Systems of Symbiotic Large FBRs and Small CANDLE-Thorium-HTGRs

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Multi-component nuclear system is a system in which several types of nuclear reactors and related fuel cycle facilities are operated with mutual material exchange. A mainstay of the system is a centralized nuclear park that consists of large-scale FBRs and nuclear fuel facilities for fabrication, reprocessing and cooling/storage of nuclear fuels. The role of the FBRs is simultaneously to produce electricity and support small satellite-reactors by providing nuclear fuel. The satellite-reactors can supply energy to remote small areas. In the present study, natural uranium and thorium are charged into the FBRs in distinct fuel pin types. Under the equilibrium state, the fuels are continually discharged and separated with a certain discharge constant. Actinides, excluding ^{233}U-only or uranium-element, are returned to the FBRs while discharged-uranium is used for fresh fuels of small HTGR thorium cycle satellite-reactors. Fissile support capability of the FBR to the satellite-reactors is investigated as function of both the FBR uranium-thorium fraction and uranium discharge constant parameters. The system shows that larger number of uranium pins is better for the FBR criticality while larger number of thorium pins and larger uranium discharge constant give better support capability.

KEYWORDS: multi-component, nuclear park, FBR, small satellite-reactors, thorium, HTGR, uranium discharge constant, support period

I. Introduction

The main challenge to the 21st century is to ensure adequate, affordable and reliable energy services in a sustainable manner. In addition, it should avoid the destructive environmental impacts of energy sources utilization, as shown by fossil fuels so far. On that issue, nuclear energy is a good candidate for energy supplier due to its superiority, e.g. clean, cheap and reliable technologies at the present time.

For a long range, a multi-component power production nuclear system can be proposed to provide a great amount of energy for development of the world. A mainstay of the system is a centralized nuclear park that consists of large-scale reactors and the related fuel facilities. Operational targets of such multi-component system can be aimed for nuclear power production and simultaneously reducing nuclear waste, supporting small reactors outside the park by providing nuclear fuel, or other relevant purposes.

In the present study, we investigate such a system which employs both large scale reactors and small scale satellite-reactors. A large FBR (3000 MWth) fueled with both natural uranium and thorium is operated in a nuclear park and small HTGRs (30 MWth) are operated as satellite-reactors outside the park. Fissile support capability of the large FBR to small HTGR satellite-reactors is investigated as function of both the FBR uranium-thorium fuel fraction

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and uranium discharge constant parameters. Detailed system's scenario of the study will be explained in next section.

II. System's Scenario

System's scenario of the present study is shown in Fig. **1**. The multi-component system consists of a large FBR inside a nuclear park, equipped with related nuclear fuel facilities, and small HTGR satellite-reactors outside the park. In the present study, natural uranium and thorium fuels are charged to the FBR in distinct fuel pin types. Under the equilibrium state, the fuels are continually discharged and separated with a certain discharged constant. At the same time, the FBR is constantly supplied by natural uranium and thorium. After separation process, actinides are returned (confined) to the FBR core. Some part of ^{233}U isotope or uranium element (^{232}U ~ ^{238}U), which is determined by uranium discharge constant parameter, is used for the small HTGR satellite reactor fresh fuel mixed with thorium after undergo fuel fabrication. The fuel fabrication should be done inside the park to guarantee that the fuel will not be used for illegal purposes. We investigate two different cases, i.e. (i) only ^{233}U is discharged (*isotopic*) and (ii) uranium element, consists of ^{232}U ~ ^{238}U, is discharged (*elemental*). All fission products (FPs) are discharged from both pin types of the FBR at a 0.33/year fixed rate (similar to 3-batch refueling scheme) and go to storage facility.

The 30 MWth CANDLE-HTGR [1] with thorium cycle is taken as the design basis for the small satellite-reactor. Long core life, in a range of 20 ~ 40 years (depend on fresh fissile enrichment) was achieved on the design by applying a new CANDLE [2] burnup strategy.

Basic reactor design, including cell parameters, of the FBR are shown in Table **1** and those of the small CANDLE-HTGR are shown in Table **2**.

III. Calculation Method

Calculation of this study used the **E**quilibrium **C**ell **I**terative **C**alculation **S**ystem (ECICS) code [3] that intensively used by our equilibrium research group. ECICS method employs an iterative procedure of cell calculation and equilibrium one as shown in Fig. **2** using SRAC-2005 and JENDL-3.2 cross-section library. Nuclear fuel cycle at the nuclear equilibrium state is called equilibrium fuel cycle and it satisfies the following conditions:

- Number density of each nuclide in reactor does not change.
- Refueling process is a continuous process.

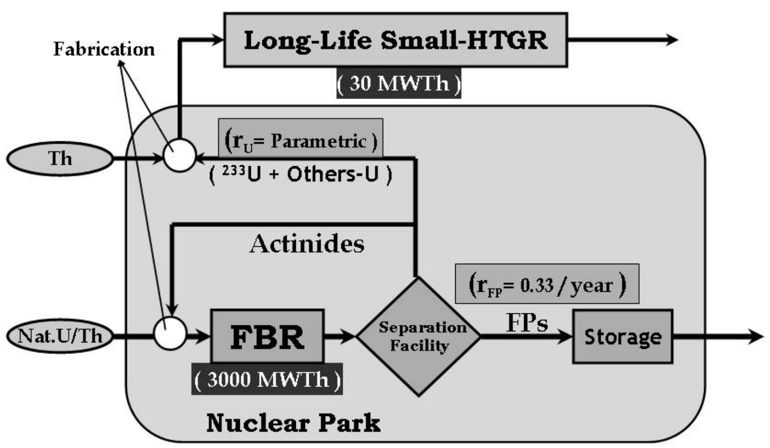

Fig.1. System's scenario

In these conditions, the number density of ***i***-th nuclide, $\boldsymbol{n_i}$, should satisfy the following equilibrium fuel cycle burnup equation:

$$\frac{dn_i}{dt} = -\left(\lambda_i + \phi\sigma_{a,i} + r_i\right)n_i + \sum_j \lambda_{j\to i} n_j + \phi \sum_j \sigma_{a,j\to i} n_j + s_i = 0 \qquad (1)$$

where ϕ : neutron flux

λ_i : decay constant of i-th nuclide

r_i : discharge constant of i-th nuclide

$\lambda_{j\to i}$: decay constant of j-th nuclide to produce i-th nuclide

$\sigma_{a,j\to i}$: microscopic absorption cross-section of j-th nuclide to produce i-th nuclide

s_i : supply rate of i-th nuclide

$\sigma_{a,i}$: microscopic absorption cross-section of i-th nuclide

In this study, parameter named support period (***SP***), is proposed. This parameter enables performance evaluation of a multi-component nuclear system. Equation, describing this parameter is expressed in the following manner:

$$SP = \frac{V_{HTGR} \cdot \sum_i n_i}{V_{FBR} \cdot r \sum_i n'_i} \qquad (2)$$

V : is the volume of corresponding cores

n_i : is the number density of the i-th nuclide

r_i : is the uranium discharge constant $\left(\frac{1}{year}\right)$ of the large reactor (FBR)

i.e. a period of time in which an amount of uranium necessary to build a single HTGR satellite reactor core will be accumulated by discharging it from a single large FBR operation.

IV. Results and Discussions

This study investigates two major parameters of the FBR performance in the system, i.e. criticality and fuel support capability. The criticality indicates FBR operation performance while fuel support capability, in terms of ***SP***, indicates the FBR capability to support the small CANDLE-HTGR satellite-reactors.

The FBR criticality (k_{inf}) of both *isotopic* and *elemental* cases as function of both FBR thorium fraction and uranium discharge constant ($\boldsymbol{r_U}$) is shown in Fig. **3**. The figure shows that the criticality decreases as the increasing FBR thorium fraction because a larger thorium fraction contains less ^{235}U (fissile) due to smaller number of the uranium pin type in the reactor. The criticality also decreases as the increasing uranium discharge constant because a larger uranium discharge constant gives a larger amount of discharged fissile from the FBR core. It is also shown that criticality of *isotopic* cases is slightly higher than that of *elemental* ones at the same values of the FBR thorium fuel fraction and of the uranium discharge constant. This result can be understood because in *isotopic* cases, other uranium isotopes (^{232}U ~ ^{238}U, excluding ^{233}U) are returned to the reactor and ^{235}U can increases the criticality.

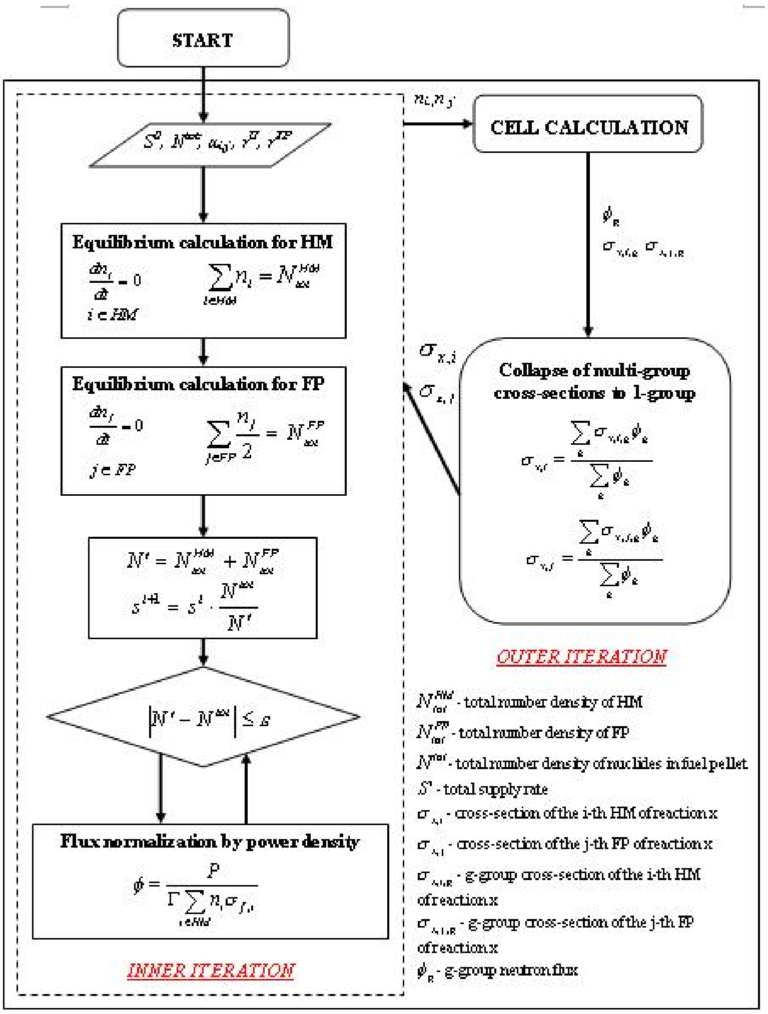

Fig. 2. Flowchart of ECICS calculation

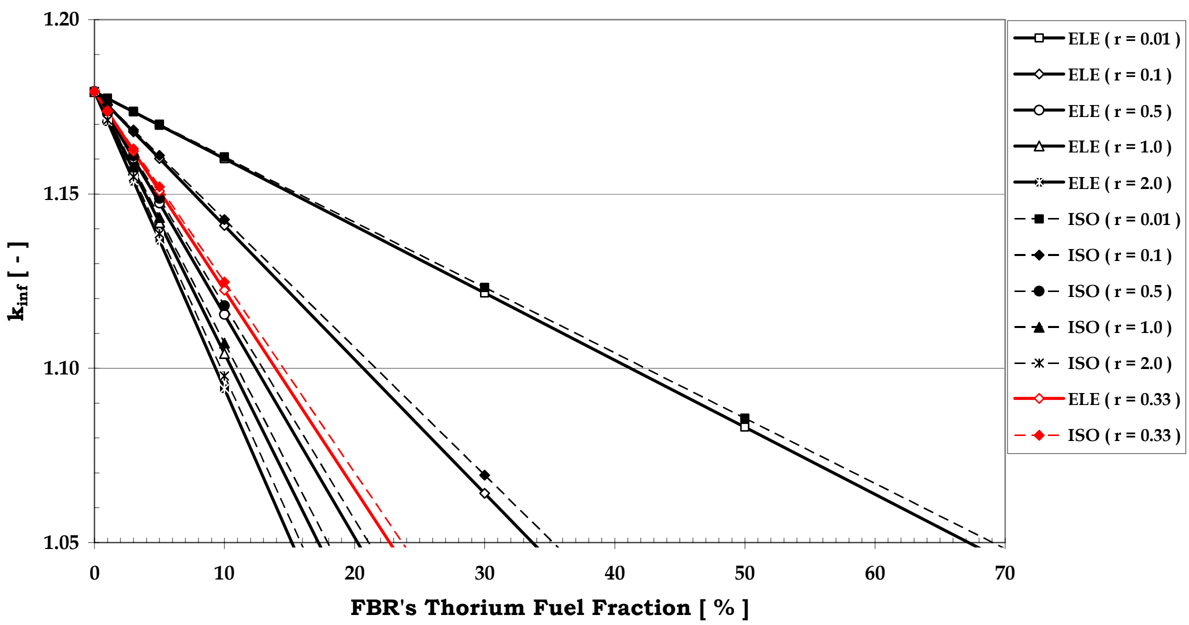

Fig. 3. FBR criticality of both *isotopic* and *elemental* cases

k_{inf} = to 1.05 is chosen as a criticality threshold for the metal fuel FBR employed in this study. At the criticality, it can be fixed the corresponding FBR uranium-thorium fraction. Surplus of uranium in the FBR core is discharged as much as possible while the reactor operation should be kept in this critical condition.

Discharged ^{233}U amount as function of both FBR thorium fuel fraction and uranium discharge constant parameters is shown in Fig. **4**. The figure shows that the amount increases as the increasing FBR thorium fuel fraction because ^{233}U is discharged from the FBR thorium pins type only. The amount can also be increased by the increasing uranium discharge constant. The trend of this parameter is inversely proportional to the FBR criticality. The figure also shows that the amount of *elemental* cases is higher than that of *isotopic* ones at the same values of FBR thorium fuel fraction and of uranium discharge constant, because the equilibrium number density of uranium in *elemental* cases are higher than that in *isotopic* case at the same discharge constant ($\boldsymbol{r_U}$).

SP of *elemental* cases (as a representative one) at k_{inf} = 1.05 is shown in Fig. **5**. The figure shows the system's feasibility at $k_{inf} \geq 1.05$ for the small HTGR enrichment of 6.5%, 10% and 15%. In this critical operation, ***SP*** is consistently decreased by increasing the uranium discharge constant ($\boldsymbol{r_U}$), and the increasing $\boldsymbol{r_U}$ affects simultaneously on decreasing the FBR thorium fraction.

At the same value of $\boldsymbol{r_{FP}}$ and $\boldsymbol{r_U}$ = 0.33 per-year, the critical systems of a large FBR achieve about 0.8, 1.2 and 1.7 years of ***SP*** for 6.5%, 10% and 15% of HTGR enrichment, respectively. These ***SP*** indicate minimum period required for discharged uranium accumulation from the FBR to meet the needed fissile amount of fresh fuel for the corresponding satellite-reactor operation. Although it is not shown in the figure, actually ***SP*** of *isotopic* cases is slightly higher than that of *elemental* ones because the *isotopic* cases provide slightly less ^{233}U than the *elemental* ones.

V. Conclusions

The performances of a large FBR (3000 MWth) centralized in a nuclear park to support small HTGR (30 MWth) thorium cycle satellite-reactors outside the park was investigated. Focus of the present study is to optimized fissile support capability of the FBR to HTGR satellite-reactors. The study shows a feasibility of the systems to be operated with the following characteristics:

(1) FBR criticality decreases as the increasing both its thorium fuel fraction and uranium discharge constant ($\boldsymbol{r_U}$)

(2) Support period (***SP***) decreases as the increasing both the FBR thorium fraction and uranium discharge constant ($\boldsymbol{r_U}$). A lower ***SP*** indicates a shorter discharged uranium accumulation time to meet the satellite-reactors fresh fuel necessity

(3) Any exertion to decrease ***SP*** affects simultaneously on decreasing the FBR criticality

At the same discharge constant values of fission products and uranium, *i.e.* $\boldsymbol{r_{FP}} = \boldsymbol{r_U}$ = 0.33 *per*-year (similar to 3-bacth refueling scheme), the systems of a large FBR in *elemental* cases need about 0.8, 1.2 and 1.7 years for 6.5%, 10% and 15% HTGR enrichment, respectively; to provide the required uranium amount of fresh fuel for the satellite-reactors operation; and the system in *isotopic* cases need slightly longer accumulation time than *elemental* ones.

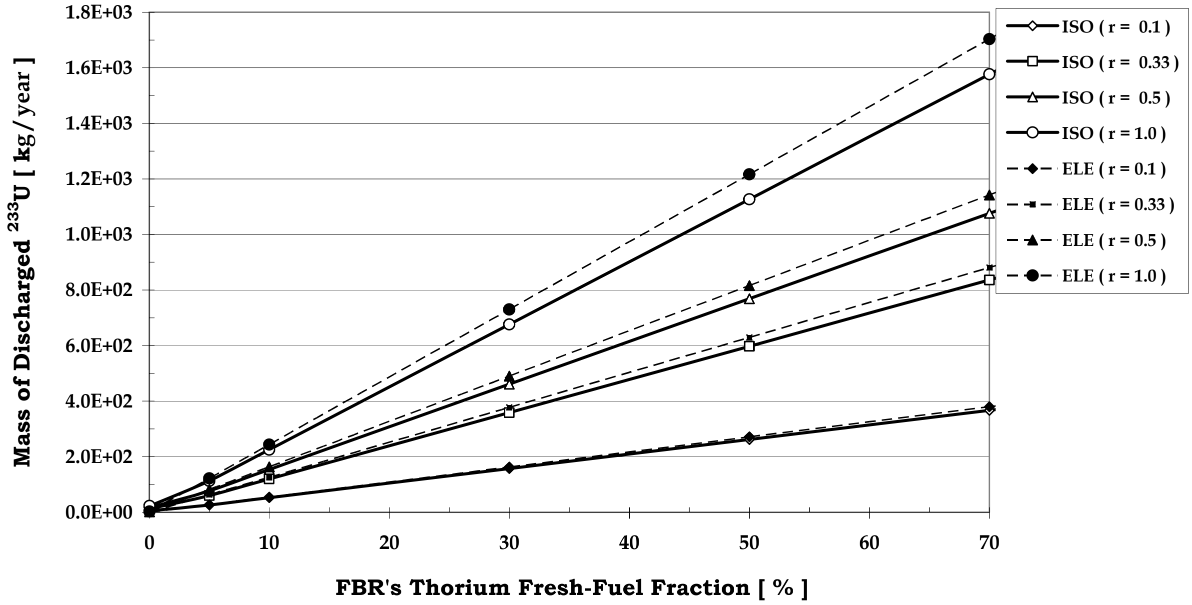

Fig. 4. Mass of discharged ^{233}U from FBR in both *isotopic* and *elemental* cases

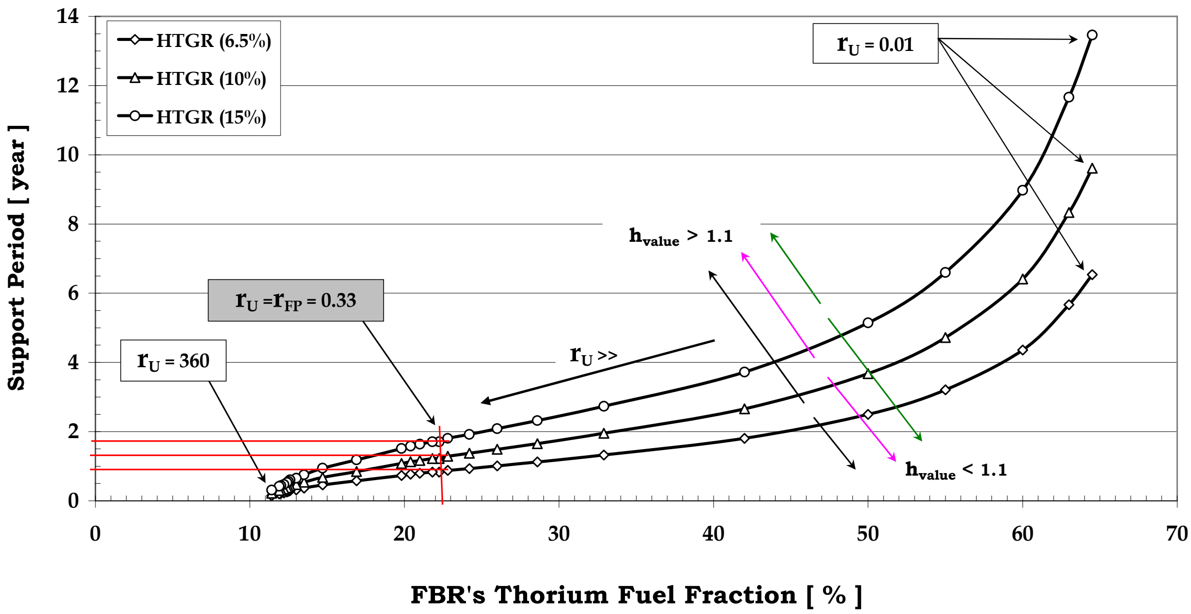

Fig. 5. Support period of *elemental* cases at $k_{inf} = 1.05$

Table 1: Basic design and cell parameters of the FBR

Basic FBR design parameters	
Total power [MWth]	3000
Power density [W / cc]	280
Coolant	Sodium
Fuel type	Metal
Cell parameters	
Fuel	(U and Th)$Zr^{10\%}$
Theoretical density, [g/cc]	15.90
Fuel-pellet diameter, [mm]	7.09
Pin diameter, [mm]	8.50
Pin pitch, [mm]	9.85
Cladding thickness, [mm]	0.48

Table 2: Basic design parameters of Small CANDLE-Thorium-HTGR

Total power [MWth]	30
Fuel	$(^{233}U,Th)O_2$
Burnable poison	Gadolinium
Coolant	Helium
Moderator	Graphite
Enrichment [%]	6.5 ~ 15
Fresh fuel inventory [kg] (6.5% / 10% / 15%)	194 / 292 / 423
Core lifetime [years] (6.5% / 10% / 15%)	20 / 28 / 40

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