Design of a human error analysis experiment by eye tracking technology for soft control in MCR of nuclear power plant

WANG Junbo[1], YANG Ming[2], and ZHANG Yuxin[1]

1. College of Nuclear Science and Technology, Harbin Engineering University, No.145 Nantong Street, Harbin 150001, China (wangjunbo@hrbeu.edu.cn; yuxinzhang@hrbeu.edu.cn)

2. School of Electric Power, South China University of Technology, No.381 Wushan Road, Guangzhou 51000, China (yangm@scut.edu.cn)

Abstract: With the rapid development of digitalized technology, adoption of advanced Main Control Room (RCM) in Nuclear Power Plants (NPPs) has become an inevitable trend. However, the Human Machine Interface (HMI) and Man-machine Interaction (MMI) based on digitalized technologies will also introduce new types of human error and new risks into main control room. Traditional human error analysis is based on post-test interview and questionnaire survey which suffers from difficulty in backtracking the experiment for tracing to the sources of human errors of operators. This paper presents an experimental research on utilizing an eye tracking device for studying the characteristics of operators during they interact with NPP through HMIs by soft control. The presented approach can also be applied for the statistics of human errors and analysis of causes which will useful for the Probabilistic Safety Assessment (PSA), improvement of HMI design and operator training

Keyword: soft control; eye movement analysis; reliability engineering; human error

1 Introduction

Nuclear power is a clean and renewable energy, but accompanied by the risk of radioactive materials release. Ensuring safety functions the basis of the existence and development of nuclear power. Human error is considered the major contributor to the occurrence of the events or accidents in the nuclear power plants around the world. According to the World Association of Nuclear Operators (WANO), human errors by operators had contributed to 551 running events from the year of 1993 to 2002, over 58 percent of the total numbers of events. The Main Control Room (MCR) where implements centralized monitoring and control is the most frequent place for Man-Machine Interactions (MMI) and plays a vital role in the safe operation of nuclear power plants. Human error in MCR has being paid much more attention since Three Miles Island (TMI) nuclear accident which was caused by mechanical failure and human error.

Nowadays, more and more nuclear power plants (NPPs) utilize digital instrumentation and control (I&C) systems to improve plant performance and maintain higher levels of safety. Digital technology has incomparable advantages in acquiring, transmitting and processing information, as well as the execution and coordination of tasks. As an integral part of the I&C systems, the control rooms with Human-Machine Interfaces (HMI) are also equipped by modern digital equipment. Different from the traditional discrete analogy controls and displays, the modernized digital control rooms have many new characteristics, including large screen displays, Video Display Units (VDU), soft controls, computerized procedures, advanced alarm systems and so on. Soft control refers to the operation of a virtual icon on the computer screen to complete the operation control. In the context of soft control, devices, systems, and display systems are indirect rather than direct physical connections through software [1]. Operators control the plant using soft controls that are accessed through computer workstations, and use computer-based procedures (CBPs) that offer the potential to undertake control actions directly from the procedure display, including semi-automated control measures where the operator authorizes the procedure to perform a series of actions [2]. Comparing with the conventional hardware-based control mode, the HMIs and MMIs in soft control environment have changed significantly: On one hand, more system and

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equipment operation information can be available which will help to improve the operators' situation awareness and the plant operation by operators becomes more flexible and more convenient, On the other hand, the new types of HMIs and MMIs will also introduce new types of human error and new risks into MCR [3]. As a large amount of plant information is distributed into a number of screens, operators need to switch between multiple interfaces in order to obtain sufficient information, interface management become difficult. Human error is most likely to occur in emergency and unfamiliar environment because the operators will suffer great mental pressure and workload in monitoring and dealing with more operation information than ever. In addition, human error reduction by cross-checking becomes also difficult.

Human Error Analysis (HEA) is to analyze the abilities (probabilities) of operators interacting with nuclear power plant by soft control in specific environment and specific mission time. HEA could be applied for the following purposes [4-5]: (1) Provide data input for Probabilistic Safety Assessment (PSA); (2) Identify the human errors and trace to their sources; (3) Provide well-directed suggestions for the operator training, improvement of HMI and operating procedures.

Traditional human error analysis is based on post-test interview and questionnaire survey. This method can identify and record the human error mode, but there are also shortcomings. The mental and psychological state cannot be observed when human error occurs, and the mental stress and cognitive load caused by some specific factors to operator cannot be revealed. It also usually suffers from difficulty in backtracking the experiment for tracing to the sources of human errors.

Eye tracking system is used to record the binocular movement of operators video-oculography technology during they interact with system through HMIs. Since eye movement belongs to nerve reflex activity as human muscle movement, the conscious action of human is inevitable during external stimuli activate the eye movements through the central cortex of the brain [6]. This involuntary nerve reflex can reflect the physiological and mental state of human when human error occurs. By further analyzing the binocular movement data of operators, such as the point of gaze, the motion of Line of Sight (LOS), which will change as they implement specific tasks through HMIs, the cognitive process and workload of operators can be reflected and the sources of human errors may be revealed. Physiological data acquisition from eye tracking system is faster than the data acquired through subjective questionnaire survey [7]. Furthermore, the physiological data from the eye tracking system is more objective and accurate. The eye movement experiment by eye tracking system is also one of the most important experimental means for the HMI evaluation [8].

This paper presents an application of eye movement technology in human reliability experiment for human error statistics and human error cause identification under a condition of starting the Chemistry and Volume Control System (CVCS) at Pressurized Water Reactor (PWR) by soft control.

2 Eye movement experiment design

2.1 Experimental facility

Figure 1 shows the facilities used in the eye movement experiment including:

(1) Head-mounted eye tracker made by SMI Company: is used for recording the eye movement of participants;

(2) iViewPC: is used for driving the eye tracker and collecting eye movement data;

(3) BeGaze software: is used for analyzing the eye movement experimental results;

(4) Instructor station: is installed with a full-scale simulation program of PWR for simulating the actual operation of NPP;

(5) Control terminal: communicates with simulator for providing the plant information and operating procedures by two LED screens and providing soft control functions.

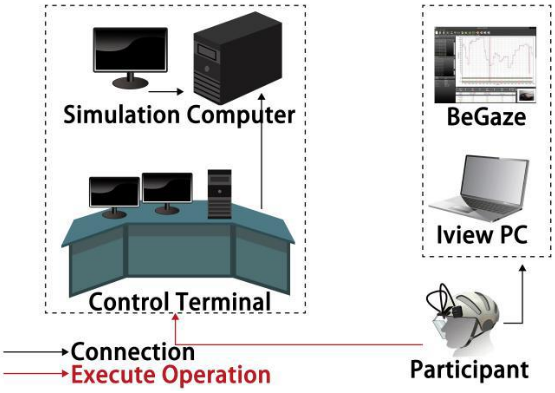

Fig. 1 An example of figure.

2.2 Experimenters

The personnel participating in eye movement experiment include the following persons:

(1) One examiner: is in charge of simulating the experimental scenarios.

(2) Ten participants: are majored in nuclear engineering program and classified into two groups in which one (Group I) consists of unskilled persons and the other (Group II) consists of skilled persons. The participants are equipped with eye tracker and implement required missions by means of soft control on the control terminal.

(3) One supervisor: is familiar with nuclear power plant operation and soft control and provide cross-check functions for the participants under a situation of participants with supervision.

(4) One technician: is in charge of eye tracker settings. In addition, it is necessary to add that all the participants in the study were undergraduates or graduate students at the university. Some of them have background knowledge of nuclear science, and others do not have relevant knowledge. The experimental results may be different from the operation of a nuclear power plant operator, but the purpose of this study is to provide an approach to eye movement experiments.

2.3 Experimental procedures

The eye experiment involves the following steps.

(1) Mission training: make all participants clear the operation of targeting system and the relative manipulation by means of soft control.

(2) Experiment preparation: start iViewPC and connect with eye tracker. The examiner is seated, equipped with eye tracker, and keep 70±10cm away from the display.

(3) Eye tracker settings: firstly run eye movement data record program, then calibrate the system by using five points at middle, upper left, upper right, lower left and lower right, finally validate the calibration. If the accuracy meets the experimental requirements, then start the experiment.

(4) Mission execution: the participants select the screens of CVCS. The screen on the left side provides operating procedures, while the screen on the right side provides CVCS configurations. The participants execute the operating procedures according to the operating procedures.

(5) Data collection: the eye movement parameters and experimental videos are saved after every examiner finishes his experimental missions.

(6) Human error mode analysis: analyze the human error modes and count their numbers through backtracking the experimental videos.

(7) Cause analysis: identify the causes of each human error by backtracking the experimental videos and investigating the visual indicators of participants.

Table 1 Task sequence of CVCS starting procedures.

<table>
<tr><th>Task</th><th colspan="2">Subtasks</th></tr>
<tr><td rowspan="14">Purify the reactor coolant by charging pump NSSS was already depressurized</td><td colspan="2">Close the letdown valve</td></tr>
<tr><td colspan="2">Close the charging valve</td></tr>
<tr><td colspan="2">Fully open the isolating valve of RRA-RCV line</td></tr>
<tr><td colspan="2">Open the containment isolating valve "130VD"</td></tr>
<tr><td rowspan="2">Establish the injection flow of shaft-seal #1</td><td>Open the isolating valve of seal-water injection</td></tr>
<tr><td>Instantaneously open the injection valve of shaft-seal#1□maximum to 15%□</td></tr>
<tr><td colspan="2">Open the containment isolating valve "082VP"</td></tr>
<tr><td colspan="2">Open the isolating valve of charging line</td></tr>
<tr><td rowspan="3">Gradually open the low-pressure letdown valve to avoid water hammer</td><td>Connect the switch to RCP037MP</td></tr>
<tr><td>Set the handed control console to be "Automation"</td></tr>
<tr><td>Adjust the 013VP controller to ensure the RCP pressure at initial valve</td></tr>
<tr><td colspan="2">Manually increase the charging flow to ca. 10m3/h according to the readings of the water level of 002BA (018MD)</td></tr>
<tr><td colspan="2">Connect the tee valve to demineralization plant</td></tr>
<tr><td colspan="2">Adjust RCV013VP controller to keep the system pressure of RCV, check the letdown flow readings and monitor the water level of 002BA (018MD)</td></tr>
</table>

2.4 Experimental mission

In this study, starting CVCS under a normal cold shutdown condition is taken as the experimental mission. One of the major tasks in this condition is to purify the reactor coolant by charging pump of CVCS. The involved operating procedures consist of 19 subtasks and 70 steps which will be implemented on 4 computer screens. The task and relative subtasks involved in the eye movement experiment are shown in Table 1.

3 Human error mode analysis

Table 2 shows the human error modes involved in the implementation of soft control in eye movement experiment. Each error mode corresponds to one of the following operation type, *i.e.*, operation selection, screen selection, device selection, and operation execution [9]. The criteria for human error mode identification are as follows:

Table 2 Human error modes in soft controls.

Operation type	Human error mode	
	Number	Explain
Operation selection	E0	Operation Selection Omission
Screen selection	E2SS	Wrong Screen Selection
Equipment selection	E2DS	Wrong Device Selection
Operation execution	E1	Operation Execution Omission
	E3	Wrong Operation
	E4	Mode Confusion
	E5	Inadequate Operation
	E6	Delayed Operation

(1) Operation Selection Omission (E0): miss a necessary task during the execution of an operation procedure.
(2) Wrong Screen Selection (E2SS): select a wrong screen while performing a task.
(3) Wrong Device Selection (E2DS): select a wrong device while performing a task.
(4) Operation Execution Omission (E1): select the right step and right control device, but the operation is not performed due to taking improper soft control.
(5) Wrong Operation (E3): execute a wrong operation, for example, when the participant ought to press the “open” button of valve, but he mistakenly pressed the "close" button.
(6) Mode Confusion (E4): perform a wrong mode if the window contains multiple modes. For example, if the level controller and pressure controller of pressurizer are arranged in the same window, a participant may wrongly increase the pressure when he initially hopes to increase the water level.
(7) Inadequate Operation (E5): perform a correct operation, but not adequately.
(8) Delayed Operation (E6): one cannot complete the operation in the required mission time due to unskilled operation, complicated procedures involved, or bad design of HMI.

If a participant can independently find any error he made and recover it, then the mission can be implemented successfully, otherwise, the mission will be failed. The human error of an participant failing in recovering above mention human error modes Ei are called recovery failures (Ri) of Ei (i=0, 2SS, 2DS, 1, 3, 4, 5, 6). In addition, the error caused by the supervisor’s failure in finding any error mode of participant is called supervisory error.

Table 3 Form exemplar for human error statistics.

Step	Number of Human errors							
	0	1	2SS	2DS	3	4	5	6
4.1 Select Subtask4								
4.2 Click "310VP" button								
4.3 Click "AUTO" button								
4.4 Click "OK" button								
4.5 Set 100% Opening								
4.6 Click "OK" button								

By backtracking the experimental videos, the types and the number of human errors can be identified and counted conveniently. Table 3 presents form exemplar for human error statistics in the eye movement experiment. These data will be used for the statistical analysis of human error probability in soft control.

4 Cause analysis

In this study, the three criteria including fixation, saccade and pupil diameter were selected for identifying the causes of human error.

4.1 Fixation analysis

The fixation points and fixation time are crucial indicators for the amount of visual attention of participants observing stimuli. Fixation is the LOS of a participant staying in a certain area of the HMI. Fixation time indicates whether the subject information in this area is sufficient to cause the attention of the participant, or to make him hesitate. A fixation area of participant is indicated by a heat map where the high temperature area with red color represents a long time of fixation. The heat maps revealed that the participants' visual attention was focused on the center of the explosion form from which the visual focus gradually extended outward. Fixation analysis can be used for revealing the skill level and cognitive load of a participant, as well as the design level of a HMI.

Figure 2 shows the fixation heat map of a participant who made a "device selection error" (E2DS) during preforming subtask 4 "Fully open the isolating valve of RRA-RCV line". It can be seen that the participant's fixation area stayed at 036KG control button while the step he was required to perform is "Click 310VP button". This indicates that the participant is not so familiar with the system configuration shown in the operating screen.

Figure 3 shows the fixation heat map of a participant who made an "Operation Execution Omission" error during performing subtask3 "Close the charging valve". During the participant performed this subtask, his LOS did not stay at the confirm button, instead he directly clicked the close button and exited operation. This reflects the shortcomings of the HMI design that it didn't give a tip that the related operation was not executed.

From fixation analysis, the fixation points or fixation areas of participants can be available which could be helpful in identifying the causes of several human error modes including "Operation Selection Omission", "Wrong Screen Selection", "Wrong Device Selection", "Operation Execution Omission" and "Delayed Operation", *etc.*

4.2Saccade analysis

Saccade is controlled by the central nervous system of voluntary movement, showing a sudden change of eyeball gaze or watch range. Human when watching a scene, the eye is not fixed, but moving around and positioning in the scene of interest, to establish the corresponding mental map in the brain, and the establishment of the topological structure of the saccade map on the retina. Its function is to change the fixation point, so that the next vision of the target falls in the most sensitive area of the retina, so that the observed object is clearly seen. Saccade is a quick, simultaneous movement of both eyes between two or more phases of fixation in the same direction. The radius of fixation area indicates the time of fixation, the longer the time, the greater the radius. The directed line segment between the central points of the two fixation regions represents the cognitive process as well as the sequence or correlations between operating procedures.

Fig. 2 Fixation heat map of a participant in performing subtask 4.

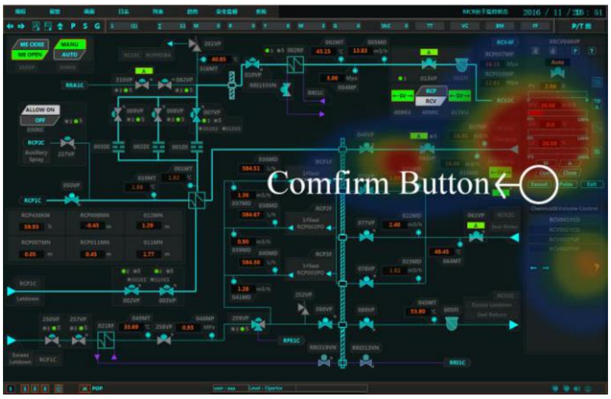

Fig. 3 Fixation heat map of a participant forgetting to confirm the operation.

Figure 4 shows the saccade situation of a participant in Group I during the implemented the subtask 13.1 "Connect the switch to RCP037MP ". It can be seen that the LOS of the participant jumped repeatedly (see the area1 in Fig.4) which indicates the participant encountered an obstacle in identifying the correct item. The reason is 409KC and its items have similar names. When the participant found the correct item and performed "Set 409KC to RCV", he made a “Wrong Operation” error. It can be seen that the LOS of this participant switched many times between "RCV" and "RCP"(see Area2 in Fig.4). The reason of this error is that there was a defect in state indication of control. The valid state was not highlighted. Therefore, several suggestions were given to the HMI designer to improve the shapes, naming method and display mode of controls in order to avoid the occurrence of same error. Figure 5 shows the saccade situation of a participant in Group II who correctly perform the same task. It can be clearly seen that for executing the same mission both jumping times of LOS and fixation areas of skilled participants are relatively smaller than unskilled ones which indicates improving the operation skill of persons can effectively reduce the occurrence of human errors.

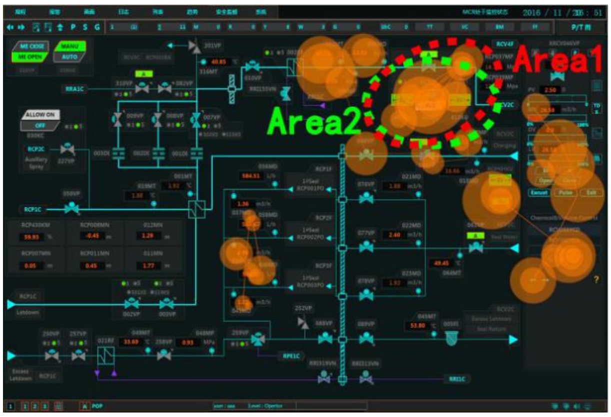

Fig. 4 The saccade situation of a participant in Group I making a wrong operation error.

Fig. 5 The saccade situation of a participant in Group II implementing the same operation successfully.

4.3 Pupil diameter analysis

The pupil is a hole located in the center of the iris of the eye that allows light to strike the retina. In theory, the pupil diameter of a participant will vary with the changes of mental stress and cognitive load. Transient pupil dilation can be evoked following the appearance of salient stimuli, and is systematically modulated by stimulus saliency, with faster and larger evoked responses for higher stimulus contrast. Salient events in the environment initiate orienting responses including saccade and pupil dilation. The pupil diameter of a participant will have a trend of increasing in case the mission involves a large number of information to be processed.

Figure 6 shows the changes of pupil diameter of 10 participants during the eye movement experiment. It can be seen that the pupil diameters of all participants have the similar trend of increasing during the implementation of subtasks 4, 13 and 14. The statistical results also show that the participants have more human errors in these phases. It is because subtask 13 involves the largest number of steps and subtasks 4 and 14 are difficult to execute. It indicates that there is a certain correlation between the pupil diameter and the probability of human error. Therefore, the effects of MMI improvement on the reduction of human errors, such as simplification of operating procedures and introduction of technical support, could be evaluated by comparing the pupil diameter changes of participants before and after the introduction of improvement.

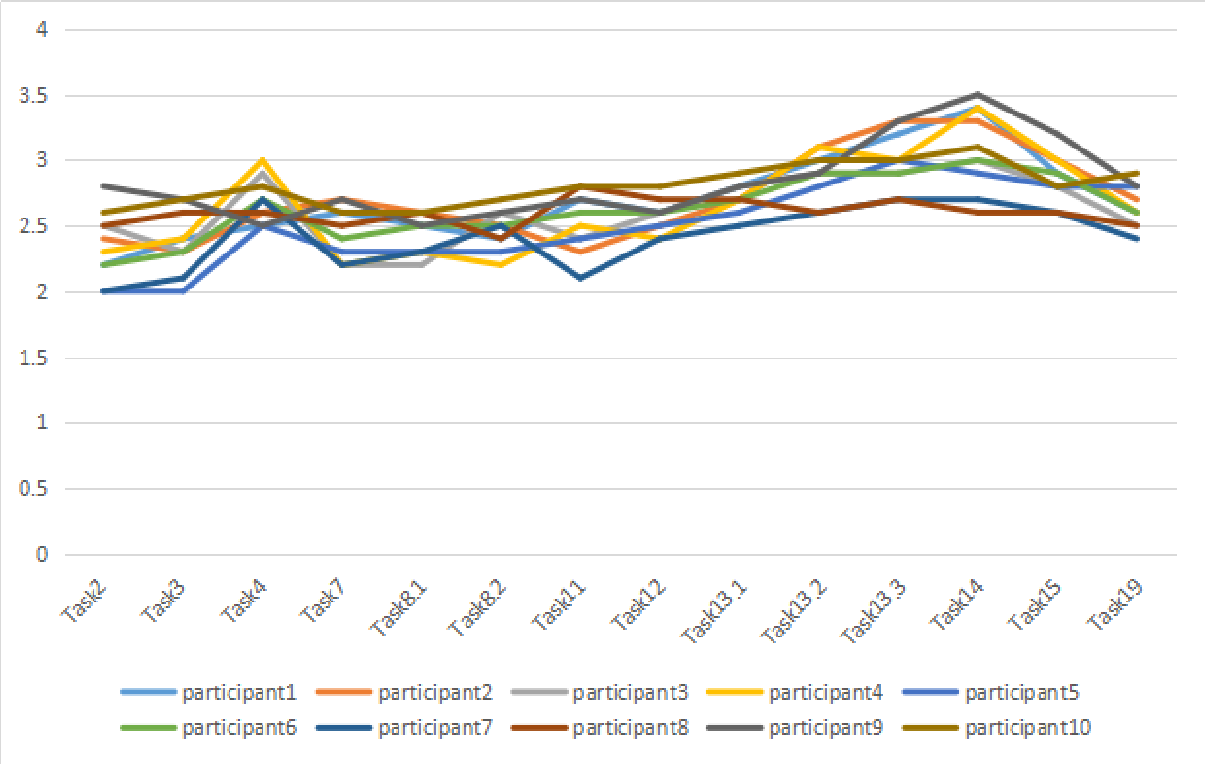

Fig. 6 Pupil diameter in mm versus 14 different tasks
(Different color of each graph indicate each of 10 participants measured in the experiment).

5 Conclusions

Soft control makes the monitoring and controlling of nuclear power plant more convenient on one hand, and introduces new types of human error modes on the other hand. Bad designs of HMI and MMI may increase the probability of human errors. The traditional human error analysis is based on post-test interview and questionnaire survey which suffers from difficulty in the identification of the root causes of human errors.

This paper presented an eye movement experiment in human error analysis for soft control in advanced MCR at NPP using a case study of starting CVCS in a normal cold shutdown condition. It should be noted that the participants in this research were students of university, the cognitive process revealed by the experiment results may be different from that of the operators in implementing the same tasks by soft control. However, this paper demonstrated that by backtracking the eye movement experimental video, not only various human error modes of soft control can be identified which will provide a basis for data statistics, but also the causes of human error modes can be traced by comprehensively taking the mission, the visual criteria of users and the characteristics of HMI into account which will provide useful and well-directed suggestions for the improvement of operator training, HMI design and operating procedure optimization. Eye movement experiment can be considered as a valuable supplement to the traditional post-test interview and questionnaire survey.

Acronyms

CBP:	Computer-Based Procedures
CVCS:	Chemistry and Volume Control System
HEA:	Human Error Analysis
HMI:	Human Machine Interface
LED:	Light Emitting Diode
LOS:	Line of Sight
MCR:	Main Control Room
MMI:	Man-machine Interaction
NPP:	Nuclear Power Plant
PSA:	Probabilistic Safety Assessment
PWR:	Pressurized Water Reactor
TMI:	Three Miles Island
VDU:	Video Display Units
WANO:	World Association of Nuclear Operators

References

[1] STUBLER, W.F., O'HARA, J.M., and KRAMER, J.: "Soft Controls: Technical Basis and Human Factors review guidance" NUREG/CR-6635. Washington D C: USNRC, 2000.

[2] O'HARA, J.M., GUNTHER, W., and MARTINEZ-GURIDI, G.: "The Effects of Degraded Digital Instrumentation and Control Systems on Human System Interfaces and Operator Performance: HFE Review Guidance and Technical Basis", Las Vegas NV: BNL, 2010: 7-11.

[3] SONG, M.C., YANG, M., and GOFUKU, A.: "Functional Modeling for Operating Procedure Tasks of a Chemical and Volume Control System in PWR", Nuclear Safety and Simulation, 2015, 6(2): 155-166.

[4] HASHIM, M., YOSHIKAWA, H., and YANG, M., *et al.*: "Development of Reliability Monitor by GO-FLOW Methodology for the Safety related Sub-systems in PWR", International Journal of Nuclear Energy Science and Technology, 2014, 8(1): 21-36.

[5] HASHIM, M., YOSHIKAWA, H., and MATSUOKA, T., *et al.:* "Quantitative Dynamic Reliability Evaluation of AP1000 Passive Safety Systems by using FMEA and GO-FLOW Methodology", Journal of Nuclear Science and Technology, 2014, 51(4): 526-542.

[6] HYOENAE, J., RADACH, R., and DEUBLE, H.: "The Mind's Eye: Cognitive and Applied Aspects of Eye Movement Research, North Holland: Elsevier, 2003.

[7] FANN, S.C., CHUANG, M.C., and HSU, C.C.: "Relationship between Eye Fixation Patterns and Kansei Evaluation of 3D Chair Forms", Display, 2017, 50: 21-34.

[8] NYSTROEM, M., HOOGE, I., and ANDERSSON, R.: "Pupil Size Influences the Eye-Tracker Signal during Saccades", Vision Research, 2016, 121: 95-103.

[9] LEE, S.J., KIM, J., and JANG, S.C.: "Human Error Mode Identification for NPP Main Control Room Operation Using Soft Controls", Journal of Nuclear Science and Technology, 2011, 48(20): 902-910.