A SCWR Core Design with a Conceptual Fuel Assembly Using a Cruciform Moderator

Kang-Mok Bae, Hyung-Kook Joo, Hyun-Chul Lee, Jae-Man Noh and Yoon-Yong Bae
Korea Atomic Energy Research Institute, Yuseong Post Office 105, Daejeon, Korea

1. Introduction

A super critical water cooled reactor (SCWR) system has a potential to compete with the advanced fossil plant by achieving a high thermal efficiency up to 44% and a plant simplification by eliminating steam generators, steam dryers, steam separators, and recirculation pumps. Due to these advantages, a SCWR is considered as one of the most promising nuclear plants for the Generation-IV (Gen-IV) system.[1] As a first step of a feasibility study a rectangular fuel assembly with a cruciform solid moderator was suggested as a conceptual assembly design at the Korea Atomic Energy Research Institute (KAERI) for the SCWR on a thermal neutron spectrum.[2]

In this paper, based on the system parameters proposed by the Gen-IV road map, a preliminary SCWR core design was performed using a conceptual assembly design focused on the power shape control, reactivity coefficients, and cladding temperature limit.

2. Methods and Results

2.1 Assembly Design Concept Based on Cruciform Solid Moderator

One of the main characteristic features of a SCWR concept compared with a Light Water Reactor(LWR) is that the average coolant temperature variation along the core height ranges from 280 ^oC to 510 ^oC with the higher pressure of 25 MPa than the critical pressure of 22.1 MPa. So, the water density varies dramatically from ~0.7 g/cm^3 to ~0.1 g/cm^3 under a normal operating condition and it needs an additional moderator in order to slow down fission neutrons for the SCWR core to have a thermal neutron spectrum. Figure 1 shows the conceptual assembly design of the SCWR fuel assembly with twenty-five cruciform solid moderators.[3] The material of a solid moderator is ZrH_2. The fuel assembly has 21×21 fuel rods array with a pitch of 1.15cm. The fuel assembly pitch is 25.15 cm including the 1 cm gap between the fuel assemblies. The pellet diameter and the outer diameter of the cladding are 0.82 cm and 0.95 cm, respectively. The clad material is a nickel-based alloy which is resistant to a high temperature.

2.2 Axial Zoning of Burnable Poison

Since a high coolant density variation along axial direction in a SCWR core induces a distortion of axial power shape toward the core bottom, the different number of gadolinia burnable poison rods is used axially in fresh fuel assemblies. According to the axial loading of burnable poison rods, two types of the fuel assembly are used for the conceptual SCWR core design. One is containing 24 gadolinia burnable poison rods in the bottom region with 12 gadolinia rods in the top region and the other is containing 28 gadolinia rods in the bottom region with 12 gadolinia rods in the top region.

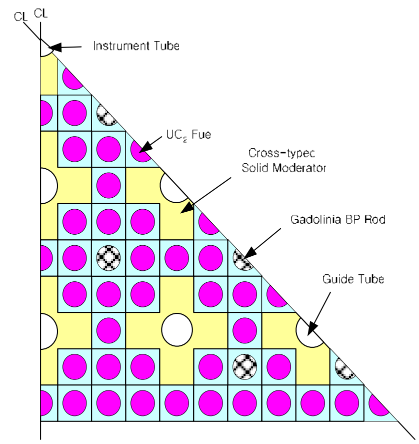

Figure 1. A conceptual SCWR fuel assembly.

2.3 Calculation Tools

The HELIOS/MASTER code system was used for the analysis of the SCWR core design concepts.[4,5] HELIOS is a two-dimensional neutron transport analysis code using the current coupling collision probability method for a neutron transport calculation. The MASTER is a three-dimensional nodal core analysis code developed by KAERI and is used for the core analysis of the conceptual SCWR core with two-group constants. The MASTER considers the thermal hydraulic feedback effect in the neutronic core calculation by implementing either a simple channel-wise T/H feedback model or a multi-channel T/H analysis like that in COBRA.

2.4 Core Design Concept

According to the design parameters suggested by technical road map for the Gen-IV, a conceptual SCWR core was constructed. The design parameters proposed by Gen-IV are the power rate of 1700 MWe, the thermal efficiency of 44% and the average discharge burnup of 45

GWd/tHM. The active core height was determined to be 3.8m like the APR1400. In order to meet the design goal of the fuel burnup, the enrichment of the UO_2 fuel of 6.5 w/o was firstly tested. The core diameter was 4.3m and 193 fuel assemblies could be contained in the SCWR core in order to reduce a linear power density by 175 w/cm. A typical fuel loading pattern for the equilibrium core with a four-batch reload scheme is assumed as shown in Figure 2.

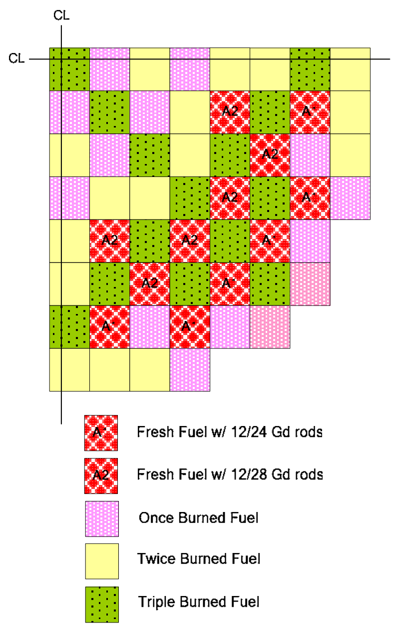

Figure 2. Fuel loading pattern with four-batch reload scheme.

2.5 Core Calculation Results

The average discharged fuel burnup is 37.2 GWd/tHM when 6.5 w% of UO_2 with gadolinia burnable poison rods are loaded. There is a need of using higher fuel enrichment than 6.5w% to meet the design goal of the fuel burnup, 45 GWd/tHM. The excess reactivity of the SCWR core is 4% $\Delta k/k$ at the beginning of the cycle(BOC) which should be minimized to less than 1% $\Delta k/k$ for the boron free operation. The peak assembly-wise relative power during the burnup occurs in the middle region of the core where the fresh fuel assembly is located and that is 1.334 at the BOC. By using the different loadings of the burnable poison rods in the two axial regions in the fresh fuel assemblies, we managed to make the maximum relative power lower than 1.46, almost the same as that of conventional PWR, at the zero burnup. The maximum coolant temperature occurs at the top of the core and it was calculated by 730 ^{o}C during a normal operation due to the assumption of a uniform flow distribution in the core analysis. It is expected that the maximum coolant temperature can be reduced by adjusting the coolant flow distribution for each fuel assembly. The maximum coolant temperature can be decreased by 635 ^{o}C when the flow rates of the each assembly are adjusted to their corresponding assembly-wise relative power ratios at the 7.64 GWd/tHM burnup point. However, in this case, the power peaking factor of the core is slightly increased by 7% due to the flow rates change. The reactivity parameters such as the coolant temperature and the fuel temperature coefficients were calculated for the SCWR core. The coolant temperature coefficient tends to be more negative with the fuel burnup, varied from -15.1 pcm/^{o}C at the BOC to -20.3 pcm/^{o}C at the end of cycle(EOC). The coolant temperature coefficient here includes the effect of the coolant density change with a temperature variation. So the coolant void coefficient of the conceptual SCWR is expected to be negative, too. The fuel temperature coefficient becomes slightly more negative with the fuel burnup, from -2.2 pcm/^{o}C at the BOC to -2.4 pcm/^{o}C at the EOC. Therefore, it is found that a negative feedback effect following a power transient accident inherently exists for the conceptual SCWR core.

3. Conclusion

The feasibility of the SCWR core was investigated by using a conceptual assembly design in viewpoints of the radial and axial relative power shapes, reactivity coefficients, and the maximum coolant temperature. The relative power shapes of the SCWR core are nearly same those of the conventional UO_2 core. However, the excess reactivity of the core is still high enough to require some challenges, including the management of the burnable poison, to control the excess reactivity without deteriorating the power distribution. It is also found that an adjustment of the coolant flow distribution is required to avoid a high coolant temperature.

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