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Human Factors Issues and Measures in Advanced NPPs

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***Abstract*—**Various advanced technologies will be adopted in Advanced Control Rooms (ACRs) of advanced Nuclear Power Plants (NPPs), which is thought to increase operators' performance. However, potential human factors issues coupled with digital technologies might be troublesome. Human factors issues in ACRs are identified and strategies (or countermeasures) for evaluating and analyzing each of issues are addressed in this study.

***Keywords*—**Advanced control room, human factor issues, human performance, human error, nuclear power plant.

I. Introduction

FOR the safe operation of Nuclear Power Plants (NPPs), a well-designed Control Room (CR) has to be installed. Modern computer techniques have been gradually introduced into the design of Advanced Control Rooms (ACRs) of NPPs as processing and information presentation capabilities of modern computers are increased [1], [2]. The design of Instrumentation and Control (I&C) systems for various plant systems is also rapidly moving toward fully digital I&C [3], [4]. For example, CRT- or LCD-based displays, Large Display Panels (LDP), soft controls, a Computerized Procedure System (CPS), and an advanced alarm system were applied to APR-1400 (Advanced Power Reactor-1400) [5]. The main role of human operators in NPP MCRs is generally to supervise and operate the system. As the design of Instrumentation and Control (I&C) systems for various plant systems including NPPs is rapidly moving toward fully digitalized I&C [6], [7], the role of the operators in advanced NPPs shifts from a manual controller to a supervisor or a decision-maker and the operator tasks have been more cognitive works. APR-1400, which is developed and constructed in South-Korea and constructed in UAE, adopts this kind of ACR. There have been raised many challenging human factors issues regarding the ACR Human-Machine Interface (HMI) design. However there have been little extensive experimental studies on these areas, because this area requires multidisciplinary approaches blending nuclear engineering with industrial engineering, behavioral psychology, anthropometry, and physiology.

The author has developed several human performance measures for the evaluation of APR 1400 ACR [8]. These human performance measures include various instruments regarding plant performance, personnel task performance, situation awareness, workload, teamwork, and anthropometric/ physiological factor. The author has developed an analysis system for human factors study in ACR which is named as "HUPESS (Human Performance Evaluation Support System)" based on the developed human performance measures [9]. The HUPESS supports evaluators and experimenters to effectively measure, evaluate, and analyze human performance. The author has developed a systematic HMI evaluation method named "difficulty evaluation method in information searching (DEMIS)" for the studies during monitoring and detection phase [10]. Based on lessons learned from the previous studies [8], [9], important human factors issues associated with ACRs are identified and strategies for evaluating and analyzing each of issues are addressed in this study. In the following sections, the HUPESS and its capabilities are described in brief and human factor issues and strategies (or countermeasures) for evaluating and analyzing each of issues are addressed one by one. If an ACR has deficiencies in its HMI design, the design improvement should be made on the basis of human factors evaluation and analysis results. An evaluation system should have capabilities of finding out that kind of deficiencies in order to correct design deficiencies. It should be noted that strategies (or countermeasures) addressed in this study are attributed to human factors evaluation not design improvement or modification. In other words, the study focuses on how to find out, evaluate and analyze human factors issues rather than how to cope with those issues.

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II. Human Performance Evaluation Support System

Human Performance Evaluation Support System (HUPESS) has been developed for human factors validation in ACRs, specifically for the ACR of APR-1400. The HUPESS consists of hardware systems and software systems. The HUPESS supports evaluators (or experimenters) to effectively measure and analyze a variety of human performance in an integrated manner to produce consistent conclusions.

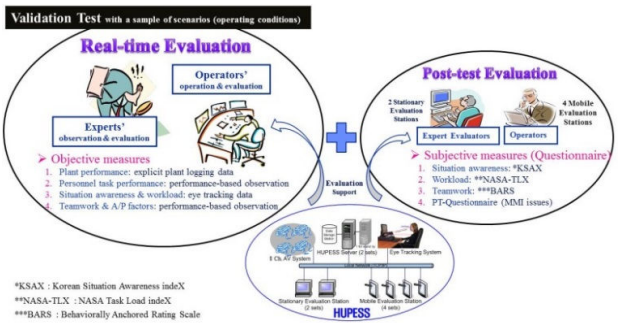

Fig. 1 Overall scheme for the evaluation with HUEPSS

Measures for the evaluation of human performance are evaluated in real-time and post-test steps, as shown in Fig. 1. Plant performance is connected to personnel task performance by time-tagged information. The HUPESS is connected to a simulator of the plant system to acquire logging data

representing the plant state (e.g., process parameters and alarms) and control activities performed by operators. Process parameters are observed and evaluated to see how well the plant system is operated. Design faults or shortcomings may require unnecessary work or an inappropriate manner of operation, even though plant performance is maintained within acceptable ranges. This problem is solved by analyzing plant performance (or process parameters) with operator activities. Inappropriate or unnecessary activities performed by operators are compared with logging data representing the plant state if operator activity is time-tagged. This analysis provides diagnostic information on operator activities. For example, if operators should navigate the workstation or move around in a scrambled way in order to operate the plant system within acceptable ranges, the HMI design of the ACR is considered inappropriate. As a result, some revisions are followed, even though the plant performance is maintained within acceptable ranges. An eye tracking system equipped with five measurement cameras records eye movement of a moving operator on a wheeled chair, as shown in Fig. 2 and provides data for evaluation of situation awareness, cognitive workload and personnel task. Eye-tracking measures for evaluations of situation awareness and cognitive workload are connected to personnel task performance with time-tagged information.

Fig. 2 Five-camera Eye Tracking System (ETS) installed in HUEPSS

III. Human Factors Issues and Counter Measures

Important human factors issues in ACRs have been identified from the previous studies [8], [9] and the literature [11] and strategies for evaluating and analyzing each of issues with the HUPESS are addressed in this section.

A. Poorly and Ill Defined Tasks

Inadequate allocation of function strategy might result in poorly organized and ill-defined tasks. This issue can be evaluated in the integrated analysis with the HUPESS. The times of operator activities are recorded in order to effectively evaluate human performance. Operator activities include unit tasks considered in the evaluation of personnel task performance, example behaviors and critical behaviors in teamwork evaluation, and activities belonging to anthropometric and physiological factors. Time-tagging is easily conducted with the HUPESS. All that evaluators have to do is check items listed in the HUPESS based on their observation. The HUPESS records automatically the checked items and the relevant times. Time-tagged information facilitates the integrated evaluation of human performance in the analysis steps. The evaluations of personnel task performance, teamwork, and anthropometric/physiological factors are analyzed in an integrated manner with time-tagged information, which provides diagnostic information for the evaluation of function allocation.

B. Issues Coupled with Situation Awareness and Workload

Even though operators are expected to be better aware of situation with new technologies in ACRs, there is also possibility that the changed operational environment can deteriorate situation awareness of operators. It is likely that there will be difficulty in navigating through and finding important information which was fixed at dedicated area in conventional control rooms. Operators are trained and experienced with well-learned rapid eye scanning patterns and pattern recognition from spatially fixed parameter displays in conventional CRs. However those abilities might be lost in ACRs, because they navigate through the HMIs in ACRs. Loss of the operator's situation awareness can result from automation and operator aids system. In addition an operator's ability to monitor and process all relevant data might be impaired with shift from physical to high cognitive workload.

Measurement techniques which were developed for situation awareness measurement can be categorized into 4 groups such as performance-based, direct query & questionnaire, subjective rating, and physiological measurement techniques [12], [13]. Performance-based techniques have both logical ambiguities in their interpretation and practical problems in their administration. Direct query & questionnaire techniques can be categorized into post-test, on-line-test, and freeze techniques according to the evaluation point over time [14]. Among them, it takes up much time to complete the detailed questions and answers generally used in the post-test technique, which can lead to incorrect memory problems of operators. In addition, the operator has a tendency to overgeneralize or rationalize their answers [15]. The on-line-test techniques require questions and answers during the test to overcome the memory problem. However, the questions and answers can be considered as another task, which may distort the operator performance [11]. The freeze techniques require questions and answers by randomly freezing the simulation to overcome the demerits of the post-test and on-line-test techniques. It has advantages of being easy to use (in a simulator environment), possessing good external indices of information accuracy, and possessing well-accepted face validity [16]. However a criticism has been that the periodic interruptions are too intrusive, contaminating any performance measures, which is related to the concern that the questions may cue participants (e.g., operators) to some details of the scenario, setting up expectancy for certain types of questions [11]. Subjective rating techniques typically involve assigning a numerical value to the quality of situation awareness during a particular period of

event. Subjective ratings techniques are popular because these techniques are fairly inexpensive, easy to administer, and non-intrusive. However, there have been criticisms. First, participants' (or operators') knowledge may not be correct and the reality of the situation may be quite different from what they believe [17]. Second, situation awareness may be highly influenced by self-assessments of performance [16]. Third, operators will probably be inclined to rationalize or over generalize about their situation awareness [17]. Physiological measurement techniques have been used to study complex cognitive domains such as mental workload and fatigue and very few experiments have been conducted to study situation awareness [18]. Even though physiological measures are likely to require high cost of collecting, analyzing, and interpreting the measures, compared with the subjective rating and performance-based measurement techniques, they have unique properties considered attractive to researchers. First, it does not require intrusive interference such as freezing the simulation. Second, it can provide continuous indication in contrast to the above-mentioned techniques. Third, it is possible to go back and assess situation, because it is continuously recorded.

Generally, techniques for measuring cognitive workload can be divided into two broad types: predictive and empirical [11]. Predictive techniques are usually based on mathematical modeling, task analysis, simulation modeling, and expert's opinions. These techniques do not require operators to participate in simulation exercises. Thus, they are typically used in the early stages of design process and therefore, are thought not to be suitable for human factors validation stage [11]. Empirical techniques can be divided into three types: performance-based, subjective ratings, and physiological measures [19]. Performance-based techniques are categorized into primary task measures and secondary task measures. Primary task measures are not suitable for the measurement of cognitive workload associated with monitoring or decision-making tasks like in NPPs and secondary task measures have the drawback that it can contaminate human performance by interfering to the primary tasks [20]. Subjective ratings techniques measure the cognitive workload experienced by a subject (or an operator) through a questionnaire and an interview. Since subjective measures have been found to be reliable, sensitive to changes in workload level, minimally intrusive, diagnostic, easy to administer, independent of tasks (or relevant to a wide variety of tasks) and possessive of a high degree of operator acceptance, they have been most frequently used in a variety of domains. Physiological techniques measure the physiological change of autonomic or central nervous system associated with cognitive workload [20]. There have been lots of studies which suggested that the eye movement related measures could be used as effective tools for the evaluation of cognitive workload [21]-[25].

For the evaluation of cognitive measures such as situation awareness and workload in a human factors validation, a series of tests which require considerable resources (e.g., time, labor, or money) from preparation to execution should be conducted. Hence economic methods which are able to save resources are required. In order to satisfy this constraint, techniques proven to be empirically practical in various industries should be used as main measures and complementary measures are developed to supplement the limitations associated with main measures. Both the main measure and the complementary measure are used for the evaluation of plant performance, personnel task performance, situation awareness, and workload in the HUPESS. Teamwork and anthropometric and physiological factors are evaluated with only main measure. In addition, all the measures should be developed to be evaluated simultaneously without interfering with each other. For example, if simulator-freezing techniques such as SAGAT (situation awareness global assessment technique) or SACRI (situation awareness control room inventory) are adopted for the evaluation of situation awareness, it is thought that the simultaneous evaluation of workload might be interfered by that of situation awareness. With the HUPESS several questionnaires are evaluated by evaluators and operators after the real-time evaluation, as shown in Fig. 1. The questionnaire-based evaluations include KSAX for situation awareness, NASA-TLX for workload, BARS for the teamwork and the PT (post-test) questionnaire for other issues, respectively. All the questionnaires are provided in computerized form in HUPESS. Evaluators and operators simultaneously evaluate relevant questionnaires after running a scenario. The subjective measure of KSAX is complemented by a continuous measure based on eye fixation data which is a kind of physiological measures with the HUPESS. Since KSAX is evaluated subjectively after a test, it is not possible to continuously measure the operator's situation awareness and to secure the objectivity. The physiological measures are known as being objective and can provide continuous information on activities of subjects. These days, there are developed eye tracking systems which have capability to measure a subject's eye movement without direct contact. Hence the measurement of the eye movement is not intrusive to the operators' activities. In the majority of cases, the primary means of information input to the operator are through the visual channel. An analysis of the manner in which the operator's eyes move and fixate gives an indication of the information input. The eye fixations on areas of interest (AOIs) that are important for solving problems can be considered as an index of monitoring and detection, which then can be interpreted into the perception of the elements (level-1 situation awareness). As we think about or manipulate perceived information in working memory, an action is delayed or not executed at all [20]. Consequently, time spent on the AOIs by the operators can be understood as an index for the comprehension of their meaning (level-2 situation awareness). As mentioned before, the selective attention is associated with expectancy for the near future. The projection of their status in the near future (level-3 situation awareness) is, therefore, can be inferred from the sequence of the eye fixations. In the similar way to the evaluation of situation awareness, the subjective measure of workload (NASA-TLX) is complemented by continuous measures based on eye movement data. Blink rate, blink duration, number of fixation, and fixation dwell time are used as indices representing the cognitive workload. Blinking refers to a complete or partial

closure of the eye. Since visual input is disabled during eye closure, a reduced blink rate helps to maintain continuous visual input. The duration and the number of eye blinks should decrease when the cognitive demands of the task increase. A recent study showed that blink rates and duration during the diagnostic tasks in simulated NPP operation correlated with NASA-TLX and MCH scores, which means that they can be used as a cognitive workload index [25]. In addition, with the HUPESS situation awareness and workload are evaluated in each task step by considering the cognitive aspects specified by the task attribute, which is expected to increase the level of detail for the measurement. Eye fixation data are used for determining if the operators are correctly monitoring and detecting the environment. This information is also used for evaluation of personnel task performance.

C. Workload Increase due to Secondary Tasks

Increase in the operator's cognitive workload might be associated with managing the interface, which is not the primary task. Workload due to primary and secondary tasks is evaluated with the NASA-TLX and eye movement measures provided in the HUPESS, which is in an integrated manner evaluated with other time-tagged information regarding personnel task, teamwork, and anthropometric/physiological factors. Audio-video (AV) recording data provides information which may be missed or not processed by evaluators during a test. Scenes and sounds in ACRs, including the operator activities and HMI displays during specific time periods are replayed with AV recording data. The time-tagged information is compared and analyzed with the AV recording data.

D.Performance Evaluation Criteria

It is not easy to determine evaluation criteria for acceptable levels of performance. The literature [12] summarizes approaches to establishing criteria, which vary based on types of comparisons such as requirement referenced, benchmark referenced, normative referenced, and expert-judgment referenced. Firstly, the requirement referenced is a comparison of the performance in the integrated system considered with an accepted and quantified performance requirement based on engineering analysis, technical specification, operating procedures, safety analysis reports, and/or design documents. Specific values in the plant parameters required by technical specification and time requirements for critical operator actions can be used as criteria for the requirement referenced comparison. When the requirement referenced comparison is not applicable, the other approaches are typically employed. Secondly, the benchmark referenced is a comparison of the performance in the integrated system considered with that of a benchmark system which is predefined as acceptable under the same or equivalent conditions. There was a project for the human factors validation of a modernized NPPCR which is based on the benchmark referenced comparison [26]. The CR of the 30-year-operated NPP was renewed with modernization of the major part of the CR HMI. In the project, it was judged that the human performance level in the existing CR could be used as an acceptance criterion for the human performance in the modernized CR. Hence if the human performance in the modernized CR is evaluated as better than or at least equal to that in the existing CR, the modernized CR can be considered as acceptable. On the other hand, if a totally new CR (i.e., an ACR) is considered for the human factors validation, this approach is also applicable. For example, if the operator workload in an advance CR is not exceeding that in a reference CR (conventional one) which is identified as acceptable, this can be used as criteria for the benchmark referenced comparison. Thirdly, the normative referenced comparison is based on norms established for performance measures through its use in many system evaluations. The performance in the integrated system considered is compared to the norms established under the same or equivalent conditions. In aerospace industry, the use of the Cooper-Harper scale and the NASA-TLX for workload assessment are examples of this approach [11]. Finally, the expert judgment referenced comparison is based on the criteria established through the judgment of subject matter experts (SMEs).

E. Bridging Evaluation and Design Improvements

Even though the HUPESS provides evaluation results in each of the performance aspects for human factors validation, additional researches have been needed to develop methods on how to find out design deficiency leading to poor performance and give a solution for design improvement in HMI. The authors have developed a method of HMI design improvement for the monitoring and detection tasks which was named as "DEMIS (Difficulty Evaluation Method in Information Searching)" [10]. The DEMIS is a HMI evaluation method which bridge poor performance and design improvement for the monitoring and detection phase. Lessons learned from the DEMIS study show that sound human performance model in each of cognitive stages (such as monitoring, detection, situation assessment, diagnosis, decision-making, response planning, and response implementing) and relevant objective performance measures should be developed for successful bridging of human factors evaluation and HMI design improvement.

F. Product vs. Process Measures

Process measures (e.g., personnel task performance, eye tracking measures) generally have more diagnostic attributes than product measures (e.g., KSAX, NASA-TLX) which can lead to design improvement. Recently, researchers in HPE have much interest in development of process (task-oriented) measures. Several process measures are provided with the HUPESS which have diagnostic capabilities coupled with integrated analyses using various time-tagged data. Also teamwork is required for operator personnel tasks. Example behaviors and critical behaviors attributable to teamwork are investigated in a series of operator tasks with time-line analysis. Behaviors attributable to teamwork are evaluated whether they contribute to good or poor performance of the operator tasks. On the other hand, overloaded operator tasks are evaluated whether they inhibit teamwork or not.

G.Individual vs. Integrated Evaluation

Individual performance measures in isolation do not provide sufficient information. The HUPESS can provide integrated evaluation capability. An integrated analysis for a test and statistical analyses for several tests of interest are performed in the HUPESS. All the items evaluated during and after a test are investigated through time-line analysis in the integrated analysis for a test. However, the integrated analysis for a test provides only insights regarding a test. The integration of the insights from the tests representing various operating conditions is conducted by statistical analyses. The results of the statistical analyses are considered to be important criteria, because the design of ACRs must support safe operation of the plant system regardless of shifts, scenarios, and other operating conditions. An acceptable performance level is assured from the evaluation results of a series of tests, which is done by statistical analyses. The HUPESS provides statistical analyses, such as descriptive statistics, linear regression analysis, t-test, z-test, ANOVA, and correlation analysis.

IV. Conclusions

Various advanced technologies will be adopted in ACRs which is thought to increase operators' performance. However, potential human factors issues coupled with digital technologies might be troublesome. Important human factors issues in ACRs have been identified and strategies (or countermeasures) for evaluating and analyzing each of issues with the HUPESS are addressed with the help of the HUPESS (a systematic human factors evaluation and analysis system) in this study. Even though strategies or countermeasures for each issue are addressed in terms of using the HUPESS, other systems which have similar functions and capabilities also are applicable on the basis of the proposed strategies or countermeasures. The important conclusion from existing studies is that more objective human performance measures and an evaluation system (e.g., the HUPESS) which has extended capability of more integrated analyses should be developed for a successful human factors validation.

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