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Development of BANDI-60S for a Floating Nuclear Power Plant

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1. Introduction

KEPCO-E&C has been developing a small modular reactor (SMR), named BANDI-60S. Among a wide spectrum of SMR applications, KEPCO E&C has focused on the option for a nuclear power plant floating in the sea and set up a business plan and associated R&D strategy. Rather than competing with the land-based large nuclear or fossil power plants which have long been optimized for the centralized electrical grids, the BANDI-60S will find its own way in rather non-conventional areas, so called the niche market: for instance, distributed power and heat supply to remote communities, sea water desalination, and hybrid energy systems with the renewables, etc. through a collaboration with the marine & shipbuilding industries.

The design of BANDI-60S is mainly rooted in proven technologies and KEPCO E&C's experience of over 40 years in the conventional nuclear power plant engineering services in Korea and overseas.

2. Design Features

2.1 Basic Design Features

BANDI-60S is a block-type PWR with 200MWt as shown in Fig. 1. The block-type design in which main components are directly connected, nozzle-to-nozzle, instead of using connecting pipes can eliminate the large break LOCA from the design basis and also provide improved operational surveillance and maintenance ~~as~~ compared to the integral type design.

For the steam generator (SG), a U-tube recirculation type is employed as the basic option since its performance has been proven with a plenty of operational experiences over a long history of commercial nuclear power plants. As an advanced design option, KEPCO E&C is now working on a new steam generator based on the plate and shell heat exchanger technology, which would reduce the size by 3~5 times.

The pressurizer is integrated into the upper head of the reactor pressure vessel where a relatively large water and steam volume is provided, compared with that of conventional nuclear power plants. The pressurizer pressure is controlled by heaters and sprays. The control element drive mechanism (CEDM) is installed inside the reactor vessel. Reactor coolant pump (RCP) is equipped with a leak-tight canned motor. The major technical parameters of BANDI-60S are shown in Table. 1.

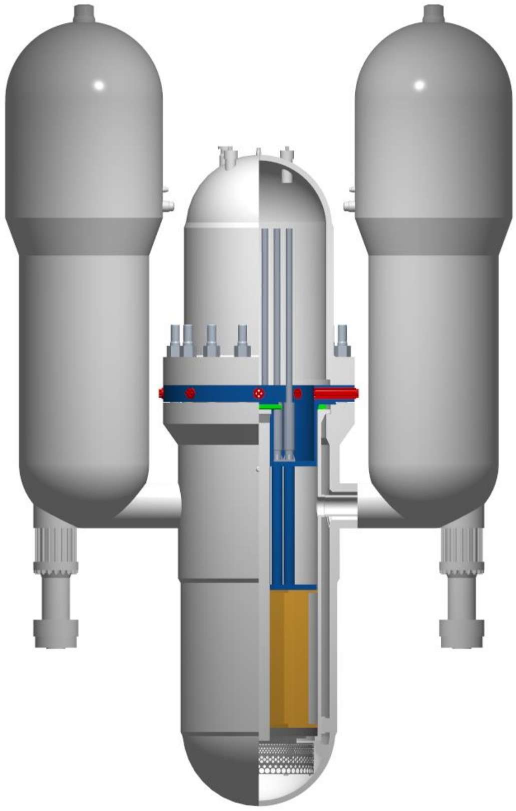

Fig. 1 RCS Configuration of BANDI-60S

Table 1. Major Design Features and Parameters of BANDI-60S

Parameter	Value
Reactor Type	PWR
Coolant/moderator	Water
Thermal/electrical capacity, (MWt/MWe)	200/60
Primary circulation	Forced circulation
System pressure (MPa)	15
Core inlet/exit temperatures (℃)	290/325
Fuel type/assembly array	UO2 pellet/ 17x17 square
Number of fuel assemblies	52
Fuel enrichment (%)	< 5
Fuel burnup (GWd/ton)	35 (average)

Fuel cycle (months)	48~60
Steam generator type	Recirculation U-tube
Steam pressure(MPa)	6
Main reactivity control mechanism	In-Vessel CEDM and secondary shutdown system
Approach to engineered safety systems	Passive
Design life (years)	60
RPV height/diameter(m)	11.2/2.8
Distinguishing features	Block-type RCS design In-vessel CEDM, Top-mounted ICI, Boron-free operation Integrated pressurizer Canned motor RCP Passive safety systems

2.2 Advanced Design Features

Key advanced design features of BANDI-60S for improved safety and operability include:

- Block-type reactor coolant system arrangement
- Extended refueling cycle of 4~5 years
- Soluble boron-free (SBF) operation
- In-vessel CEDM
- In-core instrumentations mounted on the reactor vessel head (Top-mounted ICI)
- Passive safety injection system (PSIS), Passive residual heat removal system (PRHRS) and Passive containment cooling system (PCCS)
- Canned-motor RCPs
- Integrated pressurizer, etc.

Although the soluble boron in the conventional PWR has provided effective means of core reactivity control over the core life, it causes several design and operational problems. High boron concentration at the beginning of core cycle makes the moderator temperature coefficient (MTC) less negative and is unfavorable for the safety. The SBF operation enables us to eliminate the complicated boron treatment system and, thus, simplify the chemical & volume control system of a nuclear power plant [2][5]. The corrosive operating conditions are alleviated, and the liquid radioactive waste would be reduced. The more negative MTC enhances the nuclear safety. However, in order to substitute for the conventional functions of soluble boron, more burnable absorbers are added to suppress and control the excess reactivity of fuel over core life time [2][3]. A new secondary or alternative shutdown system has been developed as a diverse means of reactivity control to comply with the general design criteria (GDC) 26 and 27 of U.S. NRC 10CFR part 50 [4][5][6].

While the conventional CEDMs are mounted outside the reactor vessel on its upper head, the BANDI-60S has it inside, which is called the In-vessel CEDM [7]. The control rod ejection accident has much severer impact on the boron free reactors since their individual control elements have more reactivity worth. The In-vessel CEDM within the pressure boundary eliminates the safety issue of the control rod ejection accident for the boron free reactors. However, the environmental design conditions imposed on the In-vessel CEDM are challenging due to high temperature, pressure, radiation and submerged conditions. Through a government funded R&D project, key technologies of the In-vessel CEDM have been developed and validated with a full-scale demonstration test for its operability in such harsh environmental conditions, including the performance of lifting load, driving pitch, driving speed, etc [7]. New boron free water chemistry control strategy has also been developed and a basic corrosion experiment has been performed [5][6].

2.3 Reactor Core Design

The BANDI-60S reactor core is composed of 52 fuel assemblies. The fuel is a conventional UO_2 fuel enriched up to 4.95 % in 17x17 square array. Low power density is achieved by adopting a core configuration consisting of 52 fuel assemblies with a 2 meter long active fuel length, and a nominal thermal power of 200 MWt as shown in Fig. 2. Control rods for BANDI-60S have more burnable absorbers to control the excess reactivity of fuel over core life time to maintain a boron free operation during normal condition [2][3]. Twenty two (22) fuel assembly locations for the control rods and eighteen (18) locations for the secondary shutdown system are reserved for the reactivity control.

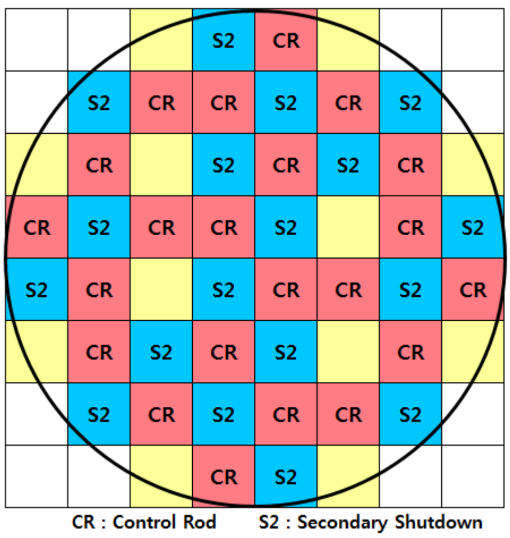

Fig. 2 Reactor Core Arrangement of for BANDI-60S

2.4 Safety Features

The BANDI-60S has inherent passive safety features. The passive safety systems consist of the PSIS, PRHRS, and PCCS, which rely on natural forces to enhance the safety in case of a postulated accident and thus will decrease the core damage frequency (CDF).

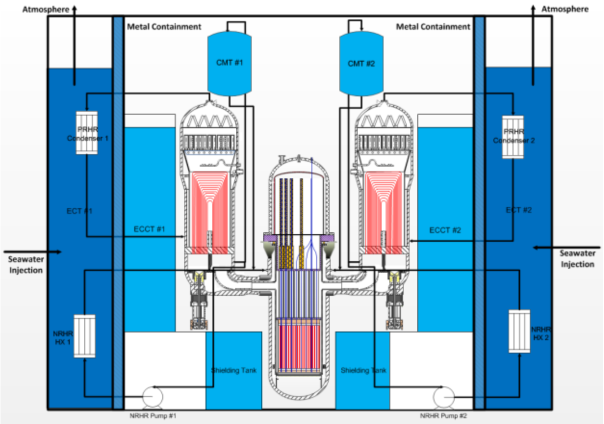

Fig. 3. Basic Concept of the Passive Safety Systems

The PSIS provides an RCS inventory makeup for any loss of coolant events other than LBLOCA by a gravity driven flow. The core makeup tank (CMT) is pressurized to the RCS pressure by the pressure balance line (PBL) connected to the SG inlet. Isolation valves between the CMT and direct vessel injection (DVI) nozzle remain closed during normal operation, and are opened when the RCS depressurizes, the pressurizer level decreases or the containment pressure increases beyond their set points. When the RCS pressure further decreases, the coolant stored in the emergency core cooling tank (ECCT) is injected by gravity. Spilled water from the break is collected at the bottom of the containment and eventually the whole reactor vessel becomes submerged in the water and is continuously cooled by convection and natural circulation.

The PRHRS provides decay heat and RCS sensible heat removal when the normal cooling of RCS through SGs and condenser is not available after reactor trip at any power level. Steam from the SG condenses in the PRHRS heat exchanger, which is located inside the emergency cooldown tank (ECT), and the condensate returns by gravity to the SG via the feedwater nozzle. It cools down the RCS to the safe shutdown condition and maintains it for an extended time without refilling the ECT. The ECT is located outside the containment and in contact with the metal wall of the containment. When the ECT water temperature is high or the ECT level is low during a postulated accident, seawater can be injected into the ECT by gravity and density difference to provide heat sink. This is possible because the reactor and the ECT are located below the sea level.

Heat from the containment is continuously removed to the water stored in the ECT through metal wall during a postulated accident to reduce pressure and temperature of containment.

3. Conclusion and Future works

KEPCO E&C has been developing an SMR, BANDI-60S, for a floating nuclear power plant. Its design is mainly based on proven technologies and our experience of over 40 years in the conventional nuclear power plant engineering services in Korea and overseas. To enhance the safety and performance, several advanced design features are adopted such as soluble boron-free operation, in-vessel CEDM, and top-mounted ICI.

The conceptual design of the BANDI-60S is now underway. In the next phase, safety and performance analyses will be performed to see the feasibility of the conceptual design and the sizing of the main components and systems, including passive safety features will be performed.

Study on advanced technologies for their feasibility and applicability will also be continued such as a new plate and shell SG, and a simple core monitoring and protection systems. For use in the floating nuclear power plant, the BANDI-60S will comply with the design standards and regulations of the international maritime organization (IMO) as well as the conventional nuclear power plants.

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