Conceptual Nuclear Core Design of a LBE Cooled Cartridge type Small Modular Reactor

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1. Introduction

Various type of Small-sized modular reactors are being developed around the world. Development trend is shifting from light water reactor to non-light water advanced reactor and many innovative concepts are introduced especially in small power reactor, including 4S of Japan and Heat Pipe of the United States. In this study, new concept of reactor design that composes a core by placing multiple Cartridge Fuel Modules radially wide was proposed. The entire cartridge can be operated as a single reactor because the neutronic coupling of fast reactor core is generally strong in comparison with light water reactor core. Also the Module does not have to act as pressure boundary in fast reactor system operating at atmospheric pressure, it is possible to make a thin and light Fuel Cartridge Module by just combining a few fuel assemblies. In addition to designing a cartridge with small power density, if LBE filled in the inner empty space to serve as a coolant, safety margin can be increased due to its excellent cooling and natural circulation capacity. Cartridge Fuel Module enables quick refueling 2 days after reactor shutdown by replacing the Module itself loaded with spent nuclear fuel and transportation by shipping cask. However the entire size of the reactor becomes extremely large and has concern that neutron leakage is too much to be critical. In this paper, a LFR core applied Cartridge concept was designed and examined for the feasibility of the new concept.

2. Reactor Design Concept

1. Fuel Cartridge Module

A schematic drawing of the Fuel Cartridge Module is shown in Fig. 1. Approximately 900 fuel pins make up of each Fuel Cartridge Module of seven fuel subassemblies with a pitch to diameter ratio of 1.2. Similarly to the conventional fuel subassemblies, all these elements are combined by a core support grid, several spacer grids, and are assembled into a fuel cartridge of 25 cm in diameter and 3.1 m long, instead of the conventional hexagonal duct. The target power of Fuel Cartridge Module is 6.25MWe metal fueled with LBE inlet and outlet temperature of 380 and 530℃, respectively.

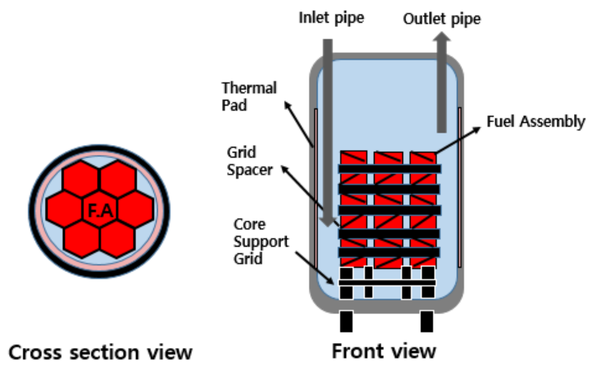

Figure 1. Fuel Cartridge Module structure

In order to design an independent coolant flow system, the coolant was allowed to enter and exit only in the upper pipe and circulate inside area of Fuel Cartridge Module. Also by simply connecting pipes with each other, Core layout can extend or reduce according to the circumstances. Cartridge height is designed to be long in the axial direction of D/H to (0.09), so that the natural convection is utilized effectively for cooling and reduce the burden of the pump. Fuel Cartridge Module is light enough to be transported by the cask without discharge LBE coolant and the Module eliminates the need to be opened during refueling. Significant improvement in proliferation resistance could be assured by Cartridge concept combined with a closed fuel cycle.

2. Reactor structure

The structure of the core layout is shown in Figure 2. Square lattice layout is selected to emphasize the flexibility and scalability of Cartridge type core. The reference core consists of 16 Fuel Cartridge modules in 4 x 4 batch. Core horizontal and vertical length are 2.4 m. The total power of the core is 100 MWe, and this concept is also possible to overcome the power demand of more than 100MWe by just connecting plants of these 16 cartridge configurations in parallel. Fuel Cartridge Modules are designed to operate 10 EFPY to compensate low economic due to low power density. The key feature of this concept is empty space exits between the Cartridges Module and the diverse shutdown system can be applied there to control the reactivity outside the Cartridge Module.

In terms of In-service inspection, as core entirely immersed in opaque liquid metal, it is difficult to validate structure integrity and this issues exits as an unresolved problem. However this concept makes it easier by filling void area between Cartridge Modules with visible air. Under this situation, inspection and monitoring of Fuel Cartridge Module become simple and easy. Because the number of Detector and Control Rod and locations can be determined by designer decision. Therefore rapid action can be taken when abnormal situations occurs. Furthermore, if Cartridge type reactor used for burn-up monitoring through gamma ray scanning, it can be used as research reactor. Due to the flexibility of connection between modules, it is possible to change the core layout according to the situation and it is easy to manipulate power level.

In addition, emergency core cooling water can be injected into an empty space while accident occurs and activates to remove residual heat.

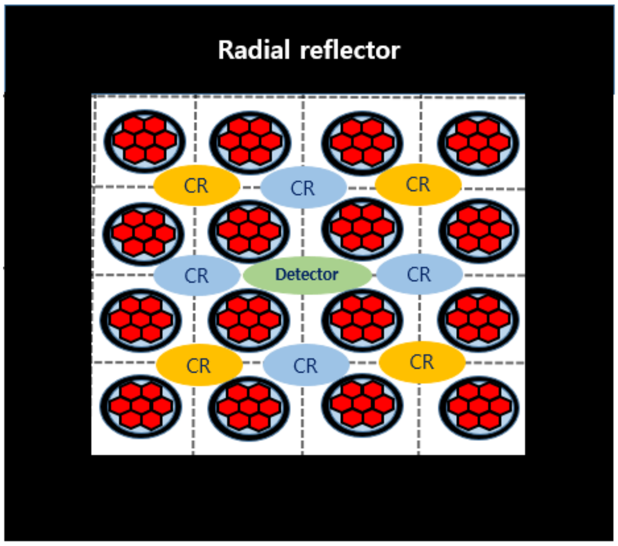

Figure 2. Reactor structure and Cartridge Module layout

3. Reactor core design

1. Reference Core Model

The unit Fuel Cartridge Module is a homogeneous design with three regions: a core height of 120 cm for inner active fuel, 90 cm for gas plenum and long upper and lower LBE reflectors. At this stage, without Control Rod design selected as reference model to evaluate whether the core could reach critical and achieve the target cycle length.

The reference core consists of 16 Fuel Cartridge modules in 4 x 4 batch. Core horizontal and vertical length are 4 m. The fuel chosen for the core consists of U-10Zr metal fuel elements. In order to reduce neutron leakage of Fuel Cartridge Module, Enrichment of Fuel assembly inside a single Cartridge was separated into two zones and enrichment combinations were iteratively determined to meet target core performance. Burnup calculations were performed using neutron diffusion theory and 24 neutron energy groups on 2-dimension R-Z models shown in Fig. 3 and 4.

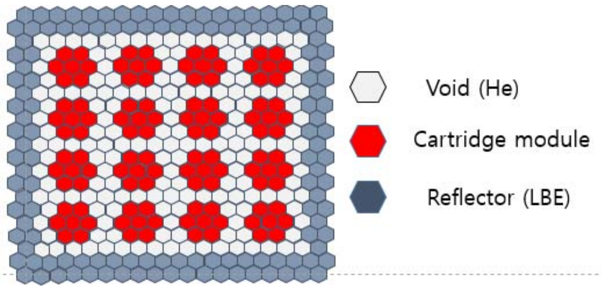

Figure 3. Radial core layout

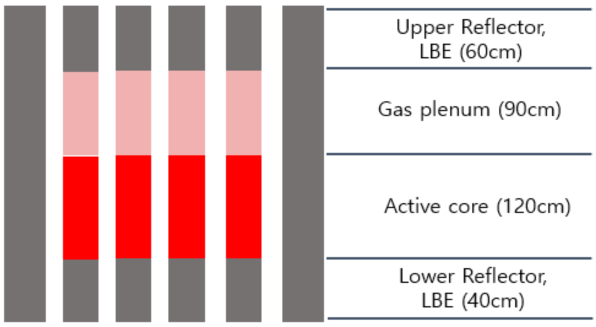

Figure 4. Axial core layout

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Fig. 5 shows k-eff letdown curve during the operation of Fuel Cartridge Module separated by enrichment of 13.5 w/o and 18 w/o from Fuel Cartridge Module using only 16 w/o enriched single assembly design. Due to its low power density, it achieved less than 800 pcm reactivity swing, despite the low conversion ratio and enrichment zoning achieved consistently high positive reactivity of 9.2 % throughout the operation period. Also average flux distribution was calculated over radial distance relative to the core center. Since power shifted from outside of the core to inside after enrichment zoning, the flux tilting was reduced and difference in discharge burnup according to location also decreased.

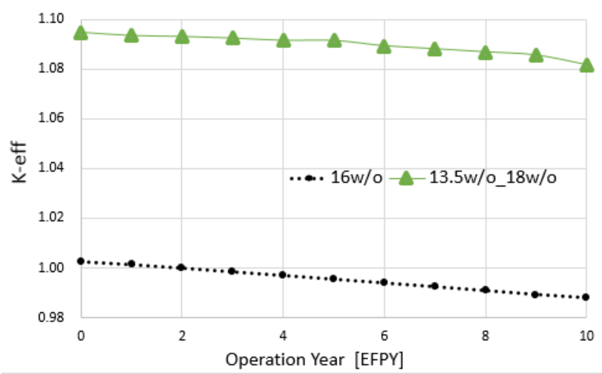

Figure 5. K-eff letdown curve

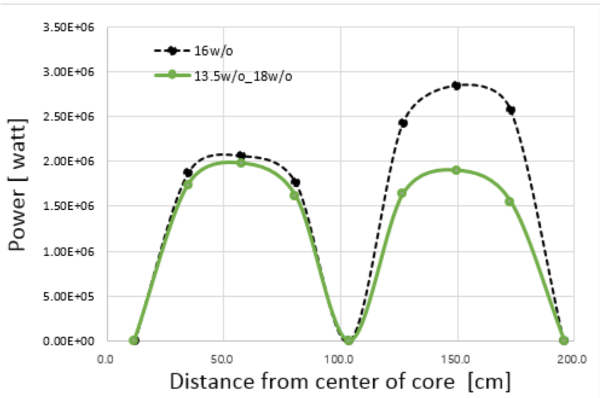

Figure 6. Radial flux distribution

4. Conclusions

A preliminary design study of the 100MWe metal fueled Cartridge type SMR with high degree of inherent safety and proliferation resistance has been performed. The high thermal conductivity of the metal nuclear fuel and the characteristics of fast reactor that has strong neutronic coupling properties made Cartridge concept feasible. Reference design satisfied within the Burnup reactivity 800 pcm while satisfying the target cycle. Through the strategy of placing multiple Fuel Cartridge Modules radially wide and enrichment zoning, the target cycle can be achieved by effectively reducing radial leakage. However the results shown in this paper is calculated based on preliminary core design before detail optimization on fuel design and Control Rod design. Therefore following job and safety analysis should be done later.

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