

Effect of a multi-module operation environment on the reliability of human operators: Overview

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1. Introduction

According to recent statistics, many small modular reactors (SMRs) are currently under development in many countries [1]. Although the definitions of an SMR are slightly different (e.g., US NRC [Nuclear Regulatory Commission] definition applies only to light water reactors, whereas IAEA [International Atomic Energy Agency] includes a broader range of advanced reactor technologies, such as gas-cooled, liquid metal-cooled and molten salt designs including microreactors), IAEA stated that: “Small Modular Reactors (SMRs) are defined as advanced nuclear reactors combining a fraction of the power capacity of traditional plants with factory-controlled modular construction. They are characterized by a capacity of up to 300 MW(e) per unit, factory-assembled components, and the ability to produce electricity and/or power industrial applications [2].” From this definition, it is anticipated that SMRs are designed not only to generate electricity but also to support diverse industrial applications in a safer and more economical manner. These benefits justify the reason why many countries have spent a huge amount of resources for the development of SMRs.

At the same time, however, it is evident that the materialization of these benefits requires either the elaboration of existing techniques to enhance the safety of SMRs (e.g., the installation of passive safety systems with highly automated systems) or the creation of a brand new technology (e.g., the pebble-bed core design for a high temperature gas-cooled SMR) [3]. This strongly implies that new technical challenges affecting the safety of SMRs should be addressed in a rigorous and systematic way. In this light, NEA (Nuclear Energy Agency) recently published a technical opinion paper outlining the catalog of research recommendations for the safe operation of SMRs [4]. Of them, several cross-cutting safety issues that should be considered regardless of the types of SMRs are as follows:

- Application of defense in depth with passive safety systems/features
- Probabilistic safety assessment (PSA) for innovative or FOAK (first of a kind) designs
- Human factors (e.g., remote operations and multi-unit/multi-module plants)
- Multi-unit/multi-module design aspects to determine the impacts on safety including shared

systems, adjacent unit/module accidents and common mode failures

- Interconnections between SMRs and associated process applications (e.g., hydrogen production and heat generation process)

From the abovementioned safety issues, as the impact of a multi-module operation environment on the performance of human operators is crucial, it is necessary to suggest research directions to clarify how to incorporate the unique features of SMRs in estimating the reliability of human operators responsible for their safe operations.

2. Analysis of human reliability: Its role in the PSA

In terms of visualizing the safety of a nuclear facility, including both conventional nuclear power plants and SMRs, one of the traditional approaches is to conduct the PSA. Figure 1 depicts the simplified process of the PSA.

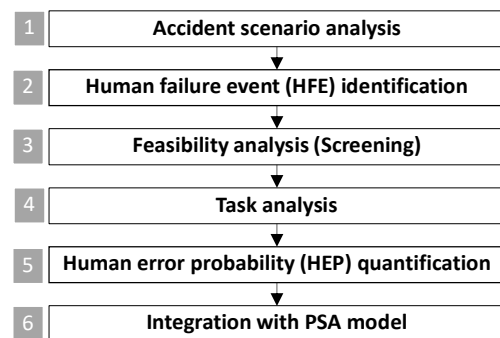


Fig. 1. Simplified PSA process with six steps [5].

From Fig. 1, the first step is to identify the progression of an initiating event with the functional failure of safety critical systems (e.g., engineered safety features) that could result in an unexpected consequence (e.g., core damage). After that, in the second step, the list of human failure events (HFEs) that can cause the functional failure of the safety critical systems should be distinguished. For this, PSA models including event trees (ETs) and fault trees (FTs) are generally used to represent the combination of both HFEs and mechanical failures that could result in system malfunctions. If HFEs that significantly contribute to the safety of a nuclear facility are

determined as the result of a sensitivity analysis (or feasibility analysis) in the third step, detailed task analysis should be followed in the fourth step in order to identify detailed actions included in each HFE with information on task environment (e.g., when and how the detailed actions should be carried out?). Based on the information obtained from the fourth step, the likelihood of human errors in conducting the detailed actions should be quantified in the fifth step by using well-established human reliability analysis (HRA) methods. Finally, the results of the HRA have to be integrated into the PSA models in order to visualize the safety of a nuclear facility.

3. General conclusion: Suggesting research direction

As outlined in Section 1, one of the important cross-cutting safety issues is the influence of unique SMR features on the performance of human operators. For example, the operation experience of autonomous systems has revealed that human operators are apt to make more errors when they are faced with specific conditions including transients or unexpected events [6]. Accordingly, in terms of visualizing the likelihood of human errors that could occur during the operation of autonomous vehicles, it is essential to capture the potential impact of autonomous system features on the occurrence of human errors.

In this light, as human operators have to simultaneously manage two or more modules, their performance could be degraded in certain situations. Accordingly, it is natural to say that the impact of a multi-module operation environment on the likelihood of human errors should be carefully incorporated into HRA results. To this end, it is possible to propose at least two kinds of research directions as highlighted in Fig. 2.

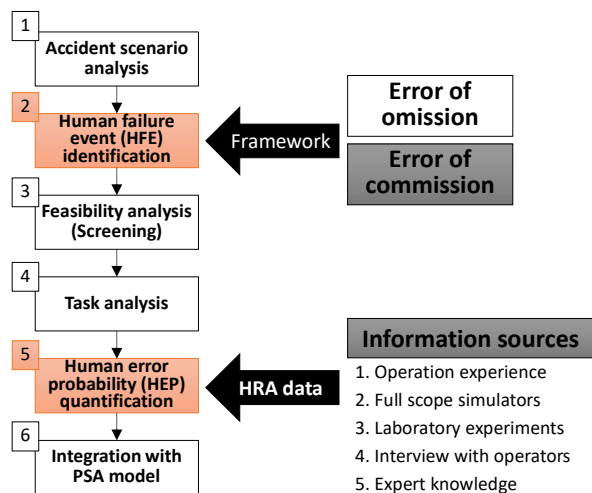


Fig. 2. Research directions to consider unique features of SMRs on the estimation of human reliability.

The first research topic is related to the second step of Fig. 2, in which the identification of HFEs in a multi-module operation environment should be accomplished.

In the case of a conventional nuclear facility, as many human operators have managed a single unit under a relatively lower level of automation environment, a lot of manual responses are indispensable for its operation. In this single unit operation environment, accordingly, the omission of manual responses (i.e., error of omission; EOO) that could result in the functional failure of safety critical systems has been emphasized for many decades. However, as the operation of SMRs requires human operators to simultaneously manage multi-modules with the support of both highly automated systems and passive safety systems, it is inevitable to develop a framework that can be used to clarify the commission of a wrong response stemming from an inappropriate situation assessment or decision making (i.e., error of commission; EOC).

The second research topic concerns the preparation of HRA data to quantify the likelihood of human errors in the fifth step of Fig. 2. In the case of conventional nuclear facilities (i.e., the single unit operation environment), diverse information sources are available for the collection of human performance data. For example, extensive operation experience and full-scope training simulators allow researchers to collect human performance data that are useful for estimating the likelihood of human errors under a wide spectrum of situations (from normal operating conditions to accident scenarios). In addition, it is possible to ask the support of many subject matter experts who are familiar with the operation of the conventional nuclear facilities. Unfortunately, as most SMRs are currently under development, it is difficult to directly follow existing approaches established for the conventional nuclear facilities. Accordingly, it is indispensable to determine how to secure a sufficient amount of HRA data that should serve as a technical basis to capture the characteristics of human performance observable in a multi-module operation environment.

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