Preliminary Study for Inventories of Minor Actinides in Thorium Molten Salt Reactor

Choong Wie Lee* and Hee Reyoung Kim
Ulsan National Institute of Science and Technology, Ulsan 689-798, Republic of Korea
**Corresponding author: dhkgjwjq@unist.ac.kr*

1. Introduction

MSR (Molten Salt Reactor) is one of GEN-IV reactor types, of which the coolant and the fuel are mixtures of molten salt. Thus, it has different characteristic with the conventional reactors which use a solid fuel. It can continually supply the fuel by online refueling and reprocessing of minor actinides so that those can be separated and eliminated from the reactor. The MSR maintains steady state except initial stage and the reactor becomes stable. In this research, considering online refueling, bubbling and reprocessing, the basic concept for evaluation of the inventory of minor actinide in the molten salt reactor is driven using the Bateman equation. The simulation results, where REM and MCNP code from CNRS (Centre National de la Recherche Scientifique) applied to the concept equation are analyzed.

2. Numerical calculation concept

Bateman equation and concept equation for MSR are introduced to derive the basic concept on inventories of minor actinide.

2.1 Bateman equation

To evaluate minor actinide inventories of PWR, the Bateman equation is commonly used. The Bateman equation is a mathematical model for describing the number of isotope at decay chain reaction, therefore, it is used to describe quantitative change of nuclei in the fuel. It is generally expressed like equation (1).

$$\frac{\vartheta N_i}{\vartheta t} = \sum_{j\neq i}\left(\lambda_{j\to i}N_j + <\sigma_{j\to i}\phi> N_j\right) - \lambda_i N_i - <\sigma_i\phi> N_i \qquad (1)$$

where N_i is number of nuclei of the isotope i, $\lambda_{j\to i}$ is production rate of decay of the nucleus j (s^{-1}), $\sigma_{j\to i}$ is cross section of the production of the nucleus i from neutron capture at the nucleus j (cm^2), ϕ is Neutron flux ($cm^{-2} * s^{-1}$), λ_i is decay constant of the isotope i (s^{-1}), and σ_i is microscopic absorption cross section (barn).

The Batman equation which is represented in equation (1) has to be modified for evaluation of the minor actinide inventories considering the fluid effect by online refueling, the bubbling and the reprocessing in the MSR unlike PWR which has the fuel of the solid state of fuels.

2.2 Concept equation for MSR

In the MSR, it is continually refueled during operation, that is, the MSR is refueled online. Therefore, an isotope i in the reactor will be supplied as the rate of A_i. While refueled, the wastes such as minor actinides and fission products produced after fission reaction are removed from the inside of the MSR. Chemical reprocessing is used to extract minor actinides from salts and transfer those to the reprocessing unit. By this reprocessing, the wastes in the reactor are extracted regularly without reactor shutdown. It increases the operation stability of the reactor and decreases the generation of the radioactive waste. Supposing that the probability to chemically extract a nuclide from the reactor is λ_i^{chem}, then, total rate which is chemically extracted is $\lambda_i^{chem} N_i$.

Volatile fission products and some insoluble isotopes can't be extracted by chemical extraction, so a bubbling unit is used to extract these materials. Bubbling is an online gaseous extraction technique to remove gaseous fission products, Xe, Kr and some insoluble isotopes by using bubbles. To extract these, mixture of helium, krypton and xenon gases are injected, and bubbles are built up in the core. Volatile fission products and some insoluble isotopes are trapped in these gas bubbles, and these bubbles are quickly extracted from the core at the bubble-salt separator and transfer to the tank. Like chemical extraction, isotopes are continually extracted from the reactor by bubbling from the reactor. Thus, supposing the probability to extract by bubbling a nuclide, i, from the reactor is $\lambda_i^{Bubbling}$, then total bubbling extract rate is $\lambda_i^{Bubbling} N_i$.

Substituting three terms of online refueling, chemical reprocessing and bubbling which are to be considered to the Bateman equation, the basic concept equation for evaluating minor actinide inventories in the reactor are derived as seen in equation (2).

$$\frac{\vartheta N_i}{\vartheta t} = \sum_{j\neq i}\left(\lambda_{j\to i}N_j + <\sigma_{j\to i}\phi> N_j\right) - \lambda_i N_i - <\sigma_i\phi> N_i - \lambda_i^{chem} N_i - \lambda_i^{Bubbling} N_i + A_i \qquad (2)$$

In equation (2), the refueling term is added and both extraction terms of the reprocessing and bubbling are subtracted at the right side. In reprocessing unit, there is no neutron flux, therefore, the radioactive decay by neutron captures does not occur. The number of nuclei increases by transferred nuclei from the reactor to reprocessing unit, and nuclei are chemically eliminated in the reprocessing unit. Thus, the concept equation in the reprocessing unit is changed as represented in equation (3).

$$\frac{\vartheta N_i}{\vartheta t} = \sum_{j\neq i} \lambda_{j\to i} N_j - \lambda_i N_i - \lambda_i^{chem,P} N_i + \sum_{p\neq P} \lambda_i^{chem,p\to P} N_i + \sum_{p\neq P} \lambda_i^{Bubbling,p\to P} N_i \qquad (3)$$

The equation (3) shows the transformation of nuclei at the reprocessing unit P. $\lambda_i^{chem,P}$ is chemically eliminated rate of the nucleus i from the location P. $\lambda_i^{chem,p\to P}$ and $\lambda_i^{Bubbling,p\to P}$ represent the transfer rate of a nuclide i, from the location p to the reprocessing unit P by chemical reprocessing and bubbling. Therefore, $\frac{\vartheta N_i}{\vartheta t}$, the rate of the nuclide, i, is reduced by $\lambda_i^{chem,P} N_i$, and increased by $\lambda_i^{chem,p\to P} N_i$ and $\lambda_i^{Bubbling,p\to P} N_i$.

3. Analysis of the Simulation at CNRS

Centre national de la recherche scientifique (CNRS) is governmental research organization in France. Minor actinides inventories was evaluated for the conceptually designed MSR from the simulation by MCNP code and REM code they developed.

3.1 Reactor core Design

The conceptual design of the MSR by CNRS was represented in Figure 1. The core is a single cylinder whose internal diameter is approximately equal to its height. Table 1 shows some properties of this conceptual reactor.

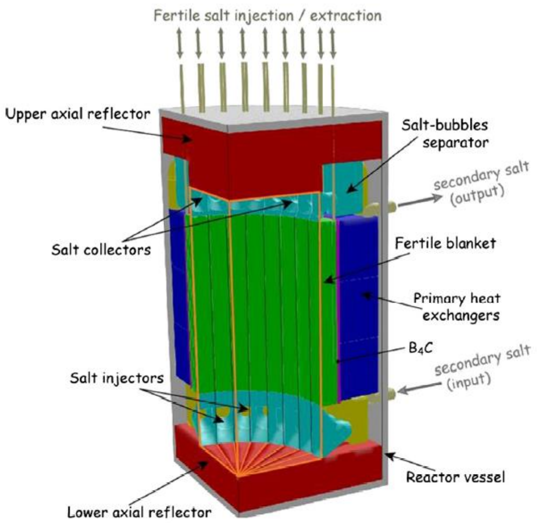

Fig 1. Schematic view of a quarter of the MSR

Table 1. MSR design for simulation at CNRS

Thermal power (MWth)	2500
Thermal efficiency (%)	40
Fuel molten salt composition (mol%)	LiF-ThF4-UF4 (77.5-20-2.5)
Fertile Blanket Molten salt composition (mol%)	LiF-ThF4 (72-28)
Melting point (℃)	550
Operating temperature (℃)	630
Initial Th inventory (kg)	46100
Initial ^{233}U inventory (kg)	5700
Density (g/cm3)	4.3
Dilatation coefficient (/℃)	10^{-3}
Core dimensions (m)	Radius: 1.25 Height: 2.60
Fuel Salt Volume (m^3)	20.5 6.5 out of the core 14 in the core
Blanket Salt Volume (m^3)	9
Thorium consumption (ton/year)	1
^{233}U Production (kg/year)	120
Breeding ratio	1.12

3.2 simulation results

For simulation of the reactor evolution to find the minor actinides characteristic in MSR, MCNP code was used for neutron transport. REM code was used for solving the Bateman equation to compute the evolution of the composition isotope of the material considering reprocessing and the online refueling. Figure 2 shows the result of the heavy nuclei inventory by REM code simulation.

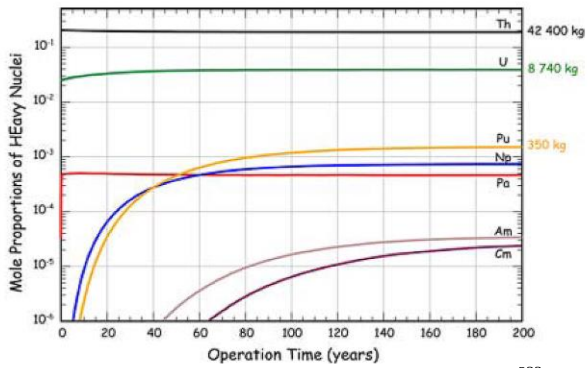

Fig. 2. Heavy nuclei inventory in mole proportions for the ^{233}U-started TMSR configuration with 22.5 mole%

In Figure 2, the inventories of protactinium, neptunium, americium and curium are 100 kg, 170 kg, 8 kg and 6 kg, respectively, at the equilibrium state in the MSR, while in the PWR which has same power as 1000 MWe, those of neptunium, americium and curium are, 91.5 kg, 248 kg and 124 kg, respectively, in the PWR when the reactor is stopped [4]. Protactinium is not found in the PWR because it is not produced.

The inventories of minor actinide in the PWR reach the highest value within several years, but, in the MSR, the inventory of the minor actinides are saturated after a few years at least. Therefore, the actual difference between the minor actinides load on the core of the MSR and the PWR will be larger than the simple comparison of both inventories by simulation. As a result, it is grasped that inventories of the minor actinide from the MSR could be much less than that of the PWR.

4. Conclusions

The analysis of the basic concept was carried out for evaluation of the inventory of the minor actinides in MSR. It was thought that the inventories of the minor actinides should be evaluated by solving the modified Bateman equation due to the MSR characteristic of online refueling, chemical reprocessing and bubbling. It was understood that the inventories of the minor actinide of MSR could be in general much less than that of PWR although the simulation was performed by the code developed for the purpose of the conceptually designed MSR with the specific specification.

REFERENCES

[1] Doligez, X., et al. "Coupled study of the Molten Salt Fast Reactor core physics and its associated reprocessing unit." Annals of Nuclear Energy 64 (2014): 430-440.
[2] Merle-Lucotte, Elsa, et al. "Optimization and simplification of the concept of non-moderated thorium molten salt reactor." Proceedings of International Conference on the Physics of Reactors «Nuclear Power: A Sustainable Resource». 2008.
[3] Delpech, S., et al. "Reactor physic and reprocessing scheme for innovative molten salt reactor system." Journal of fluorine chemistry 130.1 (2009): 11-17.
[4] Le Brun, Christian, et al. "Impact of the MSBR concept technology on long-lived radio-toxicity and proliferation resistance." Technical Meeting on Fissile Material Management Strategies for Sustainable Nuclear Energy. Iaea, 2007.