No. Registrasi: 0702010113010475

Material Researches and Energy Engineering

Edited by
Yijin Wu

TRANS TECH PUBLICATIONS

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Advanced Materials Research Vol. 772 (2013) pp 501-506
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doi:10.4028/www.scientific.net/AMR.772.501

Application of Modified CANDLE Burnup to Very Small Long Life Gas-cooled Fast Reactor

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Keywords: Modified CANDLE, Gas-cooled Fast Reactor, Metallic Fuel, Natural Uranium, Long life fast reactor

Abstract. Gas-cooled Fast Reactor is a good candidate for fourth generation nuclear power plant that projected to be used started in 2030. In this study, modified CANDLE burn-up strategy is adopted to create 300 MWt long life Gas-cooled Fast Reactor with metallic fuel U-10wt%Zr without enrichment. This design demonstrated excellent performance with the average discharge burn-up is about 25.9% HM.

Introduction

Gas-cooled Fast Reactor (GFR) is a high-temperature, helium-cooled fast reactor with a closed fuel cycle. GFR is a good candidate for fourth generation nuclear power plant that projected to be used started in 2030 [1,2]. It combines the reliability of fast spectrum systems and high temperature systems. The fast spectrum were able to use more sustainable sources of uranium and minimizing waste through burning of actinides and fuel recycling. High temperature produces high-thermal cycle efficiency and heat generated is used for industry (to produce hydrogen).

CANDLE (stands for Constant Axial shape of Neutron flux, nuclide densities, and power shape During Life of Energy production) burnup strategy since published in 2000/2001 [3], has been extensively studied by many researchers in Japan and other countries [4-11].

In this research a feasibility design study of very small 300 MWt GFR which can utilize natural uranium as fuel cycle input has been investigated. Modified CANDLE burn-up scheme is adopted to obtain the capability of consuming natural uranium as fuel cycle input [6,7,9,12-14].

Core Model and Calculation Method

This design adopted modified CANDLE burn-up scheme for adjustment fuel in the reactor core. In this design the reactor core is divided into 10 regions with the same volume in the axial direction (see Fig.2). Each region is filled with fuel with different content. In the first cycle of burn-up region-1 which contains fresh fuel (natural uranium) is placed near the region-10 which contains the active fuel. After the first cycle of burn-up (10 years of burn-up) it means enter the second cycle of burn-up: fuel from the region-1 is shifted to the region-2, fuel from region-2 shifted to region-3, fuel from the region-3 is shifted to the region-4, fuel from region-4 is shifted to the region-5, fuel from region-5 is shifted to the region-6, fuel from region-6 is to shifted region-7, fuel from region-7 is shifted to the region-8, fuel from region-8 is shifted to region-9, fuel from region-9 is shifted to region-10, and fuel from the region-10 removed from the reactor core, then region-1 is replenished with fresh fuel.

The calculation is done using the SRAC code system; PIJ and CITATION module [15] with the principal parameters in Table 1 and description sample cases shown in Table 2. PIJ-SRAC module is used for the calculation of burn-up of fuel cell. At the beginning of the calculation, the data for the power density level is the result of assumptions and then done calculations using this data. The result are eight energy group macroscopic cross section data to be used in two dimensional R-Z geometry multi groups diffusion calculation in CITATION-SRAC module. The average power density in each region resulted from the diffusion calculation is then brought back to PIJ-SRAC module for cell burn-up calculation. The iteration is repeated until a convergence condition.

Table 1. Sample design parameter

Parameter	Value/Description
Power (MWt)	300
Number of equal volume region	10
Fuel Material	U-10wt%Zr
Cladding Material	Stainless Steel
Coolant Material	Helium
Fuel Volume fraction	60%
Cladding Volume fraction	10%
Coolant Volume fraction	30%
Active core diameter	220 cm
Active core height	280 cm
Reflector radial width	50 cm
Reflector axial width	50 cm
Pin pitch	1.4 cm
Sub cycle length	10 years
Reactor life	100 years

Table 2. Sample description

Sample case	Description
Case A	Parameter described in Table 1
Case B	Similar to the Case A but power thermal is 275
Case C	Similar to the Case A but power thermal is 250

Results and Discussion

In this study we perform the calculation for the reactor core with a sample design parameters as shown in Table 1 and 2. The parameters survey results of the calculation are the values of effective multiplication factor, infinite multiplication factor, relative power density, burn-up level, intergral conversion ratio, and atomic density discussed in this section.

Fig.3 shows the effective multiplication factor (k-eff) change during burn-up for one cycle of operation over the past 10 years from the reactor core that is designed. The value of k-eff that obtained at the beginning of the cycle is approximately 1.013(critical condition) after that monotonically increases until the end of the cycle(k-eff = 1.042).

Fig.4 shows relative power density axial distribution and its change during 10 years of burn-up in the beginning of cycle(BOC) till the end of cycle(EOC). Mesh number 1 through 30 are active core while the mesh 31 to 40 is the axial reflector. Mesh number 1-3 associated with region 1, mesh number 4-6 associated with the regions 10, mesh number 7-9 associated with the region 9, and so on. Fig.4 is shown peaking factor in EOC decreased compared to BOC, which means that the power distribution becomes more flat.

Fig.5 shows the change of burn-up level during 100 years fuel history in the core. This figure shows the burn-up level at the beginning of life increased slowly until the midle of life, but after that the burn-up level increases rapidly until the end of life. The burn-up level at the end of life is about 259166 MWd/ton HM or about 25.92% HM.

Fig.6 shows the infinite multiplication factor, and the integral conversion ratio change during burn-up history. Sharp increase of the infinite multiplication factor (k-inf) value occurs at beginning of life due to the region 1(fresh fuel) located near the region 10(see Fig.2) which contains a lot of fissile material. The k-inf value continue to increase until it reaches a maximum value of 1.287 at 74th year burn-up history. After that k-inf value decreases slowly until the end of life due to the accumulation of fission product and significantly reduced the amount of U-238.

The conversion rasio value drop about 63% at the beginning of life (the first 10 years) due to the accumulation of plutonium so that the ratio of fertile material to fissile material is significantly reduced. The conversion rasio value decreases slowly after the midle of life until the end of life also due to reduction of fertile material inventory.

Fig.7 shows the Pu-239 and the U-238 atomic density change during burn-up history. The Pu-239 increased significantly at the beginning of reactor operation (10th burn-up history) due to fresh fuel that fills the region-1 is located near the region-10 which contains the active fuel. This correlated with a reduction of U-238 that produced Pu-239 during burn-up. The accumulation of plutonium continues until it reaches the maximum value at the 74th burn-up history and after that decreases.

Figs.8-12 show the results for cases A, B and C. It is shown in Fig.8 that k-eff change during burn-up for the case A is higher than in the cases B and C, apparent also that in the case C not achieved critical condition. Figs.9 and 10 show the k-inf and the PU-239 atomic density changes during burn-up for the cases A, B and C. It is shown that the most important differences among them appear from about 30th – 70th year of burn-up history. The values of k-inf and the Pu-239 atomic density grows faster than cases B and C. However the case A, after the 80th year of burn-up history its values decreases faster than the other cases. Fig.11 shows the U-238 atomic density change during burn-up history for case A, B and C. It is shown that decreases of the U-238 atomic density occurs faster on the case of A than B and C. Fig.12 shows the burn-up level change of fuel during its burn-up history for cases A, B and C. It is shown that burn-up levels are higher for case A than the others. These are consistent with the different power level among the cases A, B and C.

Conclusion

The conceptual design study of 300 MWt long life GFR with natural U-10%wtZr as fuel cycle input has been performed. The reactor discharge burn-up is about 25.9% HM for case A. The present investigation showed that the design of these reactors can operate for 10 years without refueling and fuel shuffling and just need natural uranium as fuel cycle input.

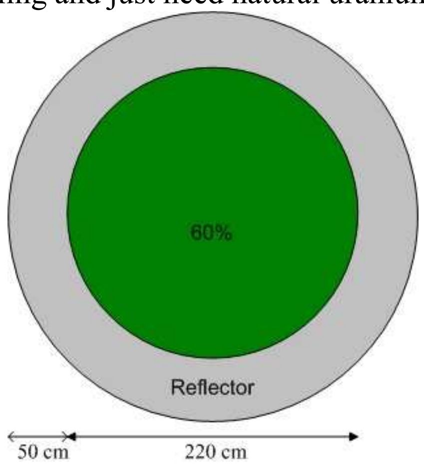

Fig.1 Cross section view of core

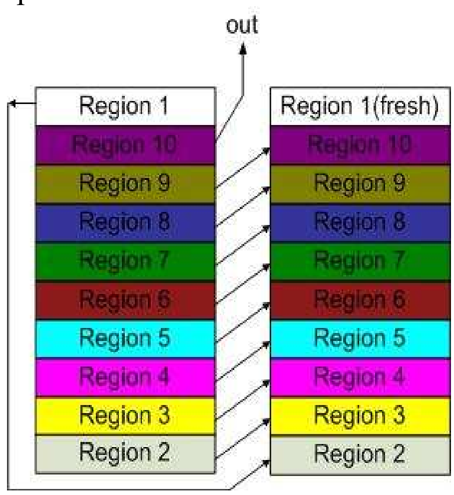

Fig.2 Region division and shuffling using Modified CANDLE burn-up scheme

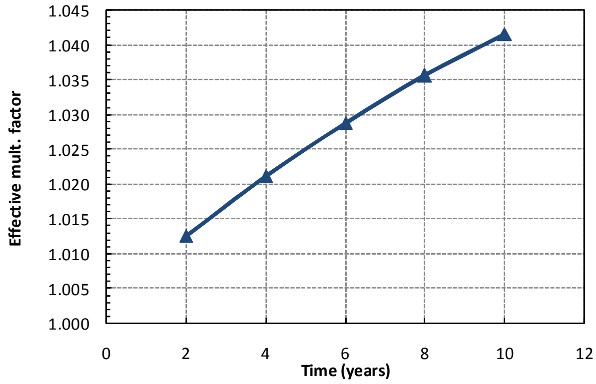

Fig.3 Effective multiplication factor change during burn-up.

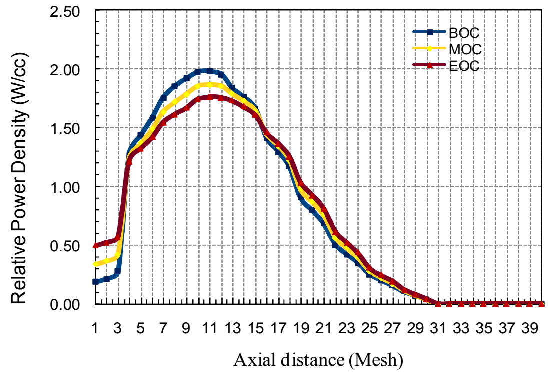

Fig.4 Relative power density axial distribution and its change during 10 years of burn-up.

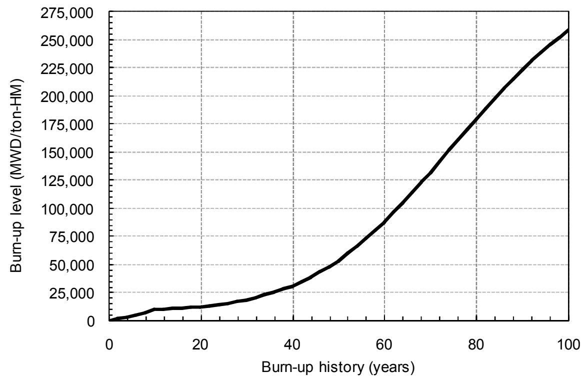

Fig.5 Burn-up level change during burn-up history

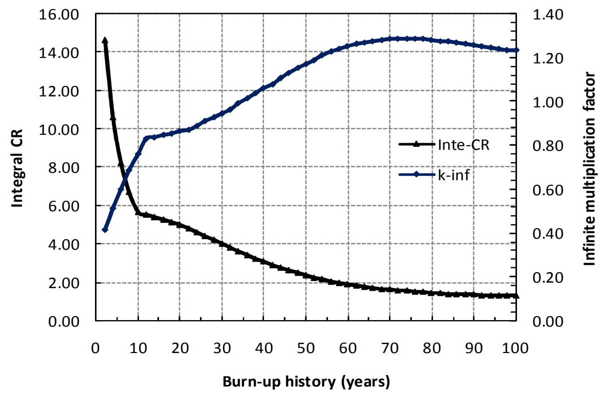

Fig.6 Integral conversion ratio (left), and k-inf change during burn-up history(right)

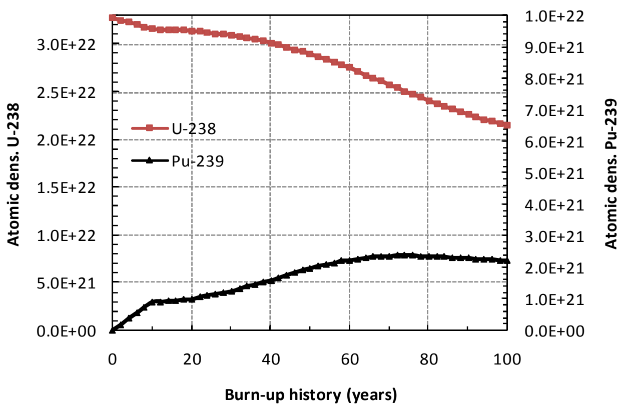

Fig.7 Pu-239 and U-238 atomic density change during burn-up history

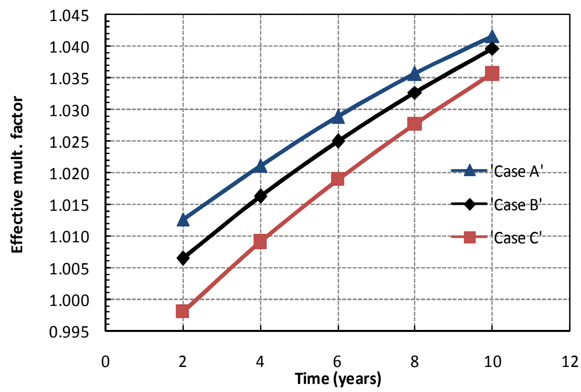

Fig.8 Effective multiplication factor change during burn-up for case A, B, and C

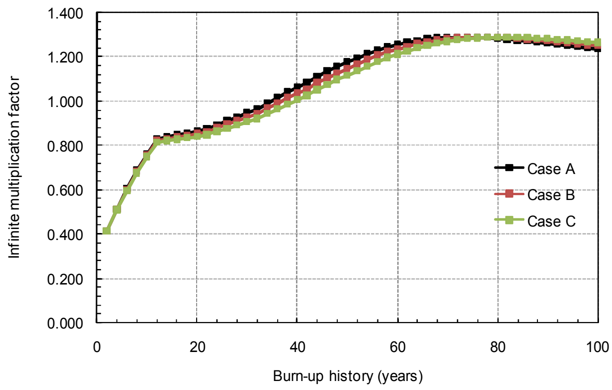

Fig.9 Infinite multiplication factor change during burn-up for case A, B, and C

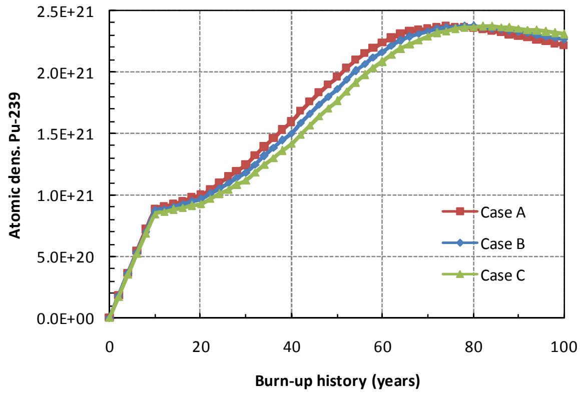

Fig.10 Pu-239 atomic density change during burn-up history for case A, B, and C

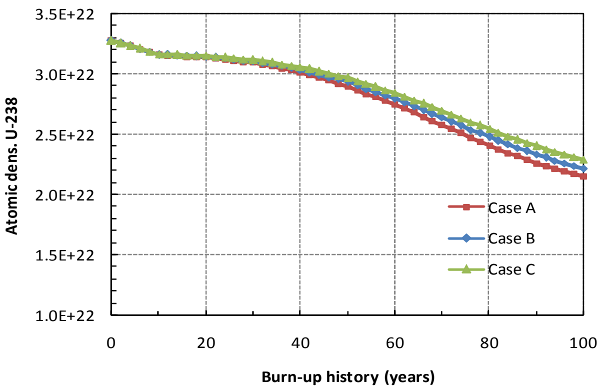

Fig.11 U-238 atomic density change during burn-up history for case A, B, and C

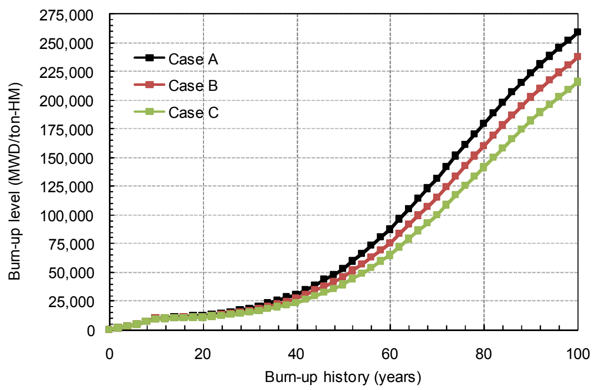

Fig.12 Burn-up level change of fuel during its burn-up history for case A, B, and C

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