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An Enhancement Study on the Human Factors Engineering Approach to Safety Verification of Nuclear Systems for the 21st Century

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1. Introduction

The safety of the nuclear system was rather actively strengthened by utilizing human factors engineering through accident experiences such as TMI. The problem of human factors in system safety was the greatest uncertainty, but the concept of man-machine system was introduced and MMIS system was developed to solve it. This was the lead in the era of human error 2.0, which advanced the system and its utility through the interface. But in the 21st century, nuclear systems faced new challenges. Unexpected natural disaster situations as well as new human-factor issues arising from organizational and cultural limitations have cast new challenges on highly reliable nuclear systems. Even if the starting line of all accidents is a natural disaster or a social safety culture, we are ultimately responsible, so it can be said that it is a task related to a wide range of talents and human factors. In this paper, the method of evaluating and verifying ergonomic safety that has been steadily applied in the nuclear field was reviewed from the perspective of a new era. In particular, we discussed ways to review and supplement the limitations of the safety verification methods of nuclear systems in the 21st century, which requires preparation for the so-called unknown-unknown risk (IAEA 2015) after the Fukushima accident.

2. Human Factors Engineering Safety Verification

A Review on current human factors engineering (HFE) safety verification in the nuclear field has continued to develop. There are various areas and approaches to human factors engineering safety verification (2019 Lee).

Areas and scopes to HFE V&V Review
- design plan and process
- design basis and criteria
- team organization
- method, tools and documents
- design outputs
- accepted scope, issues and objectives

Practical Approaches for HFE V&V
- product-based: outcome to measures
- elements-based: e.g. check-lists
- process-based: e.g. NUREG-0711
- model-based: e.g. cognitive model
- issues-based: stress test etc.
- task-based: task to confirm
- acceptance-based: user acceptance
- experience-based: expert opinion

Process-based verification was established by systematically linking element-based verification as well as issue-based or criteria-based verification. In the field of nuclear power, NUREF-0700, which is a review guideline for each design element, is applied as well as NUREG-0711 as a review model over the entire life cycle. As the design is embodied from the functional allocation for initial conceptual design, individual issues are continuously managed as well as verification of design procedures and methods in job analysis.

Finally, it can be said that human factors engineering safety is secured through Integrated System Validation (ISV). The integrated system verification uses an experimental method that measures the operator's performance with respect to interface design, such as a control room. In ergonomics, experimental verification has the following fundamental limitations and inevitable problems. (modified from OECD/NEA 2016)

- Test Scope and Objectives
- Validation Test beds
- Validation Team and Plant Personnel
- Measure and Measurement
- Test Design and Data Analysis
- HED Identification
- Validation Conclusions

Integrated system verification is an human factors engineering safety evaluation method that is frequently applied to design and development of new systems such as accident response and management facilities, periodic safety evaluation of existing systems, and stress tests. However, due to limitations and problems related to the feasibility and validity of the integrated system verification, it is difficult to be confident that the human factor safety of the nuclear system is sufficient public acceptance in the 21st century as well as engineering completeness.

3. Enhancements of Human Factors Verification for 21st century Safety

In general, ergonomic experimental evaluation is to confirm the optimality of the entire system by checking the performance and convenience and satisfaction of workers or users under a given condition. However, for human factors engineering safety evaluation verification, there are matters to be noted and supplemented as shown below.

First, performance and safety may be separate areas. Safety verification is the most basic area of evaluation that checks the preparedness for the possibility of human error. However, performance demonstrated through subjects may differ from safety because it is primarily optimized in terms of convenience and satisfaction. Human factors engineering safety verification should be presented separately and clearly, not as part of the performance. The simulator-based subject functional performance should be verified based on the minimum limit, not the average. It is difficult to say that the existing method of checking whether the minimum performance time limit of a unit job is satisfied along with fatigue and workload is sufficient for the newly required safety verification.

Second, conditions such as subjects and facilities should be set from a conservative perspective. The characteristics of personnel and organizations applied to subjects should be verified under conservative or reinforcing experimental conditions by adopting conservative or worst-case conditions, such as minimum qualifications, familiarity, experience, physical and mental conditions, etc. specified in the design. Conservative conditions should also be applied to the facilities and environment of the experimental evaluation. In general, failure conditions of the system provided by the simulation as well as failure and defects of the interface equipment should be included in the test scenario. In addition, variations in lighting, noise, vibration, temperature and humidity, cladding, equipment, etc. can be added as experimental conditions. This verification of the harsh environment was partially highlighted in the stress tests caused by the Fukushima nuclear accident, and such conservative conditions should be added to the existing safety evaluation. Reinforcement experiments on these limiting conditions are essential for turmeric of safety verification.

Third, from the perspective of human error, it is necessary to significantly expand to various types beyond the traditional range. Traditionally, in human reliability evaluation, simple slip/lapse for task functions assigned by design, as well as mistake, have been considered from a stochastic perspective, but should also be systematically considered in experimental verification. However, it is necessary to expand significantly beyond the scope of these traditional human errors to violations and sabotage. For example, as identified in the Fukushima nuclear accident, the evaluation should include target conflicts and conflicts of authority between personnel due to organizational and cultural characteristics, interventional instructions, confusion in communication, and delay in decision-making. These are the extended range of human error types to be considered in general nuclear design verification as well as stress tests and periodic safety assessments. Security-related verification highlighted before and after Fukushima is a new requirement. Uncertainty in safety, such as insider threat by violations, is a new challenge in safety verification.

Fourth, the concept of continuous safety establishment beyond one-time verification is needed. Although safety is expected to be improved in the 21st century due to the development of technology, new standards and requirements should be applied as safety perspectives and demands are continuously changing. This is contrasted by the current issue tracking management function included in the safety life cycle model. It is easy to overlook that experimental verification only satisfies safety under the given conditions at that time, but does not guarantee future safety. Despite its conservative characteristics, verification due to continuous rise in expectations for safety and changes in related standards should be guaranteed. To this end, it is necessary to significantly reinforce the issue tracking function that is already applied to establish continuous verification over the entire life cycle, such as periodic safety evaluation repeated during operation.

4. Proposed Approach to Enhanced Human Factors Engineering Safety Verifications

An example of an implementation plan is as follows to satisfy the requirements for human factors engineering verification discussed above for the safety of the 21st century in the nuclear field. An example of typical methodology is the additional considerations of a systematic experimental plan that can ensure statistical significance, for SAR, PSR, stress test, and others, as an example of the methodology, in addition to the experimental verification applied primarily to the current integrated system verification is followings

- Subject: In addition to the operator, support organizations and managers such as maintenance laboratories are included in the subject. It verifies the security of the assignment of roles and authorities through communication with support personnel and defect conditions in personnel composition, especially through intervention by the management organization. Subjects are evaluated conservatively by applying the minimum qualifications, experience, and job competence stipulated in the design. The organization and training requirements for securing appropriate personnel and job competencies should be checked by evaluating the human error and failure possibility of the subject's limit conditions.
- Experimental equipment: In addition to simulation of

system and equipment failure, abnormal and emergency operation, and accident situation, instrument failure and information defect are added. This is because the problem of information that is wrong or of uncertain quality is the key to human error and ultimate failure. Significant addition to the existing control room and operation simulator-based experimental facilities should be considered.

- Environmental conditions: As experienced in Fukushima, the level of completion is verified under deteriorated environmental conditions such as lighting, temperature and humidity. In particular, the wearing of protective clothing and equipment is added, and conditioning ensures that the subjects are in an abnormal cognitive condition (upset or scrambled). (Considering monitoring method through bio-signal such as EEG)
- Experimental tasks: The job includes marginal performance, not normal work, in the experimental plan. Marginal job performance can be evaluated by providing boundary conditions just before or within the occurrence of job failure or error. The performance of partners in a team or organization should also be considered in the experimental plan. In particular, peer mistakes or incomplete performance and organizational decision-making/communication defects are essential limitations for verification. This is because marginal performance provides valid conservative evidence of the possibility of success for a given job. It must be confirmed that the limiting performance conditions of the experimental job are specified in the education and training of the job.
- Safety measures and criteria: In human factors engineering verification, safety-related measures are applied separately from performance. Achievement is evaluated whether the lowest value, not the average, satisfies the criteria, and the conservatism of the values applied to the criteria is checked and applied. For example, the satisfaction of the minimum performance time required for the job is not completely conservative in itself. Since the results of the system achieved depending on the performance nature of the job, such as discrete/continuous intermittent/repeating, may vary, unique and detailed safety measures should be applied for each job.

Above will follow the formal experimental design approach to satisfy the statistical significance test from the traditional time-and-motion, anthropometry, and layout/arrangement issues to the information design and intelligent supports such as AI and digital twin. Human factored techniques such as Human-FMEA and Human-HAZOP might be helpful to enhance the design process for safety review and final verification. Enhancements proposed above may not satisfy the new demand on nuclear safety, however, enhanced human factors V&V could be beneficial to persuade the public to accept the nuclear systems existing and/or newly-developed.

4. Conclusions and Discussions

This paper discusses the human factors engineering safety verification approach including practical enhancement measures necessary to achieve the new level of safety required in the 21st century in the nuclear field. Focusing on experimental verification, supplementary matters necessary for verification were discussed from five perspectives, including Who, Why, What, When, and How, and proposed supplementary measures. However, above proposal just includes a few additional considerations that could satisfy the fidelity and validity of design verification of nuclear systems. The requirement for the safety of nuclear systems must be verified beyond individual engineering standards to verify actual safety, which seems to be one of the most effective views for this purpose. Therefore, it would be desirable to significantly supplement and improve the existing human factors engineering evaluation scope and method described in HFE review model such as NUREG-0711 as well as the practical methodology and technology incorporated in HFE V&V.

The proposal in this paper could be applied to new nuclear facilities such as SMR as well as severe accident management systems incorporating new ICT technology.

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