Human Factors Considerations of Function Allocation on Levels of Automation in Small Modular Reactors (SMRs)

Sa Kil Kim*, Young Do Koo
SMR Reactor Technology Development Division, Korea Atomic Energy Research Institute, Daejeon, Korea
**Corresponding author: sakilkim@kaeri.re.kr*

1. Introduction

Small Modular Reactors (SMRs) are introducing an innovative operating concept that allows a relatively small number of personnel to operate multiple reactor modules from a single integrated main control room (MCR). This innovative operating concept is advantageous in terms of SMR operation and maintenance costs. An innovative approach to SMR operation and maintenance technology is made possible through the integration of advanced ICT technology. In other words, it is a technology that improves the level of automation in SMRs. The functions of SMRs with improved automation levels should be allocated according to their automation levels as part of human factors engineering program activities. This paper presents human factors considerations for function allocation according to automation levels for use in human factors safety review.

2. Automation and Function Allocation

The automation of SMRs can be broadly divided into functional automation and task automation. Functional automation refers to the SMR system performing numerous functions required to achieve its objectives (e.g., safety and power generation) without human intervention. Such functional automation is already being applied to a considerable extent in existing large-scale nuclear power systems. For example, this includes the automation of protective functions, which are central to power plant safety, as well as the automation of feed water control, water level control, and turbine control functions. Task automation refers to a specific system performing work that would otherwise be performed by humans. For example, this includes automation where a system performs specific work defined in operating procedures to check specific conditions and perform tasks under those conditions.

SMRs are being developed with these automation technologies incorporated from the initial conceptual design stage to enable safe and efficient operation. In South Korea, it is known that such automation technologies are being actively introduced and applied in the development of innovative SMRs (i-SMRs).

Improvements in the automation level of SMRs are one of the key concerns in safety reviews from a regulatory perspective. Particularly from a human factors regulation perspective, in-depth safety reviews are required not only for the safety of the automation system itself but also for the interaction between the automation system and the operator. In other words, safety review criteria are needed to determine what level of automation of system functions can ensure the safety of the power plant. These proposals are closely related to technical standards for function allocation between automation functions and operator functions.

Function allocation is one of the human factors engineering program activities that assigns the functions of complex systems to automated systems and operators. Function allocation has been performed based on the strengths and weaknesses of humans and machines, which were summarized in Fitts' research in the 1950s [9]. NUREG/CR-3331 is a document that provides technical criteria for function allocation in nuclear power plants and provides a preferred matrix decision-making model for humans and machines [6]. The Figure 1 describes a direction for function allocation criteria for improving automation levels based on NUREG/CR-3331[8].

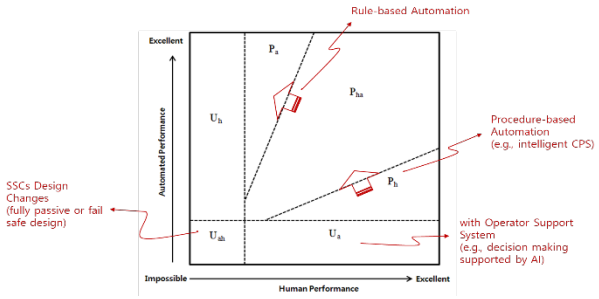

Figure 1. Acceptance Criteria for Function Allocation

- The U_a area represents functions where automation performance is too low to consider automation, and such functions are assigned to humans.
- The U_h area is an area where human limitations prevent assignment to humans, and automation functions are required.
- The U_{ah} area is an area where assignment to both humans and automated systems is impossible, and a reevaluation of function design is necessary.
- The P_h area represents functions where human advantages are leveraged, and if there is no alternative automation system to replace them, they are assigned to humans.
- The P_a area represents functions that can be designed for automation systems and are economically viable, and unless there is a special reason, they are assigned to automation systems.
- The P_{ha} area represents functions that can be assigned to both humans and automation systems,

and they are assigned to either humans or automation systems based on cost or preference.

The functional allocation criteria provided in NUREG/CR-3331 are broadly divided into those for humans, automated systems, or areas shared by humans and automated systems [6]. In the case of nuclear power plants, including SMRs, where automation levels are improving, there are limitations to applying the functional allocation criteria of NUREG/CR-3331 as is. This is because nuclear power plants with high automation levels must be allocated according to at least the following five categories of automation levels [5], and functional allocation based on automation levels cannot be performed simply based on the advantages and disadvantages of humans and automated systems.

I. Manual Operation: No automation, operators manually perform all tasks.
II. Shared Operation: Automatic performance of some tasks, operators perform some tasks manually.
III. Operation by Consent: Automatic performance when directed by operators to do so, under close monitoring and supervision. Operators monitor closely, approve actions, and may intervene to provide supervisory commands that automation follows.
IV. Operation by Exception: Essentially autonomous operation unless specific situations or circumstances are encountered. Operators must approve of critical decisions and may intervene.
V. Autonomous Operation: Fully autonomous operation. System cannot normally be disabled but may be started manually. Operators monitor performance and perform backup if necessary, feasible, and permitted.

Research on functional allocation criteria applicable to the design of nuclear power plants with high levels of automation has been limited over the past 20 years, but there are two representative and significant studies. The first study by R. Parasuraman, T.B. Sheridan, C.D. Wickens is a cognitive engineering approach to determining the level of automation based on the type of human interaction as shown in Figure 2[9]. This study provided functional allocation criteria to consider when automating human functions based on human information processing models. The second study is by C.J. Jeffrey et al., who proposed considering team dynamics in functional allocation [1]. Jeffrey et al.'s study suggests that functional allocation should consider not only the individual cognitive and computational abilities of humans and automation but also the social factors that affect teamwork. The approach that while teams composed of humans have mutual trust, teams composed of humans and automation systems have biases in trust is an interesting and important point.

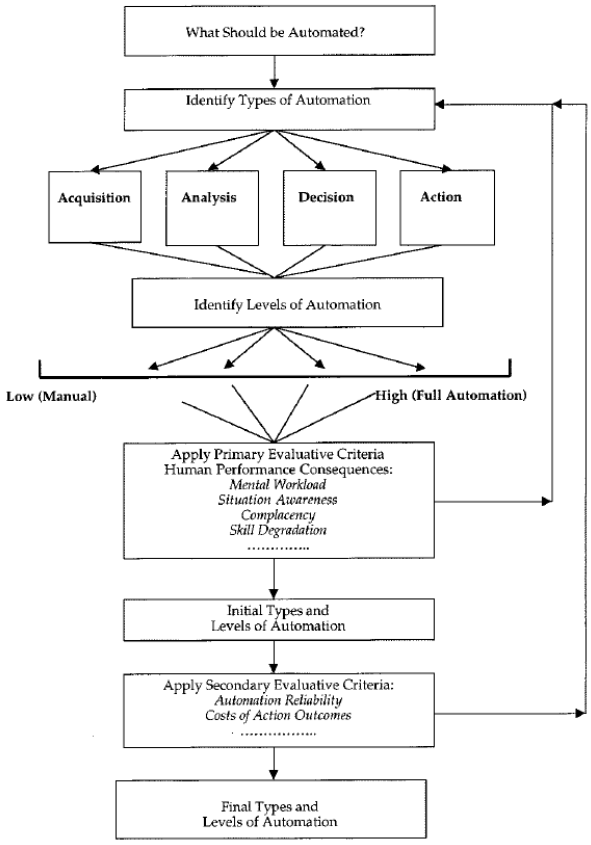

Figure 2. A model for types and levels of human interaction with automation by R. Parasuraman et. al.

3. Human Factors Considerations of Function Allocation on Levels of Automation

When assigning functions in nuclear power plants designed with various automation levels, such as SMRs, the followings should be considered.

3.1 Mental workload

Automated systems involved in the processes of information recognition, analysis, and decision-making affect the mental workload of operators. If the amount of information that the operator must monitor is large, that information must be processed and provided to the operator in a reduced amount of analyzed information. A large amount of information means that there is a high degree of uncertainty regarding the status or situation of the power plant that the operator must understand, and only information centered on the results of analysis combining individual monitoring variables at the power plant site should be provided to reduce that uncertainty.

Additionally, if there are too many options for the decision-making process to determine the control actions that the operator must perform based on the monitoring information, the optimal alternative with the highest priority in terms of safety must be provided to reduce the operator's mental workload.

Therefore, the considerations for function allocation to optimize the operator's mental workload are summarized as follows.

- Automation systems must monitor individual variables at the power plant site, process them into status and situation information about the power plant, and provide this information to operators.
- Automation systems should quantitatively provide operators with uncertainty regarding the plant's status and situation information.
- Automation systems should provide operators with options for control actions based on the plant's status and situation information. If there are two or more options, priority information should be provided based on safety.

3.2 Situation awareness

The functions of automated systems can have a positive or negative impact on the situation awareness of operators. Situation awareness refers to the extent to which operators can predict future conditions based on the current status of the power plant [2, 3]. Therefore, if the information provided by the automated system regarding the current status of the power plant is contaminated, operators will be unable to accurately predict future conditions. Furthermore, if the operator is unaware of the functions performed automatically by the automation system, the operator will predict the status of the power plant based on limited information, resulting in reduced situation awareness. However, if the automation system can accurately provide the operator with information on the current status and near future status of the power plant, the operator's situation awareness can be greatly improved.

Therefore, the considerations for assigning functions to improve the operator's situation awareness are summarized as follows.

- Automation systems should provide operators with supportive information that helps them understand the plant's status or situation.
- Automation systems should provide operators with information about the plant's near-future status or situation through visual and auditory means.
- Automation systems should provide operators with historical data and technical background information about the automated processes.

3.3 Complacency

Operators can view automated systems as team members who assist in power plant operations. In other words, operators and automated systems form a team. Operators develop a level of trust in automated systems, and that level of trust can vary depending on the situation. If the operator loses trust in the automated system, the automated system is no longer a team member of that operator team. Conversely, if the operator places excessive trust in the automated system, they may become complacent about the automated system's performance and fail to recognize functional failures in the automated system.

Therefore, the functional allocation considerations related to complacency can be summarized as follows.

- The automated system must provide the operator with situational reliability information regarding the functions it performs automatically. The situational reliability information of the automated system must be provided based on the uncertainty information of the information acquired by the automated system.
- The operator must periodically check the performance history information and technical background information of the automated system.
- The automated system must provide means of interaction to communicate with the operator.

3.4 Skill degradation

The introduction of automated systems positively supports the plant operators' duties, enabling them to operate the plant efficiently and safely. However, in the long term, the introduction of automated systems may lead to a decline in the skills required for plant operation. While the introduction of automation systems changes the duties of plant operators, in the event of a malfunction or failure of the automation system, plant operators must be able to perform the functions of the automation system. Ultimately, the allocation of functions between automation systems and plant operators must consider the prevention of skill degradation among plant operators.

The following summarizes the considerations for function allocation related to this issue.

- If operators must be prepared for the degradation or failure of functions performed by automated systems, the level of automation for such functions should not be too high.
- Automated systems should provide operators with the technical logic and processes involved in performing functions, ensuring that operators maintain the ability to perform such functions directly.

3.5 Automation Reliability

The reliability of automation systems affects the mental workload, situational awareness, and complacency of operators. Automation reliability must be sufficiently acceptable in terms of safety. The inherent reliability of automation systems must be sufficiently ensured at the design stage. If automation reliability may be affected by the operating environment, information on changes in reliability must be obtained. Considerations for functional allocation related to automation reliability are as follows:

- If automation reliability is not ensured, the function must be assigned to the operator.

- Even if automation reliability is ensured, if it may change depending on the operating environment, the operator must be aware of the changing reliability information.

3.6 Costs of Automation Failure

Automation functions can provide economic and operational efficiency by replacing the duties of operators. However, it is impossible to exclude the additional duties of operators in preparation for the failure of automation functions. In addition, issues related to power plant safety that may arise due to automation failure must be managed in terms of risk. Risk management refers to the expected costs that may arise due to automation failure. Considerations for assigning functions in terms of automation failure costs are as follows:

- Operator backup functions in preparation for automation failures must be considered from a safety perspective. In other words, if the costs of automation failures exceed the benefits in terms of risk, the automation functions should be considered as operator functions.
- If the costs required to maintain operator functions in preparation for automation failures are high, the functions should be assigned to operators.

3.7 Human Factors Regulatory Safety Reviews

In the case of complex nuclear power plants where automation systems are applied, safety must be prioritized, so the level of automation may vary depending on the status or situation of the plant. Therefore, it is reasonable to consider the variability of the automation level when assigning functions. Adaptive automation, which is a concept of situation-dependent automation, should be prioritized when assigning functions related to the automation level.

The human factors regulatory approach to adaptive automation in SMRs is that even if the level of automation in SMRs is improved, the concept of operation without operators cannot be permitted. This basic regulatory approach can be summarized in the following three points [8].

- High-level supervision and management functions should be assigned to operators rather than automation systems.
- Operators must be able to respond appropriately to unplanned or unforeseen events or accidents.
- Operators must be able to respond appropriately to functional degradation or failure of automated systems.

Ultimately, the focus of safety reviews for adaptive automation is to verify that the optimal level of automation has been set in terms of safety. The optimal level of automation is directly related to the functional allocation criteria set by the operator. Therefore, reasonable technical criteria must be established to appropriately allocate functions defined according to the design characteristics of SMRs (especially safety functions) to automation systems and operators. The safety review of adaptive automation needs to be based on the following functional allocation criteria [8].

- Fully automated functions must ensure safety without operator intervention under any circumstances. However, means to monitor the performance status of fully automated functions must be provided.
- Functions involving knowledge-based decision-making should minimize automation. However, automation functions may be assigned as a means of supporting knowledge-based decision-making.
- For functions involving tasks that are expected to impose a high cognitive load due to the technical limitations of automation, automation functions should be added to tasks that allow operators to perform those functions with minimal cognitive burden by accepting procedural information.
- When automation of functions minimizes the operator's workload, the operator must be able to continuously monitor the status of automated functions. Additionally, immediate operator intervention must be possible in the event of a malfunction or failure of automated functions.

3. Conclusion

Innovative SMRs developed in Korea must ensure safety from a regulatory perspective in order to be competitive in the global market. Therefore, human factors review guidelines for large pressurized water reactors need to be improved so that they can also be used in the review of SMRs. From a human factors regulatory perspective, the introduction of a multi-module integrated control room operating concept may give rise to new human factors issues. In particular, as automation levels improve, functional assignments must be performed according to automation levels, and new standards for functional assignments for adaptive automation must be established. The functional allocation considerations for automation levels proposed in this study are expected to serve as a technical foundation for safety reviews of functional assignments in nuclear power plants designed with high automation levels, such as SMRs.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Safety Research Program through the Regulatory Research Management Agency for SMRS (RMAS) and the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 1500-1501-409).

REFERENCES

[1] C. J. Jeffrey, J. O'Hara, J. V. Hugo, J. H. Oxstrand, Function allocation for humans and automation in the context of team dynamics, Procedia Manufacturing, Vol. 3, 6th International Conference on AHFE 2015, p.1225-1232, 2015.
[2] Endsley, M., Automation and situation awareness. In R. Parasuraman and M. Mouloua (Eds.) Automation and Human Performance: Theory and Applications (pp. 163-181). Mahwah, NJ: Lawrence Erlbaum, 1996.
[3] Endsley, M., A survey of situation awareness requirements in Air-to-Air combat fighters, International Journal of Aviation Psychology 3(2) (pp. 157-168), 1993.
[4] Kaber & Endsley, The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task, 2004.
[5] NUREG-0700, Rev. 3, Human-System Interface Design Review Guidelines, U.S. NRC, 2020.
[6] NUREG/CR-3331, A Methodology for allocating nuclear power plant control functions to human or automatic control, U.S. NRC, 1983.
[7] O'Hara & Higgins, Adaptive Automation - Current status and challenges, RIL 2020-05, U.S. NRC, 2020.
[8] Sa Kil Kim, Young Do Koo, Regulatory Basis for the Safety Evaluation of Increased Level of Automation in relation to the Concept of Multi-module Integrated MCR Operation, NPIC&HMIT 2025, Proceedings, p.944-949, 2025.
[9] R. Parasuraman, T. B. Sheridan, C. D. Wickens, A model for types and levels of human interaction with automation, IEEE transactions on system, man, and cybernetics – Part A: System and Humans, Vol. 30. No. 3., p.286-297, 2000.