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DEVELOPMENT of ADVANCED SMALL MODULAR REACTORS in KOREA: A PROMISING PATH TOWARD NET-ZERO GOALS

Seokjean Lyou, Jinbok Cho, and Si Hwan Kim
Users Inc.
#530 Hansin S-MECA, 1359 Gwanpyeong-dong, Yuseong-gu, Daejeon, Korea
uskin@users.co.kr, jinbok77@user.co.kr, shkim8656@hotmail.com

Joon-Ku Lee
Korea Atomic Energy Research Institute
111 Daedeok-daero, 989 beon-gil, Yuseong-gu, Daejeon, Korea 34057
jklee@kaeri.re.kr

ABSTRACT

The development of advanced Small Modular Reactors (SMRs) has been actively pursued in Korea as a key strategy to achieve its net-zero emissions target by 2050. This paper provides a comprehensive overview of two SMRs under development in Korea: immediately deployable System-Integrated Modular Advanced Reactor (SMART) and innovative SMR (i-SMR), highlighting key projects, technological advancements, and ongoing challenges. In addition, this paper focuses on various advanced design features adopted in the SMART and the i-SMR with respect to safety enhancement and economic improvement. On July 4, 2012, the SMART with a rated thermal power of 330MWt was the first integral nuclear reactor in the world, which obtained standard design approval from the government, signifying the completion of technology development. Since then, passive safety systems and improved design functions were added to the SMART to enhance safety, reliability, and economic efficiency through simplification, modularization, and shortened construction period. Based on SMART technology, the i-SMR with 170MWe integral type PWR has been initiated in 2020 focusing on more safe and economic efficiency. Through modularization and factory production, construction cost can be improved to the level of commercial nuclear power plants. Korean nuclear industries established a development roadmap for the i-SMR.

***Keywords**: System-integrated Modular Advanced Reactor (SMART), Innovative Small Modular Reactor (i-SMR), Standard Design Approval (SDA), Passive Safety System, Desalination*

1. INTRODUCTION

The global nuclear energy market is being reorganized around small modular reactors (SMRs). The SMR market size is expected to be approximately 270 billion USD by 2050. Currently, about 70 types of SMRs with an output of 300 MWe or less are being developed worldwide [1]. A SMR adopts the integrated reactor concept in which reactor core, steam generator, pressurizer, and reactor coolant pump are placed in a single reactor pressure vessel. Safety can be greatly improved by eliminating large pipe breakage accidents.

The SMART has been developed since early 1990s with the goal of providing sufficient electricity (90 MWe) and fresh water (40,000 tons) to a city with a population of 100,000 or an industrialized complex. In the beginning stage of the SMART development, top-level requirements for safety and economics were imposed for the SMART design features [2]. To meet the requirements, highly advanced design features enhancing the safety, reliability, performance, and operability are introduced in the SMART design. From 1997 to 2002, Korea Atomic Research Institute (KAERI) performed basic design for SMART 330MWt nuclear reactor system and seawater desalination system, safety analyses, and preliminary economic evaluation [3]. In this design phase, the participating industries include Doosan Heavy Industries and Construction Company (DSHIC), Korea Power Engineering Company, Inc. (KOPEC), Korea Institute of Nuclear Safety (KINS) and various universities in Korea.

On July 4, 2012, it was the first integrated nuclear reactor in the world to obtain SMART standard design approval from the government. Since 2016, the Korea Atomic Energy Research Institute and the King Abdullah City for Atomic and Renewable Energy (K.A. CARE) have been promoting the development of an improved SMART. The complete passive safety system was incorporated into the SMART design. By applying these safety improvement technologies, we are currently pursuing standard design change approval.

The i-SMR is an integral type of PWR with a 680MWe-class plant installing four (4) 170MWe-class modules and a design life of 80 years. The design concept of the i-SMR focuses on improving safety, economy, and flexibility [4]. Passive safety systems for core cooling, residual heat removal, and containment cooling are introduced to virtually eliminate the possibility of serious accidents and dramatically increase resistance to accidents. The i-SMR safety can be improved by approximately 1,000 times that of commercial nuclear power plants, eliminating resident evacuation. Construction cost can be improved to the level of large nuclear power plants through modularization, system sharing, simplification, and operation maintenance.

Korea Hydro & Nuclear Power Co., Ltd. and KAERI completed the development of the i-SMR concept and establishment of a development plan in 2020. The basic design began in January 2021 is scheduled to be completed in 2024. The goal of the i-SMR development is to obtain approval and verify technology for an innovative SMR standard design with market competitiveness in the 2030s. Korean nuclear industries established a goal of completing design by the end of 2025, obtaining a license for the standard design approval (SDA) from the government in 2028 and then the first module installation by 2031 [5].

2. SMART DEVELOPMENT

2.1 SMART Design Features

The SMART design combines firmly established commercial reactor design technologies with new advanced technologies [6]. An integral type of reactor concept eliminates Large-Break Loss of Coolant Accidents (LBLOCA) from design-based accidents. The reactor pressure vessel (RPV) contains reactor core, steam generator (SG), reactor coolant pump (RCP), and pressurizer. Figure 1 shows schematic diagram of the SMART desalination plant. The primary cooling system is forced to circulate by RCP during normal operation and has a natural circulation function that can be used in emergency situations. The SMART has SGs with helical coiled tubes to generate superheated steam under normal operating conditions.

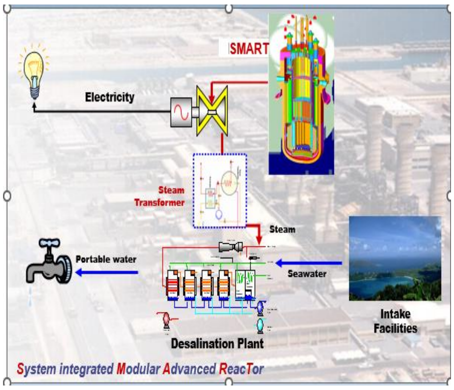

Figure 1. Schematic Diagram of the SMART Desalination Plant

In case of an accident, the SG can be used as a heat exchanger allowing independent operation of the passive residual heat removal system (PRHRS). The pressurizer utilizes the free volume at the top of the reactor vessel. Primary system pressure is kept nearly constant due to the large pressurizer vapor volume and heater control. Reactor overpressure in the hypothesized design basis accident can be reduced through operation of the pressurizer safety valve.

The low-power density SMART core with low-enriched UO_2 fuel ensures a thermal margin of more than 15% and can accommodate expected transients. The core contains 57 fuel assemblies (FA) with an enrichment of less than 5%. The two-batch fuel loading method without reprocessing provides a maximum effective power cycle. During normal operation, reactivity is controlled by control rods and soluble boron. Key design parameters of major SMART system are summarized in Table 1.

2.2 SMART Safety Systems

In developing SMART, safety enhancement was one of the most important considerations. The safety requirements on the SMART were top tiered by the core damage frequency per reactor year less than 10^{-7} and the large off-site dose release rate of less than 10^{-8} per reactor year. These requirements have been achieved by applying safety enhancement, passive safety system, and radiation protection to the SMART design features. The safety system consists of the reactor shutdown system, passive safety injection system (PSIS), passive residual heat removal system (PRHRS), and reactor building pressure and radiation suppression system. Additional safety systems include automatic pressure relief systems, pressurizer safety valves, and serious accident mitigation systems.

There are several inherent safety features in the SMART design such as a large negative moderator temperature coefficient, a low core power density etc. Besides the inherent safety characteristics of SMART, further enhanced safety is accomplished with highly reliable engineered safety systems. The engineered safety systems designed to function passively on the demand consists of a reactor shutdown system, passive residual heat removal system, emergency core cooling system, reactor overpressure protection system and containment overpressure protection system. With all those enhanced safety features, the core meltdown frequency is expected to one hundredth of that of a conventional reactor.

Table 1: Major SMART Design Parameters

Design Parameters	
Reactor Type	Integral PWR
Plant Capacity MWe	107
Thermal Capacity MWt	365
Reactor Coolant pump	Canned motor type
Steam Generator	Helical once-through type
Safety Systems	Fully passive
design life, years	60
Core inlet/Outlet coolant temperature ℃	296/322
Fuel Type/Assembly array	UO2/17x17 square pitch
Number of fuel assemblies in the core	57
Core discharge burnup, MWD/MTU	<54,000
Refueling cycle, month	36

2.3 SMART DESIGN VERIFICATION PROGRAM

Advanced design features implemented into the SMART require tests to confirm the performance of design and to produce data for design code verification. SMART verification program includes basic thermal-hydraulic experiments, separate effect test on major components and integrated tests of safety system [7]. Fundamental thermal-hydraulic experiments were carried out during the concept development to assure the key technology of the advanced safety systems. These experimental data have been utilized for the conceptual design of SMART.

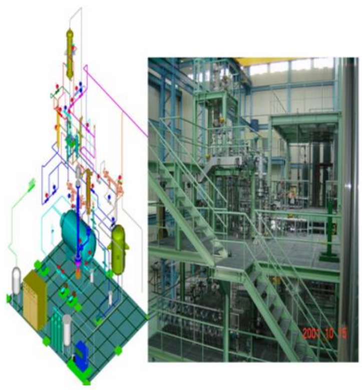

Figure 2. High-Temperature and High-Pressure Test Facilities

Separate effect tests of SMART major components are performed to get the fundamental database and computer analysis models [8] are developed. Advanced design features implemented into the SMART were proven or qualified by testing, or analysis. Thermal-hydraulic behavior for operational transients and design basis accidents has been experimentally investigated using the thermal-hydraulic integral test facility, VISTA (Experimental Verification by integral Simulation of Transients and Accidents). The high-temperature and high-pressure test facilities designed and installed at KAERI is shown in Figure 2.

3. i-SMR DEVELOPMENT STATUS

3.1 i-SMR Design Concept

General design principle for the i-SMR is to seek simplified design, ensure sufficient design margins, advanced human factor engineering, eco-friendly design, and application of innovative technology for construction and operation. The i-SMR eliminates LBLOCA by adopting integrated reactor concept. Passive safety system includes natural forces completely passive system for core cooling, residual heat removal, and containment cooling. To improve economics, the i-SMR introduces multiple modules in a single reactor building, modulization, factory manufacturing, and component design optimization. A 680MWe-class plant installing four (4) 170MWe-class modules is set as the main concept, but output can be varied by adjusting the number of modules depending on market demand. Key technologies to be applied to the i-SMR include passive safety, built-in CEDM, innovative nuclear fuel, autonomous operation, modularization, flexible operation technology, boric acid-free operation, innovative manufacturing technology, and integrated control room [4].

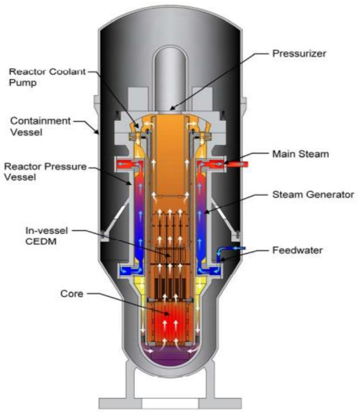

Figure 3: a Schematic diagram of the reactor coolant system

Table 2: Major i-SMR Design Parameters

Design Parameters	
Reactor Type	Integral PWR
Plant Capacity (number of Reactors) MWe	680(4)
Thermal/electrical Capacity per Reactor,	540(MWt)/170(MWe)
Reactor Coolant pump	Canned motor type
Steam Generator	Helical once-through type
Safety Systems	Fully passive
design life, years	80
Core inlet/Outlet coolant temperature ºC	295.5/320.9
Fuel Type/Assembly array	UO2 / 17x17 square pitch
Number of fuel assemblies in the core	69
Core discharge burnup, MWD/MTU	<62,000
Refueling cycle, month	24

All major equipment of the reactor coolant system such as the core, reactor coolant pump, steam generator, and pressurizer are installed in one pressure vessel. By boric acid-free operation, the amount of radioactive waste generated can be reduced and the system can be simplified. By using a built-in control rod drive device along with a boric acid-free core design, safety was improved by eliminating control rod separation accidents. Figure 3 shows a schematic diagram of the reactor coolant system. The primary system coolant flows from top to bottom outside the steam generator heat pipe and the secondary water flows from bottom to top inside the inclined heat pipe. The optimized design of the reactor vessel, containment vessel, discharge valve, and circulation valve make it possible to maintain core cooling in the event of an accident without complex systems such as tanks or pumps for emergency coolant injection. Major design parameters are summarized in Table 1.

3.2 Development of High-Precision Measuring Instrument

To improve autonomous operation performance and safety for the i-SMR, a high-precision measurement system is being developed such as high-precision environmental distribution sensor systems, low-power wireless sensing, process measurement sensors, and off-road neutron flux monitoring facilities. Since miniaturization, integration, and optimization of process variable/condition monitoring measurement sensors are essential at the i-SMR, a distribution sensing system is thus developed for high-precision measurement and environmental characteristics. Due to the nature of the i-SMR's design, the main devices on the primary side are integrated within the reactor vessel, so there are limitations on the installation and placement space for sensors and instruments for safety diagnosis. Therefore, multiple sensors and measurement cables are simplified with an ultra-small single line. We are currently pursuing the development of wireless low-power complex sensing capable of wide-area precise diagnosis. Three types of process measurement sensors to measure coolant flow rate, pressure, and water level inside the reactor vessel are currently under development. The outer wall of the reactor vessel and containment vessel where the instrument is installed is a high-temperature, high-radiation environment and the installation space is very narrow, so a configuration is being developed in which only essential parts of the sensor components are installed in the reactor vessel and the rest are separated outside the shield.

The Ex-core Neutron Flux Monitoring System (ENFMS) is a facility that provides signals to the reactor control system and protection system. In the ENFMS installation, the space between the reactor vessel and the containment vessel is narrow, so the size, installation, and placement space of the sensor are limited. The environment, such as temperature, pressure, and radiation, inside the containment vessel is expected to be harsher than that of an existing operating nuclear reactor. In line with the i-SMR operating conditions and performance requirements, ENFMS installation requires the introduction of new monitoring sensors and signal processing systems. The development of a digital ENFMS has been promoted aiming for digitalization of the entire nuclear power I&C system.

3.3 i-SMR Safety System

The safety system of the i-SMR consists of an emergency core cooling system, a passive auxiliary water supply system, and a passive containment vessel cooling system. The i-SMR is designed as a steel-type containment vessel in a large concrete containment building. The steel-type containment vessel minimizes the amount of coolant leakage by creating early pressure balance between the reactor and containment in the event of an accident and minimizes the capacity of the safety system [5].

Fully passive safety system design with unique safety characteristics is adopted to the i-SMR so that severe accidents are free. Safety system design and operator intervention measures such as removal of residual heat using natural convection in the event of an accident are minimized. On the other hand, the i-SMR maximizes the ability to respond to natural disasters (earthquakes, tsunamis, etc.) through safety design such as strict earthquake-resistant design. It also minimizes spent nuclear fuel generation through long-term operation. Consequently, it minimizes environmental impact by minimizing the possibility of radioactivity released through high-pressure steel containment containers. By improving safety and minimizing the site, the impact of radiation is reduced to a level where resident evacuation is not necessary.

4. CONCLUDING REMARKS

Korea's SMR development program exhibits considerable progress and commitment, contributing to clean and reliable energy solutions for a sustainable future. Various advanced design features are adopted in the SMART and the i-SMR with respect to safety enhancement and economic improvement.

The SMART is an integral reactor with new innovative design features aimed at achieving a high enhanced safety and improved economics. The SMART design adopted an integrated system configuration, modularization, and an advanced passive safety system to improve safety, reliability, and economic efficiency. Economic feasibility was improved through system simplification, factory manufacturing, reduced construction time and high-power plant utilization. Since the SMART technology level is at the stage just prior to construction, it is expected that commercial operation will be possible in the 2020s. Potential SMART construction projects are currently under discussions in Canada and middle east countries.

The i-SMR with 170MWe integral PWR has been evolved from SMART technology and lessons learned focusing on more safe and economic efficiency. The i-SMR dramatically increases resistance to accidents and reduces the possibility of safety accidents by approximately 1,000 times that of large nuclear power plants. Through factory production of integrated reactor modules, economic improvement will be realized to the level of large nuclear power plants through modularization, system sharing, simplification, and operation maintenance using innovative technology. The milestone of the i-SMR is obtaining the Standard Design Approval (SDA) from the government in 2028 and the first module installation by 2031.

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