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The Investigation of Innovative Operation and Maintenance Technology to develop a Road Map for i-SMR

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1. Introduction

Nuclear power generation plays the baseload that stably supplies power. Therefore, the nuclear field focused on large-scale generation to reduce power generation costs even 10 years ago. However, after the Fukushima Daichi accident, one of the severe accidents, negative perceptions about large-scale nuclear power plants are prevalent. In addition, the preference for large-scale nuclear power plants is decreasing due to the huge initial investment cost for construction and the increase in investment payback period and interest costs when construction is delayed. Hence, small modular reactors (SMRs) have been proposed worldwide. SMRs have design features such as integrated design, passive safety systems, design modularization, operational flexibility, and multi-purpose utilization. Due to the design characteristics of SMRs, such as safety and operational flexibility, interest in SMRs is increasing.

When the cost of nuclear power generation is subtracted from the cost of construction worldwide, operating and maintenance costs account for a large percentage of the unit cost of generation [1]. Furthermore, the previous method of operation and maintenance depends on the interaction of humans. The intervention of humans makes the nuclear power plant unpredictable and provides additional factors for severe accidents [2]. Therefore, innovation is required in terms of economy and stability of operation and maintenance for SMRs. This paper proposes the development direction and road map in connection with the innovative SMR (i-SMR) technology development project to innovate the technology of operation and maintenance, considering the regulations proposed by NRC. The proposal of development direction for innovative operation and maintenance contribute to the development of i-SMR in obtaining a license by offering insight.

2. Consideration of regulations

NRC regulations should be considered for the i-SMR technology development project based on applicable innovative operation and maintenance technologies. In this paper, appendix A of Chapter 10 Part 50 of the Code of Federal Regulations (10 CFR) - General Design Criteria for Nuclear Power Plants was considered as the regulatory basis [3]. However, in the case of SMRs, there would be differences in regulatory policies related to operation and maintenance, such as inspection, requirements, and intervals during operation, compared to traditional large-scale nuclear power plants. Since the regulatory policy for SMRs has not yet been established, additional investigations on the operation and maintenance of SMRs are required. Therefore, the differences in operation and maintenance between large-scale NPP and SMRs are investigated and analyzed to consider the regulations related to the operation and maintenance of NPPs. The large-scale NPP to be investigated is the APR-1400, and the SMR is Nuscale SMR, which is a comparative type of i-SMR. The safety evaluation report of each reactor type is considered to investigate the difference between large-scale NPP and SMR [4-9].

In terms of operation and maintenance, the difference between large-scale NPP and SMR was not distinct. Most regulations include that protection systems must be secure, can demonstrate performance, and satisfy reliability, redundancy, independence, and requirements. Procedures alert the operator to abnormal conditions that require the action of the operator, then guide the operator to an appropriate response, and assist the operator in determining and maintaining the condition of the NPP and systems or functions. In addition, the human factor should be considered to apply innovative operation and maintenance technology. The impact of assumptions and constraints, period of program, applicability, procedures, training, and modifications from the configuration of existing NPP should be considered for human factor engineering. The operational experience should be considered to apply the operation and maintenance technology to NPPs. The operational experience of other facilities, which utilize the newly suggested technology, should be reviewed and described, when the technology is applied. For monitoring of NPPs, including APR-1400 and Nuscale SMR, the limit of safety and safety system settings, limiting condition of operation, requirements for monitoring, design features, and administrative controls should be considered. The frequency of component monitoring coincided with the refueling cycle. Based on the operational experience, surveillance of these components typically has passed when performance once per refueling cycle.

Most of the regulations for SMR are similar to large-scale NPPs of pressurized light water reactors. However, the significant difference between large-scale NPP and SMR is that the module protection system should be included. The module protection system should contain information from safety-related sensors that monitor temperature, neutron flux, and pressure data. Nuscale SMR utilizes natural circulation without the pump, which excludes pump-related accidents such as loss of flow accidents. Therefore, the module protection system of Nuscale mainly focused on neutron monitoring. Although Nuscale SMR has inherent and passive safety than other NPPs, NRC recommends one operator per module, considering the diversity of function, human, and component. Numerous regulatory policies should be considered to propose innovative operation and maintenance technologies. As shown in the safety evaluation report of large-scale NPP and SMR, the exclusion of humans, frequent component inspection, and absolute automation would be considered impossible. Therefore, innovative operation and maintenance technology, which improves economic feasibility and safety in consideration of regulations, should contain the intervention of humans such as technology that can reduce human error and help the operator.

3. Applicable innovative operation and maintenance technology.

Several innovative operating technologies have been suggested to help the operator or reduce human errors in the nuclear field. Because the nuclear power plant has been controlled by data-based responses, which have real-time decisions making difficult, the study was conducted to predict the condition of NPPs and enable early intervention using a long short-term memory and convolutional neural network structure [10]. The method of diagnosing multiple components of the nuclear power plant with infrared sensor equipped unmanned aerial vehicle by applying deep learning was proposed to improve the safety and maintenance efficiency of NPPs [11]. Since the maintenance cost of nuclear power plants is considerable, the prediction of the remaining useful life of electric valves for NPPs based on acoustic emission signals was suggested to prevent equipment failure for effective maintenance and to consider the state of electric valves [12]. The digital twin of neutron flux and power distribution in the reactor core was proposed to predict power output by physics-informed approaches using an approach combining physical models and machine learning [13]. Furthermore, the prediction of the moisture carryover, which represent the amount of water mixed with steam leaving the separator has been applied in NPPs using the machine learning method [14].

The innovative operating technologies, which have been proposed to reduce human errors or help the operator, are based on the 4th industrial revolution technology. The artificial intelligence-based prediction methods could be more accurate and faster than the previous prediction method. Furthermore, artificial intelligence-based prediction methods enable NPPs to instrument what was previously impossible such as moisture carryover. Therefore, the application of 4th industrial revolution technology to innovative operation and maintenance technology is important to improve the safety, operability, and global competitiveness of i-SMR. Diagnosis, prognosis. and prediction of significant variables using artificial intelligence and digital twin, which are based on the 4th industrial revolution technology, could contribute to the enhancement of efficiency and safety. The diagnosis and prognosis of components facilitate the maintenance and make the frequency of regular maintenance less by predicting the useful life or behavior. With the development of robotics and automation, the combination of prediction and diagnosis technology and robotics contributes to maintenance automation such as a smart factory. A smart factory is an intelligent production plant that improves productivity and quality by applying information and communication technology combined with digital automation solutions to production processes such as design and development, manufacturing, and distribution [15]. By shifting the smart factory's perspective from production to maintenance, automating the maintenance of components can reduce costs, improve maintenance efficiency, and reduce human intervention. The diagnosis, prognosis, prediction, and maintenance automation for significant variables and components with artificial intelligence and digital twin should be considered to enhance the efficiency, safety, and global competitiveness of i-SMR. Hence, the direction of development and road map is proposed based on artificial intelligence and digital twin-based diagnosis and prognosis with autonomous operation and maintenance automation to innovate the operation and maintenance of i-SMR.

4. Road map for innovative operation and maintenance technology of i-SMR

Although various studies on operation and maintenance are being conducted to improve the safety and economic feasibility of NPPs based on innovative operation technology, most studies have been conducted for the purpose of applying large-scale NPPs. Since SMRs utilize natural circulation, passive safety systems, or inherent safety, the uncertainty of measurement would be significant compared to large-scale NPPs. There would be differences in performance and application methods of innovative technologies for operation and maintenance, which are developed for large-scale NPPs. Therefore, the development direction of innovative operation and maintenance technology should be established for SMR. In this paper, the road map is constructed by reflecting the road map of i-SMR for the purpose of licensing by 2028. The road map of i-SMR is shown in Fig. 1.

i-SMR was designed with the goal of differentiated safety from previous NPP and drastically reducing operating personnel. Before the Preliminary feasibility analysis for i-SMR, i-SMR tried to apply autonomous operation and digital twin. However, innovative operation and maintenance technologies were not permitted in the Preliminary feasibility analysis for i-SMR. The interest in autonomous operation and the digital twin has weakened in the i-SMR technology development project. Above all thing, the number of workers must be reduced for differentiated safety and a drastic reduction of operating personnel. Autonomous operation and maintenance automation should be considered to reduce the number of workers with safety enhancement. For that, prediction and diagnosis through artificial intelligence and digital twin should be applied. Considering the road map of i-SMR, the development period goal for innovative operation and technology is set to 6 years to take the license.

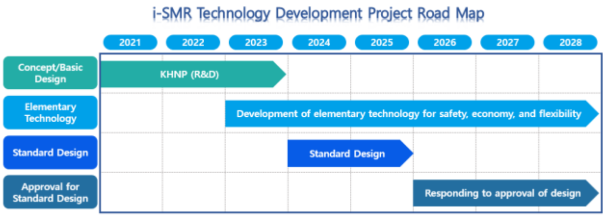

Fig. 1. Road map for i-SMR technology development project in Korea.

Performance verification is required for licensing innovative operation and maintenance technologies such as artificial intelligence, digital twin, diagnosis, prediction, autonomous operation and maintenance automation to be applied to i-SMR. When new concepts for NPPs are proposed to improve safety and efficiency, a typical procedure of performance verification is to apply to NPPs after conducting the performance test through the integral effect test based on the result conducted by the separate effect test facility. Representatively, when Kairos power proposed SMR operated by molten salt, the direction of development was constructed to implement the performance verification using integral and separate effect test facilities. After the performance evaluation conducted by the separate effect test facilities, the application of innovative operation and maintenance technologies to the integral effect test facility has considerable advantages. When the technologies evaluated by the separate and integral effect test facility are applied to the i-SMR, the performance can be improved or the amount of data required for training can be reduced by the transfer learning. Transfer learning refers to a method of using a network that was used to extract features from previous data to extract features from similar data sets. Therefore, this paper suggests the performance verification method using integral and separate effect tests for innovative operation and maintenance technologies such as artificial intelligence, digital twin, diagnosis, prediction, and automation of maintenance. The separate effect test facility would be considered to conduct the performance test of artificial intelligence or digital twin based diagnosis and prognosis. Considering the performance evaluated by the separate effect test, the innovative operation and maintenance technology with maintenance automation would be implemented to integral effect test facility for performance verification.

In the first year, key variables and components to be predicted and accidents to be diagnosed in i-SMR should be adopted using artificial intelligence and digital twin, and the range for maintenance automation should be decided. In the second year, the performance verification of component diagnosis method, prediction of useful life, and variable prediction should be conducted by separate effect test facility with artificial intelligence. The digital twin application method should be devised, based on the results from the separate effect test facility. Furthermore, the signal-processing method of i-SMR should be developed for the automation of maintenance. In the third year, the application method for component diagnosis, prediction of useful life and variables, and accident classification should be constructed to integral effect test facility. The feasibility of the digital twin for key parameters or components should be confirmed. Considering the signal processing method, the feasibility of the maintenance automation should be verified. In the fourth year, the performance of the multi-component diagnosis, the accident classification, and multiple variables prediction are evaluated in the integral effect test facility, using artificial intelligence with measurement data. The design and application of digital twin to integral effect test facility should be required. In addition, the implementation of maintenance automation to integral effect test facility should be conducted to evaluate the performance. In the fifth year, the monitoring and application method of developing innovative operation and maintenance technologies for i-SMR should be devised. In the last year, the process for license should be conducted based on the performance of each technology. The road map is shown in Fig. 2. Therefore, the development of innovative operation and maintenance technologies should be conducted with the i-SMR technology development project.

Fig 2. Road map of innovative operation and maintenance technologies development proposed for i-SMR

5. Conclusion

Recently, the interest in SMR has increased due to the low initial investment, fast investment payback period, enhanced safety, and multi-purpose utilization. Therefore, Korea has been accelerating the development of i-SMR. However, innovative operation and maintenance technologies should be considered to strengthen the global competitiveness, safety, and economic feasibility of i-SMR. The cost of operation and maintenance is the most expensive except for the construction cost and the intervention of humans in operation and maintenance makes the nuclear power plant unpredictable. Innovative operation and maintenance technologies have been suggested to help the operators or reduce human errors using the 4th industrial revolution technology. Hence, the safety and economic feasibility of i-SMR can be enhanced by applying the 4th industrial-based innovative operation and maintenance technologies. Considering the regulations, diagnosis, prognosis, prediction, and maintenance automation for key variables and components with artificial intelligence and digital twin can be applied as innovative operation and maintenance technologies of i-SMR. Because the performance verification of innovative operation and maintenance technologies should be conducted for i-SMR, the method, which evaluates the performance from separate and integral effect test facilities, is suggested in this paper. Considering the roadmap of the i-SMR technology development project, the development direction and roadmap are presented over 6 years.

In detail, the digital twin, autonomous operation, and maintenance automation require electrical lines and systems, which are more important compared to previous NPPs. The monitoring system for the logic system, electrical line, and electrical system should be supplemented. The scope of autonomous operation must cover normal operation, abnormal operation, emergency operation, and severe accident operation. In the event of an accident, procedures for abnormal operations, emergency operations, and severe accident operations should be presented to the operator through accident classification. The digital twin technology should reflect the actual phenomenon and update the phenomenon in real time, considering the influence of multiple units. Furthermore, the digital twin technology should be constructed by developing the physical-based or artificial intelligence-based method for the primary and secondary systems, such as pumps, steam generators, reactor cores, etc. The maintenance automation should include tests and inspections in normal or abnormal conditions, such as overhaul inspections for regular inspections.

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