structure; • Written in units of functional tasks; • A function generally does not exceed two MOP; • Single screen display, no pull-down bar There is no dynamic information display in CBP	Display of CBP partition: • The steps are shown on the left • Detailed actions are shown on the upper right • Diagnostic logic for the current step is displayed at the bottom right • Sequential structure with pull-down strips • The steps are divided into the expected response and the expected response is not met

(*continued*)

Table 4. (*continued*)

Contrast items	CPR1000	EPR	AP1000
Format	Hypertext Link HTML	Hypertext Link HTML	Secondary development based on XML
Level of automation	1) Some automatic diagnosis and comprehensive information are set up in the related dislpay 2) The comprehensive information is equipped with an auxiliary decomposition display; 3) Manual diagnosis leads to corresponding emergency procedures	1) A large amount of comprehensive information is set up in the related dislpay; 2) Added automatic diagnosis (AD) logic and display of emergency procedures; 3) AD automatically diagnoses entering the event condition guidance procedure or the corresponding emergency procedures	1) Each step sets corresponding diagnostic logic; 2) The critical safety function status trees is monitored in real time, and automatic diagnosis leads to corresponding procedures
Upgrade Maintenance	The regulations are easy to upgrade and maintain and have no influence on the logic of the process system	Mark the currently inapplicable procedures through the "Invalid" button; Each MOP page can be upgraded separately, which is easy to upgrade and maintain	Westinghouse provides offline editing tools for procedures; The upgrading of the procedures involves relevant logical modifications, and the workload and difficulty of upgrading the regulations are relatively large

4 Analysis and Proposal for CBP System Improvement

The digital human-computer interaction model proposes four general cognitive tasks that operators need to complete, including: Monitoring and diagnosis, situational awareness, response formulation and response execution [12]. For CBP system, The development trend in the future mainly improve the situational awareness of operators through the operator support system, help operators to assist in decision-making and reduce workload, thus reducing the risk of human errors and improving the safety of nuclear power plants.

In the aspect of situational awareness improvement, a more intelligent diagnosis auxiliary system is developed to help operators quickly and accurately diagnose the current crew status and improve the level of situational cognition. To improve the auxiliary function level of CBP system, such as developing automatic sequence of procedures, CBP system can complete automatic execution of procedures and steps according to

operator orders, including issuing control instructions, etc., which can further reduce operator workload and personnel error risk.

As the main carrier of response plan, the future CBP system should consider friendly procedure structure design from the beginning of its development to reduce the call of response plan to other auxiliary subsystems. Friendly protocol structure design can reduce operator screen switching, such as a protocol display structure with large-size screen, and a display scheme integrating the functions of program main frame and matching pictures.

With the rapid development of artificial intelligence technology in recent years, CBP should have more application of intelligent technology in the future, such as applying artificial intelligence technology to mine the error-prone contents in the operator's execution operation procedures and making optimization and improvement. The fault detection and diagnosis system using advanced algorithms of artificial intelligence technology runs an expert system to assist operators to quickly diagnose faults and make decisions so as to better support cognitive function. The iterative optimization function of big data learning is applied to analyze and learn iterative optimization by collecting and recording data such as daily training, fault diagnosis and accident treatment procedure paths in actual units, and to recommend the optimal accident procedure treatment path to operators.

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