Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Redefinition of Performance Shaping Factors (PSFs) Pertinent to Small Modular Reactors (SMRs)

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***Keywords: Small modular reactors, Multi-module HRA, Performance shaping factors**

1. Introduction

Due to the global warming crisis and the Paris Agreement, which is an agreement by the participating countries to collectively reduce the global temperature by 2°C above pre-industrial levels, countries worldwide have been trying to adopt cleaner energy sources, and that includes nuclear energy. For nuclear energy, a new fleet of reactors that is distinct from the conventional large-scale nuclear power plants (NPP) operation has emerged and they are called small modular reactors (SMRs). Some operational concepts of SMRs, such as reduced staffing and multi-module (MM) operation, differ significantly from those of their conventional counterparts. Due to this radical change in operational concept, regulatory licensing process is important before we can get these plants up and running [1]. One of the key parts of this regulatory licensing process is a method called human reliability analysis (HRA). At its core, all HRA methods involve a structured analysis of performance shaping factors (PSFs) to gain insights into how operators impact, prevent and mitigate the overall plant safety for multiple operating conditions and scenarios.

The objective of this study is to suggest the criteria that can be insightful for HRA analysts to consider upon selecting their own MMSMR PSFs. Additionally, the definition for each PSF is going to be suggested to potentially clarify why these suggested PSFs are still relevant in the context of MMSMR operation.

2. Refinement of MMSMR Taxonomy

In this section, the criteria used to refine the MMSMR taxonomy are going to be introduced. The criteria are used as a means to justify the addition and removal of PSFs in the overall taxonomy. The filtration criteria include, but are not limited to:

i. Remove suggestions that lack the quantifiable metrics to be evaluated (e.g., level of trust, comprehension level, etc.).
ii. Remove the PSFs that are already addressed in conventional NPP (e.g., availability of procedures, dynamic/step-by-step task, etc.).
iii. Remove the PSFs that are out of scope and focus on the PSFs that correspond to the SMR design characteristics that are different from conventional NPP (e.g., emergency preparedness, task location, etc.).
iv. If the suggested PSFs are redundant and can be merged into one, do so (e.g., information availability and HSI).

As can be seen below, the previously extensive taxonomy is reduced from a total of 25 PSFs to 7 PSFs by utilizing the criteria mentioned. The currently considered PSFs in the taxonomy are expected to cater to most of the pressing human factors (HF) concerns of MMSMRs.

Previously considered PSFs (25):

- Experiences with real multi-module scenarios
- Years of experience in NPP operation
- Type of activity (e.g., diagnosis, monitoring, etc.)
- Dynamic/step-by-step task
- Task criticality
- Availability of multi-module procedures
- Clarity of task prioritization
- Availability of decision-making criteria for new hazards
- Number of simultaneous transients between modules
- Priority between affected modules
- Presence of conflict with auxiliary tasks
- Task location (e.g., MCR, local site, etc.)
- Accessibility to affected modules
- Clarity in R&R definition
- Presence of supervision
- Adequacy of staffing
- Adequacy of communication protocols across modules
- Emergency preparedness for new hazards
- Level of trust in passive system/ automation
- Operator’s comprehension level of the automation system
- Information availability
- Human-centered/ technology-centered HSI
- Degree of module distinguishability
- Degree of contrast between controls

Currently considered PSFs (7):

- Experience/Training
- Workload
- Presence of supervision
- Adequacy of staffing
- Adequacy of communication protocols across modules
- Task complexity
- Human/Technology-centered HSI

3. Redefinition of the Refined PSF Taxonomy

The refined PSFs from the previous section are then going to be individually defined in this section to justify how they would fit in the SMR context. This section is arranged using the PSFs in the previous section as subsections and their definitions are provided in each of them.

3.1. Experience/Training

SMR is an example of a first-of-a-kind (FOAK) plant which is defined as the very first industrial plant of a specific design, in which past operational experiences and lessons learned will be useful, but in the end, the majority of experience will be obtained while operating this particular plant design [2]. This alludes to the fact that learning can be applied to production, building and assembly, operations and maintenance, and the gradual development and building of identical units or modules in the case of an SMR as there is a consensus that with every new module constructed, installed, and run, the staff members involved will acquire expertise [ibid]. In addition, the Nuclear Energy Agency (NEA) highlights that as more subsequent SMR modules are installed at the same site, errors could be reduced due to shared infrastructure, personnel collaboration, and operational experience [3]. This PSF refers to how the operators' experience or training with real multi-module scenarios and how their prior experience in operating a conventional NPP may affect human performance in a multi-module SMR environment.

3.2. Workload

The increased automation/passive system present in an SMR might introduce a paradoxical situation. It means that this increased automation can ease the operators in operating the SMR, but at the same time, it may also introduce new HF issues, which include some workload-related HF issues. For instance, due to the high workload involved in manual activities, operators experience challenging workload transitions when taking over after an automated failure, which causes delayed responses. On the contrary, increased automation may also introduce the issue of complacency due to operators having a low workload because all the tasks are being automated [4]. In addition, operators may have various extra jobs derived from other SMR missions (such as hydrogen production, seawater desalination, etc.) on top of the needs of managing multiple reactors. Operator stress and workload may rise as a result of customer demands and pressures from people who are not versed in the nuclear side of operations, which could lead to a higher failure rate [5]. This PSF refers to how the unique SMR design characteristics might influence the level of workload that an operator might have.

3.3. Presence of supervision

SMRs have auxiliary functions (e.g., district heating, water desalination, hydrogen production) that each have different objectives to be achieved [1]. To achieve said objectives along with the auxiliary functions, a good team coordination is needed. The human operators must be able to coordinate their actions and, consequently, communicate with one another in some way to work together as a team to reach a common goal. Whether a plan is stated explicitly or implicitly, coordination can be guaranteed to accomplish the shared objective [6]. The role of leading said coordination is always given to the supervisors. However, as stated in NUREG-1792, a common practice in the probabilistic safety assessment (PSA) is to include some recovery actions that the post-initiator HRA can credit that are not included in the emergency operating procedures (EOPs). These recovery actions are intentional measures done by the operators that are not precisely modeled in the PSA to prevent serious core damage as well as a large early release of radioactive materials. Despite these recovery actions not being modeled in the PSA initially, omitting them would result in a failure event addition to the accident sequence model's logical structure [7]. The question is, should the presence of supervision be credited as one of the recovery actions? While supervision is not directly mentioned in the NUREG-1792 as one of the recovery actions, it does satisfy some of its aspects. The aspects include but are not limited to "*whether sufficient crew resources exist to perform recovery*" because the supervisor plays a vital role in coordinating crew activities and allocating resources, which are both scarce in an SMR. Next, the supervisor identifies anomalies in the system and communicates them to the operators, which aligns with "*compelling feedback*" in the pre-initiator recovery actions, which could be crucial in a multi-module operation. Lastly, the supervisor may serve as a "second checker" to ensure that an operator has carried out an action correctly for the "independent verification" consideration for the pre-initiator recovery actions. With this in mind, this PSF refers to how the existence of supervision could be attributed as one of the recovery actions that could improve human performance within an SMR operation.

3.4. Adequacy of staffing

One of SMR's operational aspects that indicates a significant departure from its conventional equivalent is the reduced staffing levels made possible by the higher use of automation, utilization of passive systems (e.g., natural convection and gravity for core cooling) that require no external power or fewer systems and components in the case of integral PWR (iPWR) SMRs [8]. As a result of this, there are some concerns about this smaller workforce's ability to react to off-normal conditions within a multi-module SMR rapidly, which might result in a drop in human performance [5]. Aside from reduced staffing, at multi-module plants, additional staffing is also required in the event of frequent external events. According to Hidayatullah et al. (2015), it should be mandatory for additional staff to be present at each module during these kinds of events [8]. Due to this, a clear roles and responsibilities (R&R) definition must be defined to ensure that each personnel (including the additional staff) fully understands their respective roles properly [9]. Considering this, this PSF refers to how the reduced and flexible staffing that is introduced in SMR is going to impact how quickly and efficiently the operators can react to transients and off-normal conditions within an MMSMR environment.

3.5. Adequacy of communication protocols across modules

One of the HF issues stated in the Brookhaven National Laboratory report titled "Human Reliability Considerations for Small Modular Reactors" is that an information slip might happen in SMR during shift handovers because of the amount of information that has to be communicated between operators [4]. As mentioned in a study conducted by Park (2012), examining the features of crew communications is thought to be one of the most logical places to start when trying to improve the safety of large process systems, including lowering the likelihood of improper communications [10]. To add on that, in a case study carried out at a Nordic NPP, using a framework called the Human-Performance Tools (HPTs), the researchers have found out that two-way communication is still a useful strategy in group circumstances, even though three-way communication is a structured HPT for avoiding misconceptions in safety-critical interactions. Additionally, several HPTs rely heavily on written protocols, rules, and documentation to guarantee accurate information transmission, the sharing and learning of lessons learnt, and the use of consistent practices to improve efficiency and safety [11]. Even that is the case, Boring (2012) believes that a decrease in SMR workforce numbers would result in the operators not benefitting from a three-way communication in which the shift supervisor (SS) voices the necessary action, the operator carries it out and reports back, and the SS verifies that the action has been completed [5]. By paying heed to the findings of effective communication protocols in the conventional NPP, this PSF refers to what kind of communication protocols are available within an SMR environment, whether it is a written, two-way or three-way communication protocol, and how the presence and absence of each of these protocols might influence operators' performance in the case of resolving emergencies within an MMSMR environment.

3.6. Task complexity

SMR introduces new missions aside from electricity generation, which include hydrogen production or steam for industrial applications, which will require the operators to comprehend all those new missions' interfaces, resulting in a more complex training program needing to be structured [8]. According to the SPAR-H HRA methodology, task complexity is influenced by a number of factors [12]. Some of them are consistent with the human factor issues that may arise from the design characteristics of SMRs. For instance, shared systems are common in several SMRs [1], which, in case of a system failure, would cause multiple modules that share the same system to experience the same problems, which align with the complexity factor of "multiple equipment unavailable" [12, p.22]. Another HF issue that might arise from SMR design characteristics is that an operator might make a wrong decision due to losing awareness that a system was down for maintenance. This is most likely because of the sheer amount of information that had to be shared that comes from multiple modules during shift handover, and this aligns with another complexity factor in SPAR-H, which is the factor of "large amount of communication required" [5, 12]. This PSF refers to how the unique SMR design characteristics might influence the difficulty for the operators to perform a task in a given situation.

3.7. Human/Technology-centered HSI

The nuclear industry is one of the few industries that have not adopted a human-centered approach to their human-system interface (HSI) design contrary to many other industries. Typically, process control engineers develop system specifications and interfaces based on their own understanding, with minimal early involvement from operators. Design decisions are influenced by technological constraints, regulations, and resource limitations, making significant changes late in the process difficult and costly. Because of this, operators must learn to adapt to the HSI, which may not fully support their needs [13]. A study conducted by the OECD Halden Reactor Project emphasized the importance of increasing the observability of automation via HSI design. They believed that by making the automatic system's activity more observable, the operators would also be able to see the systems' objectives since skilled nuclear power plant personnel are familiar with the final objectives of the different high-level automated devices [6]. This PSF states that if the HSI in SMR is designed in a way that provides the operators with adequate information and feedback to maintain a safe operation of the plant, and the automation/passive system is observable, then it is human-centered, which will most likely promote human performance. If those aforementioned factors of the HSI are inadequate, then it is technology-centered, which will result in the opposite.

4. Conclusion

In this study, the SMR-specific PSF taxonomy was further refined using a list of criteria to justify the addition and removal of PSFs in the overall taxonomy. Furthermore, each currently considered PSFs in the taxonomy is defined to elucidate how these PSFs might still be relevant in the MMSMR operation. This PSF taxonomy addressed a number of constraints that the previous HRA methods did not consider in their PSF taxonomies. Primarily, the suggested taxonomy pays heed to the design characteristics of SMRs that are different from conventional NPP, including the HF issues that arise from these differences. The taxonomy also includes PSF that aren't the primary concern in the previous HRA methods, such as the adequacy of staffing. As a continuation of this study, one PSF from the taxonomy is going to be selected to be validated in a multi-module SMR simulator environment.

ACKNOWLEDGMENTS

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government (No. RS-2023-00258118).

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