DESIGN FEATURES OF SMART FOR BARGE MOUNTED APPLICATION

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Abstract

SMART is an integral reactor of 330MWt capacity with passive safety features being developed for a wide range of applications including the barge mounted co-generation plant. Its design strives to combine the firmly-established commercial reactor design with new advanced technologies. Thus the use of the industry proven KOFA (Korea Optimized Fuel Assembly) based nuclear fuels is pursued while such radically new technologies as self-pressurizing pressurizer, helical once-through steam generators, and advanced control concepts are being developed.

The safety of SMART centers around enhancing the inherent safety characteristics of the reactor and salient features include low core power density, integral arrangement to eliminate large break loss of coolant accident, etc. The progression of emergency situations into accidents is prevented with a number of advanced engineered safety features such as Passive Residual Heat Removal System, Passive Emergency Core Cooling System, Safe-guard Vessel, Passive Containment Over-pressure Protection. This paper presents the status of current SMART development, characteristics of SMART safety systems and the possibility of SMART application to barge mounted environment.

1. OVERVIEW OF SMART

SMART (System-integrated Modular Advanced ReacTor) is an advanced integral PWR(Pressurized Water Reactor) that produces 330MWt at full power. Major primary components are housed within a single pressure vessel. New, advanced and innovative features are incorporated in the design to provide the reactor with significant enhancements in safety, reliability, performance, and operability. Major design and safety characteristics of SMART can be summarized as follows:

a) inherent safety
b) simplification of systems
c) passive engineered safety systems
d) no large break of loss of coolant accident
e) new generation of man-machine interface systems
f) low core power density
g) large negative moderator temperature coefficient due to soluble boron free core
h) integrated arrangement of primary systems
i) large volume of primary coolant providing large thermal inertia and long response time
j) large volume of passive PZR to accommodate wide range of pressure transients
k) canned motor pumps remove the need of MCP seal
l) low level fast neutron fluence on the RPV
m) passive removal of the core decay heat by the natural
n) The core melt-down frequency is expected to one hundredth of that of conventional reactor.

The design combines firmly established commercial reactor design with new advanced technology. Thus substantial part of the technology and design features of SMART has already been proven in the industries, and new innovative features will be proven through various tests.

Despite disadvantages in the power production cost due to the small power output, SMART can derive the economical advantages from ;

a) simplified system with reduced number of pumps and valves, piping, instrumentation and wiring, etc.
b) flexible operation
c) modularized components
d) on-shop fabrication of components
e) better match to the grid
f) low financial risks, etc.

The overall design parameters of the SMART is shown in Table 1. SMART is expected to fully satisfy the Korean as well as the international safety and licensing requirements. The program for the SMART and its application system development is being carried out jointly by KAERI (Korea Atomic Energy Research Institute), and several nuclear organizations and universities in Korea.

2. SMART REACTOR ASSEMBLY

SMART is an integral type reactor and all of the major primary system components such as fuel and core, twelve steam generators (SG), pressurizer (PZR), four main coolant pumps (MCP), and forty-one control element drive mechanisms (CEDM) are housed in a single pressurized reactor vessel (PRV). The section view diagram of SMART reactor assembly is shown in Fig. 1. With this integral arrang-ement, there is no large size pipe connection and thus no possibility of large break loss of coolant accidents. The primary coolant flows up through the core and then through the MCPs to enters the shell side of SG from the top. The secondary side feedwater enters tube side of the helically coiled SG tubes from the bottom and flows upward. The heat is removed from the primary and superheated steam exits the SGs. Large volumes at the top part of RPV constitute the pressurizer. The pressurizer volumes are occupied by water, steam and nitrogen gas. The pressure is determined by the the partial pressures of steam and gas. These pressures vary in correspondence to the change in the core exit temperature and thus to reactor power. With appropriate combination of MTC and pressurizer size and conditions, the pressurizer can self-regulate the pressure at a desired level without any active control. Twelve SG cassettes are situated at equal-spacing in the annlus region between the RPV and support barrel. To provide sufficient driving force for the natural circulation of the coolant, SGs are located relatively high above the core. This design feature and the low flow resistance endows the system with 25% full power operation capability with natural circulation. The internal shieldings surrounding the core at sides and bottom reduces the neutron fluence of the RPV.

2.1. Fuel and Reactor Core

SMART core consists of fifty-seven (57) fuel assemblies which are based on the industry proven U7xU7 square array Korea Optimized Fuel Assembly (KOFA). Each fuel assembly holds 264 fuel rods, 2U guide tubes for control rods, and 4 instrumentation thimbles. A fixed incore instrumentation is located in one of the 4 thimbles. 5 space grids hold the fuel rods in position. Top and bottom spacer grids are made of inconel, and the 3 middle space grids are made of zircaloy. Specially designed bottom end piece offers improved resistance to the debris entering the core. 4.95 w/o enriched uranium oxide fuel is enclosed in zircaloy clad and has sufficient reactivity for three year or longer operation cycle. The fuel assembly is designed to accommodate power ramps during load-following maneuvers.

Table 1 SMART Design Data Information

GENERAL INFORMATION	
Reactor Name	SMART
Reactor Type	Integral PWR
Thermal Power (MWt)	330
Electric Power (MWe)	100
Design Life Time (yr)	60
FUEL AND REACTOR CORE	
Fuel Type	17x17 Square FA
Active Fuel Length (m)	2.0
Fuel Material	Low enriched UO_2
No. of Fuel Assembly	57
Core Power Density (w/cc)	62.6
Refueling Cycle (yr)	> 3
REACTIVITY CONTROL	
No. of Control Element Banks	41
No. of Control/Shutdown Banks	9/32
No. of Absorber Elements per CEDM	21
Material of Control Banks	Ag-In-Cd
Material of Shutdown Banks	B_4C
Burnable Poison Material	Al_2O_3-B_4C & Gd_2O_3-UO_2
REACTOR PRESSURE VESSEL	
Overall Length (m)	9.8
Outer Diameter (m)	3.96
Average Vessel Thickness (mm)	19.8
Vessel Material	SA508, CL-3
REACTOR COOLANT SYSTEM	
Cooling Mode	Forced Circulation
Total Coolant Mass (kg)	46320
Design Pressure (MPa)	17
Operating Pressure (MPa)	15
Core Inlet Temperature (°C)	270
Core Outlet Temperature (°C)	310
STEAM GENERATOR	
Type	Helically-coiled once-through
No. of SG Cassettes	12
Tube Outer Diameter (mm)	12
Feedwater Pressure (MPa)	5.2
Feedwater Temperature (°C)	180
Steam Pressure (MPa)	3.0
Steam Temperature (°C)	274
Superheat (°C)	40
PRESSURIZER	
Type	Self-controlled
Total Volume (m^3)	21.7
CONTROL ELEMENT DRIVE MECHANISM	
Type	Step Motor Driven
No. of CEDM	41
Design Pressure (MPa)	17
Design Temperature (°C)	350
Moving Distance per Pulse (mm)	0.208
Moving Speed (mm/sec)	0 - 15
MAIN COOLANT PUMP	
Type	Glandless Canned Motor Pump
No. of MCP	4
Design Pressure (MPa)	15
SECONDARY SYSTEM	
Main Steam Flow Rate (kg/hr)	555,120
Feedwater Pressure (MPa)	5.0
Type of Feedwater Pump	Multi-stage
No. of Feedwater Pump	3
Type of Startup Pump	Multi-stage
No. of Startup Pump	2
Type of Condenser	Shell and Tube
No. of Turbine	1 Main and 2 Aux.
No. of Condensate Pump	2
MAKE-UP SYSTEM	
No. of Trains	2
Volume of Make-up Tank (m^3)	2
Design Pressure (MPa)	17
EQUIPMENT COOLING SYSTEM	
No. of Train	1
Coolant Pressure (MPa)	0.5
Coolant Temperature (°C)	40
CONTAINMENT	
Type	Pressurized concrete with steel lining
Design Pressure (MPa)	0.3
Design Temperature (°C)	120

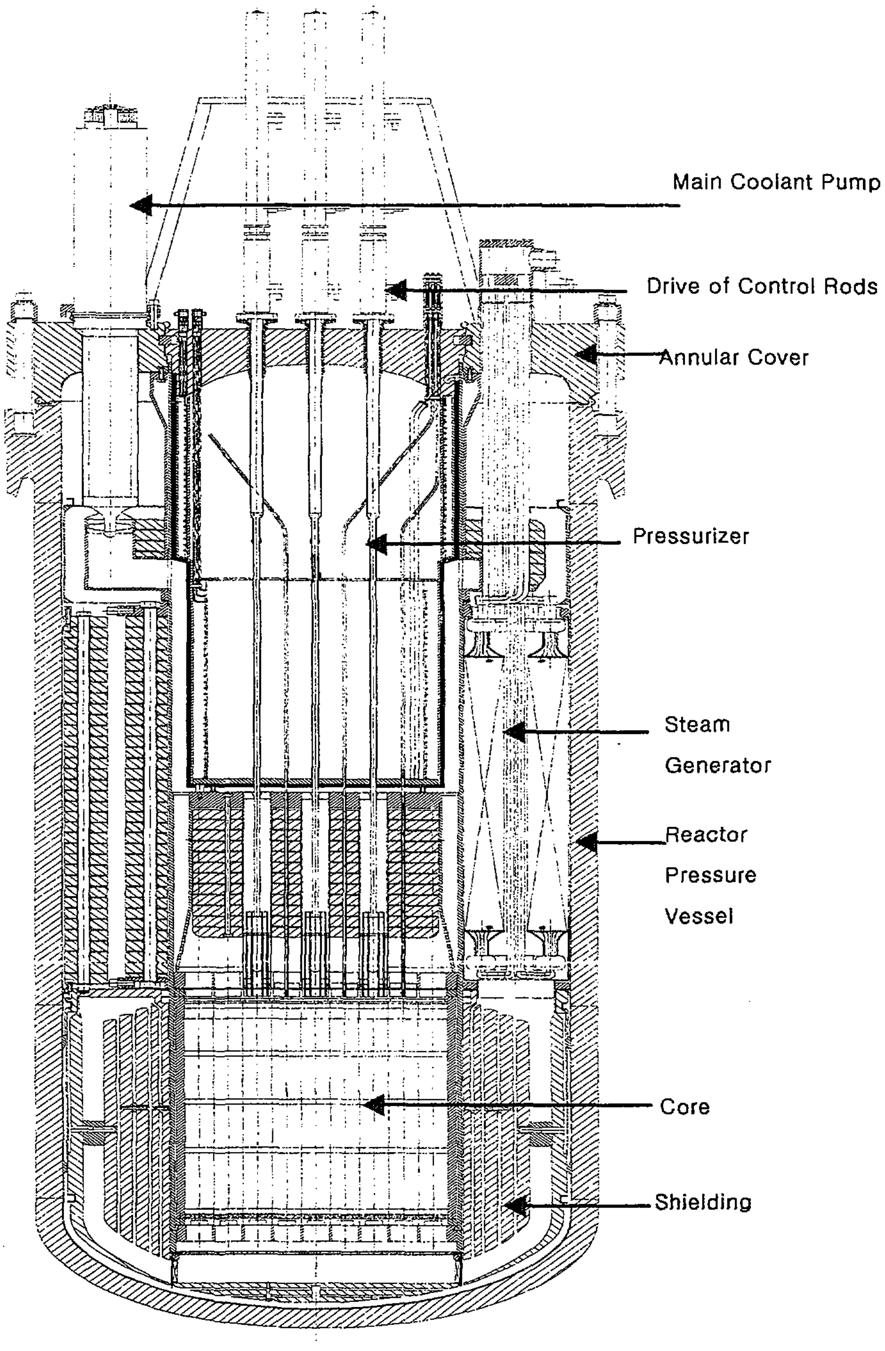

Fig. 1 SMART Reactor Assembly

The SMART core design is characterized by ultra long cycle operation with single or modified single batch reload scheme, low core power density, soluble boron-free operation, enhanced safety with strong negative MTC feedback at any time during the cycle, adequate thermal margin, inherently free from xenon oscillation instability, and minimum rod motion for the load follow with coolant temperature control. SMART fuel management is designed to achieve maximum cycle length between refueling. A simple single batch refueling scheme returns a cycle of 985 Effective Full Power Days (EFPD). This reload scheme minimizes complicated reload design efforts. A modified single batch scheme with 20 peripheral assemblies reloaded at every even numbered cycle is also possible, and thus enhance the fuel utilization. SMART fuel management scheme is highly flexible to meet the customer requirements.

2.2. Reactor Pressure Vessel

The SMART reactor pressure vessel (RPV) is a pressurized cylindrical vessel accommodating all major components of the primary system. The RPV consists of a cylindrical shell with an elliptical bottom and an upper flange part welded up to the shell. The RPV is closed at the top by the annular peripheral cover and the round central cover which also serve as the cover of the in-vessel pressurizer. The annular cover is fixed onto the vessel flange by means of stud bolt joint. The vessel-to-annular cover joint is made leaktight by a welded torus sealing. The central cover is fastened to the annular cover by a flangeless joint, using rack-and-gear mechanism. The annular-to-central cover joint is also made leaktight by a welded torus sealing. All penetrations to RPV are limited in the vessel head region. This assures that the RPV forms a leaktight container under any postulated pipe break accident. On the annular cover, there are twelve SGs, steam collecting and feedwater-distributing chambers, four MCPs, makeup piping nozzles, resistance thermometers, branch pipes, etc. On the outer surface of the central cover, there are nozzles for 4U CEDMs, rack- and-gear drives, branch pipes, etc. The core barrel with fuel assemblies and shielding tube assemblies are located in the lower part of the RPV.

2.3. Steam Generators

SMART has twelve identical SG cassettes which are located in the annulus formed by the RPV and the support barrel. SG cassette is of once-through design with helically coiled tubes wound around the central mandrel. The primary reactor coolant flows downward in the shell side of SG tubes, while the secondary feedwater flows upward in the tube side. Steam at 3.0MPa and superheated by 40°C exits the SG. For the performance and safety aspects, each SG cassette consists of six identical and independent modules with the same number of tubes per module. Each module has one feedwater intake header and one steam outlet header. Six modules from three adjacent SG cassettes - two modules per cassette are then joined into one nozzle, and three nozzles are joined to form one section. This hierarchyal grouping of SG is designed to minimize the impact of SG tube rupture accident on the reactor system. To prevent hydrodynamic instability in the parallel connected tubes, throttling devices are installed at the feedwater inlet of each helically coiled tube. Each throttling device is located in the tube sheet of the feedwater headers, and it is a sleeve with a core connected by a thread joint. Throttling orifices are also installed in the lower part of each cassette on the primary side to provide uniform primary coolant flow rate to each cassette. In the case of normal shutdown of the reactor, the SG is used as the heat exchanger for the passive decay heat removal system (PRHRS).

2.4. Pressurizer

The PZR is located inside the upper part of the RPV, and it is filled with water, steam, and nitrogen gas. The PZR is connected to the gas tank located outside the RPV, where high pressure nitrogen gas is supplied. The primary system pressure is determined by the sum of the partial pressures of nitrogen gas and steam. The pressure in the primary system of is automatically and passively regulated by the thermo-dynamic interactions of water/steam and gas in the pressurizer. The PZR design eliminates the complicated control and maintenance requirements and there is no active pressure control mechanism such as spray or heater. To prevent a relatively large variation in pressure caused by the power change, SMART employs a method for keeping the average primary coolant temperature and PZR temperature constant. The large pressure variation which may occur during power maneuvering is reduced by maintaining the constant temperature of the gas-steam space low and insensitive to the core outlet temperature variation. For this purpose, a PZR cooler is installed to maintain low PZR temperature and a wet thermal insulator is placed between the PZR and the primary system to reduce conductive heat transfer.

2.5. Control Element Drive Mechanism

The SMART Control Element Drive Mechanism (CEDM) is designed for fine-step movement and consists of a linear pulse motor (LPM), choke rack with top and bottom limit switches which also act as control element assembly (CEA) position indicator, hydro-dampers, locking device, and extension shaft connecting CEDM and CEA. The CEDM movement is accomplished with a combination of four phases. As a control command comes to the LPM control unit, the LPM phase I gets off and phase II gets on. After that, phase II gets off and phase III gets on, etc. The direction of the armature movement depends on the communication sequence of the LPM phases. The normal travel length of the control rod is 4mm per pulse, and the travel speed is in the range of 0 - 50 mm/sec. The drives separate unit is joined to each other on the flanges with studs and nuts. The drives are located on the reactor central cover and fastened to the cover by means of flange joints with studs and nuts. Sealing is provided with the use of copper gaskets rectangular in section.

2.6. Main Coolant Pump

The SMART MCP is a canned motor pump which does not require the need of pump seals. This characteristics basically eliminates a small break Loss of Coolant Accident associated with the pump seal failure which becomes one of design bases events in the reactors using conventional pump. SMART has four MCPs vertically installed on the top annular cover of the RPV. Each MCP is an integral unit consisted of canned asynchronous three-phase motor and an axial-flow single- stage pump. The motor and the pump are connected by a common shaft rotating on three radials and one axial thrust bearing. The bearings use a specialized graphite-based material, and the axial bearing performs the function of sealing. The cooling of pumps is accomplished with the component cooling water. The rotational speed of the pump rotor is controlled by a sensor installed in the upper part of the motor. To avoid the reverse rotation of the pump rotor, an anti-reverse device is installed at the motor shaft near the middle radial bearing.

3. SAFETY SYSTEMS

Besides it is inherent safety characteristics of SMART, further enhanced safety is accomplished with highly reliable engineered safety systems. The engineered safety systems designed to function passively on the demand consist of reactor shutdown system, passive residual heat removal system, emergency core cooling system, safeguard vessel, and containment overpressure protection system. Additional engineered safety systems include the reactor overpressure protection system and the severe accident mitigation system. The schematic diagram of the SMART safety system is shown in Fig. 2.

3.1. Reactor Shutdown System

The shutdown of SMART can be achieved by a function of one of two independent systems. The primary shutdown system is 32 shutdown banks of CEA of which absorbing material is B_4C. The control banks are dropped into the reactor core by the gravity force and immediately stops the neutron chain reactions. These control banks have sufficient shutdown margin to bring the reactor from hot full power to hot shutdown, even with a most reactive bank stuck out of the core. For the case of failure of the primary shutdown system, the emergency boron injection system is provided as a backup system and consists of two tanks, $6m^3$

each filled with 30 g of boric acid per Ukg water. One train is able to bring the reactor to the subcritical state. The system is an active system working with pump.

3.2. Passive Residual Heat Removal System (PRHRS)

The system passively removes the core decay heat and sensible heat by natural circulation in case of emergency such as steam extraction, unavailability of feedwater supply,

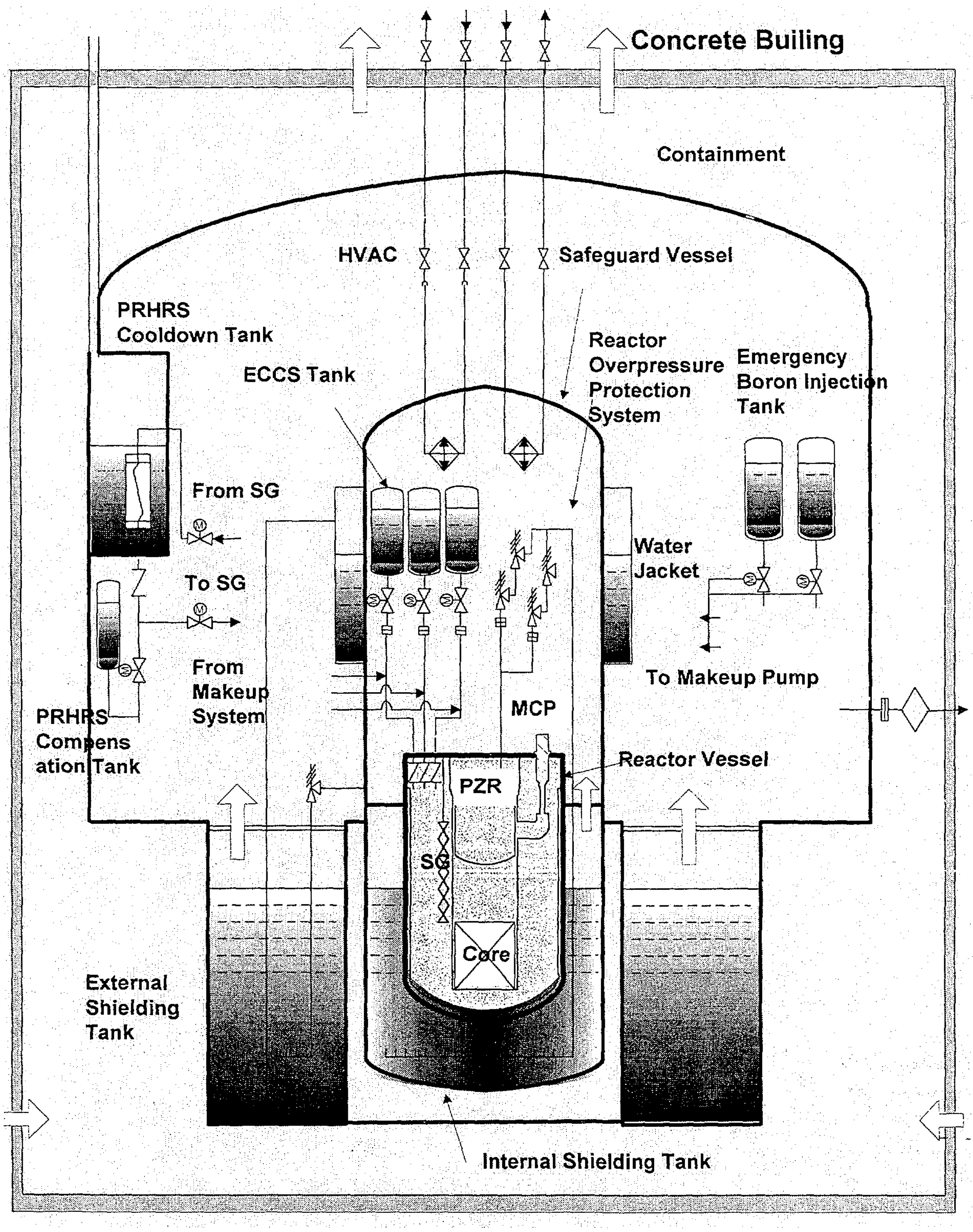

Fig. 2 SMART Safety Systems

and station black out. Besides, the PRHRS may also be used in case of long-term cooling for repair or refueling. The PRHRS consists of 4 independent trains with 50% capacity each. Two trains are sufficient to remove the decay heat. Each train is composed of an emergency cooldown tank, a heat exchanger and a compensating tank. The system is designed to keep the core un-damaged for 72hrs without any corrective actions by operators at the postulated design basis accidents. In case of normal shutdown of SMART, the residual heat is removed through the SG to the condenser with turbine bypass system.

3.3. Emergency Core Cooling System (ECCS)

The SMART design excludes any possibility of large break Loss of Coolant Accident. The largest size of pipes connected to the outside of the RPV is 20mm. The ECCS is thus provided to protect the core uncovery by mitigating the consequences of design basis events such as small break LOCA through make-up of the primary coolant inventory. When an initiating event occurs, the primary system is depressurized. The pressure difference between the primary system and the ECCS breaks the rupture disc installed in the pipe of ECCS and the water immediately comes into the core by the gas pressure. The ECCS consists of three independent trains with U00% capacity each. Each train includes a cylindrical water tank of $5m^3$ in volume pressurized with nitrogen gas, isolation and check valves, rupture disc, and a pipe of 20mm in diameter connected to RPV.

3.4. Safeguard Vessel

The safeguard vessel is a leaktight pressure retaining steel-made vessel intended for the accommodation of all primary reactor systems including the reactor assembly, pressurizer gas cylinders, and associated valves and pipings. The primary function of the safeguard vessel is to confine the radioactive products within the vessel and thus to protect any primary coolant leakage to the containment. The vessel also has a function to keep the reactor core undamaged during 72hrs without any corrective actions at the postulated design basis accidents including LOCA, with the operation of the PRHRS and ECCS. The steam released from the opening of the relief valve of the safeguard vessel at the postulated beyond design basis accidents is sparged into the external shielding tanks and immediately condensed.

3.5. Containment Overpressure Protection System (COPS)

The containment is a steel structure with concrete building enclosing the safeguard vessel to confine the release of radioactive products to the outside environment under the postulated beyond design basis accidents relating to the loss of integrity of the safeguard vessel. At any accident causing the temperature rise and thus the pressure rise in the containment, the containment cooling is accomplished, in the passive manner, by removing the heat from the containment. The heat is removed through the steel structure itself and through the emergency cooldown tanks installed inside the containment. A rupture disc and a filtering system are also provided in the containment to protect the steel structure from overpressure and to purify the released radioactive products at the postulated beyond design basis accidents.

3.6. Reactor Overpressure Protection System (ROPS)

The function of the ROPS is to reduce the reactor pressure at the postulated beyond design basis accident related with a control system failure. The system consists of two parallel trains which are connected to the PZR through a single pipeline. Two trains are also combined to a single pipeline connected to the internal shielding tank. Each train is equipped with a rupture disc and two relief valves. At the postulated beyond design basis accidents, the rupture disc is broken and the relief valve is open by the passive means of flow thrust.

The steam is then discharged into the internal shielding tank through the sparging device and condensed.

3.7. 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. The egress of corium can be avoided due to the design characteristics of safeguard vessel and containment together with the operation of the safety systems. A small air gap under the reactor pressure vessel (RPV) is filled with water from the Makeup system at the severe accident. The in-vessel cooling prevents the egress of the corium out of the RPV. In addition, the water in the internal shielding tank provides the external cooling of the RPV and prevents the egress of the corium out of the RPV. Hydrogen igniters are provided in the safeguard vessel to remove the explosive hydrogen generated during the severe accident.

4. SECONDARY SYSTEM

The secondary system of the plant with SMART has the same function of removing the heat produced from the primary system, as of the conventional nuclear power plant. However, the secondary system generates superheated steam from the feed water. The system consists of in-vessel helically coiled steam generator, main steam and feedwater system, turbine generators and associated pipings and valves. The system is divided into four independent sections arranged in such a way to minimize the heat removal unbalance in the vessel when one section fails. The turbine generators consist of a main turbine generator and two auxiliary turbine generators. One auxiliary turbine generator is standby and the other is in operation to supply the house loads, while the main turbine is used for the offsite power supply. The pressure of main steam line is always constant during power change transients. The load change is done by the change of feedwater flow rate to the steam generator with the change rate of 5%/min, or by the turbine bypass system when the load change is done immediately. The schematic diagram of the SMART safety system is shown in Fig. 3.

5. AUXILIARY SYSTEMS

The major auxiliary systems of SMART consist of equipment cooling system (ECS) and make-up system. The function of ECS is to remove the heat generated in the MCPs, CEDMs, PZR, and the internal shielding tank. The feedwater supplied from the condensate pump of the turbo-generator is used as coolant to remove the heat. The make-up system of SMART performs the following functions; fill and make-up the primary coolant in case of the primary system leak, supply water to the compensating tanks for the PRHRS and supply water to the gas filling tank during the scheduled shutdown processes. The make-up system consists of two independent trains, each train with one positive displacement makeup pump, a makeup tank, and piping & valves. The schematic diagram of the SMART safety system is shown in Fig. 4.

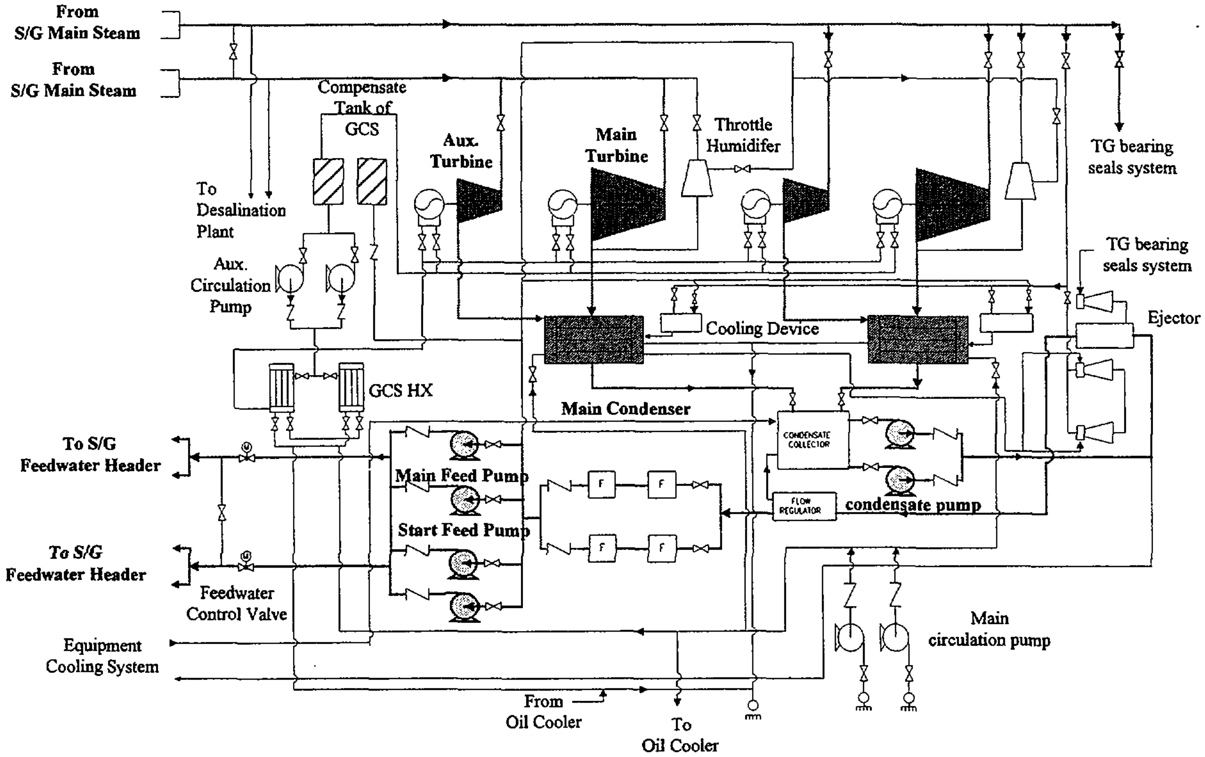

Fig. 3 SMART Secondary System

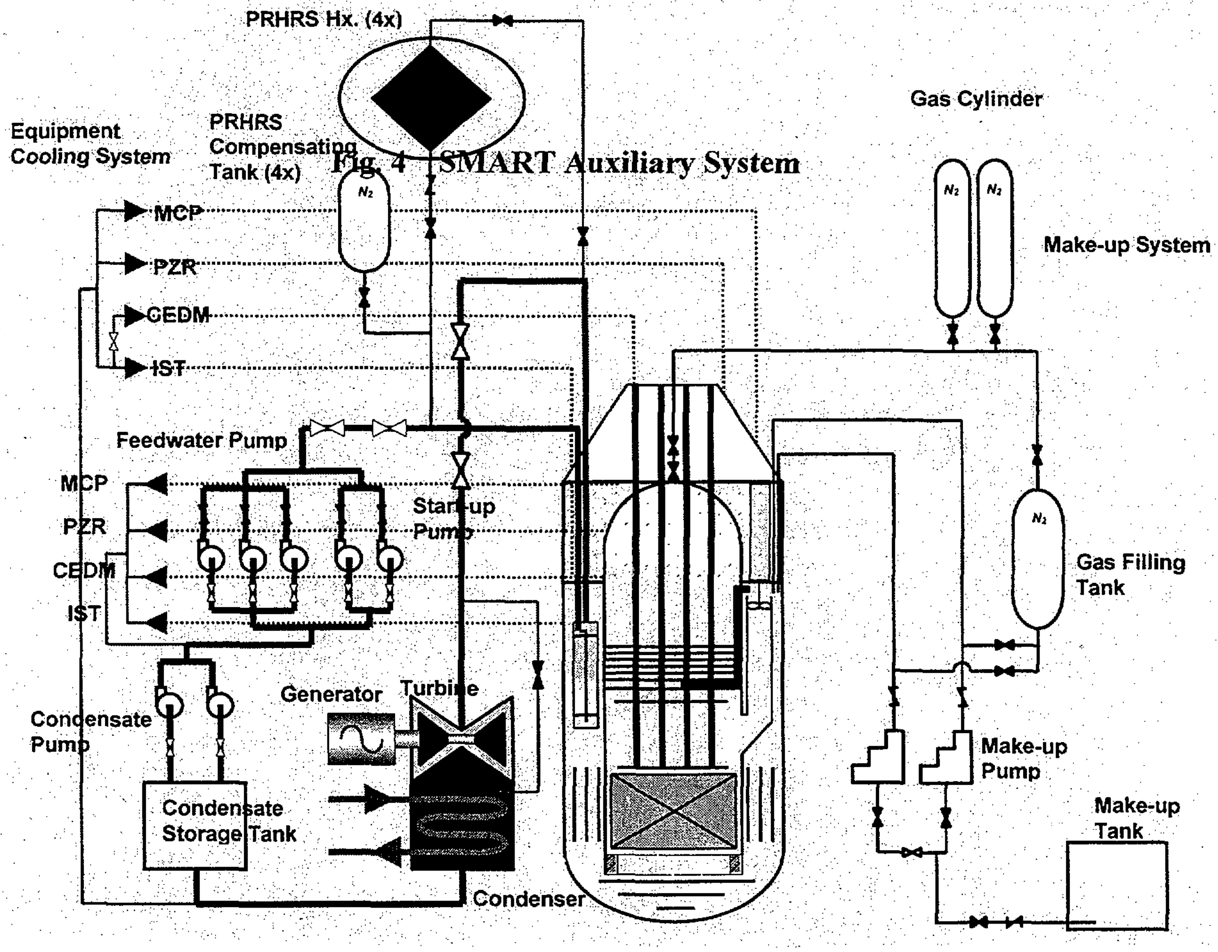

Fig. 4 SMART Auxiliary System

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