An Empirical Approach to the Relationship between Performance Shaping Factors and Operator Performances in Nuclear Power Plants

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This study designs an experiment which investigates the relationship between performance shaping factors and operator's performances. This study selects PSFs that are controllable in the experiments. The selected PSFs are 1) experience/training, 2) complexity, and 3) urgency. Six scenarios have been developed to reflect the PSFs. Licensed operators participate in the experiment and an APR1400 simulator is used. During the experiment, operator's performances such as completion time, error, secondary task, workload, and situation awareness are measured and collected. The experimental result indicates that experience/training affect operator's performances, i.e., average completion time per instruction, time to entering the cooldown of reactor coolant system (RCS), and error rate.

I. INTRODUCTION

Performance shaping factors (PSFs) are any factor that influences human performance in the Human Reliability Analysis (HRA) (Ref. 1). Most of currently applicable HRA methods to nuclear power plants (NPPs) use PSFs to highlight human error contributors as well as to adjust basic human error probabilities (HEPs) which assume nominal conditions (Refs. 2, 3, and 4). Examples of PSFs considered by HRA methods are experience, procedure, stress, and complexity of task.

For the purpose of adjustment of HEPs in HRAs, it is necessary to estimate quantitatively how much a PSF affects operator's performances in the condition of interest at NPPs. The methods to obtain quantitative estimation about PSFs' influences can be divided into three approaches as follows (Ref. 5).

- Data from actual historical measurements
- Expert judgement
- Data from simulator studies and from experimental research

Use of the data from actual historical measurements is the best way to the most realistic estimation of PSF's influences on operator's performances. However, a difficulty of this approach is the data scarcity because accidents, near misses and human errors are very rare in actual NPPs. In addition, it is impossible to control operating conditions of NPPs for studying the influences of PSFs, e.g., varying the quality of procedure in the actual operation. Second, the approach of using expert judgement relies on experts' experiences and knowledge to quantify the PSF's effect. Many HRA methods have applied this approach to the estimation of HEPs as well as PSF's impact on HEPs (Ref. 6). Even if this may be easier than the other approaches in the quantification process, it requires great carefulness to avoid subjectiveness and bias in selecting experts and aggregating their expertise. Third, using simulator studies and experimental researches is regarded as a good alternative to compensate for the weakness of the other approaches. It can collect more data than one that uses the data from historical measurement and also can minimize the effect of subjectiveness and bias issues in the expert judgement. Fidelity of experimental environment to actual NPPs' conditions is a key issue to obtain meaningful data. For instance, the simulated environment should replicate exact condition of events in the real situation of NPPs. Additionally, there is a possibility that participants may not treat the activity as seriously as a real event. In spite of this fidelity issue, several studies have recently been carried out to use simulators and experiments for collecting HEP and PSF data (Ref. 7).

Application of digital technology to the design of main control room (MCR) is a recent trend in NPPs. The features that distinguish digital control rooms from conventional, analog ones in nuclear power plants (NPPs) include advanced alarm systems, graphic information display systems, computerized procedure systems, and soft control. These features may bring out changes in operator tasks, changing the characteristics of tasks, or creating new tasks. In addition, while this new technology has the potential to improve human performance, the potential also exists to negatively influence the performance and create precursor to human error (Ref. 8).

Although the features of digital control rooms have already been implemented in new or upgraded nuclear power plants, HRAs have so far not taken much credit for these features. One issue in the HRA is lack of the data concerning how the technology affects human performance and how human error probabilities (HEPs) can be adjusted with PSFs. Some studies have been carried out about how new design features can affect operator performances, i.e., for advanced alarm systems (Ref. 9), graphic display (Ref. 10), computerized procedure systems (Ref. 11), and soft control (Ref. 12). However, very few studies have been reported about how PSFs affects operator's performances in the circumstance of digital MCR.

In this light, this paper aims at investigating experimentally the effect of PSFs on operator's performances by using a high fidelity of NPP simulator, i.e., APR1400 simulator. A randomized factorial experiment has been designed to examine whether PSFs affect operator's performances. This study selects three PSFs, i.e., operator's experience, urgency, and complexity of tasks, which are representative PSFs in the HRA as well as controllable in the experiment. Three operator's performances were measured and analyzed, such as time to entering the secondary cool-down, average completion time per instruction, and error rate. An NPP simulator equipped with a fully digitalized human-system interface has been used. Four crews of operators have participated in the experiment. A statistical analysis was also performed to show the relationship between the PSFs and operator's performances.

II. EVALUATION OF PSFS IN DIGITAL CONTROL ROOMS

II.A. Digital Main Control Rooms in Nuclear Power Plants

With the rapid progress of digital and computer technology, NPPs has been incorporating the advanced technology in the design of MCRs. Newly built NPPs around the world such as APR1400 in Korea (Ref. 13), AP1000 in USA (Ref. 14), and EPR-1600 in France (Ref. 15) adopt fully digitalized and computerized control rooms.

There are three major trends in the evolution of digital MCRs: 1) increased automation, 2) use of computer-based human-system interface (HSI), and 3) intelligent operator aids (Ref. 16). The computer-based HSIs and operator aids include the features such as advanced alarm systems, graphic display systems, computerized procedure systems and soft controls. Advanced alarm systems provide processed alarms through eliminating nuisance and/or redundant alarms, and prioritizing, filtering, and suppressing alarms (Ref. 17). Graphic display systems contain a variety of display types including graphic process displays that provide plant parameter information organized around plant system mimics, and predefined as well as operator defined trend displays of plant parameters. The graphic display system can be accessible from any of the operator workstations. Computerized procedure systems can provide different levels of functionality, ranging from systems that simply display a replica of paper-based procedures on a computer screen, to system that automatically retrieve relevant process data form a procedure step and process the step logic as an aid to the operator, to systems that include procedure-based automation (Ref. 18). Soft controls use the input interface connected with control and display systems that are mediated by software, rather than by direct physical connections in analog MCRs (Ref. 19). Fig. 1. shows the primary tasks of NPP operators and the potential supportiveness of new features in digital MCRs.

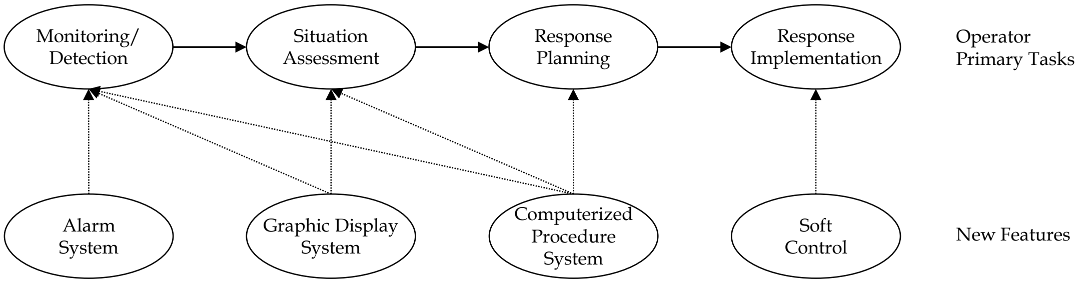

Fig. 1. The potential supportiveness of new features in digital MCRs

These features may bring out changes in operator tasks, changing the characteristics of tasks, or creating new tasks. The computerized HSI may influence how the operators function as a crew (Ref. 20). For instance, the computerized procedure system can provide the shift supervisor with the plant parameter data required to work through the procedures. This may have two direct effects: reduction of the need for low level communication between the shift operators and the board operators and reduction of board operators' cognitive workload (Ref. 21). In addition, this new technology may introduce a new task that has not existed in the analog MCR. An example is the secondary task, also called interface management task. The secondary tasks are performed to access information from workstations, including configuring, navigating, arranging, interrogating, and automating. Interface management effects have the potential of increasing the likelihood of human errors when the interface is poorly designed (Ref. 22).

II.B. Performance Shaping Factors in Digital Main Control Rooms

A PSF is defined as any factor that influences human performance (Ref. 23). In THE ATHEANA Method (Ref. 24), PSFs are a set of influences on the performance of an operating crew resulting from the human-related characteristics of the plant, the crew, and the individual operators. The most commonly used HRA methods in the nuclear industry employ PSFs to adjust HEPs in different conditions. PSFs are also referred to by different terms according to method: performance influence factors (PIFs), influencing factors (Ifs), performance affecting factors (PAFs), error producing conditions (EPCs), and common performance conditions (CPCs) (Ref. 25). HRAs methods generally provide the PSFs analyzed and guidance to assess the state of a PSF through direct measurement or extrapolation. TABLE I presents a summary of PSFs and assessment approaches suggested by HRA methods (Ref.28). Most of HRA methods rely on expert judgement for identifying PSFs and evaluating the effect of PSFs as well as assessing the PSF state for estimating HEPs.

Only a few studies have been reported about the PSFs in the digital MCR. Ref. 26 suggested a systematic approach for qualitative evaluation PSFs in the digital MCR through a literature review. This study considered the context changes that occur in the use of computerized procedure system, graphic information display and soft control. Some studies investigated empirically the effect of training and task complexity in the use of computerized procedure system (Ref. 27). However, more researches that use a high fidelity of experimental conditions to actual NPPs need to be performed to obtain the insight on the effect of PSFs on operator’s performance in the digital MCR.

TABLE I. The summary of PSFs and assessment for HRA methods (Ref. 28)

HRA methods	Suggested PSFs	Underlying theory	Evaluation approach
A technique for human error rate prediction (THERP) (Swain and Guttmann, 1983)	physiological stressors, psychological stressors Task and equipment characteristics Organismic factors Situational characteristics Job and task characteristics	A general descriptive model of human performance in an NPP	Experience and judgment of human factors specialist to assess the impact of PSFs
INTENT (Getman et al., 1992)	HSI, stress, skill, knowledge and rule based behavior (SRK), experience, safety culture, training, motivation, workload, supervision, communication, procedures.	The expert through group consensus techniques	Rating of PSF importance generated independently by each analyst
The human error assessment and reduction technique (HEART) (Williams J.C., 1986)	a channel capacity overload, a need for absolute judgments which are beyond the capabilities or experience of an operator, operator inexperience, a shortage of time available, no clear, direct and timely confirmation of an intended actions, etc.	Error producing conditions (EPC) identified by the author's experience	The effect of EPC in the contextual situation judged by analyst
Cognitive reliability and error analysis method (CREAM) (Hollnagel E., 1998)	adequacy of HSI and operational support, working conditions, adequacy of organization, adequacy of training and experience, available time, crew collaboration quality, number of simultaneous goals, time of day, availability of procedures/plans	Common performance conditions (CPCs) identified through the salient or dominant features of performances, as links in the space of man-technology-organization (MTO)	The ratings of the CPCs assigned by analyst to calculate the combined CPC score and determine the most likely control mode.
Human reliability management system (HRMS) (Kirwan B., 1997)	Time, task complexity, task organization, procedures, training/expertise/experience/competence, quality of information/interface	A large number of techniques and applications surveyed.	Factual questions about the PSFs and then PSF weightings judged.
Standardized plant analysis risk HRA (SPAR-H) (Gertman D., et al., 2005)	available time, complexity, procedures, fitness for duty, stress/stressors, experience/training, ergonomics/HSI, work process	Human behavior model and PSF comparison between HRA methods was performed.	PSF multipliers based on the authors' observation/review of event statistics and on a comparison with data in existing HRA methods.
A technique for human error analysis (ATHEANA) (U.S. NRC, 2000)	applicability and suitability of training/experience, available staffing/resources, suitability of relevant procedures and administrative controls, ergonomic quality of theATHE HSI, operator action tendencies and informal rules, environment, etc.	The context developing process to identify what PSFs and plant conditions are most relevant to the human action being addressed.	HEPs assessed by expert elicitation process.
Information,	cognitive modes and tendencies, emotional arousal,	Survey on psychological literature,	Directly determined by expert judgment,

decision and action in crew context (IDAC) (Chang Y.H.J., Mosleh A., 2007)	strains and feelings, perception and appraisal, memorized information, intrinsic characteristics, environmental factor, conditioning events, organizational factors, team related factors	actual operating evidence, and various HRA methods	field experience and experiment, and auditing system.

III. EXPERIMENT DESIGN

A randomized factorial experiment has been designed to investigate the effects of PSFs on operator's performance in the digital MCR, as shown in TABLE II. The detail of experiment design is as follows.

TABLE II. Experiment design – a randomized factorial experiment design

Time urgency	Complexity of tasks	Scenario No.	Operator's experience	
			Experienced crew	Less experienced crew
Urgent	DBA	1	Performances	Performances
	DBA + Masking	2	Performances	Performances
	BDBA	3	Performances	Performances
Less Urgent	DBA	4	Performances	Performances
	DBA + Masking	5	Performances	Performances
	BDBA	6	Performances	Performances

III.A. Performance Shaping Factors – Controlled Variables

This study chose three PSFs as controlled variables in the experiment: operator's experience, time urgency, and complexity of tasks. The PSFs are those that are commonly taken into account by many HRA methods, as shown in TABLE I.

III.A.1. Operator's experience

Subjects are divided into two groups, i.e., more experienced and less experienced crews. The more experienced crews are composed of the operators who possess operating license for the same type of reactor as the simulator. The less experienced crews are composed of the operators who possess operating license for the different types of reactor from the simulator.

III.A.2. Time urgency

Time urgency represents whether a scenario include any task which should be performed quickly. The scenarios of urgent group require operators to carry out a task within 30 minutes after the reactor trip. The tasks are identified from the assumptions of the deterministic safety analysis and operator's time windows of the probabilistic safety assessment (Ref. 29).

III.A.3. Complexity of tasks

In this experiment, the complexity of tasks refers to how complex diagnosis and execution tasks are in the scenario. Scenarios are divided into three groups along with the complexity of tasks: 1) design basis accident (DBA), 2) DBA + masking of information, and 3) beyond DBA (BDBA). In the DBA scenario, operators follow an emergency operating procedure (EOP), i.e., an event-based procedure which is well established for the accident. The scenario of DBA + masking of information has the additional failure of radiation monitoring system (i.e., N16) to the DBA, which makes the diagnosis task more difficult. The BDBAs are the accident which is assumed not to occur by the NPP design. In this scenario, operators should carry out a functional recovery procedure (FRP), i.e., symptom-based procedure which is focused on the recovery of safety function. It is generally known that the FRPs are more difficult to perform than the EOPs.

III.B. Scenarios

Six scenarios have been developed to reflect the different conditions of two PSFs, i.e., urgency and complexity of tasks. The scenarios are summarized in TABLE III. Scenarios 1, 2 and 3 include an action that should be performed within 30 minutes after the initiation of failure or reactor trip. Failure of N16 indicators, i.e., the radiation indicator of steam line, may make the diagnosis of SGTR and ESDE difficult since the detection of radiation in the steam is one of critical cues in determining those accidents.

TABLE III. The summary of scenarios

Scenario No	Failures	Urgent Action	Complexity of tasks
Scenario 1	Inadvertent opening of an atmospheric dump valve + Loss of offside power (LOOP)	Restoration of opened valve	DBA
Scenario 2	Steam generator tube rupture (SGTR) + Failure of N16 indicators (Masking of information)	Isolation of damaged steam generator	DBA + Masking of information
Scenario 3	Loss of coolant accident (LOCA) + Failure of safety injection system	Aggressive cooldown using atmospheric dump valves	BDBA
Scenario 4	Small break LOCA	None	DBA
Scenario 5	Excessive stem demand event (ESDE) + Failure of N16 indicators (Masking of information)	None	DBA + Masking of information
Scenario 6	Loss of all feedwater	None	BDBA

III.C. Operator's Performance Measurements

In the experiment, three operator's performances are measured: average completion time per instruction, time to entering the cooldown of reactor coolant system (RCS), and error rate.

III.C.1. Average completion time per instruction

This refers to the average time to complete an instruction of procedure. A procedure consists of steps and then a step consists of instructions. An instruction generally includes an operator action in the APR1400 procedure.

III.C.2. Time to entering the cooldown of reactor coolant system

This time measures the period from the reactor trip to starting the RCS heat removal through ADVs, steam bypass cutback system, or feed and bleed operation. In the APR1400, the RCS heat removal is a critical safety function that ensures the stability of NPP, so that EOPs and FRPs request operators to maintain the RCS heat removal in the accident. All the scenarios also ended when the operators successfully enter the procedural step to perform the RCS heat removal.

III.C.3. Error rate

Error rate measures the deviation of operator's task performance from the procedure. The number of errors, including errors of omission and commission, are counted and divided by the total number of tasks in every scenario.

III.D. Subjects

Four crews participated in the experiment. Each crew consists of three operators, i.e., shift supervisor (SS), reactor operator (RO), and turbine operators (TO). All the operators in two crews have operating license of APR1400 so that they are assigned to the more experienced group. All the operators in the other two crews do not have the operating license of APR1400, but other types of reactors so that they are assigned to the less experience group. The average age of all the participants is about 44 years old and the average experience of plant operation is about 13 years.

III.E. Facility and Data Acquisition

A high fidelity of NPP simulator is used as the experiment facility as show in Fig. 2. It contains a plant model of APR1400 which has a fully digitalized MCR. The simulator consists of large display panel and operator's console that can accommodate three operators. Each operator has three computer screens for the operation.

Fig. 2. KINGS simulator

Operator’s performance data such as time and error rate are collected through the observation, audio/video recording and simulator log data. Three or four HRA experts observe the operator’s task performance to collect operator’s error data in the scenario. Audio/video recording is used to analyze the time performance as shown in Fig. 3. Operator’s log data in the simulator are also stored to analyze the time and the secondary task as shown in Fig. 4.

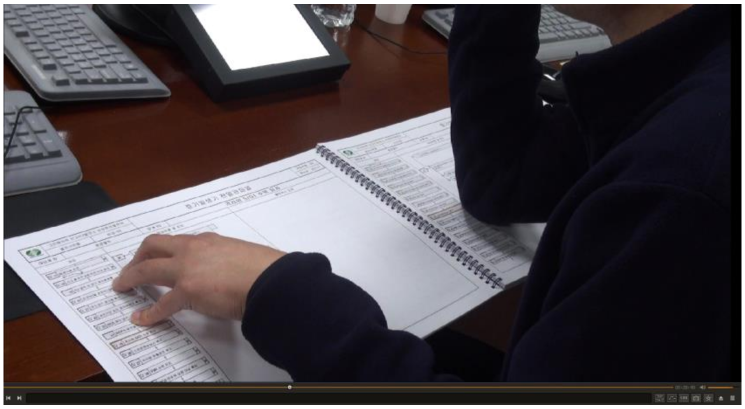

Fig. 3. Audio / Video recording

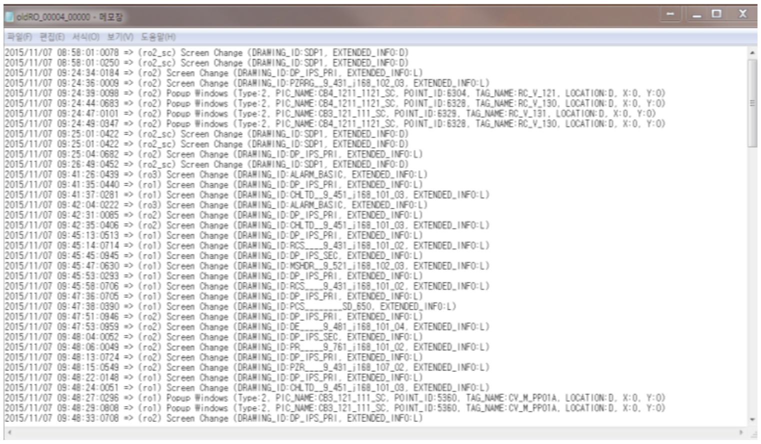

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Fig. 4. Simulator log data

III.F. Experiment Procedure

Each crew conduct six scenarios and the performance data of total 24 scenarios are collected. It takes about six hours for the operators to carry out six scenarios. The less experience group takes additionally one day-training session to get familiar to the digital MCR. Before they perform the scenario, it is confirmed through the test scenario that they show a consistent performance.

IV. RESULT

This study conducts an ANOVA test for the experiment data to analyze the effect of PSFs on the operator's performance. TABLE IV presents a summary of results from the ANOVA test. The more detail of results are as follows.

TABLE IV. A summary of results from the ANOVA test on the PSF's effect on the performance

PSFs	Operator's performances		
	Average completion time per instruction	Time to entering cool down from reactor trip	Error rate
Operator's experience	★★	★★	★
Time urgency	•	•	•
Complexity of tasks	•	•	•

Note: ★★ means that the performance shows a statistical difference for the PSF with α=0.01.
★ means that the performance shows a statistical difference for the PSF with α=0.05.
• means that the performance shows no statistical difference for the factor.

IV.A. Average completion time per instruction

The average completion time per instruction showed the significant, statistical difference only for the operator's experiences (α=0.01). The more experience group spent less time to complete an instruction than the less experienced group. Time urgency and complexity of tasks did not make any statistical difference in the average completion time per instruction. The comparison of experiment data on the average completion time per instruction is shown in Fig. 5.

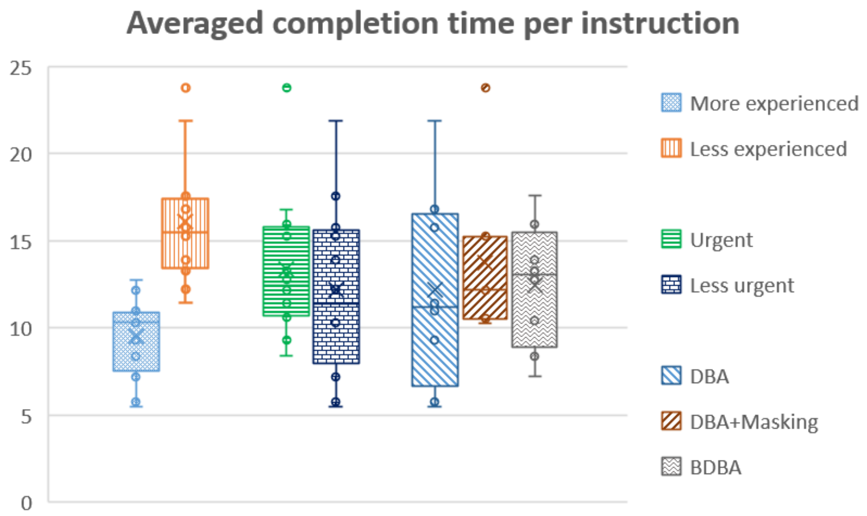

Fig. 5. Comparison of average completion times per instruction to the PSFs

IV.B. Time to entering the cooldown of reactor coolant system

Similarly, the time to entering the cooldown of RCS shows a statistical difference only for the operator's experience (α=0.01). The more experience group entered the cooldown operation of RCS more quickly than the less experienced group. The comparison of experiment data on the time to entering the cooldown of RCS is shown in Fig. 6.

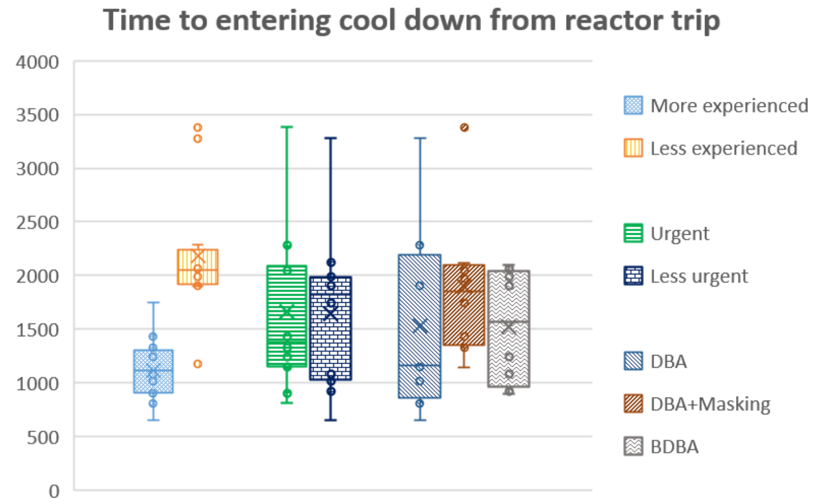

Fig. 6. Comparison of time to entering the cooldown of RCS to the PSFs

IV.C. Error rate

The result indicated that the error rate is also statistically different, depending on the level of operator's experiences (α=0.05). The error rate of more experienced group is lower than that of less experienced group. However, time urgency and complexity of tasks show no statistical difference. Fig. 7. shows the comparison of error rates between the different levels of PSFs.

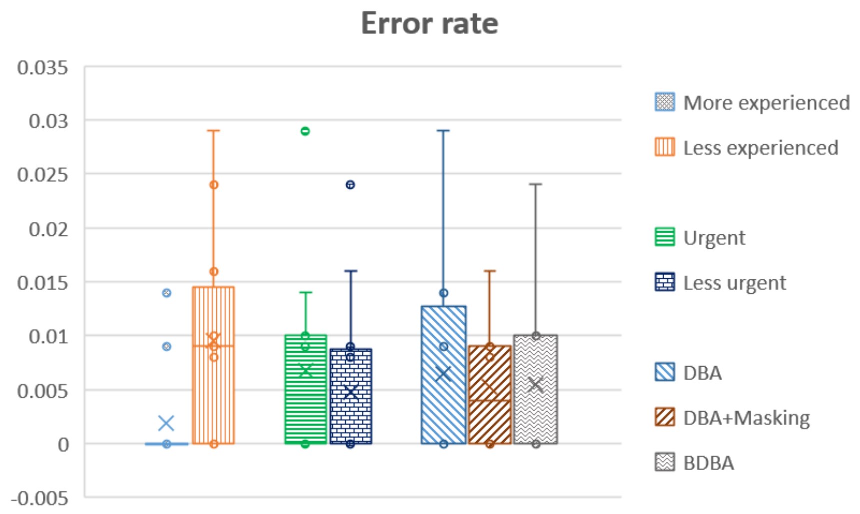

Fig. 7. Comparison of error rates to the PSFs

VI. CONCLUSION

This experiment aimed to analyze the relationship between PSFs and operator's performance in the digital control room. Three PSFs and three operator's performances are considered, and actual operators and NPP simulator are applied in the experiment. A randomized factorial experiment has been conducted with four groups of licensed operators. The experimental result indicates statistically that the PSF of experience/training affects operator's performances, i.e., average completion time per instruction, time to entering the cooldown of RCS, and error rate.

Evaluation and application of PSFs is necessary to quantify human error and calculate the human error probability in HRA. However, current HRA methodologies which are possible to apply to NPPs are relying on expert judgements in the part of PSF evaluation and application. In the case of digital MCR like APR1400, the uncertainty of HRA would be higher than that in the analog one. Therefore, in order to decrease uncertainty of HRA and assess realistic NPP risk, it is necessary to study the effect of PSFs on the operator's performances as well as operator's error through experiments. This study is an on-going research that is collecting the data on the effects on the operator's performances by different PSFs using simulator. This experiment will be conducted continuously and a further analysis on human error and correlation between the PSFs and operator's performances will be carried out. It is expected that this study will contribute to realistic estimation of human error probabilities when it can continue to collect more data.

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