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A sodium-cooled ultra-long-life reactor core having improved inherent safety with new driver–blanket burning strategy

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ABSTRACT

In this paper, two sodium-cooled ultra-long-life reactor cores are designed by using new axial blanket-driver burnup strategy such that they have ultra-long-life longer than 40 EFPYs (Effective Full Power Years), high average fuel burnup of ~180 MWD/kg, small burnup reactivity swing, and improved inherent safety in terms of self-controllability under unprotected accidents. An exploration on the arrangement of driver and blanket fuels revealed that axially blanket-driver-blanket (B-D-B) configuration with different thicknesses in inner and outer core regions is effective to achieve the design goals. The final core was determined through the reduction of sodium void worth with an upper sodium plenum above the core and with partial use of dummy rods in the lower blanket of the inner core, and through the reduction of burnup reactivity swing with the adjustment of driver and blanket heights and with partial use of dummy rods in outer driver region. The neutronic analysis shows that the final core has desirable features such as long life of 53 EFPYs, high average burnup of 182 MWD/kg, small burnup reactivity swing of 773 pcm, and satisfaction of all the conditions for self-controllability under unprotected accidents.

Introduction

Recently, there have been lots of interests in the development of long-life fast spectrum reactors [1–8] which can be operated without refueling over several tens of years. The long-life cores can be achieved with blanket or without blanket. One representative concept is the CANDLE (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy production) reactor concept [3] in which the long-life with a very simple configuration of driver and blanket is achieved with small burnup reactivity swing and a constant power distribution over time. In equilibrium state of the CANDLE concept, only blanket is required to be fed into the core. In this concept, the power distribution moves axially but the power distribution does not change as time even if it can be changed in realistic situations. This concept gave motivations for several researches in this area. The other concept for long-life core is the ENHS (Encapsulated Nuclear Heat Source) reactor [4] which achieves long-life of ~20 EFPYs with low power density and without blanket. In particular, this concept achieves the long life within the irradiation limit of the

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cladding and the average discharge burnup is about 50–70 MWD/kg. Also, the power distributions of the ENHS reactor cores are almost constant due to the uniform fuel composition and the burnup reactivity swing is less than 1$, which was achieved by adjusting the lattice pitch-to-diameter ratio. The other long-life fast reactor called 4S (Super-Safe, Small and Simple) reactor [5] was developed by CRIEPI and Toshiba. This reactor uses the moving reflector to compensate the large reactivity change versus burnup due to its large neutron leakage to make coolant void worth negative rather than the control rod. As in the CANDLE reactor core, the power distribution moves upward as the burnup proceeds in the 4S reactor core. Recently, the B&B (Breed & Burn) reactors in which the core consists of multi-batch regions and the batch fuels sequentially moved into inner regions after each cycle burning have studied by UCB and TerraPower. These B&B reactors are featured by the fact that the burning region remains stationary (cylindrical standing wave) and by their high utilizations of uranium resource. Except for the 4S reactor, most of the long-life fast reactors addressed above have large sodium void reactivity worth as the fuel burnup increases, which can degrade the inherent safety through the large positive reactivity coefficient by the coolant expansion even if they have negative or very small positive sodium void reactivity (SVR) worth at BOL (Beginning of Life). This large positive SVR is due to the small neutron leakage through the core, which is required to achieve long-life.

In this paper, we introduced new sodium-cooled ultra-long-life cores having new driver and blanket burning strategy. The cores are designed to have life longer than 40 EFPYs (Effective Full Power Years) and to keep the acceptable power distribution within the peak linear power of typical sodium cooled reactors over the whole life in order to reflect the realistic design of sodium-cooled fast reactor. The other important design target is to satisfy all the conditions for self-controllability under the typical unprotected accidents called ATWS (Anticipated Transient Without Scram) and to have small burnup reactivity swing over life less than ~1000 pcm so as to minimize the control rod movements. The self-controllability under ATWS is checked through the quasi-static reactivity balance analysis [9,10] proposed by Wade and Chang using the estimated reactivity coefficients. The conditions developed by Wade and Chang [9] are the sufficient conditions to promote the inherent safety and they are referred as the criterions for ensuring passive self-control [10]. In this work, they were used as the core design constraint. To satisfy these design targets, we explored the several different configurations of driver and blanket. As the result of the exploration, an axial configuration of blanket-driver-blanket (B-D-B) where shorter driver fuels are placed in the inner core region than in the outer core region was found to make it possible to satisfy all the design targets. Also, the sodium void reactivity (SVR) worth which is one of the problematic parameters in long-life cores is reduced by using upper sodium plenum and the new fuel assembly concepts using dummy rods in particular regions.

This paper is organized as follows: Chapter 2 provides computational procedure including codes and Chapter 3 describes the core design procedure, the core designs, and the results of the core performance analyses. The summary and conclusions are given in Chapter 4.

Computational procedure and codes

The depletion calculations were performed with REBUS-3 [11] non-equilibrium model where DIF3D [12] nodal diffusion method with HEX-Z geometry is used to obtain neutron flux by solving the multi-group diffusion equations. The 25 group cross sections were used in the DIF3D nodal calculations coupled with the REBUS-3 depletion calculations. These 25 group cross sections for each region were generated by collapsing the 150 group cross sections with the TRANSX [13] code and the region-wise neutron spectra. The region-wise neutron spectra were calculated by using DIF3D code with R-Z geometry and finite difference method option, and 150 group cross sections. The 150 group cross sections were generated by using the TRANSX code and a 150 group cross section library which was prepared using NJOY based on ENDF/B-VII.r0. The decay chains for the actinides spans the range from ^{232}Th to ^{246}Cm while the fission products were treated by using the lumping method. The fission products for each actinide are classified into two groups (i.e., normal fission product nuclides and rare earth nuclides) and the lumped cross sections for each group of each actinide are generated by weighted-averaging the microscopic cross sections of fission products with their yield values. The governing equations for depletion analysis consist of the multi-group diffusion equation for neutron flux and power, and the Bateman equation for transmutations of the nuclides. The multi-group neutron diffusion equation which is solved by using nodal method [12] in REBUS-3 [11] is given by

$$-D_g\nabla\cdot\nabla\phi_g(\vec{r})+\Sigma_{tg}(\vec{r})\phi_g(\vec{r})=\sum_{g'=1}^{G}\Sigma_{sg'\to g}(\vec{r})\phi_{g'}(\vec{r})+\frac{1}{k_{eff}}\chi_g\sum_{g'=1}^{G}\nu\Sigma_{fg'}(\vec{r})\phi_{g'}(\vec{r}), \quad (1)$$

where D_g, Σ_{tg}, Σ_{fg}, and χ_g represent diffusion coefficient, macroscopic total cross section, macroscopic fission cross section, and fission spectrum for the neutron energy group g, respectively. In Eq. (1), $\Sigma_{sg'\to g}$ means the macroscopic scattering cross section from energy group g' to energy group g and ϕ_g is the neutron scalar flux for energy group g. In Eq. (1), we used the conventional standard notations. The cross sections and the diffusion coefficients are contained in the multi-group cross section libraries of ISOTXS format [13]. In this work, we did not considered the dependency of the multi-group cross section on the burnup because this simplification is typically used in the conceptual design of fast reactors. The solution of Eq. (1) gives not only the multi-group flux distribution over the core but also the power distributions. Then, the changes of the isotopic compositions for each burnup region are obtained by the following Bateman equation in REBUS-3:

$$\frac{\partial\vec{n}(\vec{r},t)}{\partial t}=\mathbf{A}(\phi,\sigma(r),\lambda)\vec{n}(\vec{r},t), \quad (2)$$

where the vector $\vec{n}(\vec{r},t)$ represents the collection of the nuclides' atomic number densities for a position $\vec{r}$ and at time t. The elements of the transmutation matrix **A** describing the transmutations and decays of nuclides is given by