Molten Salt Breeder Reactor Analysis Methods

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1. Introduction

The Molten Salt Reactor (MSR) is a long-standing concept that was developed at Oak Ridge National Laboratory (ORNL). A major objective of MSR is to achieve a power reactor that produces electric energy at low cost, and at the same time extend the nation's low-cost fuel resources. A graphite-moderated thermal breeder reactor, utilizing the uranium-thorium fuel cycle shows considerable potential for the possibility of MSR. The concept of MSBR should be revised because of molten salt reactor's advantage such as outstanding neutron economy, possibility of continuous online reprocessing and refueling, a high level of inherent safety, and economic benefit by keeping off the fuel fabrication process.

For the development of MSR research, this paper provides the MSBR single-cell, two-cell and whole core model for computer code input, and several calculation results including depletion calculation of each models. The calculations are carried out by using MCNP6, a Monte Carlo computer code, which has CINDER90 for depletion calculation using ENDF-VII nuclear data.

MCNP6 is a contemporary code that is good for fixed solid fuel core system. However, MSR analysis needs more functions, such as online reprocessing, online refueling, and circulating fuel. This paper follows Power's method [3] suggested in 2013 for simulating the MSBR with SCALE and applies to MSBR by using MCNP6. However the other characteristic, circulating molten salt fuel, which causes delayed neutron precursor drift is not considered here.

2. Models and Method

The MSBR reactor core consists of two zones with one flow. It means the same composition of molten-salt fuel is divided into two zones in the reactor core, and the graphite to fuel ratio is different in each zone. Initial fuel loading composition is roughly the same as MSBR, 71.8 LiF – 16 BeF_2 – 12 ThF_4 – 0.2 UF_4. The boundary condition of this unit cell is reflective. The density of the molten-salt is 3.28g/cm^3 and that of graphite is 1.84g/cm^3 at 900K. The temperature of fuel and graphite is fixed at 900K.

2.1 Single-Cell Model

In the single-cell method, the two zone design is replaced by a single unit cell while maintaining the ratio between the volume of molten-salt fuel and graphite. The size of the square shaped graphite cell of Zone I and Zone II are the same. The molten-salt fuel channel radius is determined by the volume fraction of molten-salt fuel in the unit cell (20.6%) that represents the average volume fraction of molten-salt fuel in Zone I (13%) and Zone II (37%).

The MSBR is operated by removing fission products and actinides, and adding fertile material (^{232}Th) continuously. If the depletion time intervals are very short owing to the material being instantly removed, it is hard to obtain equilibrium composition because of too many depletion time steps. If the depletion time intervals are too long, it is hard to say the result represents online reprocessing and refueling well. For that reason, the unit time interval is set to 3 days that corresponds with the removal time of ^{233}Pa which is the key isotope for breeding. ^{232}Th is added to maintain the initial amount of ^{232}Th.

2.2 Two-Cell Model

In this two-cell method, the two zone design is modeled by two unit cells. The size of the square shaped graphite cell of Zone I and Zone II are the same. The fuel channel radius is determined by the volume fraction of molten-salt fuel in each zone; 13% for Zone I and 37% for Zone II. This two-cell method differentiates the characteristics of both zones; most of the fission reaction occurs in Zone I and most of breeding occurs in Zone II.

After every 3 days depletion time interval, the number density is homogenized considering the total fuel volume of each zone in the whole MSBR core. In depletion calculation, computer code needs thermal power for each unit cell. The thermal power for each unit cell is decided by considering total volume of each zone and fission power ratio between Zone I and Zone II. The fission power ratio between Zone I and Zone II is given in the MSBR design report. Except for those mixing operation and power decision, the batch-wise reprocessing and refueling strategy is applied identically to the single-cell method.

2.3 Whole Core Model

The 680cm-diameter by 610cm-high reactor vessel contains molten salt for liquid fuel and coolant, and graphite material for neutron moderation and reflection. The first zone, Zone-1 is composed of 1320-graphite element and control rods. The second zone, Zone-2 is consist of 116-graphite elements called Zone-2A, and radially spread graphite plates called Zone-2B. At the center of the reactor core, there are 4 holes for control rods. Two holes are for safety rods primarily for adequate negative reactivity for emergency situation. And two holes are graphite control rods for fine reactivity control. The withdrawal of graphite control rod will insert negative reactivity to the core due to the decrease of neutron moderation. Figure 1 shows the configurations of the whole core at expected reactor operation. The green color means graphite and the blue one means fuel salt. The yellow color means Hastelloy-N material used at plenum and vessel wall, and the red color means void space. All figures in this paper are made by MCNPX visual editor.

Because the fuel salt used in the MSBR is assigned one material regardless of zone, the reprocessing method for MSBR whole core model is same with single-cell model.

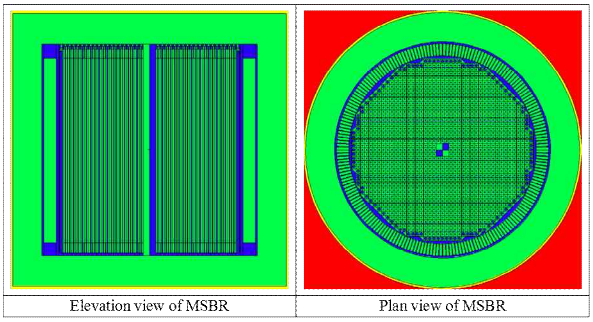

Fig.1. MSBR core configuration

3. Equilibrium Core Analysis

The MSBR core analysis was performed at the initial and equilibrium core conditions, for various reactor design parameters such as multiplication factors, neutron flux distributions, temperature coefficients, rod worths, and power distributions.

3.1 Single-Cell Model

This method just adopts a single representative unit cell for the whole MSBR core so it does not distinguish the characteristics of Zone I and Zone II. In the process of calculating equilibrium composition, the code system gives parameters that represent the MSBR physics. The multiplication factor during the depletion calculation is calculated three times per a depletion interval in MCNP6. Figure 2 represents the infinite multiplication factor during depletion calculation. The infinite multiplication factor of MCNP6 fluctuates because of a high standard deviation (around 200pcm).

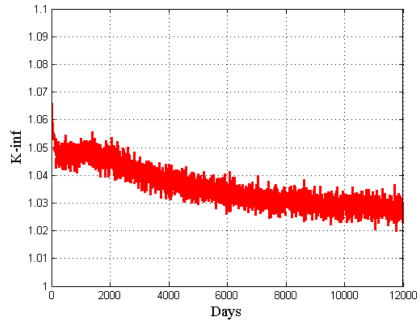

Fig. 2. Multiplication factor of single-cell method during equilibrium core search

The single-cell method only adopts a single flux spectrum to represent the whole MSBR core as shown in Figure 3. The normalized neutron flux spectrum for equilibrium state is harder than initial state because of heavy fission products.

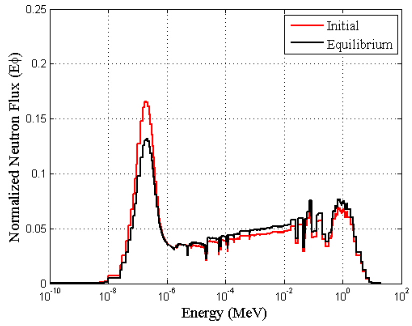

Fig. 3. Normalized neutron spectrum of single-cell method for initial and equilibrium core

3.2 Two-Cell Model

This method adopts two representative unit cells to distinguish the characteristics of Zone I and Zone II. The depletion calculation is repeated with the given reprocessing method until the infinite multiplication factor approaches the equilibrium state. The multiplication factors for both zones are plotted in Figure 5. Standard deviation is about 200pcm.

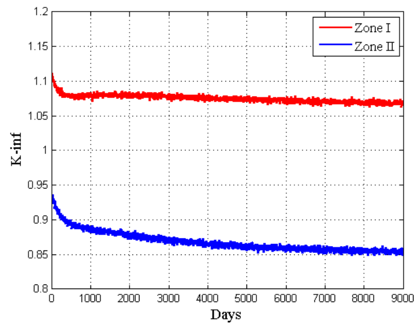

Fig. 4. Multiplication factor of two-cell method during equilibrium core search

In Figure 5, there are normalized neutron flux spectrum for the initial and equilibrium states of Zone I and Zone II. The neutron spectrum for the equilibrium state is harder than the initial state because of heavy fission products. The big difference in the neutron flux spectrum between Zone I and Zone II implies that the single-cell method has less fidelity to the whole MSBR core.

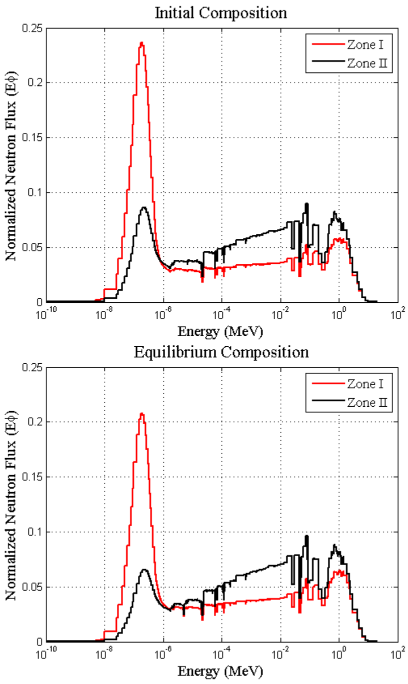

Fig. 5. Normalized neutron spectrum of two-cell method for initial and equilibrium core

3.3 Whole Core Model

Figure 6 shows the effective multiplication factors for MSBR whole core model. The effective multi-plication factors increase sharply from the initial state, and then gradually decrease to the equilibrium state. This calculation result gives the information about the equilibrium state of the whole core, and the material compositions that can be used for real MSBR core.

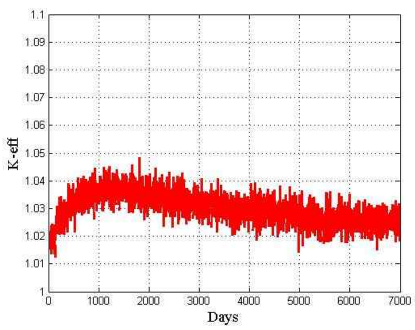

Fig. 6. Multiplication factor of whole core model during equilibrium core search

Figure 7 shows the normalized flux distribution of the initial and the equilibrium states in each zones. The above full core calculation results show that the neutron energy spectrum becomes harder at equilibrium state. It can be noted that the flux in Zone-2 located in outside of core decreases the neutron leakage from the core and captures more neutrons, which results in higher breeding in Zone 2 than Zone-1.

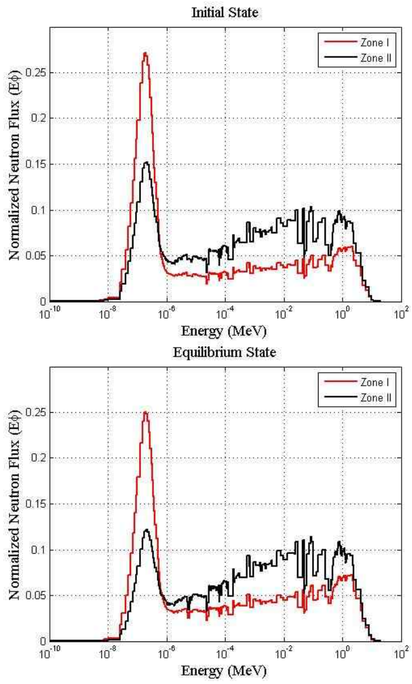

Fig. 7. Normalized neutron spectrum of whole core model for initial and equilibrium core

When fuel temperature increases, the density of fuel salt decreases and the total volume of fuel salt stays same because it is obtained by the volume of graphite. When graphite temperature increases, the density of graphite decrease and the volume of graphite expands which makes also the volume of fuel salt larger. At the initial state, both FTC and MTC values are negative. But at the equilibrium state, MTC becomes positive due to the spectrum hardening along the fuel depletion. The various temperature coefficients are shown in the Table I

Table I: Temperature Coeffiicients

Temperature coefficient	Initial state	Equilibrium state
FTC (pcm/K)	-3.20	-2.59
MTC (pcm/K)	-0.11	1.15
ITC (pcm/K)	-3.21	-1.41

Table II summarizes the rod worth calculation results. The percent values in the table represents rod insertion depth. The rod worths at several insertion depths are calculated. It is noted that the reference case, case 01, is slightly supercritical which requires additional search for design parameters, e.g., the amount of ^{232}Th feed in order to make the core critical. With the condition of ORNL MSBR design [2], the graphite rods alone cannot make the core state subcritical at the initial condition. But at the equilibrium condition, the reactivity can be made closer to the critical state by graphite rods only. It can be seen easily that the reference case reactivity is closer to the critical state with equilibrium compositions.

Table II: Rod Worths

Case number	Graphite rod insertion	Poison rod insertion	Initial state	Equilibrium state
1 *)	100%	0%	-	-
2	50%	0%	-306	-299
3	0%	0%	-530	-543
4	0%	50%	-1319	-1264
5	0%	100%	-2099	-1970

*) Ref, k_{eff} = 1.01277 (Initial), k_{eff}=1.00406 (Equilibrium)

4. Conclusions

The depletion calculation of the various MSBR core model for finding the equilibrium states is carried out by using MCNP6-PYTHON computer code system to model the online reprocessing and refueling, and the MSBR whole core analysis has been performed with the searched equilibrium material composition. During depletion calculation, the fission products are removed and fertile/fissile materials are added to fuel salt between every 3-days cycle. In this way, the important MSR characteristics, online reprocessing & refueling is implemented in the computer code system. From the depletion calculation, the multiplication factor slowly reaches to the equilibrium core. From the material data of the initial and equilibrium states, the reactor design parameters have been calculated for whole core model.

The breeding ratio of the two-cell method is closer to the MSBR design parameter, but that of the single-cell method is inaccurate and even smaller than 1. The big differences in the results of the single-cell and two-cell methods originate from the diversity of the neutron flux spectra in the two zones. The single-cell method only uses a single neutron flux spectrum but the two-cell method adopts separate neutron flux spectra for the two zones. The two unit cells make it possible to simulate the whole MSBR core accurately because the neutron flux spectrum represents characteristics of each zone. From the calculation results of various reactor design parameters, the temperature coefficients are all negative at the initial state and MTC becomes positive at the equilibrium state. From the results of core rod worth, the graphite control rod alone cannot makes the core subcritical at initial state. But the equilibrium state, the core can be made subcritical state only by graphite control rods.

Through the comparison of the results of each models, the two-cell method can represent the MSBR core model more accurately with a little more computational resources than the single-cell method. Many of the thermal spectrum MSR have adopted a multi-region single-fluid strategy. The two-cell method that is proposed in this paper can be applied to other MSR cores in order to model equilibrium core with online reprocessing and refueling.

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