Status report 77 - System-Integrated Modular Advanced Reactor (SMART)

Overview

Full name	System-Integrated Modular Advanced Reactor
Acronym	SMART
Reactor type	Integral Type Reactor
Coolant	Light Water
Moderator	Light water
Neutron spectrum	Thermal Neutrons
Thermal capacity	330.00 MWth
Electrical capacity	100.00 MWe
Design status	Conceptual Design
Designers	KAERI
Last update	04-04-2011

Description

Introduction

Overview

SMART (System-integrated Modular Advanced ReacTor) is a promising advanced small and medium category nuclear power reactor. It is an integral type reactor with a sensible mixture of proven technologies and advanced design features. SMART aims at achieving enhanced safety and improved economics; the enhancement of safety and reliability is realized by incorporating inherent safety improving features and reliable passive safety systems. The improvement in the economics is achieved through a system simplification, component modularization, reduction of construction time, and high plant availability. The preliminary safety analyses on the selected limiting accidents assure the reliability of the SMART reactor system.

Various advanced types of SMRs (small and medium reactors) are currently under development worldwide, and some of them are ready for construction. One beneficial advantage of an SMR is its easy receptivity of advanced design concepts and technology. Drastic safety enhancement can be achieved by adopting inherent safety features and passive safety systems. Economic improvement is pursued through a system simplification, modularization, and reduction of the construction time.

SMART, a small-sized integral type PWR with a rated thermal power of 330 MWt, is one of those advanced SMRs. Design characteristics contributing to the safety enhancement are basically inherent safety features such as the integral configuration of the reactor coolant system and an improved natural circulation capability. By introducing a passive residual heat removal system and an advanced LOCA mitigation system, significant safety enhancement is achieved.

The low power density design with about a 5 w/o UO_2 fuelled core is proven to provide a thermal margin of more than 15 % to accommodate any design basis transients with regard to the critical heat flux. This feature ensures the core thermal reliability under normal operation and any design bases events. Core reactivity control during normal operation is achieved by control rods and soluble boron. Burnable poison rods are introduced for the flat radial and axial power profiles, which result in the increased thermal margin of the core. Nearly constant reactor coolant average temperature program in the reactor regulating system improves load follow performance in view of a stable pressure and water level within the pressurizer.

A single reactor pressure vessel contains major primary components such as a pressurizer, steam generators and reactor coolant pumps. The integrated arrangement of reactor vessel assembly enables the large size pipe connections to be removed, which results in the elimination of large break loss of coolant accidents. The in-vessel pressurizer is designed to control the system pressure at a nearly constant level over the entire design bases events. Modular type once-through steam generator cassette consists of helically coiled heat transfer tubes to produce 30°C superheated steam in normal operating conditions. Small inventory of the steam generator secondary side water prohibits return-to-power following a steam line break accident.

Other improved design features include the canned motor reactor coolant pump which has no pump seals and thus loss of coolant associated with pump seal failure is prevented. Four channel control rod position indicators contribute to the simplification of the core protection system and to the enhancement of the system reliability. Furthermore, an advanced man-machine interface system using digital techniques and equipments reduces the human error factors, and consequently improves the plant reliability.

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 reactor overpressure protection system and severe accident mitigation system. Under any circumstances, the reactor can be shutdown by inserting control rods or boron injection. A passive residual heat removal system prevents over-heating and over-pressurization of the primary system in case of emergency events. It removes the decay and sensible heat by natural circulation of a two-phase fluid. The core is maintained undamaged for 36 hours without corrective action by the operator. The reactor overpressure at any design bases events can be reduced through the opening of the pressurizer safety valve. Preliminary safety analysis of SMART shows that SMART remains in a safe condition for all the design bases events. Detailed safety analysis for a wide range of design basis events will be carried out in the course of the standard design.

A small-sized reactor is generally considered to be economically less competitive than a large-sized reactor. However, there are many possible mechanisms for its economic improvement. In SMART, reduction of the number of pipes and valves are possible due to system simplification. Relative ease of a modularization, component standardization, on-shop fabrication and direct site installation of the components are additional advantages which can contribute to the reduction of construction cost.

Application of SMART as an energy source for multipurpose - electricity generation, seawater desalination, or district heating - promises a new era of nuclear energy utilization. SMART is expected to be one of the first new NPPs in the range of 100 MWe, which is a very useful energy for various industrial applications.

From the FY-2009, the SMART Technology Verification and Standard Design Approval Program (SMART TV-SDA Program) has commenced to obtain the SDA from the Korean licensing authority by the end of 2011. The standard design package developed through this program together with comprehensive experiments and tests for technology verification will further enhance the overall safety of the plant system and consequently, provide a concrete technical and licensing basis for the construction of the SMART plant.

Development Chronicles

Since the Kori nuclear power plant unit 1 - the first nuclear power plant unit ever dedicated in the Rep. of Korea - began commercial operations with a generating capacity of 587 MW in 1978, much research and development has been conducted by the Korean nuclear industry. In the middle 1980s, the Korean Standard Nuclear Power Plant (KSNP) was first developed under the "Nuclear Power Promotion Plan" promulgated by the government with reference to the System 80 of ABB-CE of the USA. Applying indigenously accumulated technologies and up-to-date design standards from both home and abroad, the initial KSNP project began with the construction of the Younggwang NPP units No. 3 and 4. In addition, the Korea Atomic Energy Research Institute (KAERI) designed and constructed a high-performance, multipurpose research reactor based on experience in the operation of previous reactors and accumulated nuclear technology. Timed with completion of construction in April 1995, the reactor was named HANARO (high-flux advanced neutron application reactor), which in Korean means, "uniqueness".

Since 1997, KAERI has been developing the system-integrated modular advanced reactor (SMART), an advanced integral pressurized water reactor (PWR), that can be used for seawater desalination or district heat generation as well as electricity generation. Described below is the brief history of the major SMART development milestones.

- Conceptual Design Development of the SMART-330 ('97.07 ~ '99.03)

Concept of an integral reactor SMART with a rated thermal power of 330 MWt was developed in this early period. SMART-330 aims to generate 90 MWe of electricity and produce 40,000 m^3/day of desalinated water. Preliminary design bases, functional requirements and safety requirements were established. Conceptual development was carried out for the reactor core, primary fluid system, and structural components. Basic thermo-hydraulic tests were performed including heat transfer characteristics with nitrogen gas and natural convection performance test. Feasibility studies were also performed through a mockup fabrication of the steam generator cassette, control rod drive mechanism and reactor coolant pump.

- Basic Design for the SMART-330 ('99.04 ~ '02.03)

The basic design of the integral reactor SMART with a rated thermal power of 330 MWt was completed in March of 2002. A model of reactor vessel assembly was completed and design methodologies including computer codes were set up. Preliminary safety analyses were performed to show the overall integrity of the reactor system. The concept of an integrated nuclear desalination plant coupled with SMART has been established. Design for an optimal coupling of the multi-effect distillation (MED) system with SMART focused on the economic use of energy and system safety. Preliminary analysis estimates that the amount of water and electricity produced are sufficient for a population of about 100,000.

- Development of the SMART-Pilot Plant ('02.07 ~ '06.02)

After reviewing and evaluating the 330 MWt SMART on safety, economics, and reliability, a detail design and construction project for a pilot plant at 1/5 scale (65 MWt) of the SMART, called SMART-P, was launched in July of 2002. The purpose of the SMART-P project was to demonstrate the SMART technologies and assess the overall performance and safety. The first phase focused on the design optimization and technology verification by way of tests and experiments such as high-temperature and high-pressure hydraulic tests, pressurizer heat transfer tests, and corrosion evaluation tests. At the completion of the first phase, detailed design including the fuel and BOP was established and the construction permit of the SMART-P was submitted to the Korean nuclear regulatory authority.

- Pre-Project Service for the SMART Reactor System Development ('06.07 ~ '07.06)

A pre-project service for the SMART reactor system development was carried out to conclude the scheme of the design optimization and to ascertain the economical feasibility prior to the commencement of the national R&D commercialization program. For this purpose, the results of the basic design development for SMART and the pending technical items derived during the licensing process of SMART-P were evaluated and the engineering solutions were pursued. Optimized design concept of the SMART reactor system was developed, and the fabricability and maintenance scheme of the major facilities and equipments were scrutinized and supplemented to enhance their technical completeness, licensability and economical efficiency. Thermal power of SMART was up-rated to 660 MWt to further improve its economical efficiency, and its design concepts were modified from several aspects to better adjust to the licensing requirements.

- SMART Technology Verification and Standard Design Approval Program ('09.01 ~ '12.12)

A comprehensive technology verification process including twenty or more separate effect tests and performance tests will be performed under the program. Standard design for SMART will be developed jointly with the participating industries, and a full spectrum of licensing documents will be prepared for a licensing review by the Korean license authority (KINS). This certified design material will comply with the Korean rules and regulations currently applied to the large scale PWRs in operation and under construction in the Rep. of Korea. The applied codes and standards will be equivalent to those of the internationally acknowledged ones.

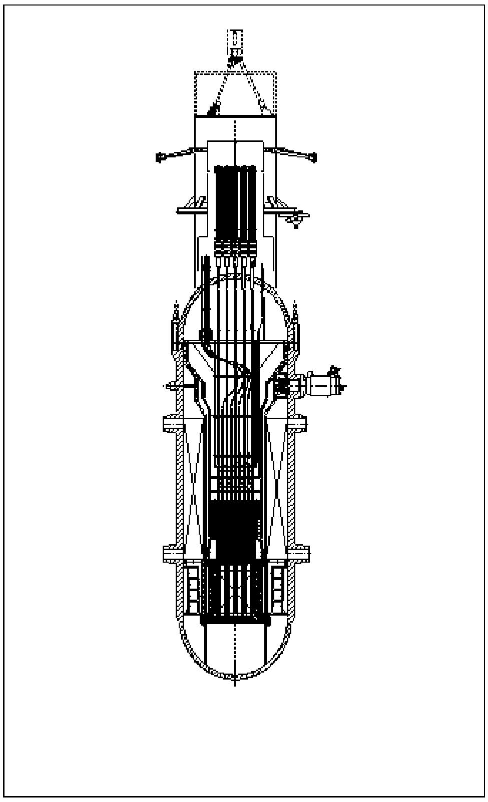


FIGURE 1-1 General Arrangement Drawings of the SMART-330

Description of the nuclear systems

2.1. Reactor Vessel Assembly

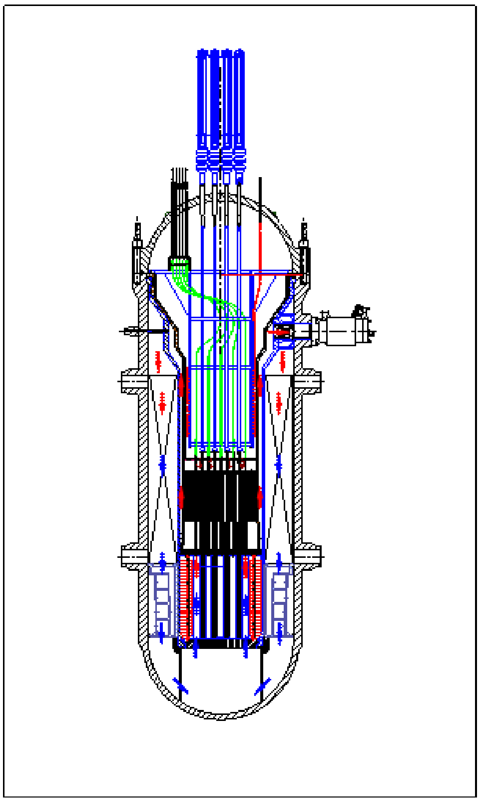


FIGURE 2-1 Primary Coolant Flow Path

The reactor assembly of SMART contains its major primary systems such as fuel and core, eight (8) steam generators (SG), a pressurizer (PZR), four (4) reactor coolant pumps (RCP), and twenty five (25) control rod drive mechanisms (CRDM) in a single pressurized reactor vessel (PRV). The integrated arrangement of these components enables the removal of the large size pipe connections between major reactor coolant systems, and thus fundamentally eliminates the possibility of large break loss of coolant accidents (LBLOCA). This feature, in turn, becomes a contributing factor for the safety enhancement of SMART. The reactor coolant forced by RCPs installed horizontally at the upper shell of the RPV flows upward through the core, and enters the shell side of the SG from the top of the SG. The secondary side feedwater enters the helically coiled tube side from the bottom of the SG and flows upward to remove the heat from the shell side eventually exiting the SG in a superheated steam condition. The large free volume in the top part of the RPV located above the reactor water level is used as a PZR region. As the steam volume of a PZR is designed to be sufficiently large, a spray is not required for a load maneuvering operation. The primary system pressure is maintained constant due to the large PZR steam volume and a heater control. The core exit temperature is programmed to maintain the primary system pressure constant during a load change. In this way, the reactor always operates at its own operating pressure range matched with the system condition. Eight (8) SGs are located at the circumferential periphery with an equal spacing inside of the RPV and relatively high above the core to provide a driving force for a natural circulation of the coolant. Design and safety characteristics of SMART can be summarized with the following emphasis:

- Low core power density provides a greatly improved passive response to a variety of transients, and increases the operating and performance margins for the fuel.
- An integrated arrangement of the primary systems eliminates the large-size piping connecting primary systems, and thus results in no LBLOCAs.
- A large volume of the primary coolant provides large thermal inertia and a long response time, and thus enhances the resistance to system transients and accidents.
- A large volume of the PZR can accommodate a wide range of pressure transients during a reactor power operation.
- Canned motor pumps remove the need for an RCP seal, and thus basically eliminate the potential of a SBLOCA associated with a seal failure.
- Normally, the core decay heat is removed by the secondary system through an SG with a turbine bypass to the condenser.

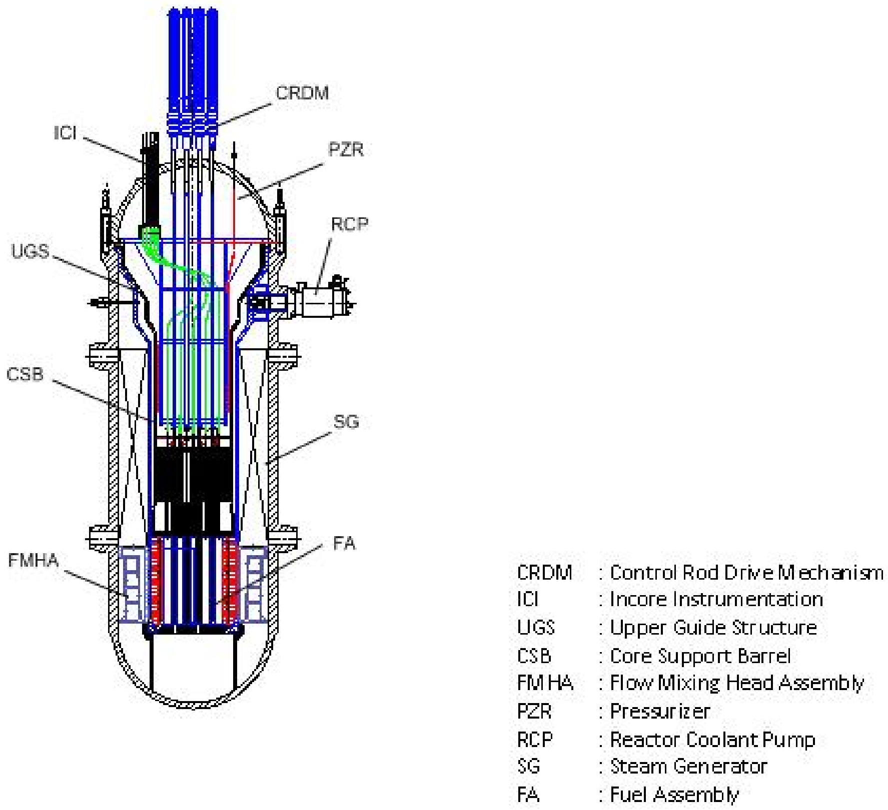


FIGURE 2-2 SMART Reactor Assembly

2.2. Fuel Assembly

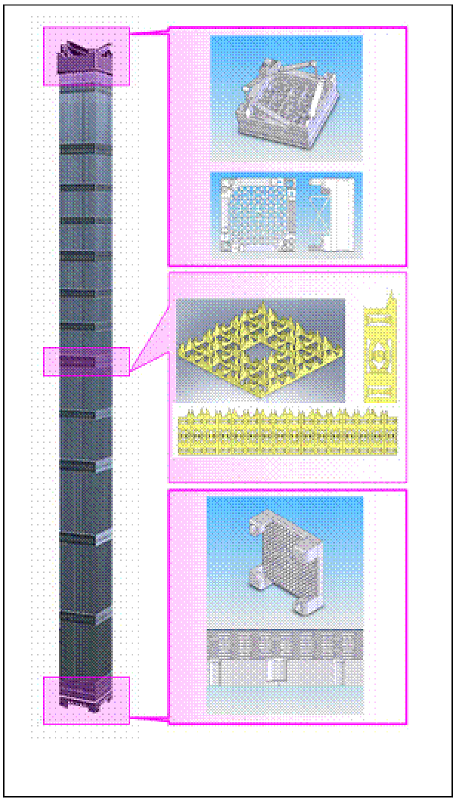


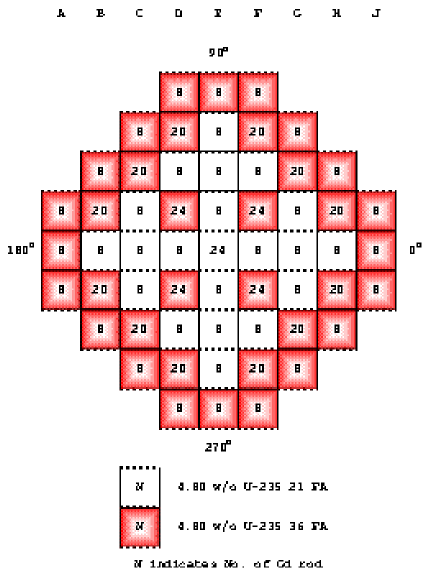
FIGURE 2-3 Typical 17x17 Fuel Assembly

2.3. Core Design and Fuel Management

The SMART core is designed to produce a thermal energy of 330MW with 57 fuel assemblies of a 17x17 array. The SMART core design providing an inherent safety is characterized by:

- Longer cycle operation with a two-batch reload scheme
- Low core power density
- Adequate thermal margin of more than 15 %
- Inherently free from xenon oscillation instability
- Minimum rod motion for the load follows with coolant temperature control

SMART fuel management is designed to achieve a maximum cycle length between a refuelling. A simple two-batch refuelling scheme without reprocessing returns a cycle of 990 effective full power days (EFPD) for a 36 month operation. This reload scheme minimizes complicated reload design efforts, and thus enhances fuel utilization. The SMART fuel management scheme is highly flexible to meet customer requirements.



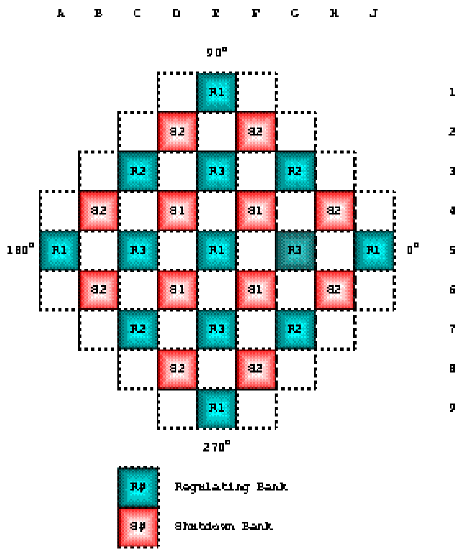


Fig. 2-4 Initial Core Loading Pattern Control Rods and Instrumentation Pattern

2.4. Primary Circuit Components

SMART has eight (8) identical SG cassettes which are located on the annulus formed by the RPV and the core support barrel (CSB). Each SG cassette is of a once-through design with a number of helically coiled tubes. The primary reactor coolant flows downward in the shell side of the SG tubes, while the secondary feedwater flows upward through the inside of the tube. The secondary feedwater is evaporated in the tube and exits the SG cassette nozzle header at a 30°C superheated steam condition of 5.2 MPa. In the case of an abnormal shutdown of the reactor, the SG is used as the heat exchanger for the passive residual heat removal system (PRHRS), which permits an independent operation of the PRHRS from the hydraulic condition of the primary system. Each SG cassette contains about 375 tubes with orifices for the prevention of a flow instability. In the case of a tube leak, each tube can be plugged by up to 10% of the total heat transfer area. The design temperature and design pressure of the SG cassette are 360°C and 15MPa, respectively. The SG cassette tube bundle is manufactured by a coiling on a central mandrel with subsequent tubes coiled over the previous ones. After a coiling, the tube bundle is subject to a heat treatment to eliminate the residual stresses and spring-back resulting from the coiling process. The result of a strength analysis for the design condition has shown that the SG cassette satisfies the strength criteria.

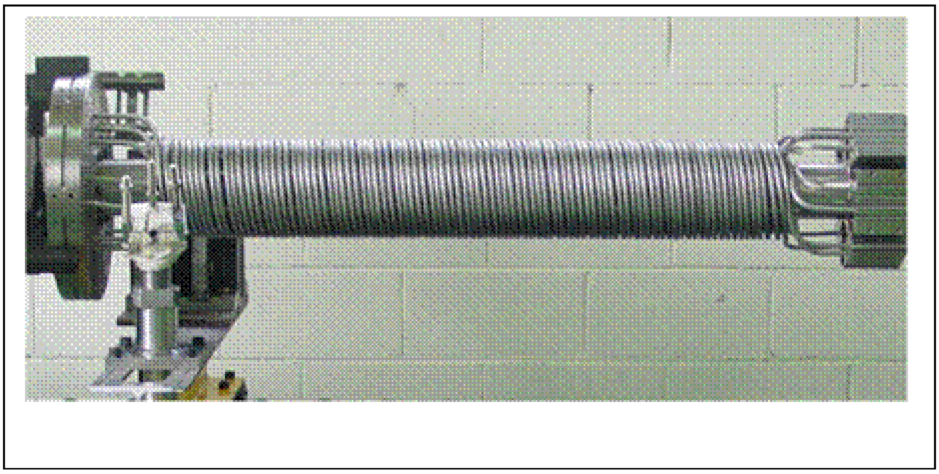


FIGURE 2-5 Coiling of the Tube Bundles for the SG Mock-up

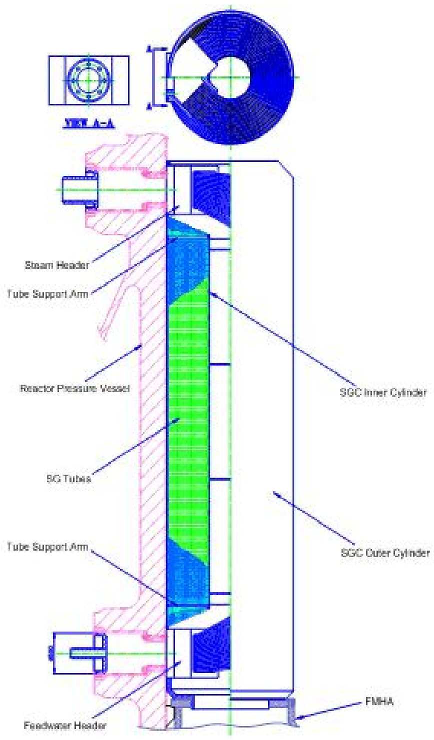


FIGURE 2-6 Interface Drawing of a SG

2.4.2 Reactor Coolant Pump

The SMART RCP is a canned motor pump which does not require pump seals. This characteristic basically eliminates a SBLOCA associated with a pump seal failure which is one of the design basis events for conventional reactors.

SMART has four RCPs horizontally installed on the upper shell of the RPV. Each RCP is an integral unit consisting of a canned asynchronous three phase motor and an axial-flow, single-stage pump. The motor rotor and the impeller shaft are connected by a common shaft rotating on two radial bearings and one axial thrust bearing, which uses a specialized graphite-based material. The cooling of the motor is accomplished with component cooling water which flows through the tubes wound helically along the outer surface of the motor stator. The rotational speed of the pump rotor, 3600 rpm, is measured by a sensor installed in the upper part of the motor.

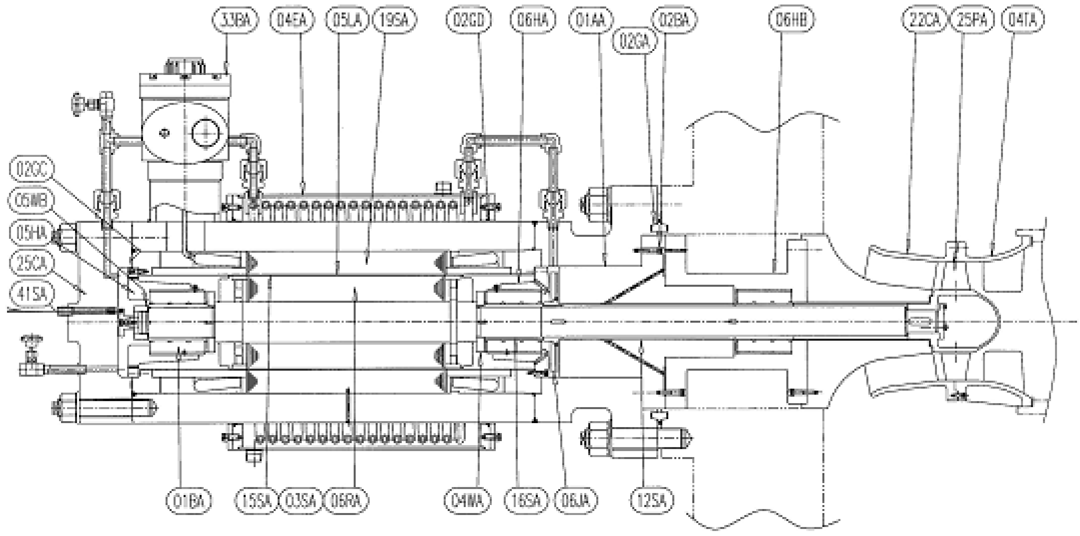


FIGURE 2-7 Cross-sectional Geometry of the Reactor Coolant Pump

2.5 Secondary System

The secondary system receives superheated steam from the NSSS. It uses most of the steam for an electricity generation, seawater desalination and the pre-heaters. The main steam pressure is controlled so as to be constant during a power operation. A load change is achieved by changing the feedwater flow rate. Seawater desalination system such as the MED, MSF, and RO may be used in conjunction with the secondary system by using proper interfacing methods.

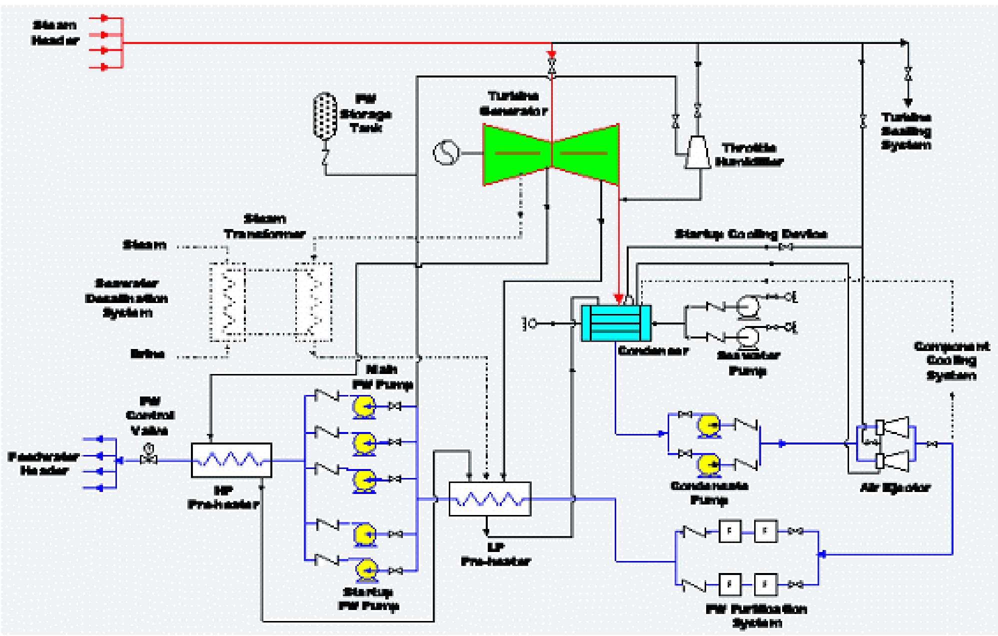


FIGURE 2-8 Schematic Diagram of the Secondary System

2.6 Coupling Concept of the Desalination System or the Process Heat

Production

The SMART desalination system consists of 4 units of MED combined with a thermal vapour compressor (MED-TVC). The distillation unit operates at 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 in steam. Thermal vapour compression is very effective when the steam is available at higher temperature and pressure conditions than required in the evaporator. The thermal vapour compressor enables the low-pressure waste steam to be boosted to a higher pressure, effectively reclaiming it's available energy. Compression of the steam flow can be achieved with no moving parts using the ejector. SMART and MED-TVC units are connected through the steam transformer. The steam transformer produces the motive steam by 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 by 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 steam transformer is made of horizontal tube bundles. 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. The preheater is a plate type heat exchanger made of welded titanium. When SMART is used for a cogeneration purpose, i.e., electricity generation and district heating, it is estimated that ~80MW of electricity and ~150 Gcal/h of heat can be delivered to the grids. The amount of delivered electricity and heat (~85°C hot water) is quite sufficient to meet the demand of more than a 70,000 population (~25,000 households), assuming that usage of electricity and heat per 10,000 population reaches ~10 MWe and 25 Gcal/h, respectively.

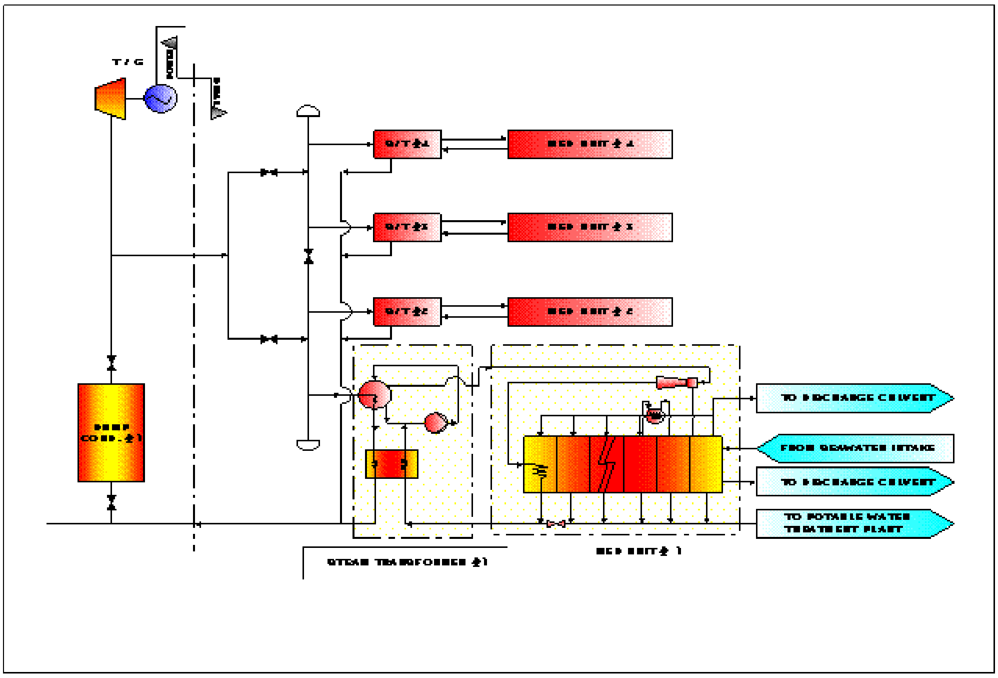


FIGURE 2-9 Coupling Concept of the SMART and the Desalination System

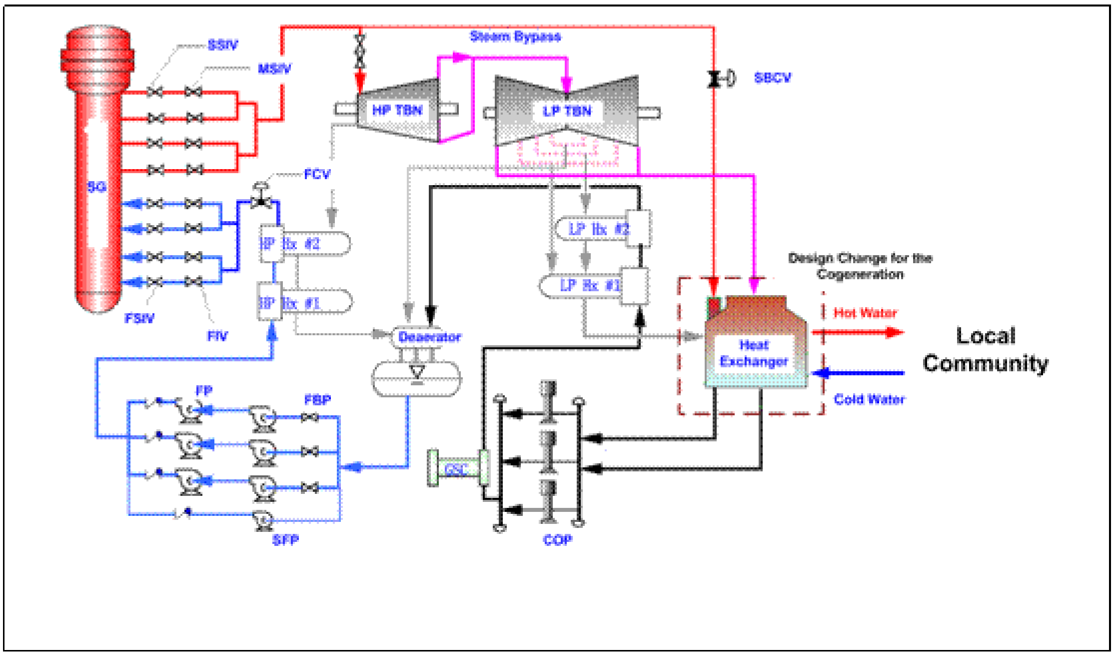


FIGURE 2-10 Coupling Concept for District Heat Generation

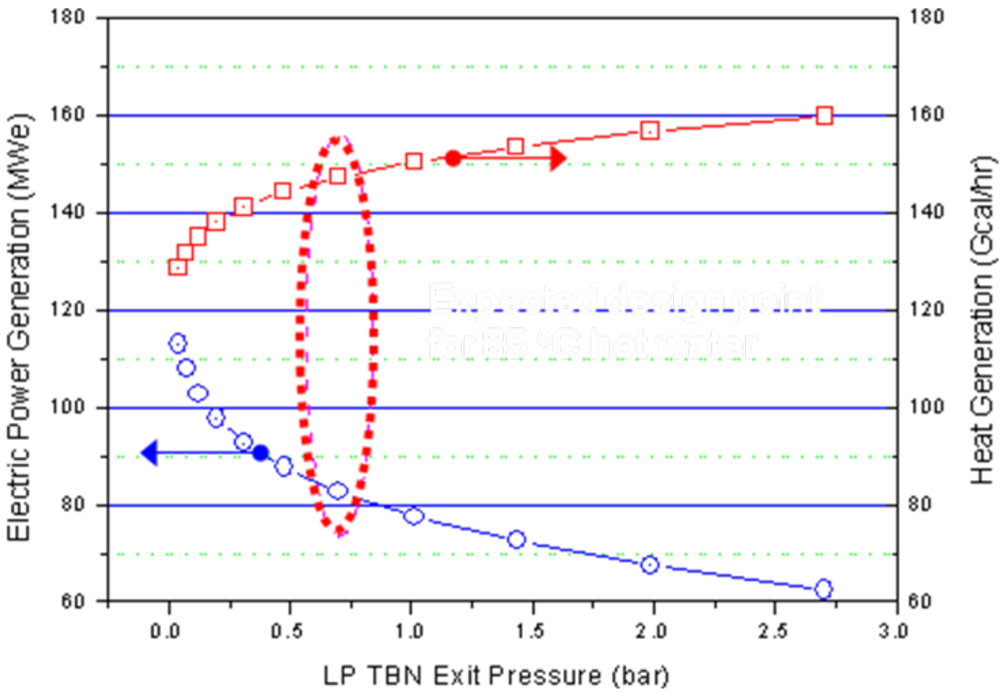


FIGURE 2-11 Design Point for District Heat Source Expected Design Points for 85C Hot Water

2.7 Elimination of a Contamination Risk

Safety concern for the radioactive transfer into the nuclear desalination plant can be easily addressed with the existing technology. For a nuclear desalination, two protection mechanisms are provided to avoid the risk of a radioactive ingress into the product water. One of the mechanisms consists of two barriers such as a steam generator and a steam transformer with a pressure reversal between the energy supply and the desalination system. The other mechanism adopted in the system is a continuous radioactivity monitoring system installed in a line of the water production system to check for any symptom of a radioactivity transfer. The function of the steam transformer is to prevent a contamination of the produced water by a radioactive material of the primary steam. In the steam transformer the primary and secondary steam flows are completely separated, thus no mixing occurs between these two flows. The shell side maintains a higher pressure than that of the tube side. Therefore, the risk of a radioactive contamination of the product water can be avoided in the case of any leakage in the intermediate heat exchanger.

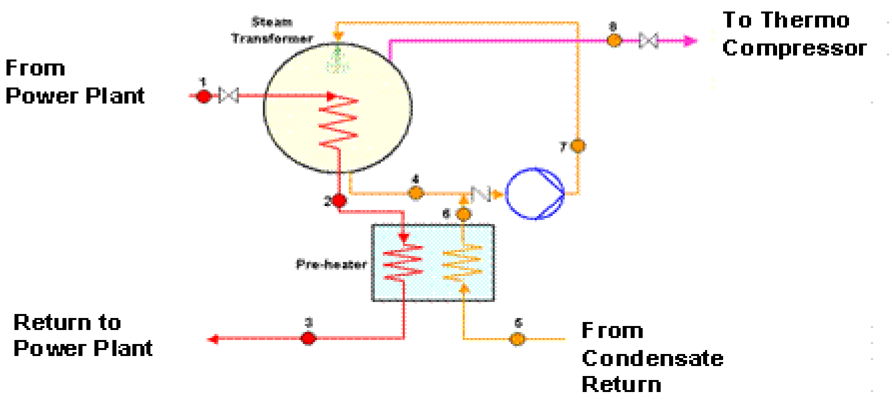


FIGURE 2-12 Schematic Diagram of Steam Transformer

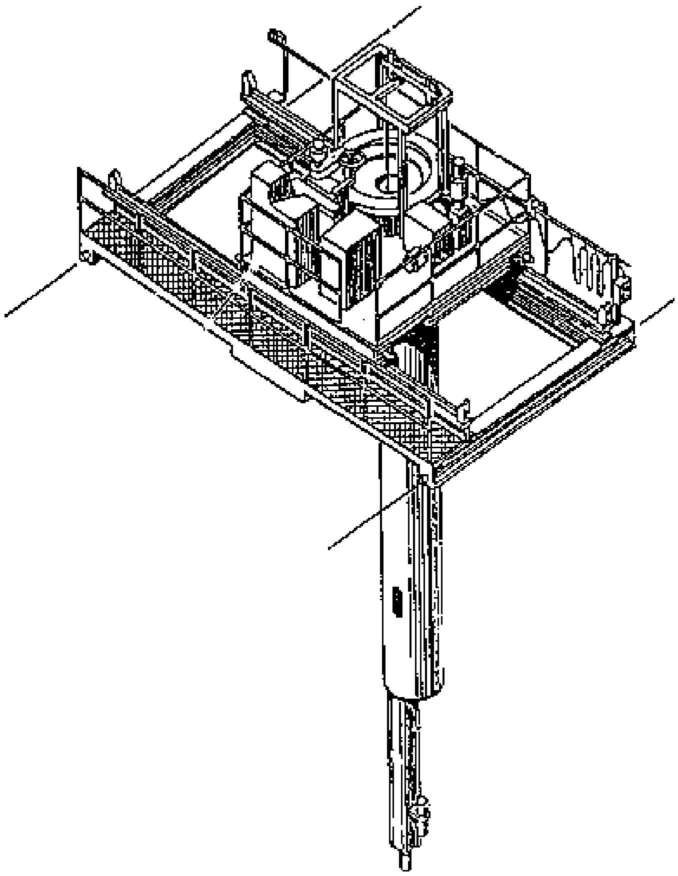


FIGURE 2-13 Refuelling Machine

In addition, a continuous radioactivity monitoring system will be installed in the water production system to check for symptoms of contamination, with an immediate system reaction to follow in case of the detection of radioactivity.

2.8 Fuel Handling and Storage

Since the SMART fuel is almost identical to the 17x17 standard PWR fuel except its height, fuel-handling equipment of SMART is similar to that of the 900MWe PWRs, which are currently operating in the Rep. of Korea. Fuel- handling equipment provides for the safe handling of fuel assemblies and control rod assemblies (CRAs) under all specified conditions and for the required assembly, disassembly, and storage of reactor vessel head and internals during refuelling.

The major components of the system are the refuelling machine, the fuel transfer system, the spent fuel-handling machine, and the new fuel elevator, CRA change fixture, and fuel storage facility including pools, racks and associated systems. This equipment is provided to transfer new and spent fuel between the fuel storage facility, the containment building, and the fuel shipping and receiving areas during core loading and refuelling operations. Fuel is inserted and removed from the core using the refuelling machine. During normal operations, irradiated fuel and CRAs are always maintained in a water environment.

The principal design criteria specify the following:

- Fuel is inserted, removed, and transported in a safe manner
- Subcriticality is maintained in all operations

Near-term management of used fuel would be improved through the large spent fuel storage pool located in the secured fuel building for the reactor life time.

Description of safety concept

The safety approach of SMART is based on a defense-in-depth concept with extensive use of inherent safety features and passive engineered safety systems combined with proven active systems. Substantial parts of the design features of the SMART have already been proven in industry.

3.1 Application of Defense-in-depth Concept

In the SMART design, adopting and implementing safety features for all levels implement the defense-in-depth concept.

- 1st level: minimization of an abnormal operation and failures.

It is achieved by system simplification, minimizing components, and fully automated digital control and man-machine interface system designs. SMART instrumentation and control, and man-machine interface systems are designed as a unified system of both operators and an I&C system. One-man operation under a normal plant operation mode is a part of the SMART control room design objectives. It can reduce the possibility of an abnormal operation.

- 2nd level: control of an abnormal operation and a detection of failures.

Fully automated control and man-machine systems minimize abnormal operations. Simplified systems and minimized components make it easy to detect failures. For example, SG inlet temperature control logic is programmed to minimize the coolant volume change for the load-following operation and the canned-motor type of the RCP does not require a seal injection system. These features maintain minimal changes in the chemical volume control system (CVCS) charging/letdown flow rates and consequently, the PZR level can be utilized to detect an unidentified coolant leakage. The SMART core monitoring system (SCOMS) and the SMART core protection system (SCOPS) contribute to the immediate response to an abnormal operation and a detection of system failures.

- 3rd level: control of accidents within a design basis.

It is satisfied by the SMART engineered safety features (ESF), which are highly reliable and designed to function actively or passively on demand, and the reactor protection systems. Active safety injection systems (SIS) with a large water reservoir in an internal refuelling water storage tank (IRWST)-sump guarantee coolant inventory control during accident. Active SIS, passive residual heat removal system (PRHRS), IRWST-sump, and a containment spray system (CSS) ensure the safety of the plant for the design basis accidents. As a final barrier for a radiation confinement, the steel-lined containment behaves as an additional defense-in-depth.

- 4th level: control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents.

This level is realized by in-vessel retention (IVR) and external reactor vessel cooling (ERVC) concepts. When a loss of coolant accident occurs, the SIS and CSS prevent a core uncover and spilled coolant from the reactor system flows down into the reactor cavity providing a heat-sink. These passive means realize the IVR and ERVC concepts.

3.2 Inherent Safety Characteristics

Inherent safety features incorporated into the SMART design enhance the accident resistance of SMART. SMART contains major primary components such as a core, eight (8) steam generators, a pressurizer, four(4) reactor coolant pumps, and twenty-five (25) control rod drive mechanisms (CRDMs) in a single reactor pressure vessel (RPV). The integral arrangement of the primary system removes large size pipe connections between major components and thus, fundamentally eliminates the possibility of LBLOCA. The canned motor RCP eliminates the need for an RCP seal, and basically eliminates a potential for a SBLOCA associated with the seal failure. The modular type once-through steam generators are located relatively high above the core to provide a driving force for natural circulation flow. This design feature along with low flow resistance enables the capability of the system to have residual heat removal with natural circulation when normal means to transfer residual heat from the core are not available. A large volume of semi-passive PZR can accommodate a wide range of pressure transients during system transients and accidents. Low core power density lowers the fuel element temperature rise under accident conditions and increases the thermal margin. Negative moderator temperature coefficient (MTC) yields beneficial effects on a core self stabilization, and limits the reactor power during accidents.

3.3 Safety Systems

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 automatically on-demand consist of a reactor shutdown system, a safety injection system and a passive residual heat removal system, a shutdown cooling system and a containment spray system. Additional engineered safety systems include a reactor overpressure protection system and a severe accident mitigation system.

- Reactor Shutdown System (RSS)

The reactor shutdown system initiates a reliable and rapid shutdown if the monitored variables deviate from the permissible operating range to a degree that a safety limit may be reached. The reactor shutdown system consists of control rods absorbing neutrons inside a core and a control rod drive mechanism (CRDM). The shutdown signal de-energizes the CRDM and then the control rods drop into the reactor core by the force of gravity and immediately stop the neutron chain reactions.

- Safety Injection System (SIS)

The SIS is provided to prevent core damage during a SBLOCA. The core is protected during a SBLOCA and covered by a large primary coolant inventory. When the pressure drops below 10 MPa in the PZR, the SIS is actuated automatically and cold water from IRWST is injected immediately into the reactor coolant system. The SIS consists of four independent trains with a 100% capacity for each train. The system provides a vessel refilling so that the decay heat removal system can function properly in a long-term recovery mode following an accident.

- Passive Residual Heat Removal System (PRHRS)

The PRHRS passively removes the core decay heat and sensible heat by a natural circulation in the case of an emergency such as an unavailability of feedwater supply or a station black out. Besides, the PRHRS may also be used in the case of a long-term cooling for a repair or refuelling. The PRHRS consists of four independent trains with a 50% capacity each. Two trains are sufficient to remove the decay heat. Each train is composed of an emergency cool-down tank, a heat exchanger and a makeup tank. The system is cooled by cool-down water in the coolant tank. The system is designed to maintain the core un-damaged for 36 hours without any corrective actions by operators for the postulated design basis accidents. In the case of a normal shutdown of SMART, the residual heat is removed through the steam generators to the condenser with a turbine bypass system.

- Shutdown Cooling System (SCS)

The SCS is a safety-related system that is used in conjunction with the passive residual heat removal system (PRHRS) to reduce the temperature of the RCS in the post shutdown periods from the hot shutdown temperature to the refuelling temperature. The initial phase of a cool-down is accomplished by a heat removal from the steam generators to the atmosphere through the condenser or the PRHRS heat exchanger. After the reactor coolant temperature and pressure have been reduced to the predefined set-point, the SCS, which utilizes the equipments such as the heat exchangers and pumps to carry out the system functions, is put into operation for the shutdown cooling to reduce the RCS temperature further to the refueling temperature, and to maintain this temperature during a refuelling.

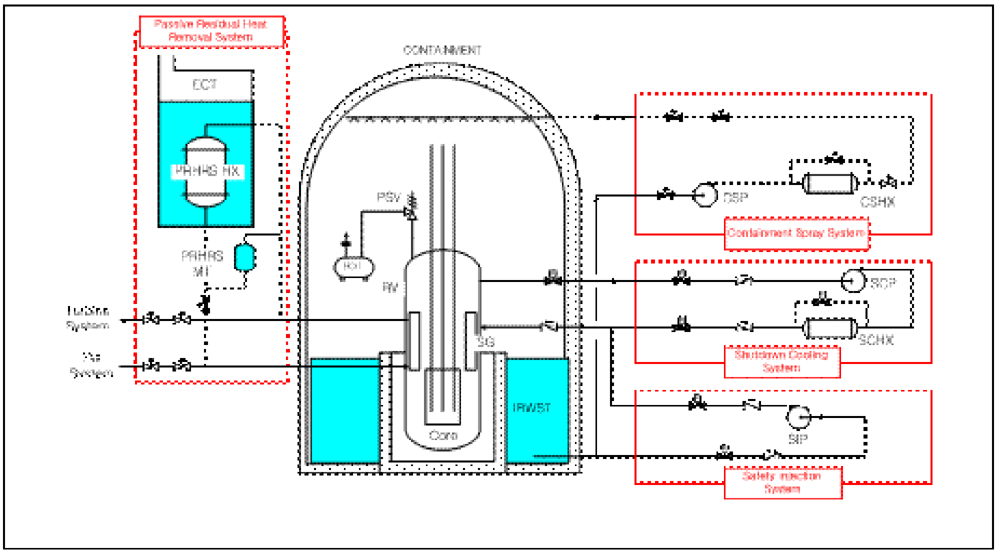


FIGURE 3-1 Schematic Diagram of SMART Safety Systems

- Containment Spray System (CSS)

The CSS reduces the containment pressure and temperature from a main steam line break (MSLB) or loss-of-coolant-accident (LOCA) and removes fission products from the containment atmosphere following a loss of coolant accident (LOCA). The CSS uses the in-containment refuelling water storage tank (IRWST) and has two independent trains. The CSS provides sprays of borated water to the containment atmosphere from the upper regions of the containment. The spray flow is provided by the containment spray pumps which take suction from the IRWST.

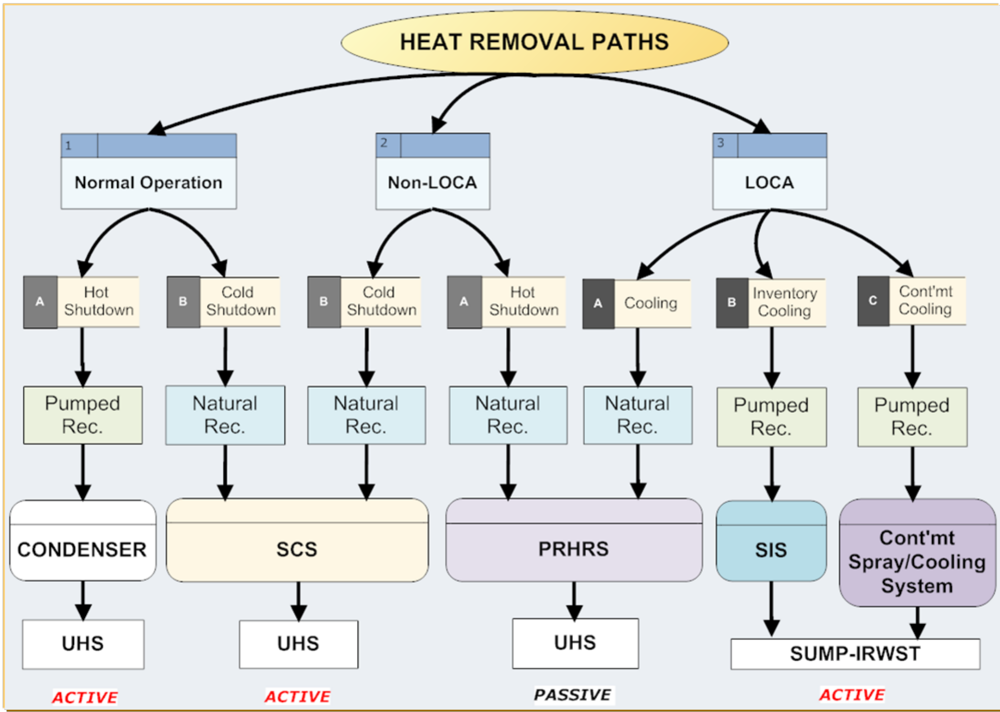


FIGURE 3-2 Heat Removal Paths of SMART

- Reactor Overpressure Protection System (ROPS)

The function of the ROPS is to reduce the reactor pressure for the design basis accidents related with a control system failure. The system consists of two (2) pressurizer safety valves (PSVs), which are installed on top of the reactor head assembly. The steam discharge lines of the PSVs are combined to a single pipeline and connected to the containment atmosphere through the reactor drain tank (RDT). When the primary system pressure increases over the predefined set-point, PSVs are opened to discharge the steam into the RDT.

- Severe Accident Mitigation System (SAMS)

The function of the SAMS is to prevent the egress of molten corium resulting from a severe accident out of the containment. This egress of corium can be avoided due to the design characteristics of the reactor cavity and containment together with the operation of the safety systems. A small air gap under the RPV is filled with water from the containment spray system (CSS) for a severe accident. The in-vessel cooling prevents an egress of the corium out of the RPV. In addition, the water in the IRWST provides an external cooling of the RPV and prevents an egress of the corium out of the RPV. Hydrogen igniters are provided in the containment to remove the explosive hydrogen generated during a severe accident.

3.4 Design Basis

For the SMART safety analysis, safety related design basis events (SRDBE) are selected in accordance with the Korean Electric Power Industry Code (KEPIC) and Safety Judgement Guideline set by the regulatory body. The SRDBE defines the transients and accidents postulated in the SMART safety analysis to classify all the unplanned occurrences that shall be accommodated by the SMART design and mitigated by the actuation of the reactor protection system (RPS), engineered safety features (ESF) or operator interventions. The SRDBE consisting of 35 events are listed in Table 3-1. For the DBE requiring the SIS actuation, its failure leads to severe accident occurrences. To anticipate a severe accident, the SMART safety systems are equipped with a severe accident mitigation system (SAMS), which prevents an egress of molten corium.

Initiating Event	Frequency
Increase in the Heat Removal by Secondary System:	
Decrease in Main Feedwater Temperature	MF*
Increase in Main Feedwater Flow	MF
Increase in Main Steam Flow	MF
Steam Line Break	Accident
Malfunction in Residual Heat Removal System	MF
Decrease in the Heat Removal by Secondary System	
Loss of External Load	MF
Turbine Trip	MF
Loss of Condenser Vacuum	MF
Inadvertent Closure of Main Steam Isolation Valve	MF
Loss of Non-Emergency AC for Plant Auxiliary System	MF
Loss of Normal Feedwater Flow	MF
Main Feedwater Line Break	Accident
Loss of Component Cooling System	MF
Decrease in Reactor Coolant Flow	
Complete Loss of Reactor Coolant Flow	IF*
Partial Loss of Reactor Coolant Flow	MF
Single Main Coolant Pump Rotor Seizure	Accident
Reactor Coolant Pump Shaft Break	Accident
Reactivity and Power Distribution Anomalies	
Uncontrolled Rod Control Cluster Assembly Bank Withdrawal from a subcritical or Low Power	MF
Uncontrolled Rod Control Cluster Assembly Bank Withdrawal at Power	
Single Rod Control Cluster Assembly Withdrawal	MF
Single Rod Control Cluster Assembly Drop	IF
Rod Ejection	MF
Start-up of an Inactive Main Coolant Pump	Accident
Fuel Misloading	MF

	IF
Increase in RCS Inventory Inadvertent Operation of the Make-up System Inadvertent Operation of the Safety Injection System	 MF MF
Decrease in RCS Inventory Inadvertent Opening of a Pressurizer Safety Valve Break of Letdown Line Outside Containment Small Break Loss of Coolant Accident Steam Generator Tube Rupture	 IF IF Accident IF
Radioactive Release from a Subsystem or Component Radioactive Gas Waste System Failure Radioactive Liquid Waste System Leak or Failure Postulated Radioactive Release due to Liquid-Containing Tank Failure Fuel Handling Accident Spent Fuel Cask Drop Accident	 Accident Accident Accident Accident Accident
Anticipated Transients without Scram (ATWS)	N/A

*MF-Moderate frequency event *IF-Infrequent event

TABLE 3-1. Event Classifications

3.5 Design for High Reliability

A high reliability is confirmed in the SMART design by taking into account the potential of a common cause failure and by including single failure criteria and a fail-safe design. The common cause failures are accommodated by implementing the principles of diversity, redundancy and independence for the systems and components important to a safety. Diversity is achieved as two distinct, independent systems are available for shutting down the reactor. Redundant and independent trains and components are installed in the safety systems such as the PRHRS, SIS, and ROPS. The single-failure criteria are applied in the SMART safety analysis to demonstrate the SMART capability of achieving an emergency core reactivity control, an emergency core and containment heat removal, a containment isolation, and its integrity, and an atmosphere clean-up. Diversity and redundancy are also implemented in the instrumentation and control systems and the structures. The principle of a fail-safe design is also incorporated such as the dropping of a CRDM after a loss of electrical energy, and the valves are designed to be fail-open or -close in the secondary, auxiliary, and safety systems.

3.6 Safety Assessments

The safety analysis of the SMART design is conducted in which methods of both deterministic and probabilistic analyses are applied. It is demonstrated that the SMART is designed to be capable of meeting the prescribed limits acceptance criteria.

3.6.1 Deterministic Assessment

In the deterministic safety analysis, it is confirmed that the operational limits are in compliance with the assumptions and intent of the design for the SMART normal operation. The safety analysis is performed on the initiating events listed in the SRDBE that are appropriate for the SMART design. The initiating events result in event sequences that are analyzed and evaluated for a comparison with the radiological and design limits as acceptance criteria. Safety analyses are performed to demonstrate that the management of a DBA is possible by an automatic response of the safety systems. For the non-LOCA initiating events, the safety analysis is 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 is utilized. Figures 3-3 and 3-4 show analysis results of typical limiting accidents, i.e., Complete Loss of Coolant Flow (CLOF) and SBLOCA (Instantaneous guillotine break of the DVI line), respectively. The analysis results show that the SMART design properly secure the safety of the reactor system under limiting accident conditions.

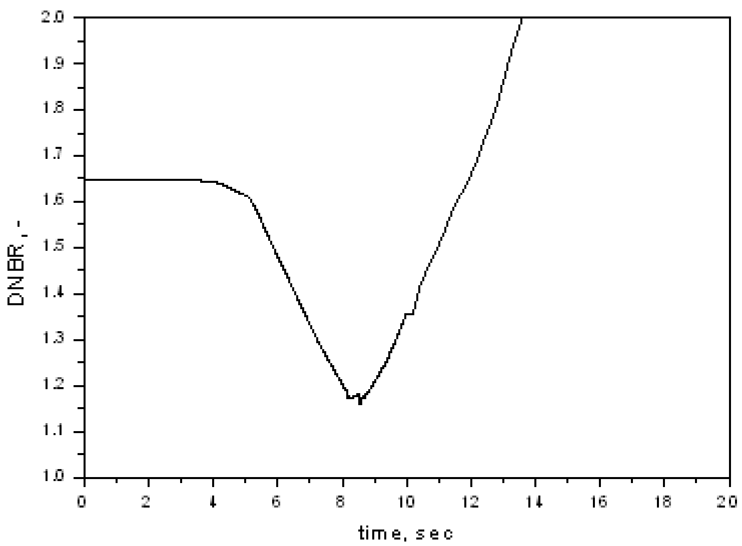


FIGURE 3-3. DNBR for CLOF Accident

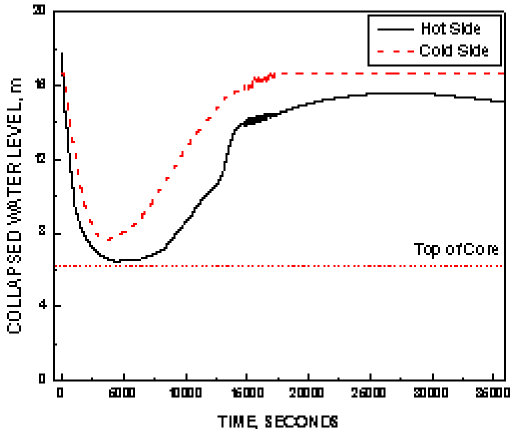


FIGURE 3-4. RPV Collapsed Water Level for SBLOCA

3.6.2 Probabilistic Assessment

In the SMART safety assessment, PSA is required to validate the event classification and plant condition, to evaluate the safety level, and to identify the weak points of the SMART design. The scope of the probabilistic safety analysis (PSA) is level 1 in the basic design stage. The level 2 and 3 PSA, external PSA, and the low power/shutdown PSA will be performed in the SDA stage. The PSA is performed using the KIRAP computer code developed by KAERI. For the level 1 PSA, scenarios of 10 events have been developed: general transients, loss of feed-water, loss of offsite power, SBLOCA, steam line break (SLB), steam generator tube rupture (SGTR), large secondary side break, control rod ejection (REA), anticipated transient without scram (ATWS), and control rod bank withdrawal (BWA). The core damage frequency (CDF) and the large early release frequency (LERF) of SMART are targeted to be less than 1.0E-07 per reactor year and 1.0E-08 per reactor year, respectively, which are about one tenth of the operating PWRs.

Proliferation resistance

Some of the important technical features of SMART, which reduce the attractiveness of spent nuclear fuel material for use in any nuclear weapons programme, are the following:

- Long refuelling cycle: SMART refuelling cycle is 3 years, and thus, the fissile quality of plutonium in discharged fuel is too low to be used for weapon programmes.
- Low enriched uranium fuel: SMART utilizes less than 5 weight% slightly enriched uranium oxide for the fuel.

In addition, integral arrangement of reactor components requires a special fuel handling system to load and unload the fuel in the reactor core, and thus it prevents easy access to the fuel. A full surveillance system with CCTVs to monitor unauthorized access to the fuel (fresh or spent) is also considered at the design stage of the reactor and fuel buildings.

Safety and security (physical protection)

A steel-lined concrete reactor containment building (RCB) accommodates all primary reactor systems including the reactor assembly and associated valves and piping. A compound building (CPB), and an auxiliary building (AB) surround the RCB. A single base-mat accommodates the RPB, CPB, and AB. The plant building layout is designed to reduce the surface silhouette and direct access to the RCB as shown in Figure 9-2. As similar to the operating PWRs in the Rep. of Korea, the RCB is to contain the radioactive fission products within the containment building and to protect against primary coolant leakage to the environment. The RCB protects the entire reactor systems from any external air collisions.

Description of turbine-generator systems

The reference concept of the turbine plant has been developed including a coupling system for seawater desalination. The overall design is similar to that of a present-day power plant. The turbine plant receives superheated steam from the nuclear steam supply system (NSSS). It uses most of the steam for electricity generation, seawater desalination and/or district heating, and to provide heat supply to the pre-heaters. The SMART and MED-TVC units are connected through the steam transformer. The steam transformer produces the motive steam using steam extracted from a turbine and supplies it to the desalination plant. It also prevents the contamination of water produced by hydrazine and radioactive material of the primary steam, as described in Sections 2.6 and 2.7.

Electrical and I&C systems

7.1 Man-Machine Interface System (MMIS) Design

The SMART MMIS consists of I&C systems and a control room. The MMIS is designed with a layered structure based on digital and information processing technology and a communication network scheme. The I&C systems of SMART are mainly composed of a protection system, a control system, an information system, and an instrumentation system. The protection system of SMART includes two major systems: the reactor protection system and the actuation system of the engineered safety features. The basic structure of the system consists of four redundant trip channels which are modularized by specific functions and segmented for a functional diversity, respectively, and it uses full digital technology with a designated safety communication network. Control grade diverse mean is additionally provided to prevent an anticipated transient without scram (ATWS).

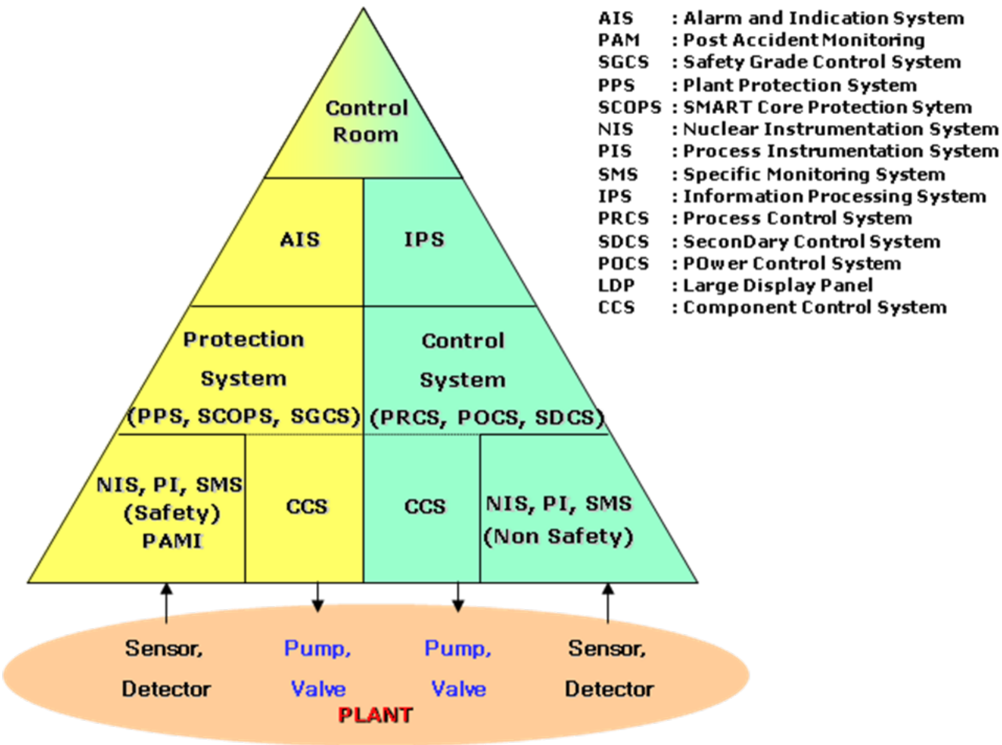


FIGURE 7-1 SMART MMIS Design Hierarchy

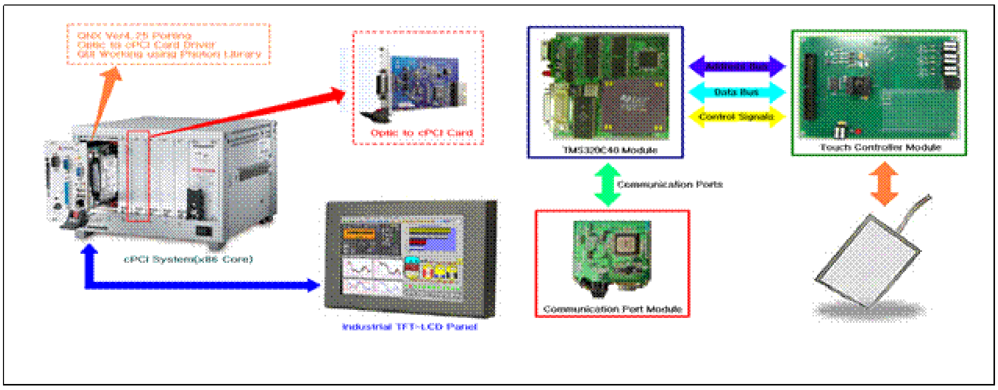


FIGURE 7-2 SMART Maintenance and Test Panel Module Configuration

The control systems adopt module-based design and standardized equipment to improve their maintainability. Also to improve the availability and reliability of the control systems, hot stand-by and duplex (redundancy) structures are introduced into each system. The high reliability and performance of the instrumentation systems is achieved by the advanced features such as digital signal processing, remote multiplexing, signal validation and fault diagnostics, and a sensing signal sharing. The purpose of the information system is to provide the plant operating staff with various supervisory monitoring aids, enable them to enhance the plant operability, and lead the plant to safe states by adopting the primary and hot-standby redundant concepts for data processing servers and distributed graphic processing clients through a standard network. Safety parameters, functions, and alarms are presented in a hierarchical display manner and the information is organized well with the optimized navigation concept.

The SMART compact control room encompasses a large scale display panel, a main control board, a safety console, and a supervisor's console. Large scale display panel provides operators with overall plant information for determining the current process and safety status of the plant. It serves operators by formulating a common mental model of the plant status. The main control board - a seated-type compact workstation consisting of LCDs, flat panel displays, keyboards, and pointing devices - provides reactor/turbine operators with a means of monitoring and controlling the plant processes. The safety console provides an operator with safe shut-down capabilities in the event of failures of the main control board. It also contains a set of hardwired switches for a manual actuation of the ESF equipment and reactor trip.

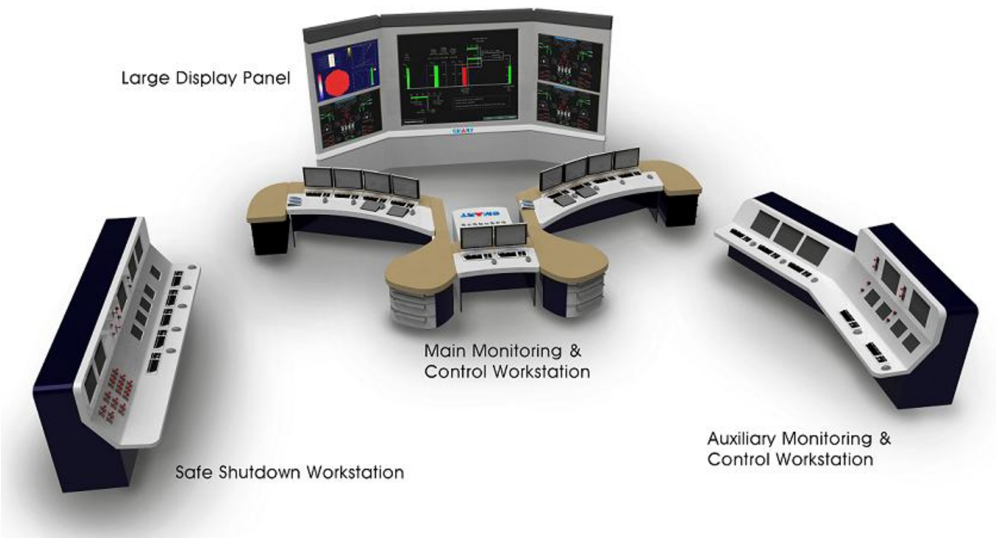


FIGURE 7-3 SMART Main Control Room Layout

7.2 Electrical Systems

The concepts of the SMART electrical systems will be basically the same as that of the PWRs presently operating in the Rep. of Korea. These systems include the main generator, main transformer, unit auxiliary transformers, stand-by auxiliary transformers, diesel generators, and batteries. The electrical systems, including the Class 1E and non-class 1E, are based on a “two train” approach.

The main generator is connected to the grid via the main transformer with auxiliary transformers connected between them. The stand-by auxiliary transformers (the off-site power source) receive electrical power from the grid. The unit auxiliary transformers and/or the stand-by auxiliary transformers supply electrical power for start-up, normal operation, and shutdown.

If normal electrical power is unavailable, the diesel generators (non-class 1E, class 1E) act as a back-up source. In the event of a station blackout (loss of off-site and on-site AC power supply), the alternate AC diesel generator (class 1E) supplies power to the class 1E loads to maintain the reactor in a safe shutdown condition. The batteries have adequate capacity to supply DC power to perform required functions in an accident assuming a single failure. To ensure the safety of the reactor, the electric power supply for the safety related systems is designed as a highly reliable power source (class 1E). Two physically separate power sources are provided to the safety related system.

Spent fuel and waste management

The solid and liquid wastes produced in SMART must be stored and disposed of in ways safeguarding human health and protecting the environment. The overall strategy is to reduce the active nuclides in gaseous and liquid wastes to a solid form, reduce the volume of the solids, solidify loose material, pack in drums, and ship to a disposal site.

For low- and intermediate-level liquid wastes, the general approach is to collect them in tanks and measure the activity. Active nuclides are removed through filters and ion exchange columns and after processing; the remaining activity is within the allowable site release limit. After liquid wastes are evaporated, the resulting sludge is solidified and then processed in the solid waste system, along with the filters and ion exchange resins. The solid waste treatment process chosen depends on the physical nature of the wastes; wastes could be classified as combustible or non-combustible but compressible, or non-combustible and non-compressible. The general approach to low-level waste solid waste is volume reduction, followed by solidification where necessary and packing, usually in drums. Drums can be temporarily stored at site buildings for 10-20 years or shipped to a disposal repository.

High-level waste management comprises of activities related to irradiated or spent fuel after discharge from the reactor and thus includes storage and disposal, with or without reprocessing. The technology solution is to leave spent fuel or waste at surface level, to cool and decrease in radioactivity for some 30-60 years, and thereafter, to safely isolate them from the biosphere by deposit in deep and stable geological formations with a number of containment barriers.

Underground disposal is based on a system of multiple, relatively independent barriers designed to ensure that toxic radionuclides in the spent fuel remain isolated from human beings and their environment. The barriers have three main components; the near field, the geosphere, and the biosphere. The near field consists of stable wastes and some corrosion-resistant packaged wastes combined with the immediate engineered barriers incorporated in the repository. The geosphere comprises the barriers offered by the host geological media. A key factor is the ability to restrict the flow of groundwater, hence the relative impermeability of low regimes such as clay, salt, and crystalline rock are considered. The biosphere may not constitute a barrier in the strict sense of the word but would serve to dilute radioactivity. An understanding of pathways through the biosphere is also important for the prediction of the eventual fate of any radionuclides.

Plant layout

A typical plant layout of the SMART Standard Design buildings is shown in Figure 9-1. Plant main building consists of the reactor containment building (RCB), the auxiliary building (AB), the compound building (CPB), the emergency diesel generator building (EDGB), and the turbine-generator building (TGB). The CPB consists of an access control area, a radwaste treatment area, and a hot machine shop. For efficient radiation management, the plant main building is sub-divided into two zones; the duty zone (shade area) and the clean zone (white area). For site-dependent internal or external hazards, design requirements will be similar to advanced evolutionary reactors, particularly with respect to:

- Earthquakes,
- Aircraft crashes,
- Explosion pressure waves,
- Internal hazards,
- Radiation protection aspects such as accessibility, shielding, ventilation, etc.

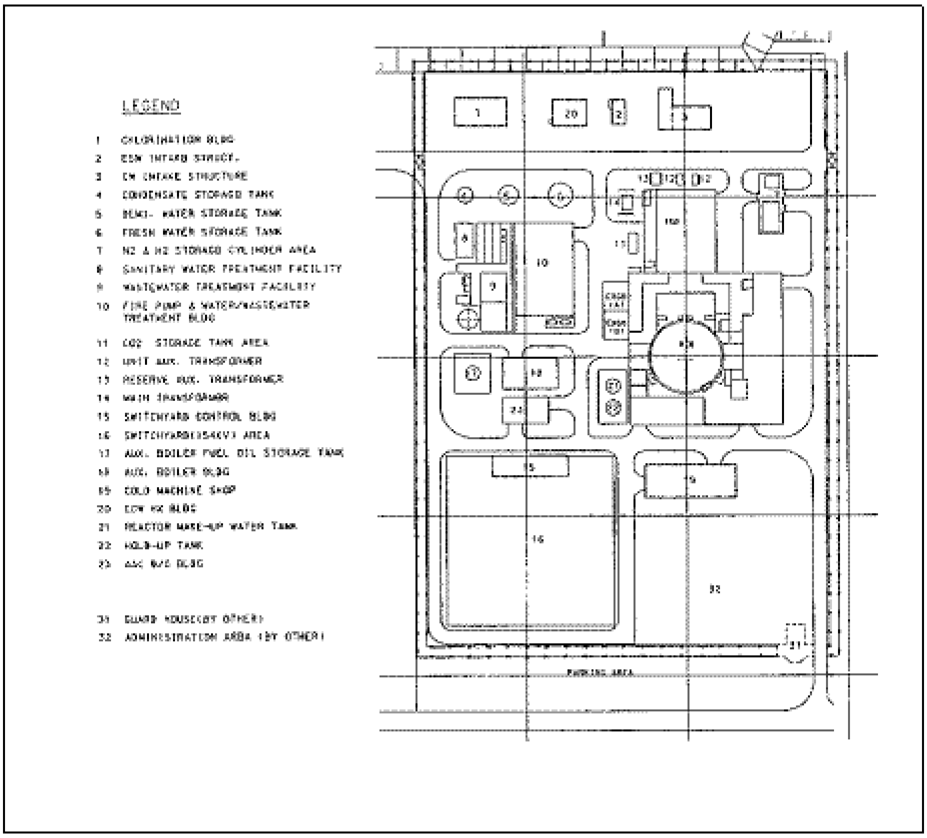


FIGURE 9-1 SMART Plant Layout – Plan A

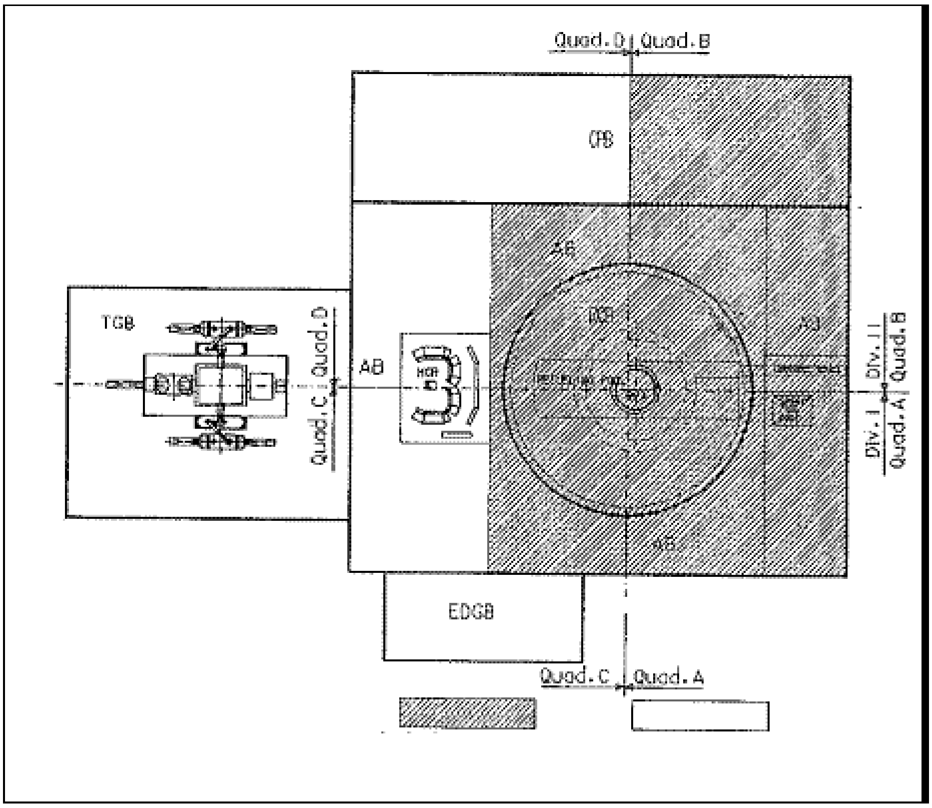


FIGURE 9-2 SMART Plant Main Building Zoning

Plant performance

10.1 Economics and Maintainability

Major economic improvements for SMART can be summarized as system simplification, component modularization, factory fabrication, direct site installation of components, and reduced construction time. The integral arrangement of the primary reactor systems requires only a single pressurized vessel and removes large-sized pipes connecting primary components. A simplified modular design approach is applied to all SMART primary components. Optimized and modularized small-sized components allow easy factory fabrication and direct installation at the site, leading to a shortened construction time and schedule. These features allow a construction period of less than three (3) years from first concrete to fuel load, based on KAERI predictions. The compact and integral primary system also eliminates complex and extra components associated with conventional loop-type reactors.

SMART uses advanced on-line digital monitoring and protection systems that increase system availability and operational flexibility. The adoption of advanced man-machine interface technology leads to the reduction of human errors and to a compact and effective control room design with respect to minimizing staff requirements. The availability factor predicted by KAERI for the SMART plant is 95%, and the predicted occurrence of unplanned automatic scram events is less than one per year.

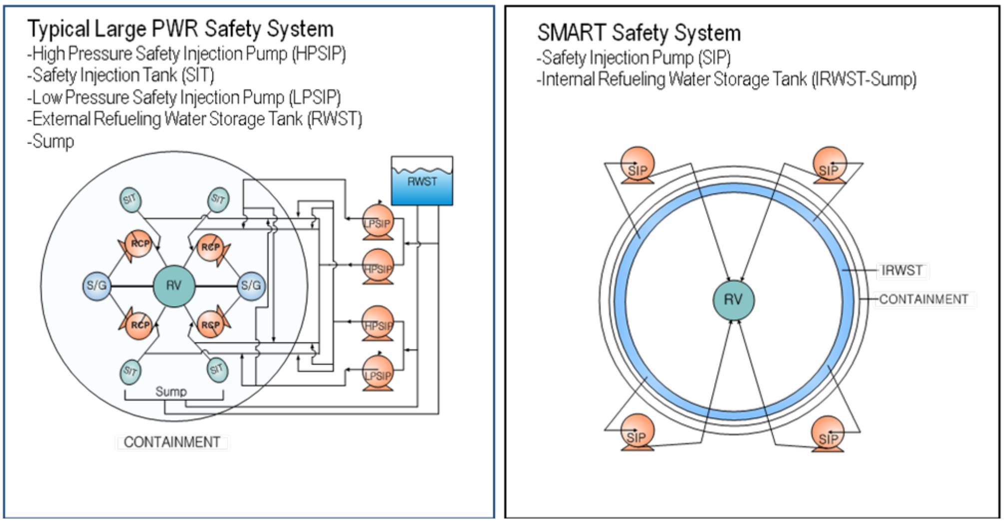


FIGURE 10-1 Simplified SMART Safety System

The passive mechanisms largely contribute to simplification of the associated systems and components; simplification of the system is achieved mostly through the elimination or reduction in tanks, valves, and pumps. Such system simplifications lead and contribute to the improvement of the economy and system reliability by reducing construction time and cost, maintenance-related human errors and the probability of system failure, etc.

Maintainability criteria require that SMART provides easier means to perform preventive and operational maintenance, the available space, ready access and devices to carry out replacement of the main components. In the basic design stage, a preliminary assessment of the maintainability and the ability to inspect the reactor pressure vessel and its internal components was performed and a programme for maintenance and inspection has been established. Design of the helically coiled SG is further optimized to accommodate the in-service inspection requirements. Reactor head assembly including pressurizer is designed to be fully inspectable during maintenance period.

The application of SMART as an energy source for the dual purpose of electricity generation and seawater desalination, promises a new era of nuclear energy utilization and offers benefits only achievable with small-sized reactors. SMART can be used not only for a dual-purpose but also for single-purpose applications based on the user's demands. It can be effectively utilized to supply electric power to isolated areas not connected to the main grid and to the relatively small-sized industrial complexes needing high quality electricity.

Development status of technologies relevant to the NPP

A list of technologies relevant to SMART-based nuclear power plant is given in Table 11-1.

Design	Safety implication	Typical DBE	Effect
Integral reactor	No large primary piping	Large LOCA	Physically eliminated LBLOCA
Reactor internal layout	Natural circulation	Loss of flow accident	Mitigation of accident consequence
Large shut down margin	Cold shutdown by control rods	Steam line break (SLB)	No possibility of return-to-power during SLB

High design pressure of SG and secondary system.	Feed / steam system designed for reactor coolant system pressure. No SG safety valve.	SG transient	Section isolation mitigates accident consequences
Helically coiled once-through SG	Shell side: primary Tube side: secondary	SG transient	Reduced possibility of accident occurrence
Semi-passive pressurizer	Self pressure control	Pressurizer control system	Pressure control system is simplified
PRHRS	Closed loop passive residual heat removal	Fuel failure events	Elimination of radioactive release path
Large water inventory	Slow transient	SBLOCA	Mitigation of accident consequence
Active safety injection	No core uncover		

TABLE 11-1. ENABLING TECHNOLOGIES RELEVANT TO SMART

Deployment status and planned schedule

Figure 12-1 shows the SMART development programme. It is divided into three phases; technology development, technology verification, and commercialization. Since 1997, the Korean government has been supporting the development of SMART technology. During this period, fundamental technologies were developed and the conceptual design was performed. After conceptual design, the basic design was completed in 2002. After the technology development phase, a SMART pilot plant design project was launched for comprehensive performance verification. Through the SMART-PPS (Pre-Project Service) phase from 2006 to 2007, the SMART system design was further optimized and a 3-year SMART Technology Verification and Standard Design Approval (SMART SDA) Program was set. In this program, the first two years are set for standard design development including experiments and tests for the associated technologies. In this program, a set of licensing application documents will be also prepared. A year for a licensing review will follow after the SDA application. Commercialization of the SMART desalination plant will be introduced beginning in 2013, just after the SDA phase.

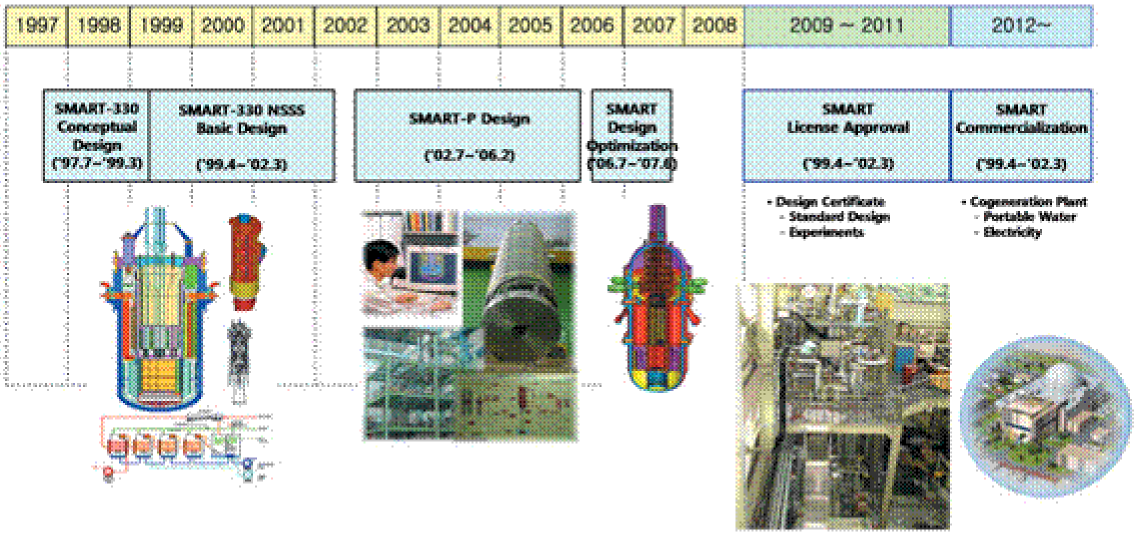


FIGURE 12-1 SMART Development Programme

12.1 Thermal-hydraulic Test

The existing proven PWR technologies are basically utilized for the SMART design. However, it also adopts new and innovative design features and technologies that must be proven through tests, experiments, analyses, and/or the verification of design methods.

A series of fundamental tests and experiments have been carried out throughout the SMART development phases to examine the physical phenomena related with the specific SMART design concepts. The main purpose of these experiments was two-fold: to understand the thermal-hydraulic behaviour of the specific design concepts and to obtain fundamental data to be used, in turn, for further feedback to the optimization of design. Among the experiments conducted, specific SMART design-related experiments are as follows:

- Boiling heat transfer characteristics in the helically coiled steam generator tube,
- Experiment for natural circulation in the integral arrangement of the reactor system,
- Two-phase critical flow tests with non-condensable gases to investigate the thermal-hydraulic phenomena of critical flow with the existence of non-condensable gases,
- Critical heat flux measurement for SMART-specific UO_2 fuel rod bundles,
- Water chemistry and corrosion tests at a loop facility to examine the corrosion behaviour and characteristics of fuel cladding, internal structural materials, and steam generator tube materials at reactor operating conditions,
- Experiments on wet thermal insulation to determine the insulating effects for the internal PZR design and to derive a heat transfer coefficient for the design,
- Experiments on phenomena and characteristics of heat transfer through the condensing mechanism of the heat exchanger inside PRHRS tanks.

Described below are brief introductions of the typical tests and experiments implemented to verify the SMART design characteristics.

12.1.1 Two-Phase Critical Flow Test with a Non-Condensable Gas

The early SMART concept adopted an in-vessel pressurizer type with an inherent self-pressure regulating capability designed to operate via the thermo-pneumatic balance between the water, steam, and nitrogen gas which are the three fluids that fill the pressurizer. In the event of a rupture of a pipe line connected to the pressurizer at a high-system pressure, a mixture of water, steam, and nitrogen is discharged through the break at critical flow conditions. The computer codes for the safety analysis of SMART need to use a verified and validated model for this critical flow. To investigate the thermal-hydraulic phenomena of the critical flow affected by the non-condensable gas entrained in the two-phase break flow, a separate effects test facility was designed and installed at the KAERI site. The test facility can be operated at a temperature of 323°C and pressure of 12 MPa with a maximum break size of 20 mm in diameter. A nitrogen gas flow rate of up to 0.5 kg/s can be injected and mixed with a two-phase mixture in the test section to simulate the transient behaviour expected during a LOCA. The test data from the facility was used for the development and verification of the critical break flow model for SMART.

FIGURE 12-2 Two-Phase Critical Flow Test Facility

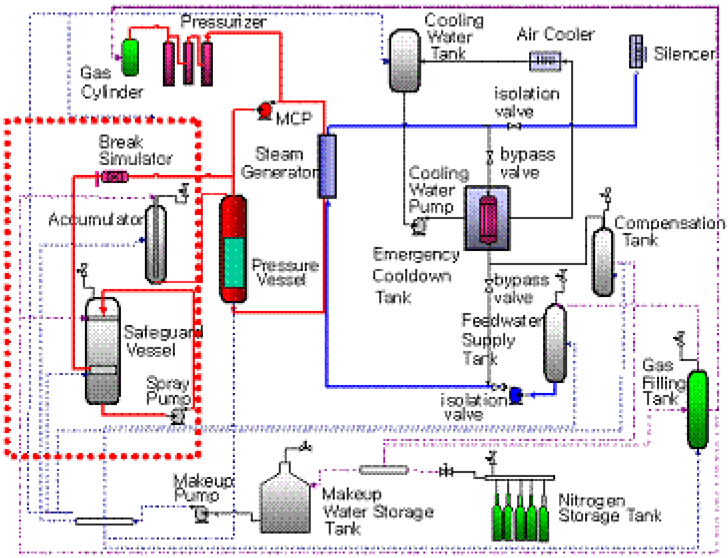


FIGURE 12-3 Schematic Diagram of the VISTA Facility

12.1.2 Integral Effect Test

The SMART-P is a pilot plant of the integral type reactor SMART which has new innovative design features, aimed at achieving a highly enhanced safety and improved economics. An experimental verification by an Integral

Simulation for a Transient and Accident (VISTA) facility has been constructed to simulate the various transient and events of an integral reactor. The VISTA facility has been used to understand the thermal-hydraulic behaviour including several operational transients and design basis accidents. During the past five years, several integral effect tests have been carried out and reported, including performance tests, RCP transients, power transients and heatup or cooldown procedures, and safety related design basis accidents. It will contribute to verifying the system design of the reference plant.

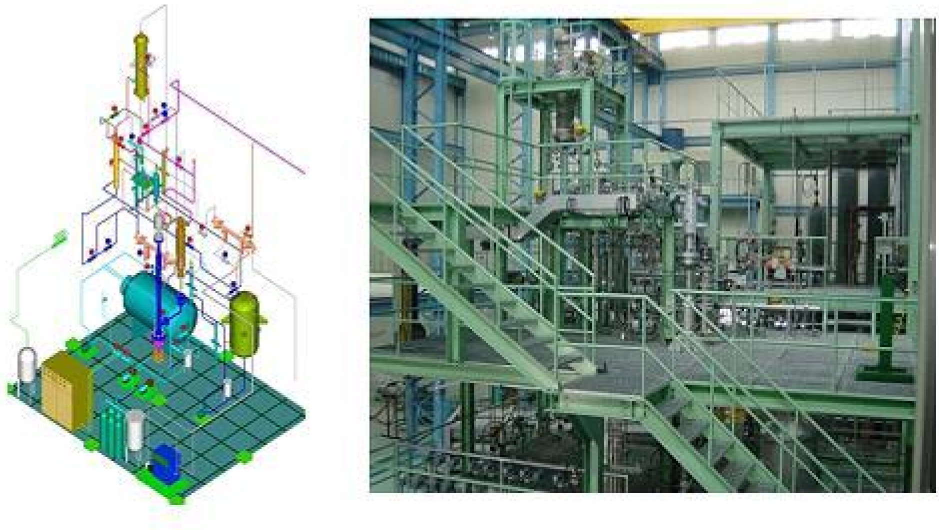


FIGURE 12-4 High Temperature High Pressure Thermal-hydraulic Test Facility (VISTA)

12.2. Major Components Performance Test

A performance test of the major components such as the RCP, SG, and CRDM was carried out. In the SMART Standard Design Approval Program, additional performance tests for the RCP and CRDM are scheduled to be performed to verify the final design models.

FIGURE 12-5 RCP and CRDM Test Facilities

References

1. INTERNATIONAL ATOMIC ENERGY AGENCY, Design and Development Status of Small and Medium Reactor Systems 1995, IAEA-TECDOC-881, IAEA, Vienna (1996).

2. CHANG, M.H., et al., SMART – An advanced small integral PWR for nuclear desalination and power generation, GLOBAL 1999, Proc. Int. Conf., Jackson Hole, USA, Aug. 29 - Sept. 3, 1999, ANS/ENS.

3. KIM, S.H., et al., Design Development and Verification of a System Integrated Modular PWR, Proc. 4th Int. Conf. on Nuclear Option in Countries with Small and Medium Electricity Grids, Croatia, June 2002.

4. CHANG, M.H., HWANG, Y.D., Coupling of MED-TVC with SMART for nuclear desalination, Nuclear Desalination, Vol. 1/1 (2003), 69-80.

5. INTERNATIONAL ATOMIC ENERGY AGENCY, Desalination Economic Evaluation Program (DEEP), Computer User Manual Series No. 14, IAEA, Vienna (2000).

6. KIM, H.C., et al. Safety analysis of SMART, Global Environment and Advanced NPPs, Proc. Int. Conf. Kyoto, Sept.15-19, 2003, GENES4/ANP2003, Kyoto, Japan (2003)

7. KIM, S.H., et al, Design verification program of SMART, Global Environment and Advanced NPPs, Proc. Int. Conf. Kyoto, Sept.15-19, 2003, GENES4/ANP2003, Kyoto, Japan (2003).

8. KIM, T.W., et al, Development of PSA workstation KIRAP, Korea Atomic Energy Research Institute, KAERI/TR-847/1997, KAERI, Taejon (1997).

9. CARELLI, M. D., IRIS: An integrated international approach to design and deploy a new generation reactor, Status and Prospects for Small and Medium Size Reactors, Proc. Int. Seminar, Cairo, May 2001, IAEA-CSP-14/P, Vienna (2002).

10. ISHIDA, T., et al., Advanced marine reactor MRX and its application for electricity and heat co-generation, Small Power and Heat Generation Systems on the Basis of Propulsion and Innovative Reactor Technologies, IAEA-TECDOC-1172, IAEA, Vienna (2000).

11. INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Advanced Light Water Reactor Designs, IAEA-TECDOC-1391, IAEA, Vienna (2004).

12. INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Innovative Small and Medium Sized Reactor Design 2005, IAEA-TECDOC-1485, IAEA, Vienna (2006).

13. CHUNG, M.K., et al, Verification Tests Performed for Development of an Integral Type Reactor, Proc. Int. Conf. on Non-Electric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and other Industrial Applications, Oarai, Japan (2007)

14. ZEE, S.K., et al., Design Report for SMART Reactor System Development, KAERI/TR-2846/2007, KAERI, Taejon (2007).

Technical data

General plant data

Reactor thermal output	330 MWth
Power plant output, gross	100 MWe
Power plant output, net	90 MWe
Power plant efficiency, net	30.3 %
Mode of operation	Load follow
Plant design life	60 Years
Plant availability target >	95 %
Operating base earthquake (safe shutdown earthquake) PGA, g	0.3 Points
Seismic design, SSE	0.3
Primary coolant material	Light Water
Moderator material	Light water
Thermodynamic cycle	Rankine
Type of cycle	Indirect
Non-electric applications	Desalination, District heat

Safety goals

Core damage frequency <	1E-7 /Reactor-Year
Large early release frequency <	1E-8 /Reactor-Year
Occupational radiation exposure <	1.0 Person-Sv/RY
Operator Action Time	36 Hours

Economic goals

Levelized unit electricity cost for NOAK plant	0.06
Levelized unit cost of a non-electrical product for NOAK plant	0.7

Reactor core

Active core height	2.00 m
Equivalent core diameter	1.8316 m
Average linear heat rate	10.965 KW/m
Average fuel power density	23.079 KW/KgU
Average core power density	62.62 MW/m^3
Fuel material	UO2
Cladding material	Zircaloy-4

Outer diameter of fuel rods	9.5 mm
Outer diameter of elements	8.192 mm
Lattice geometry	Square
Number of fuel assemblies	57
Number of fuel Elements in fuel assemblies	264
Enrichment of reload fuel at equilibrium core	4.80 Weight %
Fuel cycle length	36 Months
Average discharge burnup of fuel	36.1 MWd/Kg
Burnable absorber (strategy/material)	Gd_2O_3-UO_2
Control rod absorber material	Ag-In-Cd
Soluble neutron absorber	H_3BO_3
Mode of reactivity control	Control Rods Integrated B/A
Mode of reactor shut down	Control rods , Soluble Boron

Primary coolant system

Primary coolant flow rate	2090 Kg/s
Reactor operating pressure	15 MPa
Core coolant inlet temperature	295.7 °C
Core coolant outlet temperature	323 °C

Power conversion system

Working medium	Steam
Working medium flow rate at nominal conditions	160.8 Kg/s
Working medium supply flow rate at nominal conditions	13.4 Kg/s
Working medium supply temperature	200 °C

Reactor pressure vessel

Inner diameter of cylindrical shell	5332 mm
Wall thickness of cylindrical shell	331 mm
Design pressure	17 MPa(a)
Design temperature	360 °C
Base material	SA508, CLASS 3
Total height, inside	15500 mm

Transport weight	750 t

Fuel channel

Pressure Tube material	Zr 2.5wt% Nb alloy

Steam generator or Heat Exchanger

Number	8
Total tube outside surface area	500 m^2
Number of heat exchanger tubes	375
Tube outside diameter	17 mm
Tube material	Inconel 690
Transport weight	16 t

Reactor coolant pump (Primary circulation System)

Circulation Type	Forced
Number of pumps	4
Pump speed	3600 rpm
Head at rated conditions	27 m
Flow at rated conditions	0.89 m^3/s

Pressurizer

Total volume	61 m^3
Steam volume (Working medium volume): full power/zero power	40 m^3

Primary containment

Overall form (spherical/cylindrical)	Cylindrical
Dimensions - diameter	44 m
Design pressure	0.42 MPa
Design leakage rate	0.2 Volume % /day

Residual heat removal systems

Active/passive systems	Passive

Safety injection systems

Active/passive systems	Active

Turbine

Number of turbine sections per unit (e.g. HP/MP/LP)	1 / 0 / 1
Turbine speed	1800 rpm
HP turbine inlet pressure	5.2 MPa(a)
HP turbine inlet temperature	296.4 °C

Generator

Number	1
Rated power	111 MVA
Active power	105 MW
Voltage	18.0 kV
Frequency	60 Hz

Plant configuration and layout

Plant configuration options	Ground-based
Surface area of the plant site	99800 ha
Elevation or underground embedding of the nuclear island	11.7 m
Core catcher	No, IVR-ERVC
Protection against aircraft crash	Yes