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A Study on the Technical Status, Issues, and Approach to Human Factors Verification and Validation of Nuclear Installations in Severe Accidents

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1. Human Factors in Nuclear Installations

The safety verification and validation of the human factors had been emphasized mainly after the TMI #2 accident in 1979. The following three topics for TMI back-fitting upon the human factors were defined in 1980's and conducted to most of operating nuclear power plants(NPPs).

- D-CRDR(detailed control roon design review)
- ERF/SPDS additional support to NPP crews
- EOP upgrade by symptom-based FRG

For the new and enhanced design of NPPs, an additional chapter of SAR (safety analysis report) 18.0 should be prepared with all above three back-fitting topics and more evidences for HF V&V beside the separated quantitative result of HRA from PSA. HF V&V has been one of the core activities for the designs and development of high-reliability systems as well as their regulatory review. Though HF V&V has been conducted during the last decades, many reviews have emphasized again the concerns on the human factors in nuclear installations especially after Fukushima accident.

After Fukushima accident, the public confidence to nuclear technology has been demolished since HF V&V could not overcome the intrinsic limitation to maintain the safety through technological achievements(2015 IAEA). One of the intrinsic limitations is the safety culture raised by IAEA after Chenobyl accident in 1980's. The lessons leaned from the human factors of the accidents turned out to be an impossible-to-verify theme due to the basic nature of human-being such as *fundamental surprise* and the technical limitation to *unknown-unknown* safety issues outlined in the Figure 1.

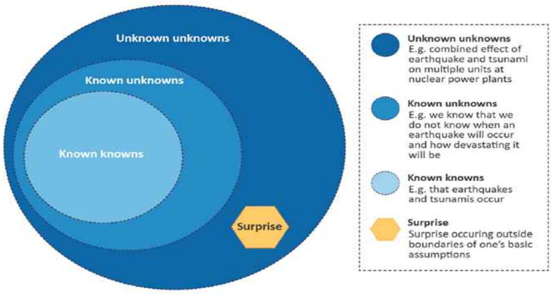

Figure 1. Unknown in Unknown (IAEA, 2015)

People reveals their strong anxiety to verify that nuclear safety is enough to fulfill the basic disciplines of HFE for all situations including unexpected beyond-DBA such as Fukushima. Safety of nuclear installations is now required to be verified with "*Prepare the Unprepared*" to the *unknown hazards in unknown* future uncertainties.

This paper describes a briefly review on the technical status, issues and recent topics of HF V&V for a more improved approach to the HF V&V in especially nuclear.

2. A Brief Review on the Current Approaches to Human Factors V&V

Several standards and guidelines for human factors application and the comprehensive V&V approaches have been developed for industry and practitioners such as IEEE-std-1023, IEC-60964, MIL-std-1472, and NUREG/CR-6343. HF V&V is to cope with the future vulnerability to the human in a system. Nobody believes that HF V&V has ever been enough to full-fill the basic disciplines of HFE during the regulatory review as well as during the design and development. It is a kind of open technical discipline even completed with the more systematic review model such as NUREG-0711 and fulfilled to the huge volume of comprehensive interface design review guidelines such as NUREG-0700.

Following categorization could be helpful to understand the nature and limitations of HF V&V.

- product-based : outcome to measures(e.g.HED)
- elements-based : e.g. check-lists(NUREG-0700)
- process-based : e.g. NUREG-0711 HFEPRM
- model-based : (cognitive models RESS, 1986)
- issues-based : stress test etc.
- task-based : a specific task to confirm
- acceptance-based : UAT(user acceptance test)
- experience-based : verifying opinion

Even with all approaches listed above for HF V&V, nobody can expect that the HF V&V might be complete enough to give us safety confidence without any human error issue and further concerns on the human factors of nuclear installations. However, some would recently require all comprehensive HF V&V approaches for coping with after-Fukushima issues in nuclear (OECD/ NEA, US-NRC). Figure 2 shows a rather-practical approach that have been taken for HF V&V during last decades in nuclear.

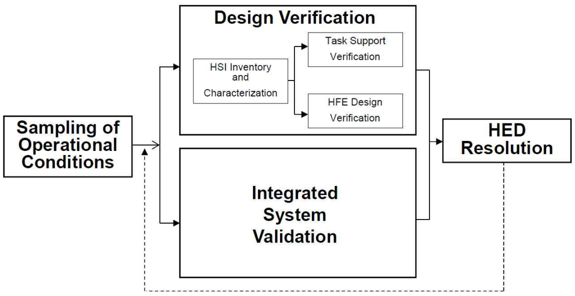

Figure 2. A Typical HF V&V (adopted from NUREG-0711, Rev.2, US-NRC)

It includes following three main activities. Each activity of HF V&V focus to each aspect of human factors practically rather than theoretically. They have come with a scrutinized tracing(with ITS: issues tracking system) and a systematic resolution process of human factors issues(in term of HED) in parallel during the whole span of system life-cycle (see Figure 2).

- Task Support Verification
- HFE Design Verification
- ISV (integrated system validation)

3. Technical Issues and Approach to HF V&V in Severe Accidents

3.1 Extended Scope of Human Factors and V&V

Traditional considerations on the tasks should be scrutinized with the extended scope of human factors. For example, IAEA has described explicitly discrepancies to be included within the regulatory oversight.(IAEA-TECDOC-1846, 2017)

- The composition of the team is different
- The experienced need to devote time to help
- A tool prescribed is not available
- The location is noe accessible
- Task interruption due to other urgent work
- Ill/non-calibrated instruments to the required
- A flange stud is stripped
- A novel task is to be taken over procedure

Those additive considerations to human factors are to be verified. And KAERI has proposed a set of desirable help functions for the development of the new HMI (human-machine interfaces) to cope with the challenges in beyond-DBA situations.(see Table 1) The scope and requirements for HF V&V is to extended to absolutely wider and might be divergent within the technical implementations in practice.

Table 1. Human Factors Requirements for the B-DBA

#	Additional Helps required for Severe Accident Mitigation
1	alarm dedicated to the severe accident entered
2	support function for the quick/correct implementation of procedure/guideline
3	information system available under harsh environment such as black-out
4	support function for creative responses to the discrepancies from pre-determined
5	coordination function among different groups participated to accident response
6	predictive function on accident progress/system behavior/radioactive release, etc.
7	support function to the operational decision making under severe accident
8	diagnosis support for the causes of the accident
9	support for implementation of accident management strategies
10	monitor and surveillance function to the critical safety functions of NPP
11	data gathering and status assessment function
12	operator support with information on the core damage and its possibility
13	operator support with information on the core inventory
14	support alarm to change from EOP to SAMG required
15	operator support with information on the core and containment
16	support function to verify the restorable/controllable status

3.2 Issues and Tasks on the Current HF V&V Approaches : (1) Task Support Verification

The task support verification means the design fulfillment of to human task accomplishment. The design support-ness can be confirmed by the detailed design requirements of the tasks/task steps/task elements. It has been conducted by checks of the comprehensive availability within design through *minimum inventory* of information and data. The minimum inventory could come from the tasks required to be conducted by human during the expected situations such as emergency operations and DBA. However it might become rather uncertain to define the minimum inventory during the design and HF V&V since there should be more unknown situations to be considered for the further safety and requirements could not be pre-specified anymore. We need to devise a set of promising approach and tasks to prepare the unprepared situation and the required minimum inventory for HF V&V. The development for the support to the unprepared is not limited since we have ever obtained a plausible countermeasure to the demanding post-TMI requirement in form of symptom-based coping strategy and FRGs.

3.3 Issues and Tasks on the Current HF V&V Approaches : (2) HFE Design Verification

The further verification of task support-ness has been conducted by the suitability verification. The suitability requirements over the availability are rather individual and come from the detailed criteria to every design factors with concerns on human aspects. The criteria traditionally come from the retrospective reviews and experiences on the design and design factors, and summarized into the guidelines and design handbook, etc. The limitation of suitability verification may come from those nature of the human factors criteria, that might be out-to-date during integrated into the guideline and segmented to a specific field individually. Moreover the criteria have shown frequently the ambiguousness since the meaning of information is obscure between the mandatory or the recommendable. Fundamentally they are closely dependent upon each other in practice.

Firstly the criteria need to be revised into the more concrete set of technical information through distinct separation of recommendations from the mandatory requirements for the safety. Secondly, the criteria should be up-to-date. Many new criteria need to be defined to new techniques that may have many compatibility issues such as VR/AR/MR and automation/AI applications. Sometimes the criteria differ from the original source of application (such as HCI since HCI has more concerns to the efficiency rather than safety). More practical logics/steps are desirable to apply the criteria during the design. Style guides have been an immediate solution to maintain the suitability during a design in practice. We need more focus to the development of our own style guides that might be verified with practices and experiences of NPP operations.

3.4 Issues and Tasks on the Current HF V&V Approaches : (3) Integrated System Validation

ISV (integrated system validation) is focused to the functional effectiveness in an integrated manner. ISV frequently means the final step to HFE V&V resolution by the formal/experimental approach with simulation of the exhaustive issues. Technical issues keep going as the concerning areas of review for ISV(2016, US-NRC).

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

OECD/NEA workshop on the HF V&V has ever summarized the technical issues on ISV as followings(2016, OECD/NEA) Firstly, the required scopes and objectives for ISV have been vague to verify in practice. Secondly, the sampling of subject crew always reveals a fundamental limitation, especially in case of new designs and/or revolutionary changes. Nobody knows whether they are accustomed to the provided simulations/HMI with enough level of expertise. Thirdly, scenarios simulated and required for the validation might be realistic and cover the enough scope of ISV. Finally, the outcomes in form of various experimental data might be integrated into a sound conclusion with statistical significances even equipped with complete fidelities of above all issues.

KAERI has developed many HF V&V techniques and methods to support those issues. For the experimental approach to HF V&V, especially for ISV, many new emerging techniques such as physiological signal-based observations on team coordination and intrusiveness are developed(such as ECG, HRV, GSR, EEG, and skin temperature, and others). Additionally, an approach to consider the unexpected situations precisely during the HF V&V. By virtue of psychological progress on risk behaviors into 3F (Flee, Fight, and Freeze), the combinatorial enumerations of unexpected encounters between human tasks and the situations could be considered to extend the scope and the validity of ISV.

3.5 V&V Arguments on the Fukushima Lessons

Very few words can be devised to cope with the safety culture verification found in conclusive paragraphs on the Fukushima lessons. Safety culture never escape the ultimate concern that means the unprepared to the unknown future challenges. Experiments have not been enough how to verify the safety decision makings in forms of individial, team and organization, even more with unknown tasks on unknown situations.

Basic studies for the characteristic in decision making under many kinds of uncertainties and risks are indispensible for HF V&V. Human decision making is a final barrier to all risk. Various kinds/levels of studies have been conducted to understand the basic mechanism, primitives and to enhance the quality theoretically and practically. These studies including mostly influenced many aspects of human life, especially in economics with several Nobel-prized achievements. In spite of these achievements we are still suffering from many problems due to the inappropriate decision makings. Many accidents revealed there happened a critical inappropriate human decision making before/ during/after the accident. Many can remind various disastrous accidents including Challenger/ Columbia Shuttle, Union Bopal Plant, Deepwater Horizon, etc. over TMI, Chernobyl, and Fukushima accidents in nuclear.

When the results after the decision making turns out to be fail and/or undesirable, the decision making is focused to the main cause of the negative consequence. The decision maker's behavior is frequently concluded into a responsible human error without any further investigation. However, there might be more than personal error of responsibility, the nature of decision making and its circumstance may have intrinsic limitations with respect to the safety.

For example, Challenger accident is known that inappropriate launching decision compelled by the managerial attitude cause the explosion during the launching of the space shuttle. However it can be re-stated into the wrong application of majority-vote process to the safety decision making. Decision by majority process is generally accepted as a best decision making rule, however, it was not properly selected at that time. Safety matter cannot resolved by the vote of absolute majority or even unanimous all.

There might be a similar kind of inappropriate application of decision making process during Fukushima accident. It was ill-structured safety decision due to the mainly ill-balanced authority to the safety matter as well as the defected and uncertain information. There need more timely and creative facilitation of remaining means to cope with the situation. The personnel in Fukushima looked psychologically suffering from typical marginal status that is summarized into 3F (Flee, Freeze, and Fight). 3F behavior comes from the intrinsic conservatism of human being and go far beyond the rational expertise that might be constructed in their competences to manage the NPPs.

4. Discussions and Further Works

During PSR activities to the operating NPPs many experimental reviews similar to ISV have been conducted in simulators and simulations of selected scenarios. However strict validations with enough fidelity and statistical validity have been limited due to the issues described in this study. Recently KINS defines a regulatory requirements for the human factors engineering approach to the severe accident and stress testes.(2017, KINS) However HF V&V of every step as well as ISV nowadays becomes more challenging after the revisit of human factors concerns after Fukushima. I suggest, first of all, the multi-diciplinary study on the basic nature of decision makings in disastrous failures of large complex systems such as NPPs and the lessons learned from a few cases need be summarized to enhance the human decision making. Secondly, any possible V&V approach, especially to the nuclear safety, should be articulated into the engineering form beneficial to cope with the accidents and mitigate the consequences rather than scientific researches. Providing decision makers more efficent/effective supports will be proposed in a form of interface and/or interactions during the severe accidents.

However, a new wider concept of human factors such as a Socio-Technical System in terms of MTO, HOF and HOT is nowadays emphasized to cope with the concerns raised from the recent experiences and accidents of NPPs. Following Figure 3 can show an example of the recent extended scope of human factors and their V&V required to nuclear installations.

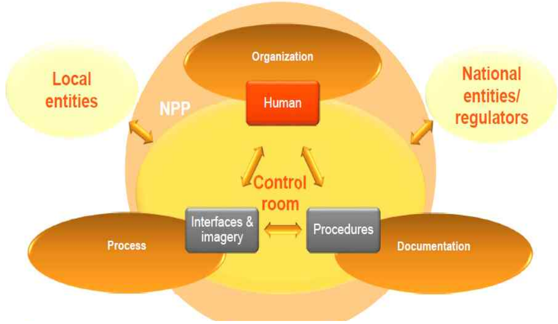

Figure 3. A Socio-Technical System Concept (adopted from De La Garza, 2016)

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