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A Human Factors Perspective to Intelligent and Autonomous I&C System for Nuclear Facilities

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1. Human Factors in Nuclear

Human has been a user and an operator of man-made artifacts rather than a part of the system. Basically human in nuclear installations should be protected from the risk of radiational hazards, and the human factors (HFs) were limited within the protection equipments and safety tools in nuclear. Nowadays HFs become wider and wider, and I&C to support HFs should incorporate more than before. The scope and contents of I&C system should be selected carefully for the future. This paper describes a human factors perspective on the I&C systems and the scope to be extended beyond the traditional monitoring and control of hardware, and a strategy proposed to cope with the challenges to, especially, the intelligent and autonomous nuclear systems.

2. Human Factors Perspective and Approaches to Nuclear I&C Systems

The instruments and controls (not an I&C system) in nuclear installations developed in form of remote ones, located close to the respectable nuclear equipments, and sometimes aggregated into a location for the spacial convenience or movements of their users. The I&C equipments were provided respectively according to the developed system. They had never been a system of I&C before TMI accident, though being aggregated in a board, a panel and a room, and provided to operators. The physical movement and visual accessability were crucial HF issues in a review report on TMI accident. The physical shape of the I&C devices and their arrangements on the board were enhanced, and the control room in nuclear installations then required a discipline of human factors engineering(HFE).

2.1 HF Approach to I&C System After TMI

HFE as a part of system engineering approach has been adopted from aerospace and military applications. HFs in a post-TMI requirement have been mainly an issue of compatibility. The incompatible I&C between the nuclear installations and the users/operators might mean a potential hazard to the safety of operation and management of a system. D-CRDR and following enhancements to I&C system has been conducted. ERF/SPDS is a typical features for further enhancements to HFs.

The exhaustive application of HFE in a control room was not enough to satisfy the high level of safety demanding after TMI, however, and a new concept of MMIS(Man-Machine Interface System) was proposed as a new requirement on ALWR to the utilities in America by EPRI. The I&C system in a nuclear power plants afterwards hae become a system with a respectable discipline during the design and operation.

HFs in nuclear become wider and hard to cope with accidents succeeding TMI, such as Chernobyl, JCO and Fukushima since human errors turned out to cause such accidents. Huge amount of efforts has been conducted back-fitting works to eliminate the human factors defects and devoted to identify any further potential of human errors in any level and/or any part of nuclear systems. Regulations and standards defined a few formal requirements in form of systematic application of HFE approaches (refer to IEC-60964, NUREG-0711, IEEE-std-1023, etc.). Every HFE process includes different kinds of system engineering method(s) and step(s) on HF requirements during the design as well as in operation. Figure 1 shows a typical scheme of NUREG-0711 by US-NRC for the HFE approach available around nuclear. The different 12 works for incorporating MMIS concept to I&C system are categorized into system engineering phases.

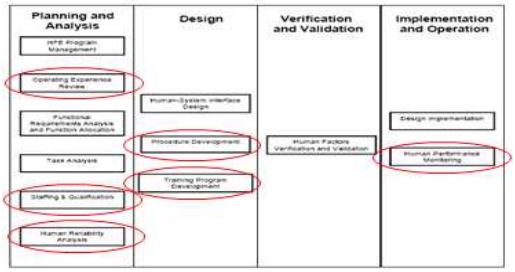

Figure 1. A Typical HFE process
(adopted from NUREG-0711, Rev.2, US-NRC)

Many technical issues and tasks on the current HF approaches were discussed in detail on *Task Support* and *HFs Design Verification* (Lee, 2018a). Most HFE applications have finally concluded into empirical evidences from the human-in-the-loop experimental test such as ISV (Integrated System Validation). Basic arguments have been raised to HFE process and the empirical/experimental HF verification approach (2018a, Lee; 2016, OECD/NEA).

2.2 Issues and Proposed Approach to I&C System after Fukushima

However it becomes doubtful that the current HFE approach might be strong enough to cover all HF concerns such as safety culture raised after Chernobyl, JCO, and Fukushima accident. IAEA, for example, raised the *fundamental surprise* issue in unprepared conditions to operational and managerial foundations as well as the operators with unknown-unknown risks to verify the HF safety (2015 IAEA).

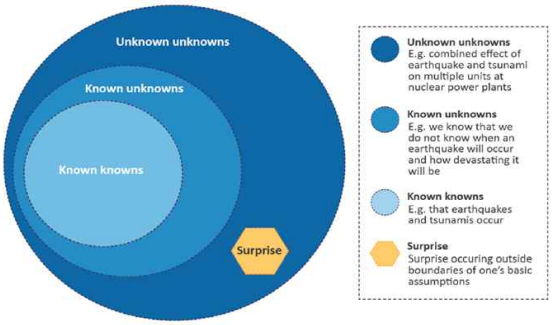

Figure 2. Three Different Risk Areas (IAEA 2015)

Current HFE approach have been so limited to I&C system to verify the full scope safety of various decision makings in forms of individual, team and organization, even more with unknown tasks on unknown situations. HFs on human involvements such as technical and managerial supports as well as the operational support from TSC/EOF can be considered to extend the scope and the functions of I&C system as followings

Firstly, I&C system may include other side of nuclear installations from HFs perspective, i.e. monitoring of human involvements. it could be beneficial to enhance and verify the safety and efficiency. It becomes feasible to incorporate monitoring the human side by virtue of *Business Process Modeling* and *People Analytics* with big data techniques (2018a Lee). Safety culture is no more a matter of socio-psychological efforts such as campaign any more, but becomes a technical task, since it can be monitored and controlled (intervened rather than controlled literally). 3F (*Flee, Fight, and Freeze*) behaviors to unexpected encounters between human and situations can not be coped with safety culture efforts.

Secondly, the scope of current I&C system could be extended to the all modes of operations, i.e. monitoring every phase of life-cycle can be integrated into a new I&C system along with the design, construction, pre-operational test and inspection, O&M, overhaul and replacement, even decommissioning(to final dismantling back to before the nuclear installation)

Additionally, many specific features such as integrated management system(IMS) proposed by IAEA. IMS may also include emerging I&C features for monitoring the human side of safety in terms of safety culture, but also the security management in an integrated manner.

3. The New Scope of I&C system and A Strategy to Intelligent and Autonomous One

3.1 Challenges of Emerging Digital Technologies

Digital technology of computerization and high-touch HMI devices have contributed to resolve the HF issues coming from post-TMI. The safety requirements to nuclear installation after Fukushima accident look extremely demanding to HFs and I&C system to prepare the unpreparedness and fundamental surprise of human. Emerging technologies such as Industrial Revolution 4.0 might enhance the nuclear power plant into an intelligent and autonomous artifact without any human involvement. In the perspective of human factors, however, the scope and contents of I&C system is not clear nor concrete enough to develop the amenable applications with emerging techniques.

The scope of I&C system could be wider than before including the instruments and controls to the all elements outside from the traditional nuclear hardwares. The safety arguments to the nuclear technology will be prevailing again, and the HFE by virtue of digital features incorporating especially intelligent techniques demands a robust confidence and complete a-priori verification.

3.2 A Strategy to the Intelligent and Autonomous I&C System Development for NPPs.

It can not be straightforward even when the design may incorporates automation as well as enhanced and intelligent functions. Recently two succeeding accidents of *Boeing-737 Max* revealed disastrously such requirements of more precise HFE strategy including HF safety verification before (and during) the design. The HFE design is required to consider the human understanding and internal states more carefully. A new plan for the HFE implementation should be proposed to cope with the arguments and considerations after Fukushima and from the challenges of

emerging technologies.

Profound efforts on function analysis and allocations should be revisited from the early stage of system development rather than the implementations of the given scope of I&C system with emerging techniques. Followings describe the new beneficial concepts and paradigms to be considered for NPPs.

- Human-Machine Interface System (1988 EPRI)
- Joint Cognitive System (1997 Hollnagel)
- Normal Accident (1983 Perrow)
- High-Reliability Organization
- Resilient Safety (2009 Hollnagel)
- Human Error 3.0 (2015, 2018 Lee)
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Though an intelligent and autonomous I&C system can be finally obtained for the un-manned nuclear installation utilizing digital devices and emerging technologies, HFs should be carefully considered to overcome the establish a balanced safety in practice. New functions that come from HF perspective can be described into a installing, starting, replacing, supervising, terminating, removal, and others in detail. Before applying emerging techniques for automation and intelligence, we need to decisde the basic scope of the detailed functions within the I&C system.

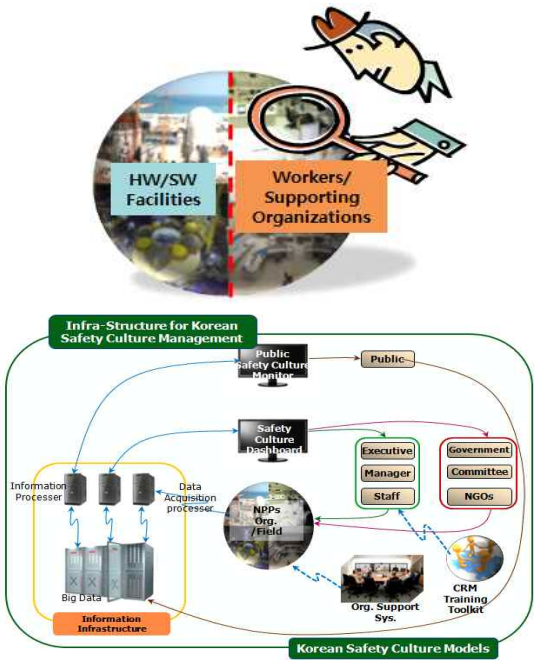
The first leading step of HFE should have an concrete figure on the functional structure of I&C system with enough confidence on the human error-free design by a detailed functional analysis, and valid functional allocations of nuclear facilities. More practical earnings may be detailed implications such as operational strategy and safety function concepts to the early design enough to enhance the design to such an error-free in iterative manner. It always requires trial and error experiences rather than an establishment of HFE theory and methods. The plan for the conceptual development of I&C system should be emphasized to function analysis and allocation again, that should be far away from the traditional concept of I&C for nuclear installations

4. Conclusions and Discussions

This paper describes arguments and discussions from a HF perspective and recent considerations on HFE application, and proposes a wider scope of I&C system and a function-based strategy for the intelligent and autonomous I&C system.

Followings can show a extended scope of I&C system for intelligent and autonomous nuclear installations in future with emerging technology.

- monitoring Human and Organizational Behavior
- I&C feature specific to each concern: Security, Low/Zero-power operation, O&M, Replacement and modification, Decommissioning, and others



The proposed strategy with a new scope of I&C system can be differentiated into I&C system 2.0, when it is articulated into a more detailed design of functional analysis and allocations and a development plan for the future of NPPs. The conceptual functional structure should be integrated and optimized to the ultimate goal of a nuclear installation.

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