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Nuclear Design Characteristics of SMART

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Abstract

Nuclear design bases for System-Integrated Modular Advanced ReacTor(SMART) core are presented. Based on the proposed design bases, a SMART core loading pattern is constructed and its nuclear characteristics are studied. The proposed core loading pattern satisfies 3-year cycle length and soluble boron-free operation requirements at any time during the cycle.

I. Introduction

Based on the self-reliance in the commercial nuclear power reactor design and construction technology in Korea, KAERI started a program for the development of System-integrated Modular Advanced ReacTor(SMART) of 330 MWt for supplying the energy for seawater desalination as well as for electricity generation.[1] The advanced integral reactor will be developed based on the firmly established commercial reactor fuel technology, Korean Optimized Fuel Assembly (KOFA) design technology.[2]

SMART is an integral type reactor and has core, reactor coolant pumps, pressurizer and steam generators in one pressure vessel. Therefore, one of the design bases accidents in nuclear power plants, Large Break Loss Of Coolant Accident (LBLOCA) is eliminated by its design.

In addition to the above new design concept, soluble boron-free operation and nuclear heating during start-up are in the major nuclear design concept different from that of commercial Pressurized Water Reactors (PWR's). Especially, the soluble boron-free operation concept should be satisfied in order to eliminate on-line Chemical and Volume Control System (CVCS).

The nominal reactor thermal output of SMART is 330 MWt (100 MWe), and steam output is 152.7 kg/s. The lifetime of the plant is 60 years. The average annual capacity factor is 90%. The reactor will be operated at constant Tavg of 290°C. Primary coolant temperatures at core inlet and outlet at full power are 270°C and 310°C, respectively.

Although a boron injection system will be provided for reactor safety, the boron-free concept requires that whole excess reactivity should be covered by burnable absorbers and control rods. Burnable absorber rods are adequate for long-term excess reactivity control with the aid of the control rods. Short-term reactivity variations due to power change, xenon oscillation and slight variation of system conditions can be controlled by control rods or strong negative MTC.

In order to perform the nuclear core design, CASMO-3/MASTER system[3,4,5] is used. CASMO-3 is developed by Studsvik and is designed to generate group cross sections used for light water reactor nuclear analysis. Assembly homogenized group cross sections and heterogeneity factors are transformed by interface code XFORM[6] for MASTER. MASTER (Multi-purpose Analyzer for Static and Transient Effects of Reactors) is a nuclear design code developed by Korea Atomic Energy Research Institute based on the two-group diffusion theory to calculate the steady state and transient pressurized water reactor core in a three-dimensional Cartesian or hexagonal geometry.

In section 2, nuclear design bases of the boron-free SMART are presented. In section 3, core loading pattern and control rod configurations are proposed. Nuclear characteristics are presented in section 4.

II. Nuclear Design Bases

Among the numerous design bases, most important nuclear design bases for SMART are summarized here. First of all, SMART core consists of 57 fuel assemblies with slightly enriched UO_2 fuels. This ceramic form of slightly enriched uranium has been used for worldwide and domestic commercial reactors. Based on the firmly established reactor fuel technology, 4.95 w/o enriched UO_2 is chosen for SMART fuel. Since 5w/o is the maximum U-235 enrichment for commercial reactors, 4.95w/o is the maximum design enrichment considering the manufacturing allowance.

Cycle length requirement for SMART is set to be 3 years. Although longer cycle length requires higher fuel cost, total energy generation cost can be lowered with the increased cycle length by reducing the average shutdown period for refueling and increasing capacity factor. With the average capacity factor of 90%, the 3-year operation period is equivalent to 985 Effective Full Power Days (EFPD).

SMART is looking for a soluble boron-free operation from refueling to hot full power operation. The control rods should be capable of maintaining the reactor in a subcritical condition when the reactor is at ambient temperature (20°C), zero power, no xenon, and with the most reactive control rod stuck at the fully withdrawn position. In order to provide greater assurance that this condition can be met in the operating reactor, the core design should satisfy k_{eff} less than 0.99, or 1% margin on the "stuck rod" condition. Once cold shutdown capability is verified, then immediate shutdown is automatically assured at any operating condition because the control rod worth is higher at hot condition and reactivity temperature coefficients are negative.

During refueling operation, the reactor should be maintained in a subcritical condition, i.e., k_{eff} of less than about 0.95. Therefore, k_{eff} at an ambient temperature, zero power, All Rod In (ARI), no xenon condition should be less than about 0.95.

Average Linear Heat Generation Rate (ALHGR) of SMART is 110 W/cm and ALHGR of KOFA is 183 W/cm for Ulchin Unit 1.[6] To establish a preliminary peaking factor limit for SMART, design peaking factors for Ulchin Unit 1 can be referenced. Since power peaking factor, Fq of 3.71 for SMART is equivalent to that of Ulchin Unit 1 in local power production, 3.6 is chosen conservatively for the preliminary design limit. Nevertheless, DNB analysis will be performed to make sure that the core is safe from DNB.

III. Core Description of SMART

Proposed core of SMART is composed of 57 fuel assemblies, which will be designed based on 17x17 KOFA that was designed by KAERI/Siemens-KWU and used for 900 MWe Westinghouse-type domestic PWR's. The active fuel height for SMART is 200 cm. The core is designed for 3-year operation without refueling.

First cycle SMART core loading pattern is shown in Figure 1. Four different fuel assemblies are used to construct a loading pattern. The core consists of 13,500 fuel rods of 4.95w/o UO_2. In Figure 2 cross sectional views of the fuel assemblies are shown. Al_2O_3-B_4C is used for the primary burnable absorber to control the excess reactivity as flat as possible and to reduce the reactivity control burden on the control rods during the 3-year cycle. 12w/o Gd_2O_3 mixed with 1.8 w/o UO_2 is additionally used as integrated burnable absorber to reduce the stuck rod worth. The number of Al_2O_3-B_4C shim rods is 1,304 and the number of gadolinia rods is 244. There are 21 control rod guide tubes and 4 instrumentation thimbles in each fuel assembly.

There are 41 Control Element Driving Mechanism (CEDM) installed on the top of the core. Each CEDM has 21 absorber elements that can be inserted into the fuel assembly guide tubes. Control rods are divided into two categories: control banks and shutdown banks. Highly enriched B_4C is used for the shutdown banks to increase shutdown rod worth. Shutdown banks are at the fully withdrawn position during power operation. Control banks can be inserted during power operation to maintain reactor criticality. To prevent helium gas buildup due to B-10 neutron interaction, Ag-In-Cd is used for the control banks. The control bank worth is 4.2%$\Delta\rho$ at the Beginning Of Cycle (BOC) and 5.2%$\Delta\rho$ at the End Of Cycle (EOC), which can effectively override the excess reactivity during normal operation.

A single batch reload scheme is chosen for SMART fuel management for the maximum cycle length between refueling. All 57 fuel assemblies are discharged after each cycle. But the average burnup of 20 peripheral fuel assemblies is about 15.4 MWD/KgU at the end of the cycle and is about half of the remaining fuels. Therefore, these peripheral fuel assemblies can be reloaded in the next cycle. A modified single batch reload scheme of odd-even cycle is considered for SMART. For odd-number (first) cycles, all 57 fresh fuel assemblies are loaded. But for even-number (second) cycles 20 burnt fuel assemblies at the core periphery can be reloaded and 37 fuel assemblies are replaced with fresh fuel assemblies. Core reactivity and cycle length are almost same between two cycles. The average discharge burnup of the 20 peripheral assemblies is about 31.0 MWD/KgU and is about same as that of the other assemblies.

There are four instrumentation thimbles in a fuel assembly. Because most of the fuel assemblies should be covered by control rods and relatively straight cable paths for the incore detectors should be provided from the top of the core to the top of the fuel assemblies, off-centered instrumentation thimbles are provided to clear the cable path. One of the four instrumentation thimbles in an assembly will be used for the incore detector.

There are 20 incore detectors to be installed in SMART. For the uniform detector distribution, each quadrant has 5 detectors. 16 detectors are assigned to four groups to give reliable data for core monitoring and protection system to calculate azimuthal power tilt. Each group consists of 4 detectors. One of them is 4-fold symmetric and the other 3 groups consist of a couple of 2-fold symmetrically located detectors.

IV. Nuclear Characteristics

Most of the nuclear parameters presented here are from the first cycle because core loading patterns and nuclear characteristics are almost the same between two cycles. The following discussion is summarized in Table 1.

4.1 Reactivity Control

The excess reactivity is required to overcome the negative reactivity defects including moderator and Doppler temperature defect from the cold zero power to hot full power operating condition and negative reactivity defects due to fission products. Excess reactivity is also required to override xenon buildup or to compensate for the fuel depletion as burnup increases. Soluble boron is used to control the excess reactivity in the commercial PWR's although some burnable absorber rods are used to reduce critical boron concentrations and to flatten the power distributions. Control rods are used for the purpose of fast reactivity changes and axial offset control.

For the same reason, excess reactivity is required for SMART. However, SMART is looking for soluble boron-free operation. Then, most excess reactivity for fuel depletion is controlled by burnable absorbers and remaining excess reactivity should be controlled by control rods. Excess reactivity for temperature defect and xenon poisoning is also controlled by control rods. Therefore, minimum and constant excess reactivity during hot full power operation is desirable to minimize control rod movement and to assure safe shutdown of the core at any time during the cycle.

Al_2O_3-B_4C shim rods are chosen for primary burnable absorber. Unlikely to the commercial reactors, 32% enriched B-10 is used to make the burnable absorber effectively control the excess reactivity for the 3-year cycle. 12 w/o gadolinia bearing UO_2 rods are selectively used to minimize stuck rod worth.

It is shown that sufficient excess reactivity is maintained for the hot full power operation during the cycle. The reactivity difference between hot and cold conditions are due to moderator and Doppler reactivity defects, and should be controlled by control rods. Although boron injection system is additionally installed for the sake of safety, control rods are effectively designed to make the reactor subcritical and to maintain the subcriticality for the long term at any time during the cycle.

Core loading pattern and control rod assignment are chosen such that 1% subcriticality margin is assured at cold zero power, no xenon and stuck rod condition. This core also guarantees k_{eff} less than 0.95 when all control rods are inserted. Conservatism of the subcriticality is assured by applying rod worth uncertainty.[8]

Moderator temperature coefficients (MTC) and Doppler temperature coefficients (DTC) are presented in Table 1. Appropriate uncertainties[8] are applied to obtain least or most negative values. DTC is always negative and about same as that of commercial PWR's. MTC is very negative during the cycle except least negative MTC at cold all rods out condition, which is still negative. Strong negative MTC is due to soluble boron-free concept. At full power, MTC is between –40 pcm/°C and –65 pcm/°C depending on control rod position and burnup. Such strong negative MTC will enhance safety of the reactor.

4.2 Peaking Factors

Axial Offset (AO) is defined by the ratio of the power difference between the top and bottom halves of the core to the total fission power of the reactor. AO is very negative at BOC and very positive at EOC. This is because very strong negative MTC and partially inserted control rods push power to the bottom of the core at BOC. As EOC approaches, control rods are withdrawn to keep the reactor critical and most of the reactive fuels are left at the top of the core.

Maximum power peaking factor, Fq, is 3.17 during the first cycle. Maximum Fq for the second cycle is 3.37 and both Fq's satisfy preliminary Fq limit of 3.6. Axially averaged radial peaking factor, Fr is slightly greater than 1.8 at BOC and relatively smooth through the cycle. Fq variation is, therefore, mainly due to axial peaking factor Fz, or axial shape. The high peaking factors compared with those of the commercial PWR's are disadvantageous but low power density assures the safety. Although full safety analyses are yet to be performed, DNBR for the normal operating condition near the end of the first cycle is estimated 2.63 using W-3 correlation[9], which is acceptable in view of preliminary design limit. Since reduced peaking factors can increase reactor safety margin, further study to reduce Fq is worthwhile. Assembly optimization to reduce Fr can be considered. To reduce Fz, axial zoning[10] can be considered. Control rod programming to minimize the peaking factor and to maximize cycle length will be useful for soluble boron-free reactors.

V. Conclusion

A core loading pattern for SMART is proposed which satisfies cycle length requirement of 3 years and subcriticality requirements without soluble boron.

41 control rods are divided into two categories: Shutdown banks and control banks. Ag-In-Cd is selected for the control banks that are inserted during power operations for excess reactivity control.

Highly enriched B_4C is used for the shutdown banks to increase bank worth and to assure a safe cold shutdown. Shutdown banks are normally at the fully withdrawn position.

Introducing off-centered instrumentation thimbles, a top-entry incore detector and a CEDM can be installed at the same fuel assembly. Preliminary 20 incore detector locations are selected for reliable power measurement.

Low power density allows relatively high peaking factors, and acceptable DNBR resulted for the normal operating conditions.

In addition, modified single batch reload scheme is studied for SMART. This reload scheme will utilize less burned peripheral fuel assemblies after the first cycle to increase fuel economy while minimize reload design works.

Safety analyses and performance analyses will be performed for the proposed soluble boron-free SMART core. Loading pattern optimization including axial zoning, assembly optimization, control rod programming will be further studied.

References

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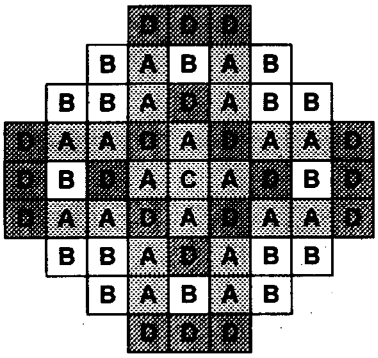
Table 1. Summary Description of SMART Nuclear Characteristics

Items	Values*
Burnup and Cycle Length	
Cycle Length, Effective Full Power Days	990
Core Average Burnup at EOC (Cycle 1), MWD/KgU	26.3
Core Average Burnup at EOC (Cycle 2), MWD/KgU	31.7
Reactivities	
Minimum Excess Reactivity at HFP, Eq. Xe and Sm, near BOC, $\%\Delta\rho$	0.50
Maximum Excess Reactivity at HFP, Eq. Xe, $\%\Delta\rho$	2.88
Maximum Excess Reactivity at Cold, No Xe, $\%\Delta\rho$	12.89
Maximum keff at Cold, No Xenon, Stuck Condition, Cycle 1 / Cycle 2	0.979 / 0.984
Maximum keff at Cold, No Xenon, ARI, Cycle 1 / Cycle 2	0.946 / 0.948
Control Rod Worth, $\%\Delta\rho$	
HFP Control Bank Worth, BOC/EOC	4.20 / 5.18
HZP Control Bank Worth, BOC/EOC	3.84 / 5.14
CZP Total Bank Worth, BOC/EOC**	18.61 / 18.34
CZP Bank Worth, Stuck Condition, BOC/EOC**	14.99 / 14.48
Reactivity Defects, $\%\Delta\rho$	
Xenon Worth, BOC/EOC	2.14 / 2.68
Power Defect (HFP to HZP), BOC/EOC	1.12 / 1.47
HZP to CZP Temperature Defect, BOC/EOC	8.03 / 5.64
Moderator Temperature Coefficients, pcm/°C	
HFP, Most Negative/Least Negative	-75.22 / -38.07
HZP, Most Negative/Least Negative	-123.24 / -34.78
CZP, Most Negative/Least Negative	-27.64 / -0.93
Doppler Temperature Coefficients, pcm/°C	
HFP, Most Negative/Least Negative	-5.69 / -2.97
HZP, Most Negative/Least Negative	-17.81 / -3.80
CZP, Most Negative/Least Negative	-26.07 / -4.78
Axial Offset, Minimum/Maximum	-0.365 / 0.289
Peaking Factors	
Cycle Maximum Fq, Cycle 1 / Cycle 2 (< 3.6)	3.17 / 3.37
Cycle Maximum Core Average Fz	1.6820
Cycle Minimum DNBR for Normal Operating Condition	2.63

*) Values are from Cycle 1 unless specified.

**) 10% uncertainty is included.



			D	D	D			
		B	A	B	A	B		
	B	B	A	D	A	B	B	
D	A	A	D	A	D	A	A	D
D	B	D	A	C	A	D	B	D
D	A	A	D	A	D	A	A	D
	B	B	A	D	A	B	B	
		B	A	B	A	B		
			D	D	D			

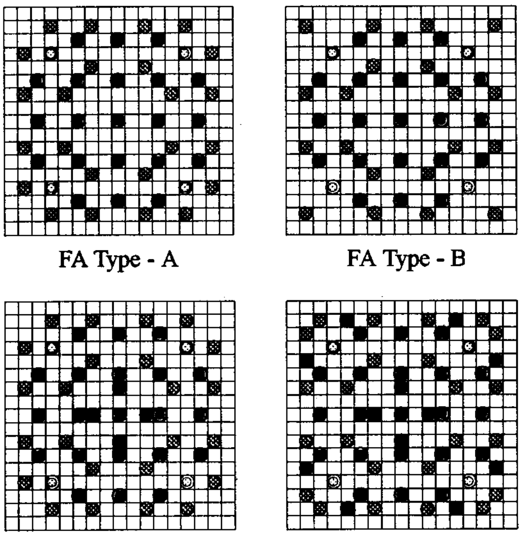
A 4.95w/o U-235 24 Al_2O_3-B_4C Shim Rods

B 4.95w/o U-235 20 Al_2O_3-B_4C Shim Rods

C 4.95w/o U-235 24 Al_2O_3-B_4C Shim Rods + 4 Gd_2O_3/UO_2 (12w/o /1.8w/o)

D 4.95w/o U-235 24 Al_2O_3-B_4C Shim Rods + 12 Gd_2O_3/UO_2 (12w/o /1.8w/o)

Figure 1. First Cycle SMART Core Loading Pattern


FA Type - A

FA Type - B

FA Type - C

FA Type - D

☐ Normal fuel

◉ Guide Tube

◎ Instrumentation Thimble

▩ 32% Enriched Al_2O_3-B_4C Shim 12 w/o

● Gadolinia-UO_2 Rod

Figure 2. Cross Sectional View of Fuel Assemblies