Journal of Energy and Power Engineering 8 (2014) 94-102

SMART: The First Licensed Advanced Integral Reactor

Keung Koo Kim, Wonjae Lee, Shun Choi, Hark Rho Kim and Jaejoo Ha

Korea Atomic Energy Research Institute, Daeduckdaero 989-111, Yuseongku, Daejeon 305-353, Korea

Received: April 23, 2013 / Accepted: August 12, 2013 / Published: January 31, 2014.

Abstract: SMART (system-integrated modular advanced reactor) is a small-sized advanced integral reactor with a rated thermal power of 330 MW. It can produce 100 MW of electricity, or 90 MW of electricity and 40,000 t of desalinated water concurrently, which is sufficient for 100,000 residents. SMART technology is a sensible mixture of new innovative design features and proven technologies through a PWR. The enhancement of safety and reliability is realized by incorporating inherent safety features and reliable passive safety systems. The improvement in the economics is achieved through system simplification, component modularization, construction time reduction, and increased plant availability. All technologies and design features implemented into SMART have been proven in industries and/or qualified through the SMART design verification program including comprehensive test and experiments. The full scope of the safety analyses carried out to confirm that the inherent safety-improvement design characteristics and safety systems of SMART ensure reactor safety. After a thorough licensing review, SDA (standard design approval) for SMART was granted on July 4th, 2012 by the Korea NSSC (Nuclear Safety and Security Commission). This marks the first license for an integral-type reactor in the world. This paper presents the SMART characteristics, safety features and technology validation. The licensing process of SMART is also described.

Key words: SMR, advanced technology, passive safety system, technology validation, standard design, SMART.

1. Introduction

After nuclear power generation became established in the 1950s, the size of reactor units has grown from 60 MWe to more than 1,600 MWe, with corresponding economies of scale during operation. Most nuclear power plants currently available on the market are large-sized plants requiring a large initial investment and a long construction period. Therefore, only a select number of countries can afford to utilize nuclear energy.

However, most countries operate small-sized power plants for their electricity supply, and 96.5% of the 127,000 power plants currently operating in the world are under 300 MWe [1]. These countries can not deploy large-sized nuclear power plants partly owing to the high capital cost and small electricity grids [2]. Therefore, several countries including Korea have entered into a race to develop small-sized reactors that can be built independently or as modules within a larger complex, with capacity added incrementally as required. The economies of scale are provided by the numbers produced. Small units are seen as a much more manageable investment than large ones. The KAERI (Korea Atomic Energy Research Institute) started developing SMART in 1997, aiming to export it to countries with small electric grids and water supply issues [3, 4].

SMART is a small-sized integral type PWR with a rated thermal power of 330 MWt, which adopts a sensible mixture of new innovative design features and proven technologies aimed at achieving highly enhanced safety and improved economics. The design features contributing to safety enhancement are basically inherent safety improvement and passive safety features. Economic improvement features include system simplification, component modularization, on-shop fabrication and site

Corresponding author: Keung Koo Kim, SMART Project Manager, research fields: SMR design and reactor dynamic analysis. E-mail: kkkim@kaeri.re.kr.

installation and other features reducing the construction time. Advanced design features implemented into SMART should be proven or qualified through experience, testing, or analysis, and if possible, the equipment should be designed according to the applicable approved standards. For the last 15 years, SMART-specific design methodologies and a computer code system have been built together through a series of validation experiments and equipment verifications. From 2009 to 2012, the SMART Technology Validation and the Standard Design Approval Project were carried out. After one and half years of intensive licensing review, the SDA for SMART was officially issued on July 4th, 2012 by the NSSC, in compliance with Article 12 of the Nuclear Safety Act. This is the first license for an integral reactor in the world.

2. SMART Design Goal

From the beginning stage of the SMART development, top-level requirements for safety and economics were imposed for the SMART design features as shown in Table 1. Safety enhancement and economic improvement are the most important considerations. The safety requirements of SMART were top-tiered based on the core damage frequency per reactor year, which is less than 10^{-6} per reactor year, and the large off-site dose release rate of less than 10^{-7} per reactor year.

To meet these requirements, highly advanced design features enhancing the safety, reliability, performance and operability are introduced in the SMART design. In particular, the enhancement of safety and reliability is realized by incorporating inherent safety improvement features and reliable passive safety systems. SMART was designed as an integral type PWR, and the reactor pressure vessel contains the major primary components. The integral reactor design features exclude the possibility of a LB-LOCA (large-break loss-of-coolant-accident) through the elimination of coolant loops, and reduce the fast neutron fluence on the reactor pressure vessel.

To compensate for the economic deterioration of SMRs compared with that of a large-sized reactor, many possible mechanisms for economic improvement are adopted in SMART. System simplification and a reduction of pipes and valves are possible owing to the implementation of advanced passive systems and highly inherent safety characteristics. Modularization, component standardization and on-shop fabrication and direct site installation of the components are additional characteristics that can contribute to a reduction of the construction cost.

3. SMART Design Characteristics

SMART is an integral-type reactor containing major components within a single reactor pressure vessel, as shown in Fig. 1.

Eight (8) modular-type once-through steam generators consist of helically coiled tubes producing 30 °C superheated steam under normal operating conditions, and a small inventory of secondary side water sources at the steam generator prohibit a return to power following a steam line break accident. Four (4) reactor coolant pumps with a canned motor, which has no pump seals, inherently prevents a loss of coolant

Table 1 Top level design requirements of SMART.

Category	Contents	Requirements
Safety	Core damage frequency	Less than 10^{-6}/reactor year
	Large radioactivity release frequency	Less than 10^{-7}/reactor year
	Thermal margin	Greater than 15%
Economics	Electric production cost	Less than that of gas TB
	Construction period	Less than 36 months
Performance	Availability	Greater than 95%
	Reactor life	60 years

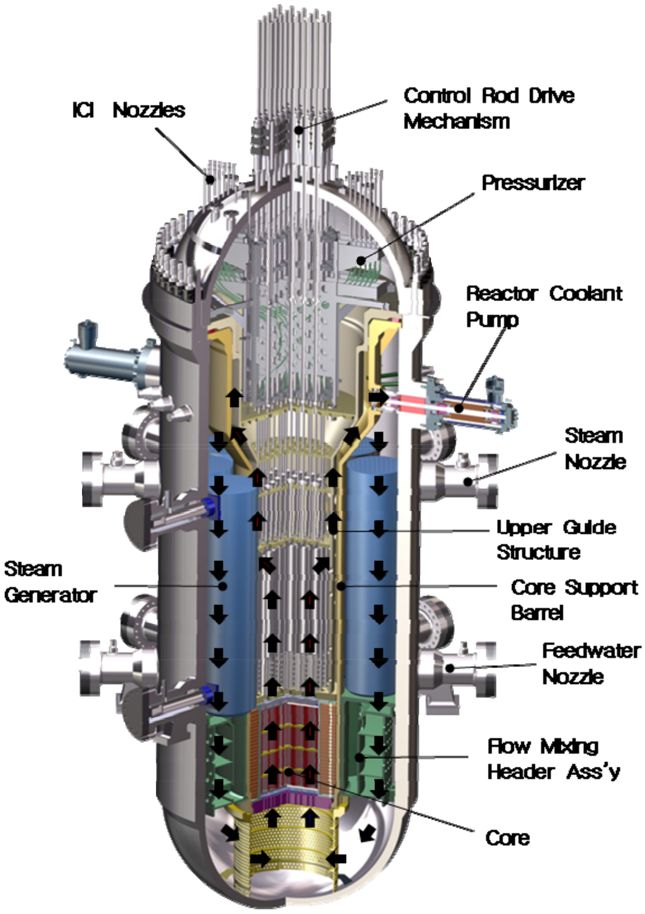

Fig. 1 SMART reactor vessel assembly.

associated with a pump seal failure. Four (4) channel control rod position indicators contribute to the simplification of the core protection system and to an enhancement of the system reliability. The in-vessel pressurizer is designed to control the system pressure at a nearly constant level over the entire design basis events.

A schematic diagram for the major fluid systems of SMART is given in Fig. 2. The major fluid systems of SMART are the reactor coolant system, engineered safety systems, a chemical and volume control system, a passive residual heat removal system, and a safety injection system together with a shutdown cooling system. There are a variety of auxiliary systems as well. The reactor coolant system is the main system of a nuclear power plant.

The heat produced from nuclear fuel is transferred to a turbine through an SG. The 4-train passive residual heat removal system keeps the reactor cooled during an abnormal shutdown. We can make a PRHRS loop with a makeup tank before operation. The safety injection system directly inserts additional coolant into the reactor in the case of a small break LOCA. Anin-containment refueling water storage tank is installed within the containment building as a water source of the safety injection. The shutdown cooling system with two trains keeps the reactor cooled from a hot shutdown condition (about 200 °C) to cold shutdown condition (about 50 °C). As safety systems, SMART is equipped with a reactor overpressure protection system and a containment spray system. The chemical and volume control system controls the chemistry or volume of the reactor coolant.

The SMART desalination system consists of four units of MED-TVC (MED combined with a thermal vapor compressor) [5]. The distillation unit operates at

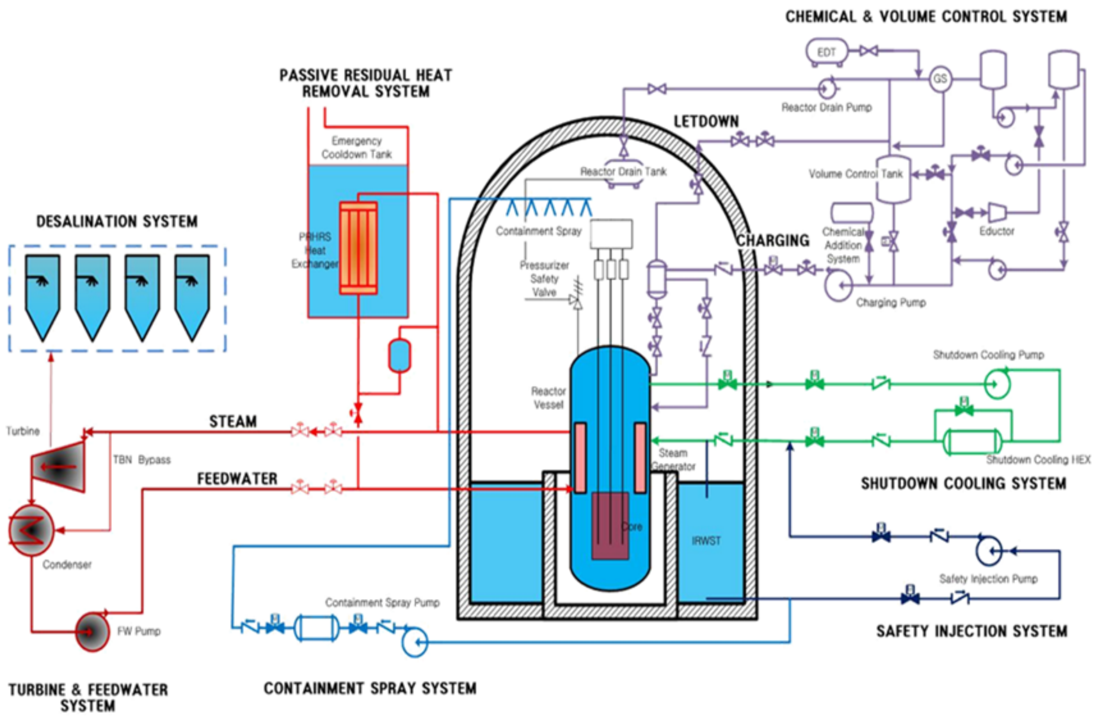

Fig. 2 Schematic diagram of SMART fluid system.

a maximum brine temperature of 65 °C and a supplied sea water temperature of 33 °C. The MED process coupled with SMART incorporates a falling film, a multi-effect evaporation with horizontal tubes, and a steam jet ejector. One significant advantage of the MED-TVC is its ability to use the energy pressure of the steam. Thermal vapor compression is very effective when the steam is available at a higher temperature and pressure conditions than required in the evaporator. The thermal vapor compressor enables the low-pressure waste steam to be boosted to a higher pressure, effectively reclaiming its available energy. Compression of the steam flow can be achieved with no moving parts using the ejector. The SMART and MED-TVC units are connected through the steam transformer as shown in Fig. 3. The steam transformer produces the motive steam using the extracted steam from a turbine, and supplies the process steam to the desalination plant. It also prevents a contamination of the produced water by hydrazine and the radioactive material of the primary steam. The steam is extracted from a turbine using an automatic (controlled) extraction method. The extracted steam control valves vary the flow-passing capacity of the stages downstream of the extraction point. This type of control is usually used when the process steam exceeds 15% of the down-stream of the extraction point. The primary steam flow is condensed inside the tubes at its saturation temperature. The brine feed is sprayed outside of the tube bundles by a recycling pump. Part of the sprayed water is evaporated and the produced steam is used as the motive steam for the thermo-compressor of the evaporator. Part of the condensate in the first cell of the evaporator is used as a make-up for the steam transformer, and this make-up water is preheated by the condensate of the primary steam before being fed into the steam transformer. When SMART is used for a cogeneration purpose, i.e., electricity generation and district heating, it is estimated that ~80 MW of electricity and ~ 150 Gcal/h of heat can be delivered to the grids.

4. Safety Characteristics of SMART

In the SMART design, the defense-in-depth philosophy is implemented by adopting and implementing

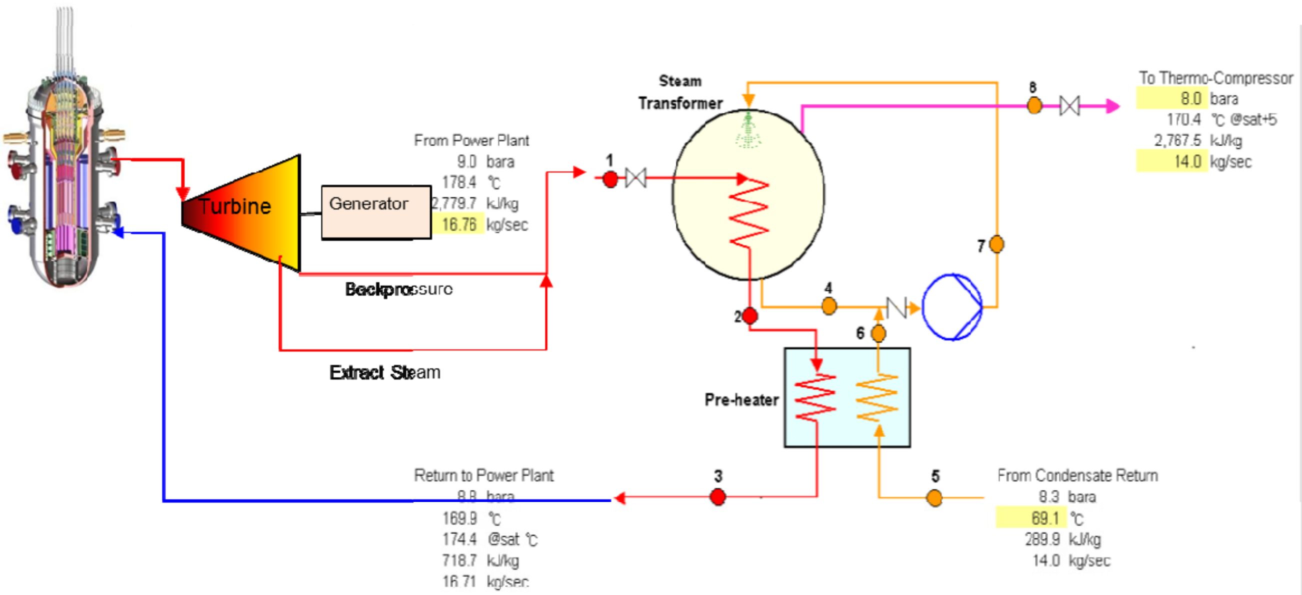

Fig. 3 Coupling concepts of SMART and the desalination system.

effective safety features for all levels of defense in depth. In addition, enhanced safety is accomplished by adopting a step-by-step design approach. In the first step, the accident occurrence possibility is minimized by eliminating large-sized pipes. Second, the possibility of a fuel failure decreases with the installation of highly reliable engineered safety systems. Finally, the radiation release paths are protected by a closed-loop residual heat removal system.

The safety systems consist of a shutdown cooling system, residual heat removal system, safety injection system, emergency boron injection tank and reactor overpressure protection system. The major engineered safety systems function passively upon demand. The reactor can be shutdown under any circumstances by inserting control rods or through a boron injection. Four (4) independent passive residual heat removal systems with 50% capacity each remove the core decay heat through natural circulation at any design basis events, and have the capability of keeping the core undamaged for 72 h without any corrective action by operators. When a small break LOCA occurs, uncovering of the core is prevented by four (4) independent safety injection systems with 100% capacity each, which automatically operate through a pressurizer pressure set-point signal. The reactor overpressure during a postulated design basis accident related with a control failure can be reduced through the opening of the PSV (pressurizer safety valve). An additional engineered safety system includes a severe accident mitigation concept. Reliable safety systems together with an exemption of an LBLOCA promise a safety goal of SMART that is 10 times higher than in existing commercial PWRs.

The integral configuration of the reactor coolant system, which eliminates large breaks in the primary pipes, provides an improved natural circulation using a large volume of coolant. Reactor safety is considerably enhanced by introducing a passive residual heat removal system, passive autocatalytic hydrogen re-combiners, a simplified safety injection system and external reactor vessel cooling.

A passive residual heat removal system consisting of a condensing heat exchanger, an emergency cooling tank, and a makeup tank prevents over-heating and over-pressurization of the primary system in the case of an emergency event. It removes the decay and sensible heat through a two-phase natural circulation. The engineered safety systems designed to function automatically on demand consist of a reactor shutdown system, safety injection system, passive residual heat removal system, shutdown cooling system and containment spray system. Additional safety systems include a reactor overpressure protection system and a severe accident mitigation system. The reactor can be shut down under any circumstance by inserting control rods or injecting boron. The core will remain undamaged for more than 36 h without any corrective action by the operator during all types of design-based accidents. The safety analyses of SMART show that it remains in a safe condition for all design basis events. The core damage frequency is about 1/10 of that of a conventional nuclear power plant.

A safety analysis of the SMART design was conducted, in which both deterministic and probabilistic analyses were applied. In the deterministic safety analysis, it was confirmed that the operational limits are in compliance with the assumptions and intention of the design for SMART under normal operation. The safety analysis was performed on initiating events listed in the SRDBE that are appropriate for the SMART design. The initiating events resulted in event sequences that were analyzed and evaluated for a comparison with the radiological and design limits as acceptance criteria. Safety analyses were performed to demonstrate that the management of a DBA is possible by an automatic response of the safety systems. For non-LOCA initiating events, the safety analysis was supported with relevant computer codes, which are compatible with the digital protection and monitoring systems of SMART. For the LOCA initiating events, a conservative methodology was utilized. The analysis results show that the SMART design properly secures the safety of the reactor system under limiting accident conditions.

In the SMART safety assessment, PSA (probabilistic safety analysis) is required to validate the event classification and plant condition, evaluate the safety level and identify the weak points of the SMART design. The scope of the PSA is level 1 in the basic design stage. Levels 2 and 3 PSAs, an external PSA, and a low power/shutdown PSA will be performed during the SDA stage. For the level 1 PSA, scenarios of 10 events were developed: general transients, loss of feed-water, loss of offsite power, SBLOCA, SLB (steam line break), SGTR (steam generator tube rupture), large secondary side break, control rod ejection (REA), ATWS (anticipated transient without scram) and control rod BWA (bank withdrawal).[6]

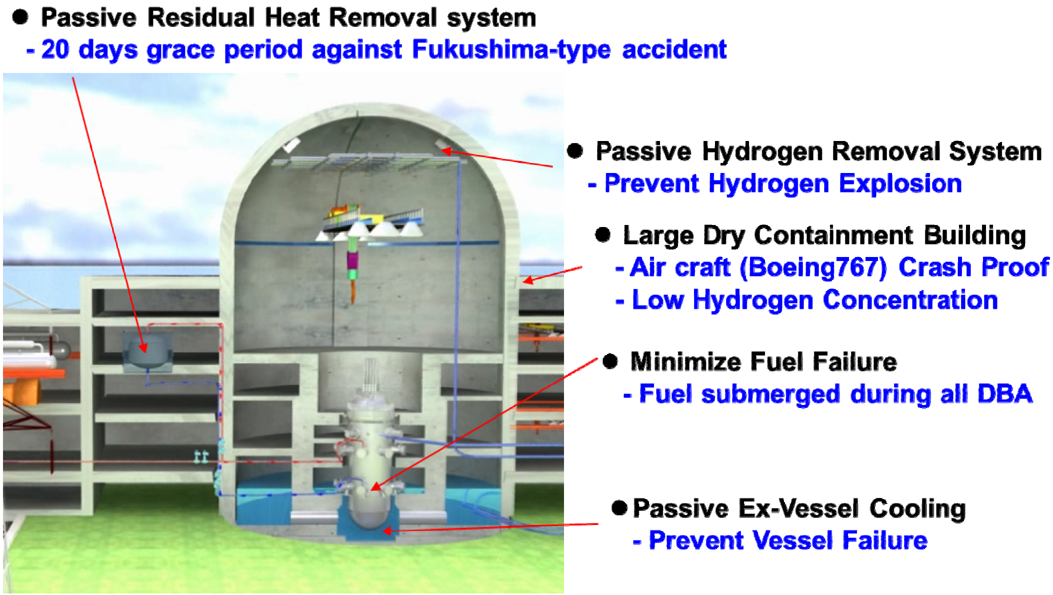

Fig. 4 SMART safety system and characteristics.

Since the Fukushima accident, mitigation measures to cope with a severe accident have become key safety issues. This shows that maintaining continuous core-cooling capability is essential. In a series of realistic simulations, the passive residual heat removal system of SMART effectively removed decay heat, maintaining the reactor in a stable condition for 20 days without external power sources or operator actions.

A steel-lined concrete RCB (reactor containment building) accommodates all primary reactor systems including the reactor assembly and associated valves and piping. A CPB (compound building) and an AB (auxiliary building) surround the RCB. A single base-mat accommodates the RPB, CPB and AB. The plant building layout was designed to reduce the surface silhouette and allow direct access to the RCB. As similar to the operating PWRs in the Rep. of Korea, the RCB is used to contain the radioactive fission products within the containment building and to protect against primary coolant leakage into the environment. With regard to aircraft crash resistance, the containment and auxiliary buildings of SMART were designed to withstand an aircraft collision (Boeing 767) without damage to the reactor or spent fuel pool. Fig. 4 shows SMART safety systems and their characteristics.

5. Technology Validation

SMART technology is a sensible mixture of innovative concepts and conventional technologies to improve the level of safety, reliability and economics. All technology implemented into SMART should be proven or qualified by experience, testing, or analysis, and if possible, the equipment should be designed according to the applicable approved standards. A SMART design verification program, including comprehensive experiments and the development of the analysis model, was planned and performed to confirm the advanced design features of SMART, which have yet to be proven through the design and operation of existing PWRs [7].

This program includes basic thermal-hydraulic experiments, separate effect tests on the major components, and integrated tests of the safety system. Basic fundamental thermal-hydraulic experiments were carried out during the concept development to assure the key technology of the advanced safety systems. After the SMART concept development, essential technologies are required for the development of SMART, such as a helically coiled tube steam generator and core cooling by natural circulation. To develop these technologies, separate effect tests of SMART's major components were performed to obtain a fundamental database, and computer analysis models were developed.

During the last stage of SMART development, a comprehensive technology validation plan was set up as shown in Fig. 5. Opinions from nuclear experts and regulators were gathered to establish a validation program, which covers safety tests, performance tests, and the development of tools and methods.

The technology validation program covers the core and fuel, thermal-hydraulics and safety, mechanics and components, and a digital man-machine interface system. The experimental validation program consists of 10 safety tests and 12 performance tests. The safety tests consist of Core CHF tests, separate effect and integral effect tests of the safety-related thermal-hydraulics and digital MMIS tests. Performance tests consist of a fuel assembly out-of-pile test, RPV thermal-hydraulics tests, performance tests of the major components and digital MMIS control room tests.

The test results were not only provided as the design bases of the SMART standard design, but were also used in validating the design tools and methods. The outcomes of the program were compiled into technical reports and submitted as technical background information for the licensing review. The test results were also used in demonstrating the performance and safety of the SMART standard design. The main objective of the large-scale IET is to validate the

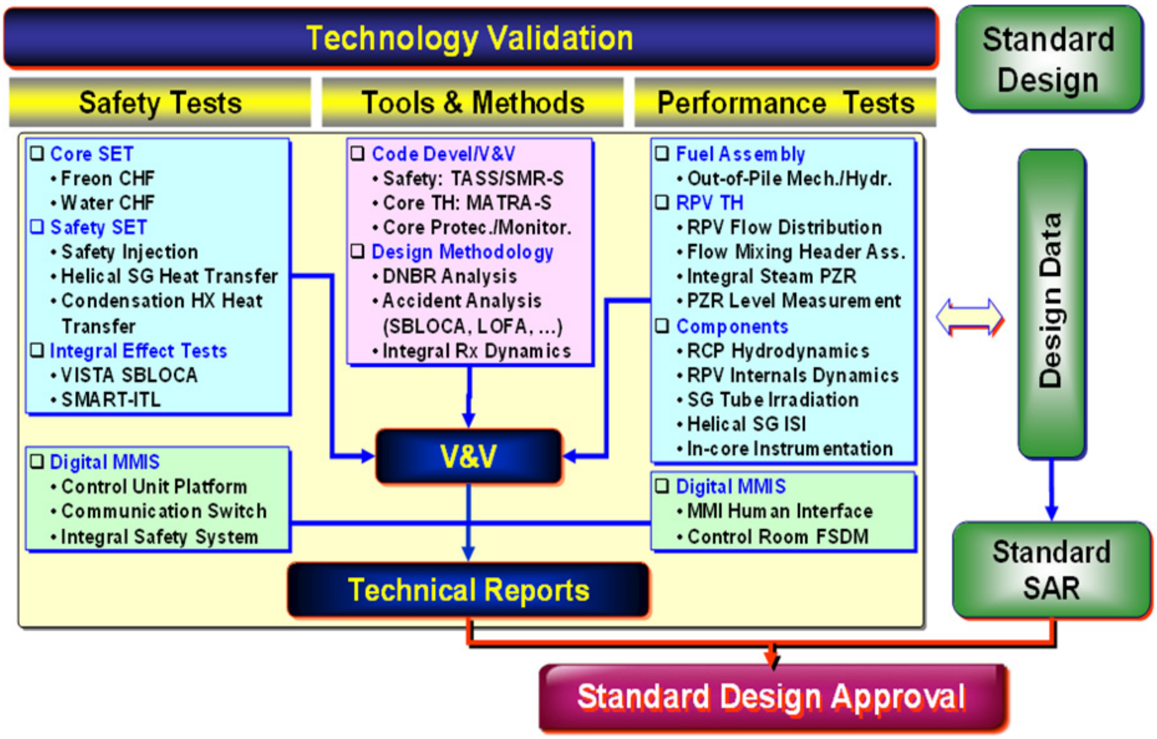

Fig. 5 Technology validation program of SMART.

overall system performance and safety in preparation for a future construction permit.

6. Licensing Review

The pre-application review started in February 2010, and was completed at the end of 2010. A full set of licensing documents for SDA, including a SSAR (standard safety analysis report), were submitted to the NSSC (Nuclear Safety and Security Commission) at the end of December 2010. During the one and half year licensing review, more than 2,000 questions from KINS (Korea Institute of Nuclear Safety: Korean nuclear regulatory expert organization) were answered with relevant engineering solutions. After an intensive licensing review, the SDA for SMART was officially issued on July 4th, 2012 by the NSSC, in compliance with Article 12 of the Nuclear Safety Act. This is the first license for an integral reactor in the world.

7. Summary

After 15 years of SMART development, the standard design and technology validation of SMART were completed. The technology adapted to SMART was fully backed up by a comprehensive technology validation program. The strong point of SMART lies in the proven technologies of its design; in addition, it has no risks or obstacles in terms of licensing or the supply of components.

By successfully obtaining SDA, SMART has become the most advanced small integral reactor in the world, and the only integral reactor that can be currently built. SMART is expected to open up the world's small reactor market and will take the leading initiative in the development of related technologies. SMART, with its enhanced safety and attractive economical design, will open up the market to the replacement of expensive, environmentally unfriendly fossil power plants for electricity-steam/water production.

Acknowledgments

This work was supported by Government Nuclear Research & Development Program as well as KEPCO Consortium.

Reference

[1] World Electric Power Plant Data Base, Platts, The McGraw-Hill Companies, 2011.

[2] IAEA Nuclear Energy Series, CUC (Common User Consideration) by Developing Countries for Future Nuclear Energy Systems, NP-T-2.1, IAEA, 2009.

[3] M.H. Chang, S.K. Sim, Y.D. Hwang, SMART—An advanced small integral PWR for nuclear desalination and power generation, in: Proceedings of International Conference on GLOBAL 1999, Jackson Hole, USA, Aug. 29-Sept. 3, 1999.

[4] S.H. Kim, K.K. Kim, J.W. Yeo, M.H. Chang, S.Q. Zee, Design development and verification of a system integrated modular PWR, in: Proceedings of 4th International Conference on Nuclear Option in Countries with Small and Medium Electricity Grids, Croatia, June 2002.

[5] M.H. Chang, Y.D. Hwang, Coupling of MED-TVC with SMART for nuclear desalination, Nuclear Desalination 1 (1) (2003) 69-80.

[6] S.K. Zee, Design Report for SMART Reactor System Development, KAERI/TR-2846/2007, KAERI, Taejon, 2007.

[7] S.H. Kim, Design verification program of SMART, in: Proceedings of International Conference on Global Environment and Advanced NPPs, Kyoto, Japan, Sept. 15-19, 2003.