Measurement of inconvenience, human errors, and mental workload of simulated nuclear power plant control operations

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Abstract

This study developed a comprehensive and easily applicable nuclear reactor control system evaluation method using reactor operators behavioral and mental workload database. A proposed control panel design cycle consists of the 5 steps: (1) finding out inconvenient, erroneous, and mentally stressful factors for the proposed design through evaluative experiments, (2) drafting improved design alternatives considering detective factors found out in the step (1), (3) comparative experiments for the design alternatives, (4) selecting a best design alternative, (5) returning to the step (1) and repeating the design cycle. Reactor operators behavioral and mental workload database collected from evaluative experiments in the step (1) and comparative experiments in the step (3) of the design cycle have a key roll in finding out defective factors and yielding the criteria for selection of the proposed reactor control systems. The behavioral database was designed to include the major informations about reactor operators' control behaviors: beginning time of operations, involved displays, classification of observational behaviors, decisions, involved control devices, classification of control behaviors, communications, emotional status, opinions for man-machine interface, and system event log. The database for mental workload scored from various physiological variables-EEG, EOG, ECG, and respiration pattern-was developed to indicate the most stressful situation during reactor control operations and to give hints for defective design factors. An experimental test for the evaluation method applied to the Compact Nuclear Simulator (CNS) installed in Korea Atomic Energy Research Institute (KAERI) suggested that some defective design factors of analog indicators should be improved and that automatization of power control to a target level would give relaxation to the subject operators in stressful situation.

I. Introduction

A variety of evaluative criteria for man-machine interface (MMI) design of reactor control panel or operator aid system were used in human factors evaluative experiments. OECD Halden reactor project using NOkia Research Simulator (NORS) has evaluated the operator supporting systems such as Handling Alarms using LOgic (HALO), Integrated Process Status Overview (IPSO), and DIagnosis System using Knowledge Engineering Technique (DISKET) with the operator behavior-related criteria: emergency detection time, detective rate, diagnostic time, quality of diagnosis, actuation time, subjective preferences for screen design, the number of actions taken on emergency period, and experts' rating for efficiency and accuracy of problem solving paths. Researchers of ENF of France have used the evaluative criteria, such as operating error rate, averaged diagnostic time, the informations processed during diagnostic period, and averaged decision making time for N4 control room evaluative experiments using the S3C simulator. Japanese PWR Advanced Control Room (ACR) and knowledge based Computerized Operator Support System (COSS) evaluatative experiments have used the criteria: degree of discriminability, response time, decision making time, level of stress, and human error rate.

The human factors research team of Korea Atomic Energy Research Institute (KAERI) is under process of developing Integrated Test Facility (ITF) for evaluation of control room panels and operator aid systems. As a part of ITF, they are developing Data Analysis and Experiment Evaluation Support System (DAEXESS) for collectively measuring the operator behavior-related evaluative criteria used in the previous researches. The major requirements of this system include the followings:

1. To collectively measure all the major behavior-related criteria used in the previous evaluative experiments.
2. To classify operator errors.
3. To measure operator's mental workload.

Two subsystems of DAEXESS were developed to satisfy the above requirements. Reactor Control Behavior Analysis System (RCBAS) is the one system designed to enter the input data: decisions made during operations, self reported emotional status, self reported opinions for MMI of control panels from debriefed video/audio records of control operations, to process these data with system input variables such as types of displays and controls involved in the operations, dialog with other operators, and system event log, and to produce the output data: behavior related criteria and human error classification required for MMI evaluation of the proposed control panel. Mentalload Evaluation System for Reactor Operation (MESRO) processing the physiological signals collected from an operator is the other system to measure the time when the operator experiences the highest mental workload during control operations. This paper introduces the frameworks of the above two subsystems of DAEXESS and how they were applied to evaluation of MMI of Compact Nuclear Simulator (CNS) installed in KAERI for research and training purposes.

II. Measurement of Inconvenience and Human Errors

RCBAS is composed of behavioral database and analysis programs (Figure 1). In debriefing session after experiments experimenters and subject operators altogether take part in preparing for input data of RCBAS. All the operators' behaviors in the control operations are fragmented into elementary operations according to the criteria guided by Niebel (1988). For each elemetary operation an experimenter asks the subject operators question about types of observing and control behaviors, decision made, emotional status, and the opinions about detectability, discriminability, readability and operability of MMI involved at the elementary operation, and enters reported reponses into the behavioral database. The data about the displays/alarms and/or the controls involved at each elementary operation are automatically or manually entered into the behavioral database from the analyzed results of a eye mark recorder and a 3D motion analyzer. The ideal operating path alternatives judged by expert reactor operators are entered

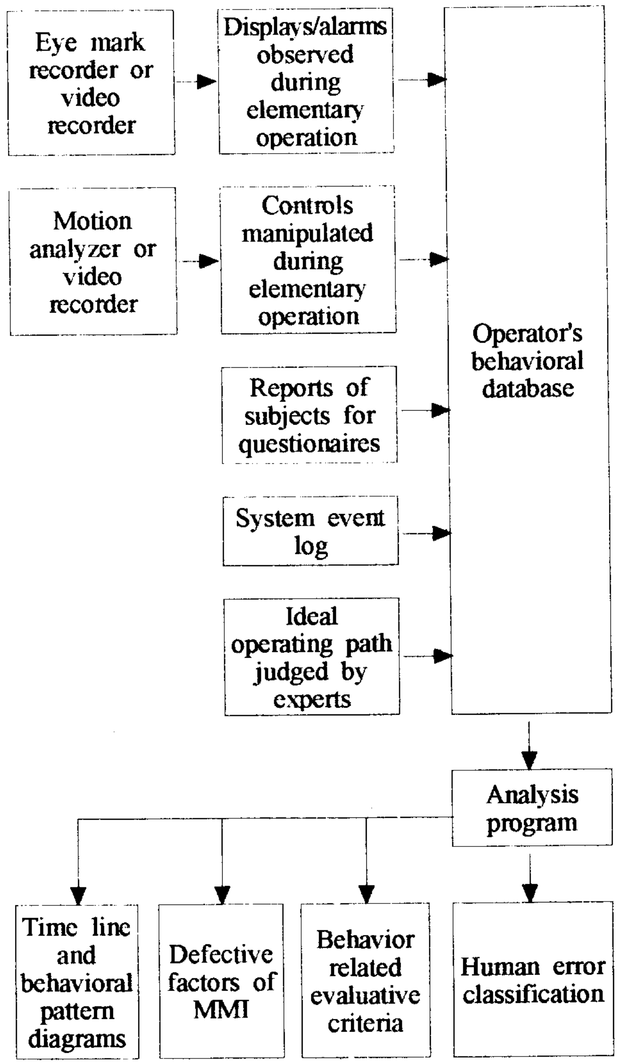

Figure 1: Composition of RCBAS.

into behavioral database. The system event log generated by a reactor control simulator is automatically or manually linked to the input of the behavioral database.

The analysis programs of RCBAS are designed to represent major control behaviors in the form of time line diagram or behavioral pattern diagram, to measure the behavior-related evaluative criteria suited for experimental purposes, and to classify the operators' errors according to a human error classification scheme developed by KAERI.

The behavioral database of RCBAS has following data fields:

1. Time: starting time of an elementary operation.
2. Display: the display involved in the elementary operation.
3. Type of observing behaviors: classification of observing behaviors taken at the elementary operation (compare, interpolate, observe, view, and etc.).
4. Control: the control devices involved in the elementary operation.
5. Type of control behaviors: classification of control behaviors taken at the elementary operation (activate-on, activate-off, increase, decrease, and etc.).
6. Decision: cognitive decision made at the elementary operation.
7. Communication: dialogue spoken among operators during the elementary operation.
8. Emotion: emotional status experienced by the operators during the elementary operation (complication, embarrassment, relaxation, tension, uneasiness, and vacancy).
9. Opinion for MMI: self reported opinions for detectability, discriminability, readability, and operability of MMI involved during the elementary operation.
10. System event log: major system event occurred during the elementary operation.

Ⅲ. Measurement of Mentalload

Mentalload is a concept related to an operator's ability to deal with a mentally imposed task. When it is said that mentalload is measured from the physiological signals, the underlying assumption is that increase in mentalload requires more psychophysiological resources requiring equivalent change of physiological mechanism and that this change of physiological mechanism can be captivated as an evidence of mentalload (Gopher and Donchin, 1986; O'Donnell and Eggemeier, 1986).

The principles of mentalload measurement of MESRO using the six physiological variables (alpha band of EEG, eye movement rate, 0.1hz band of instantaneous heart rate, mean heart rate, respiration rate, and respiration depth) collected from the operator are based on the following previous experimental results:

1. Increase in mentalload decreases the power of alpha band (8-13hz) of EEG (Earle and Pikus, 1982; Gale, 1987; Gevins and Schaffer, 1980; Kaufmann et al., 1992; Lang et al., 1988; Mecklinger et al., 1992; Natani and Gomer, 1981; Pfurtscheller and Klinesch, 1992; Pigeau et al., 1987; Rugg and Dickens, 1982; Sirevaag et al., 1988; Sterman et al., 1987).
2. Increase in mentalload has relation to decrease in eye blinking rate (Sirevaag et al., 1988; Stern and Skelly, 1984; Wilson et al., 1987).
3. Increase in mentalload decreases the power of 0.1hz band of instantaneous heart rate signals (Aasman et al., 1988; Egelund, 1982; Hitchen et al., 1980; Mulder and Mulder, 1981).
4. Internal processing of information (calculation, retrieval from long term memory, problem solving, and etc.) has relation to increase in mean heart rate (Lacey, 1967; Lacey and Lacey, 1978).
5. External information processing (visual perception, discrimination, scanning, hearing, and etc.) has relation to decrease in mean heart rate (Lacey, 1967; Lacey and Lacey, 1978).
6. Increase in mentalload increases respiration rate (Harding, 1987; Opmeer and Krol, 1973; Wilson et al., 1994).
7. Increase in mentalload decreases respiration depth (Backs et al., 1994).

MESRO is so designed as to transform each 6 physiological variables into respective binary signal reflecting the evidence of mentalload according to the following rules:

1. If each value of the power signal of alpha band of EEG is less than a reference value of resting state the value of the signal is transformed into a value 1, otherwise the value of the signal is transformed into a value 0.
2. If each value of the eye movement rate signals derived from EOG-horizontal and EOG-vertical is less than a reference value of resting state, the value of the signal is transformed into a value 1, otherwise the value of the signal is transformed into a value 0.
3. If each value of the power signal of 0.1hz band of instantaneous heart rate is less than a reference value of resting state, the value of the signal is transformed into a value 1, otherwise the value of the signal is transformed into a value 0.
4. If each value of the mean heart rate signal is either greater than a high reference value or less than a low reference value of resting state, the value of the signal is transformed into a value 1, otherwise the value of the signal is transformed into a value 0.
5. If each value of the respiration rate signal is greater than a reference value of resting state, the value of the signal is transformed into a value 1, otherwise the value of the signal is transformed into a value 0.
6. If each value of the respiration depth signal is less than a reference value of resting state, the value of the signal is transformed into a value 1, otherwise the value of the signal is transformed into a value 0.

All the transformed signals are consolidated by summing each value of the signals into one signal of which each value indicates the number of physiological variables reflecting a mentalload status (Figure 2). Although a reflecting pattern of mentalload on the 6 physiological variables is characteristic of task feature or operator feature (Wilson and Eggemeier, 1991), the scoring method of MESRO has advantage of reducing

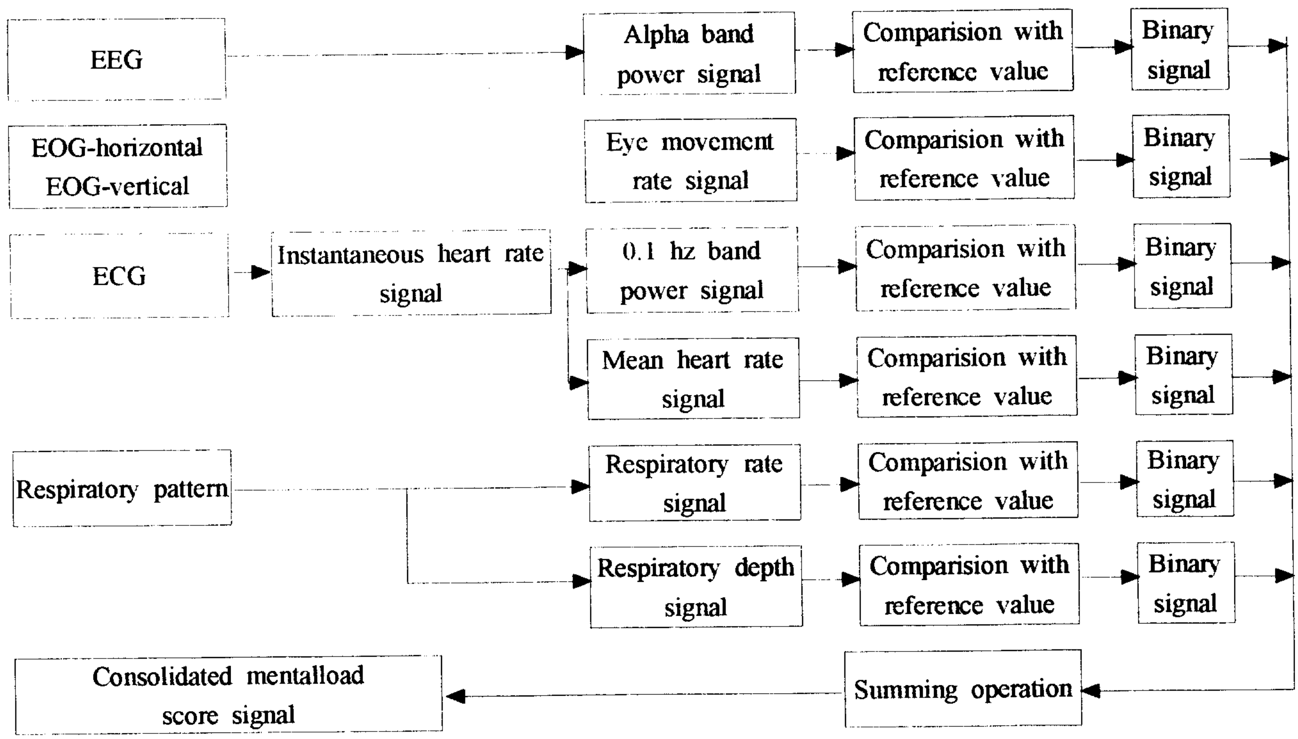

Figure 2: Procedures for processing the consolidated mentalload score signal in MESRO.

inter-operator variability in physiological responses for mentalload.

Ⅳ. Application of Measurement Methodologies to a CNS MMI Evaluation

Four subjects (2 undergraduate and 2 graduate students) were selected to participate an experiment for evaluation of MMI of CNS after training session of normal and emergency operation for 5 months. The task scenarios imposed on the subjects with a roll of a turbine operator during the experiment consisted of 5 types of disturbances: (1) loss of air ejector, (2) loss of steam generator level control signal, (3) air leakage into the condenser, (4) rupture of main steam line outside the containment, and (5) closure of all feedwater control valves. During the experiment, EEG, EOG, ECG, and respiratory pattern signals from each subject were measured to score the mentalload imposed on the subjects. Through debriefing of the video/audio records of the experiment the subjects' behavioral data were entered into the database of RCBAS.

Analysis programs of RCBAS have found out the following problems in detectability, readability, discriminability, and operability of MMI of CNS:

1. The visual angles of labels, scales, and figures of annunciators and analog type displays were so small that the subjects had difficulty in reading them.
2. Subtle changes in the analog type displays were difficult to detect.
3. The current slope (70.5 degrees) of the CNS control panel made it difficult for the subjects to read them.
4. Similarity and closeness of the displays of feedwater bypass valves made the subjects

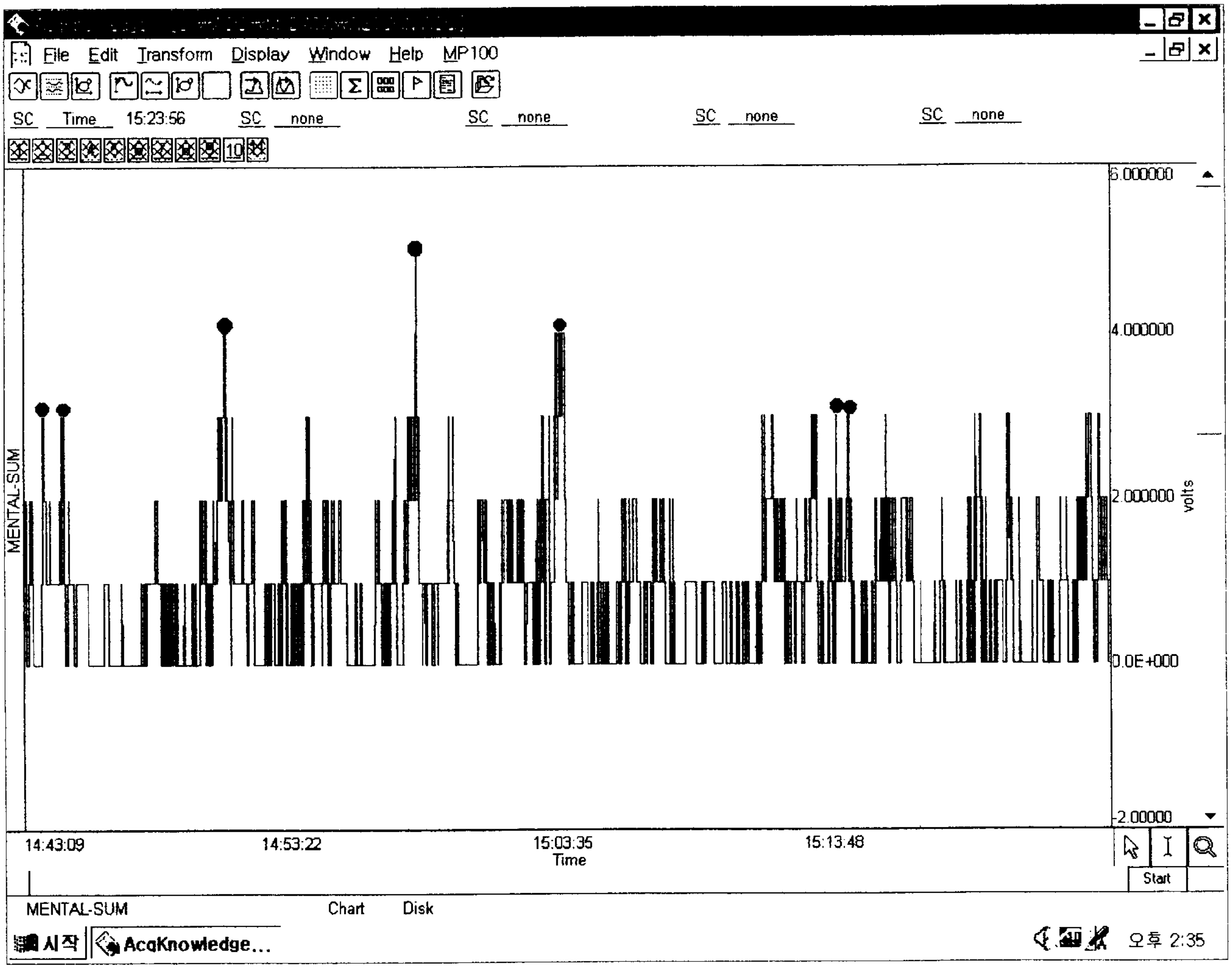

Figure 3: A Consolidated mentalload score signal where dots indicate the time when a subject manually controlled generator power to a target level.

to confuse them.

5. It was difficult for the subjects to read annunciators and to control feedwater control/bypass valves simultaneously.
6. Control directions of load rate, load set point and load increase/decrease knobs are not compatible with those of feedwater control bypass valve knobs.
7. Continual pressing operation for both feedwater control and bypass valve knobs was especially difficult.

Human error classification module of RCBAS analysis programs has found out the following 7 types of operating errors:

1. Omission error (12 cases)
2. Quantitative error (4 cases)
3. Unnecessary action error (2 cases)
4. Sequence error (2 cases)
5. Too early or too late error (1 case)
6. Wrong object error (1 case)
7. Wrong instruction/response error (1 case)

Among these errors 4 cases of omission errors and 4 cases of quantitative errors were proved to be related to wrong design of MMI. A vacuum extinguisher display is so small and humbly designed that all the subjects missed them during the operations (omission error). Incompatibility of control directions of load rate, load set point, and load increase/decrease knobs resulted in control operations of wrong directions (quantitative error).

A MESRO result for the mentalload changes of the subjects during the experimental operations revealed that manual increasing/decreasing operation for generator power to a target level imposed severe mentalload on the subjects (Figure 3). This result was consistent for all the subjects participating the experiment. The result implied that there need some improvements such as automatization for the related control devices: load rate, load set point, and load increase/decrease knobs.

V. Conclusions

An optimum design of MMI of control panels can be achieved through the following design cycle using RCBAS and MESRO:

1. Drafting the initial design with consideration of various design guidelines.
2. Finding out inconvenient, erroneous, and mentally stressful factors for the proposed design through evaluative experiments.
3. Drafting improved design alternatives considering defective factors found out in the step 2.
4. Comparative experiments for the design alternatives.
5. Selecting a best design alternative.
6. Returning to the step 2 and repeating the design cycle.

Two kinds of experiments are involved in the design cycle searching for an optimum MMI design of control panel system, the one is the evaluative experiment searching for defective factors to be improved on MMI and the other is the comparative experiment searching for a best design alternative among proposed designs. RCBAS and MESRO can be applied to both kinds of experiments. The evaluative experiment in the step 2 includes following procedure:

1. Selection of task scenarios.
2. Training of subjects.
3. Experiment with control operations proceeded on the task scenarios.
4. Inconvenient factor analysis for a proposed control panel and human error analysis using RCBAS.
5. Stressful factor analysis using MESRO.

The comparative experiment in the step 4 includes the following procedures:

1. Selection of the objects to be evaluated (independent variables).
2. Selection of the evaluative criteria (dependent variables).
3. Selection of task scenarios.
4. Training of subjects.
5. Experimental design.
6. Experiment with control operations proceeded on the task scenarios.
7. Scoring the evaluative criteria using RCBAS and MESRO.
8. Selection of a best scored design alternative.

The behavior-related evaluative criteria produced from outputs of RCBAS and MESRO include: emergency defection time, diagnostic time, emergency control operation time, accuracy of emergency detecting behavior, accuacy of control behavior, accuracy of dialog/report, mental stress, and etc.

From results of the evaluative experiment for MMI of CNS, it is proved that RCBAS and MESRO can be useful analysis tools for both the evaluative experiment searching for defective factors of MMI and the comparative experiment searching for a best design alternative.

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