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Human Reliability Analysis for Digitized Nuclear Power Plants: Case Study on LingAo II NPP

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***Abstract**: The control system of main control room (MCR) in advanced nuclear power plants (NPPs) had changed from analog control system to digital control system (DCS). The operation and control had become more automated, centralized and accurate due to the digitalization of NPPs, which improves the efficiency and security of the system. New issues associated with human reliability inevitably arise due to the adoption of new accident procedures and digitalization of MCR in the NPPs. LingAo II Nuclear Power Plant is the first digital NPP in China which applied the State Oriented Procedure (SOP). In order to address issues related to human reliability analysis (HRA) for DCS and 'DCS+SOP', the Hunan Institute of Technology (HNIT) conducted a research project based on a cooperative agreement with the LingDong Nuclear Power Co. Ltd. (LDNPC). This paper is a brief introduction of the project.*

I. Introduction

The control system of main control room (MCR) in advanced nuclear power plants (NPPs) had changed from analog control system to digital control system (DCS) (Ref. 1, 2). The operation and control had become more automated, centralized and accurate due to the digitalization of NPPs, which improves the efficiency and security of the system [3]. As compared with the traditional control system which was based on the analog technique, digitalization lead to some new and more complex issues on human factor, such as, i) the human-machine interface (HMI) of MCR become more diversified and concentrated, ii) operators' behaviors, tasks, operation mode and workload changed dramatically, iii) the team structure and operating mechanism are significantly different [4]. Meanwhile, many NPPs which adopted DCS had changed their operating procedures from the principles and structures aspects, for example, the Event Oriented Procedures (EOP) which based on single event developed into State Oriented Procedures (SOP) which based on physical state of NPP. New issues related to human reliability inevitably arise due to the adoption of new accident procedures and digitalization of MCR in the NPPs. All of these have potential negative impacts on the operators' performance, new error mode and risks may appear.

Organizations and experts worldwide have noted problems related to human factor after NPPs digitization. Many studies have been conducted. For example, the U.S. Nuclear Regulatory Commission (NRC) has sponsored research at Brookhaven National Laboratory (BNL) to better define the effects of changes in human-system interfaces (HSIs) brought about by incorporating digital technology on personnel performance[5, 6, 7]. The EPRI HRA Users Group suggested that some additional modifications and considerations must be employed when the current HRA approach and models apply to system with digital controls [8]. The Korea Atomic Energy Research Institute (KAERI) has studied some issues related to soft control, situation awareness, cognitive workload and human error probability (HEP) in NPP advanced MCR [9, 10, 11, 12].

On the other hand, compared with traditional NPPs, there are some great changes in digital NPPs, such as organizational structure, the characteristics of human factor, human-machine interface, and the system features of 'DCS+SOP'. The methods of human reliability analysis (HRA) for analog MCR cannot meet the requirements of HRA for DCS and 'DCS+SOP'. Hence the new HRA method considering the characteristics of DCS and SOP need be proposed.

LingAo II Nuclear Power Plant (also called LingDong Nuclear Power Plant) is the first digital NPP in China which applied the SOP. As a cooperative agreement between the LingDong Nuclear Power Co. Ltd. (LDNPC) and Hunan Institute of Technology (HNIT), this study was initiated on January, 2010, to address issues related to human reliability. This project lasted for five years and ended on December, 2014. This project has three purposes. The first one was to establish the methodology and model of HRA for 'DCS+SOP'. The second one was to identify the possible new human reliability issues and find operators' potentially unknown risks under accident conditions. The last one was to propose the HRA model for LingAo II NPP and completed the HRA.

In this paper, the NPP is called digital NPP when their MCR adopted the digital control system, and in that case the MCR is also called digital MCR. This paper is a brief introduction of the project. In section 2, we introduce the framework, methods, and design of this research. In section 3, we present some results of this project. Section 4 is the discussion and conclusion.

II. Research Framework and Method

II.A. Research Framework

According to the main objective of this project, there were theoretical and applied research works needed be completed. This included five tasks. The first one was operators' behavior characteristics analysis in digital MCR such as the changes and features of human cognitive behavior, team cooperation and communication, operators' error mode change, and root cause analysis of typical human factor events. All of these works help to identify the possible human factor issues related to 'DCS+SOP' technique application. The second was that a series of specialized simulating experiments and laboratory experiments were conducted to verify the results obtained in the tasks just mentioned and to collect data. The third was to develop the methodologies of 'DCS+SOP-HRA', which included the method and model of 'DCS-HRA', the method and model of 'DCS+SOP-HRA', the database system of 'DCS-HRA', and the analysis software system of 'DCS-HRA'. The fourth was to prepare the HRA report of LingAo II NPP. Finally, a proposal was submitted for a comprehensive prevention program for human error, the training course improvement program for human error prevention.

II.B. Research Method

The research method included qualitative analysis, experimental research and quantitative analysis. The specific technical methods included investigation of operators' behavior patterns and characteristics via behavioral observation, questionnaire survey, and comparative analysis. Simulation experiments and human factors engineering experiments were carried out to investigate the factors and mechanism affecting operators' cognitive behavior. Operators' cognitive behavioral model was constructed using qualitative analysis, modeling and simulation technique. Human reliability data were obtained using test method, statistics method, expert judgment, revise original data and extrapolation.

In order to ensure the applicability of the research results, this project emphasizes the simulator which in LingAo II NPP MCR as a reference. The new HRA method we developed has been applied to this project.

III. Part of Research Results

This paper only presents the results with respect to the operators' behavioral characteristics in digital MCR and the methodology of 'DCS-HRA'. We discussed the changes and features of human cognitive behavior, team cooperation and communication, operators' error mode change, and 'DCS+SOP-HRA' model.

Behavioral observation is the basic method for studying human behavioral characteristics. The purposes of behavioral observation in this project were to find out the changes of operators' behaviors with respect to traditional MCR and to identify possible error modes. The research team completed behavioral observation for more than 10 operating crews in LingAo II NPP MCR, nearly about 50 hours. Recording and behavioral observation for a total of 600 hours had been done for 20 operating crews in a full-size simulator of LingAo II NPP during requalification training. The scenarios included normal operation and accident scenarios. We conducted interviews for the operating crew after each observation.

Operators' behaviors contain a large number of skill-based (SB) and rule-based (RB) behaviors during normal operation. All of these behaviors are the basic unit of plant operators' behavior. Meanwhile these basic units formed the basis of knowledge-based (KB) behavior. Therefore, collecting and studying human factor events with respect to SB and RB was the first step to develop human error prevention program. In addition, we needed to analyze more complex human factor events with respect to KB. Analyzing this type of human factor events can helped us to understand the transformation from events led by SB and RB personnel behaviors to events led by KB personnel behaviors. Furthermore it provided basis for developing higher-level human error prevention program.

Although there were a lot of SB and RB personnel behaviors during normal operation, it was very hard to observe and record them. The researchers initially tried to obtain these data by analyzing the event reports, but there were not much valuable information found after analyzing about 100 reports because these reports were not focus on human factor issues. Later, we found the small deviation reports which seemed like diary-reports written by operating personnel. This type of report recorded the consequences of failure which was observed by operators during operation, such as pressed the wrong button, input the wrong number, and directed to the wrong screen, etc. It also recorded the situational factors and operators' own psychological process. After group discussion, we believed that these small deviation reports were very useful for studying the human error mode and mechanisms. We collected more than 400 reports. The following were the main results.

III.A. Changes of Operators' Behavioral Characteristic

Human-machine interface has been changed dramatically after digitalization of MCR, the way operators access the information and the display of information has also been changed. All of these had changed the way operator access, storage, process, and output the information, that means operators' cognitive behavior changed greatly.

- The impact of digitalization on MCR operators were: operators' cognitive load has a greater change compared with traditional MCR; operator's roles and functions had changed in operating crew; the mechanisms of communication had changed between team members; the operators' behavior patterns had changed in performing procedures.
- HMI of digital MCR expanded the sources of available data and provided operators with more available information of system. Operators could combine the information in a more flexible way to determine the system's state. Thus the DCS helped the operators to reduce the cognitive load in collecting and integrating information.
- Operators have changed their role in the total system from the manual controllers to the supervisor of automated system. In the digital MCR, operators' primary tasks have changed from operation to monitoring and decision-making. The cognitive characteristics of tasks have been increasing.
- Operators' cognitive behavioral process consists of four stages: monitoring and detection, situation assessment, response planning, and response implementation. In order to complete these tasks, operators needed to perform interface management tasks which increasing the cognitive load and working load of operators. This increased the chance of human errors occurred such as loss of situation awareness and mode confusion.
- Due to the increasing of cognitive load, operators usually implemented some operational strategies which brought new risks during perform primary tasks, such as decreasing information verification and taking the specific operation.
- Error of commission (EOC) has a significant increase. The display and distribution of information in digital MCR are more easily lead to error of omission (EOO).
- The operator has strong preferences, such as ignore some procedures habitually.
- The DCS has at least impact in five aspects on the operating crews: team performance, communication, situation awareness, electronic procedures, and secondary task management.
- When the operators were performing the SOP, the workloads of monitoring and response implementation were both significantly higher than the situation assessment and response planning. There was no significant difference between monitoring and response implementation, situation assessment and response planning.
- In LingAo II NPP MCR, the operator has their own workstation. Their operating behaviors were hard to be observed by other operators (unless the mistake has feedback). The amount of human factor event has relatively increased due to the lack of supervision.
- The main factors influencing operators' performance were interface management, the complexity of system, communication, the limited presentation of procedure and system screen, familiarity with the system, the operating experience of operators and crew.
- We investigated the process of operators' cognitive behavior, and the factor and mechanism which influence operators' cognitive behavior. The cognitive behavior model 'MAPI-B' was constructed for operators in DCS. This model integrated by monitoring model, situation assessment model, response planning model, and response implementation model. Journal papers about this part of work will be published soon.
- Based on the recording, we observed 13,276 times monitoring transfer in total. Operators' monitoring behavior mainly has three types of transfer: procedure transfer, abnormal transfer and communication transfer. Procedure transfer means operators' monitoring transfer caused by system procedures, and the ratio of this type was 36%. Abnormal transfer means operators' monitoring transfer caused by alarm or parameter changes when the system had abnormity, and the ratio of this type was 14%. Communication transfer means operators' monitoring transfer

caused by the reminding of other operator, and the ratio of this type was 29%. The ratio of other transfer which could not be grouped into these three types was 21%.

III.B. Team Cooperation and Communication in Digital MCR

The DCS resulted in changes of organizational structures and operating mechanism for operating crew in MCR, which included operating crew constitution, relationship between operators, and task allocation mechanism, etc. This project was focused on the problems in digital MCR associated with crew structure, operators' responsibility, the network and frequency of communication, the characteristics of communication content, the communication pattern, communication failure distribution and feature, and impact on human error because of communication pattern.

Based on the observation and analysis results, the frequency of communication between operators might be reduced in digital MCR, but the efficiency of communication might be higher. There were more communications among the operating crews when important decisions were to be made. Operators received the system information from different perspectives and formed a good team. Figure 1 is the network and frequency of communication among operating crew members.

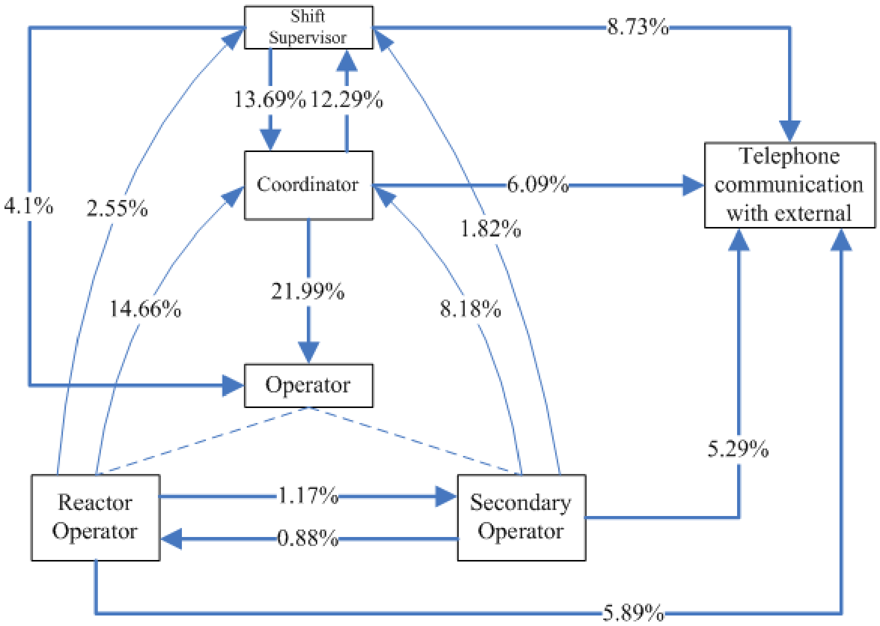

Fig.1. The network and frequency of communication among operating crew members

We carried out experiments in full-scale simulator in LingAo II NPP for investigating the characteristics of communication content, the communication pattern, communication failure distribution and feature, and impact on human error because of communication pattern. The experimental scenario was main steam line break (MSLB) superposition of steam generator tube rupture (SGTR). Five operating crews were involved in the experiment. Video equipment and audio capture device were used to record the whole experimental process. Tools and software were used to analyze these materials. We found that the timeliness of communication, means of communication, and content of communication were three important factors that influence the efficiency of communication for operating crew members. The state parameter of NPP, system function, equipment and procedure were the main contents of communication when operator performing the SOP. Communication about the parameters had the largest proportion among them and this reflected the characteristic of state oriented and non-specific accident of SOP. The main patterns of communication were inquiry, statement, reply, suggestion and call. The inquiry mode associated with the parameter, procedure, system function and equipment, call mode associated with the procedure. Lack of communication with respect to inquiry and judgment of parameters increased the burden on the operator's attention resources. This affected the decision-making of operating crews.

III.C. Human Error Mode Change in Digital MCR

We studied seven types of personnel behavior which had low cognitive level, including operation error, procedure performing, communication, panel surveillance, HMI, input error, and alarm response. Meanwhile we also investigated KB behavior which had higher level of consciousness in the DCS.

- Each stage of monitoring, situation assessment, response planning, and response implementation may occur human error. This project divided 39 types of human errors into 5 categories. There were 7 types of monitoring errors, 5 types of situation assessment errors, 3 types of response planning errors, 6 types of response implementation errors, and 18 types of interface management errors.
- There were 428 event reports related to human errors among 500 event reports and small deviation reports. The type and proportion is shown in Table I.

TABLE I. The type and proportion of human error

Type	Proportion
Work Preparation	9.5%
File Management	15.8%
Work Practice	18.8%
Operation Error	6.7%
Procedure Performing	6.1%
Communication	10.7%
Panel Surveillance	4.2%
Human-Machine Interface	5.8%
Input error	1.2%
Alarm Response	2.1%
Others	19.1%

- Some operators' SB behavior in traditional MCR (such as pressed the button) might changed to KB behavior which needed higher level of consciousness. This type of behavior errors could not be attributed to SLIP or LAPSE [13]. We called this new human error mode as 'KB-SLIP' in this project. Other new human error mode were also found in digital MCR, such as error of page configuration, mistaken click of the mouse, data entry error, error of target identification, and error of information gathering, etc.
- According to the THERP [14], the main error mode was EOO when the operator was performing the tasks. However, based on the research data, the EOC had more significant contribution due to the display control feature of DCS. The EOC accounted for 59% of overall errors and the ratio of EOO was 21%.
- Most of the reasons of EOO occurred in DCS were 'time is too long to perform procedures' or 'complex form for performing procedures'.
- Interface management tasks had big impact on human error. If interface was mismanaged, the 'enormous information with limited display areas' would be changed to 'enormous information with limited acquisition' for operators, and this lead to some information missed which operators needed to obtain when performing the tasks. Cognitive load and working load were increased because of interface management tasks, which resulted in the rising of the possibility of EOO and EOC.

III.D. DCS+SOP-HRA Methodology

Considering the features of DCS, SOP, and DCS+SOP, we established DCS-HRA methodology, included the operators' cognitive behavioral model 'MAPI-B', the reliability quantitative model of operators' cognitive behavior 'MAPI-Q', the behavioral model of operating crew 'MAPI-T', and the behavioral reliability quantitative model of operating crew 'MAPI-TQ'. The MAPI-B model was used for qualitative analysis of operators' behavior. The MAPI-Q model was the quantitative analysis model for operators' behavior. The MAPI-T model was used for behavioral qualitative analysis of operating crews. The MAPI-TQ model was used for behavioral reliability quantitative calculation of operating crews. The MAPI-T and MAPI-TQ model were engineering application model specialized for DCS+SOP.

III.E. Engineering Application

For LingAo II NPP, this project analyzed 37 human factor events by utilizing the MAPI-T and MAPI-TQ model. The HRA report of LingAo II NPP for construction design phase utilized the SPAR-H method [15]. Comparing the results of SPAR-H method and MAPI method, we found that the human error probability calculated by MAPI method was lower than SPAR-H method, which means the new method overcomes the disadvantages of overly conservative of SPAR-H method. The new approach reflects differences in HEP of the same human factor event at different accident background. The new approach we proposed has a more comprehensive analysis for operators' cognitive process. It can reflect the cognitive weakness of operators when they dealt with accident. Based on our results, it also provides some specific advices for operator training and plant improvement.

IV. Discussion and Conclusion

This project systematically studied the human reliability issues associated with digital NPPs, and some results have been applied in LingAo II NPP. This paper is only a part of introduction about this project. Our research work was based on the characteristic of LingAo II NPP, which is 'DCS+SOP'. So if the characteristic of a nuclear power plant is 'DCS+EOP', some of results should be revised. We will improve the theories, methods, and models during application process.

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