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Study on operator's SA reliability in digital NPPs. Part 3: A quantitative assessment method

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ABSTRACT

Situational awareness (SA) is a key element impacting operators' and decision-making and performance in nuclear power plants. SA reliability is an important part of human reliability analysis. In order to quantitatively assess SA reliability, the Bayesian network model of operators' SA reliability analysis in digital main control rooms is built by data analysis. Furthermore, a quantitative assessment procedure of SA reliability is established, and the conditional probability distribution of influencing factors are more objectively determined on the basis of the full-size simulator experiment data of nuclear power plants and Bayesian theory. It is used to quantitatively calculate SA reliability, and a case is used to illustrate specific application of the established model. The results show that the model can provide more reliable data and standardized analysis procedures to support operators' SA reliability evaluation in digital nuclear power plants.

1. Introduction

Situation awareness (SA), which is used within human factor research to explain to what extent operators of safety–critical and complex real systems know what is going on with the system and the environment. It is considered a prerequisite factor for effective decision making and performance (Lee et al., 2012). Due to the loss of Situation Awareness (LSA), failure to complete the complicated follow-up activities will possibly result in disastrous consequences. For example, the operator's failure to keep the right understanding of the status of primary circuit in the nuclear incident in Three Mile Island (He and Huang, 2007). The pilots' loss of the right understanding of the flying status in various air accidents (Woodhouse and Woodhouse, 1995). The research by Endsley points out that among various commercial air accidents resulted from human error, 88% of the accident reason is related to LSA (Endsley, 1994). The analysis report of incidents caused by air traffic control compiled by Jones and Endsley (1995) says that 69% incidents are somehow connected to the failure of information collection in air traffic controllers' SA.

Faced with the continuous change of the system status in the operation of nuclear power plants (NPPs), operators in main control rooms need to deal with lots of information in a dynamic environment. The system's current situation is accurately understood and the right decision is made to ensure the safety of NPPs. Therefore, it is of utmost importance to maintain sound SA in ensuring the safety of NPPs. With the upgrade of information technology and automatic level, the Human-Machine Interface (HMI) in NPPs has evolved from traditional analog system interface to digital system one. The digital Human-System Interface (HSI) has changed the context. For example, information's presence (the limited presence of huge amount of information) (Zhang et al., 2010), procedure (computerized procedure) (Huang and Hwang, 2009), control (soft control) (Lee et al., 2011), task (interface management task) (O'Hara et al., 2002), team's structure, communication and cooperation (O'Hara et al., 2000a) etc. Under the changed context, new problems caused by human factor might occur, especially the operators' SA issue (O'Hara et al., 2009). For example, the information display of control panels in traditional main control rooms is direct and fixed in location, which is helpful for operators to understand the status of the whole power plant. However, the information's locations on digital HSI are not fixed with information being discontinuous, more abstract, physically limited, with less displayed window, and more dynamically hidden. To obtain the status information of power plants, operators must complete it through complicated interface management task such as navigation, configuration screen and etc. The above-mentioned features will increase the cognitive load of operators, consume attention resources, pro-

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duce Keyhole Effect (Seong, 2009) etc., which affect operators' SA, and keep operators out of the loop (Kaber et al., 2006). Hence, operators' SA issue is more outstanding in digital main control room compared to traditional main control room in NPPs. Especially in a high risk system, operators' SA has become the hotspot for research. Endsley (1995), Bendy and Meister (1999), Adams et al. (1995) and others have all developed SA assessment model, which describes the internal process of SA's occurrence of operators in MCR. These models basically describe the basic principle and general feature of operators' dealing with the interaction of information and environment in order to acquire status perception, and contribute to the elaboration of cognitive mechanism of SA and main factors affecting SA. But it doesn't consider the SA feature in digital control system, neither conduct quantitative analysis on the reliability of SA except qualitative analysis. Miao et al. (1997), Kim and Seong (2006) and Dai et al. (2012) have developed the assessment method on quantitative analysis of reliability of operators' SA, and there are also quantitative calculation on SA in CREAM (Hollnagel, 1998) and HCR's (Hannaman et al., 1984) methods for human reliability. However, almost all data are based on hypothesis. Operators' influence by contextual environment has not be fully taken into consideration. The causal relationships of contextual factors has not be taken into consideration. It might cause the possibility of repeated calculation of its influence and lead to the wrong estimation of the failure probability of SA. Therefore, to reflect the contribution of SA reliability to human factor risk in a more objective manner, this article provides a procedure to quantitatively assess operator's SA reliability on the basis of data-driven SA causality model established in Paper 2 (Li et al., under review) to serve HRA of NPPs.

2. Operator's SA causality model

When NPPs are in an abnormal state, an operator will make a reasonable and logical explanation based on NPPs' state parameters to evaluate the plants' condition and take it as the basis for follow-up plan and action. The serial action process is called SA (O'Hara et al., 2000b). The operator's correct situation assessment on abnormal events is of vital importance to his or her correct response.

According to data-driven SA causality model in Paper 2 (Li et al., under review) and its characteristics, to better obtain data of simulator experiment. An experts' team (16 persons including the group of operators in NPPs and human factor experts, of which there are 12 senior operators with 2–5 years' experience, and 4 human factor experts) are constructed to somewhat revise the factors influencing operators' SA reliability and its causality. The assumptions have been made as follows:

(1) In abnormal situation of NPPs, operator's work attitude dealing with incidents is generally very good, errors of situation awareness (ESA) will not occur because of operator's attitude problems. Therefore, the modified SA causality model does not consider the effects of work attitude on SA reliability.
(2) The concept of organizational design is a very abstract and compound factor. It is difficult to develop appropriate standards for objective evaluation. In addition, it is root node far from the SA reliability node, so its impacts can be substituted by the specific and measurable factors. Therefore, organizational design factor is removed, which does not change the results of SA reliability.
(3) Technology system is also a very abstract and compound factor. Since it cannot be removed, so it is decomposed into two specific factors, namely the time available for accident mitigation and automation level which determined by technology systems. The time available affects operator's stress level. The automation level affects the information presentation level of system state, which is consistent with the actual situation and actual results of human factor event analysis.

Generally speaking, when an abnormal event occurs in a nuclear power plant, an operator's situation assessment involves two relevant models, namely state model and mental model (O'Hara et al., 2002). State model is the operator's understanding of the specific state of the system or components, and when new information is received, state model is usually updated. Metal model, stored in brains, is constructed by formal education, specific training and the operator's experience. Situation assessment process is to development a state model to assess the power plant's current state. If the operator wish to make a good assessment on the true state of the power plant, he or she need to utilize the mental model to identify the current state of the power plant, which is affected by the legibility of the power plant's state, the operator's mental level or model or psychological pressure. Mental level or model comes from the operator's knowledge and experience which are mainly influenced by organizational training and team's communication and cooperation. If the operator is not trained enough, his or her knowledge and experience will be affected, and team's communication and cooperation can complement individual operator's insufficiency in this regard.

The legibility of the state of the power plant (another explanation of state model) is mainly affected by the digital HMI and the automatic level of system. If the design of digital HMI is good, the information is eye-catching and can be easily collected, and the state of the system can be easily identified. If the automatic level of the system is high, the operator is not involved in specific tasks and will be easy to lose the understanding of the system state related to tasks. In addition, the level of pressure has a great influence on the operator's match to state model and mental model. The level of pressure is mainly affected by the task's complexity and the available time. The task's complexity is affected by the good or bad digital procedure design and digital HMI design. If the task is complicated in the procedure, the operator needs to complete complicated task. If the procedure is good, it is conducive to guiding the operator to make a response plan. If HMI is not good (such as many interface management tasks), the operator is unable to acquire useful information for completion of the task. Furthermore, the shorter available time it has to complete the task, the greater psychological pressure the operator faces. Therefore, through experts' discussion and analysis, the modified SA reliability is mainly affected by level of team's communication and cooperation, level of training, digital procedure, digital HMI, available time to deal with incidents, automatic level of the system and so on. Fig. 1 shows the relationship between the performance shaping factor (PSF) and the SA reliability (or Bayesian network model of SA reliability), in which the lowest SA reliability is one kind of SA reliability node.

3. Quantitative assessment of operators' SA reliability

3.1. Bayesian reasoning

Bayesian network (BN) is the directed acyclic graph (DAG) composed of nodes and edges, and can be described as $N=\langle\langle V, E\rangle, P\rangle$. The node corresponding to discrete random variable $V=\{X_1, X_2,\ldots, X_n\}$ is the node with finite state. Node can be any abstract issue, such as the state of equipment and components, test value, organizational factors, human diagnosis results etc. Directed edge E is