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A Symbiotic System Of A Large Fast Breeder Reactor And Small-Sized, Long Life, Thorium Satellite Reactors - General Introduction -

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Abstract

A SYMBIOTIC SYSTEM OF A LARGE FAST BREEDER REACTOR AND SMALL-SIZED, LONG LIFE, THORIUM SATELLITE REACTORS - GENERAL INTRODUCTION. Responding to the rapidly increasing growth of energy demand in the less- developed and developing countries, use of fission nuclear energy best mixed with other primary energy resources is inevitable short- and mid-term options. However, requirements of high capital investment and high technological capabilities, further burdened with safety, high level radioactive waste and nuclear material proliferation issues are challenging factors which have to be resolved by the countries themselves as well as by the vendor countries (mainly consist of developed countries) and international institutions through bilateral and multilateral collaborations. To contribute in resolving part of this global problem, in this study we proposed a symbiotic system consists of large scale, sodium-cooled, fast breeder reactors (3000 MWth) operated in "nuclear parks" located in developed countries or proper internationally controlled areas, and small-sized, long life, thorium satellite reactors (30 to 300 MWth) shipped to and deployed in developing countries. The FBRs owing to their leading neutron economy and breeder capability have the role of breeding their own fuels while producing ^{233}U fissile materials required by the small-sized thorium satellite reactors. A uranium-thorium mixture core is proposed where uranium and thorium metallic fuel pins are arranged side by side to achieve higher production rate of ^{233}U fissile material. The satellite thorium reactors with their fissile materials supplied by the FBRs should have simple design features such as long life and without on-site refueling activity, since they are expected to be deployed in countries or regions with less-established infrastructures and resources. As for the small-sized satellite reactors we studied the feasibility of pressurized water reactors (PWR) and block-type gas-cooled reactors (HTGR) for meeting small demands of electricity and process heat, operated under thermal neutron spectrum and thorium fuel cycle. Adoption of thorium fuel is attributed to its better neutron economy in thermal energy region (a key design factor for long life core and without on-site refueling feature), large abundance, less long-lived trans-uranium nuclides produced, and negative void reactivity coefficients.

Keywords: *Symbiotic system, fast breeder reactor, small-sized, long life, thorium, satellite reactor*

1. Introduction

Global energy demand is continuously increasing over years due to the economic and social human activities development. The *International Energy Outlook 2007* [1] projects strong growth for worldwide energy demand over the 27-year projection period from 2003 to 2030. In the mid-term outlook, Non-OECD (less developed or developing) countries account for three-fourths of the increase in world energy use and much of the growth in energy demand among the non-OECD economies occurs in Non-OECD Asia. Total primary energy consumption in the Non-OECD countries grows at an average annual rate of 3.0 percent between 2003 and 2030. The projection also shows that the electricity consumption for Non-OECD, especially in Asia, countries achieve a greatest number of average annual percent changes up to 2030. To achieve a good quality of human life, the demand should be supplied in a secure, adequate, affordable and sustainable manner. Taking into account external factors such as climate changes & global warming due to CO_2 emission, sustainability etc., the use of fission nuclear energy best mixed with other primary energy resources is inevitable short- and mid-term options. Unfortunately, requirements of high capital investment and high technological capabilities, further burdened with safety, high level radioactive waste and nuclear material proliferation issues are challenging factors which have to be resolved by the countries themselves as well as by the vendor countries (mainly consist of developed countries) and international institutions through bilateral and multilateral collaborations [2].

There are, however, different challenges and situations between developed and developing countries for utilizing fission nuclear energy to meet the demand of energy supply. The former countries encounter a relatively small growth of demand while they have acquired adequate capital and advanced technological capabilities, i.e. they are able to develop, build and operate large-scale nuclear power reactors (mostly light water reactors) and advanced nuclear fuel cycle facilities (mostly U-Pu fuel cycle) in centralized sites (which later we will call “nuclear park” in this study). The latter countries, on the contrary, as already mentioned above, encounter a great increasing demand due to the great population growth but they have limited capabilities of supply due to the less capital and technological capabilities to implement fission nuclear energy in their national energy policies. One promising option for those countries is to operate small and medium reactors (SMR, which we also call “satellite” reactors) with simple design features, such as long life core without on-site refueling activity during reactor operation. This option is in accordance with the fact that in these countries there are many regions and applications where this increased demand will be best met by power plants in the above-mentioned range, due to a small grid system or for an application in a remote area or for a special purpose [3, 4, 5, 6]. The needs of such SMR can be readily found, for an example, in the eastern region of Indonesia, where it consists of a large number of dispersed less-developed small islands yet with a great potential to be developed as an industrial center based on marine resources, as well as agro-business and agro-industries [7, 8]. It is obvious that for these regions, besides electricity supply, a high portion of process heat supply is required for this regional development.

The organization of the paper is as follows. In the following Chapter 2, the proposed symbiotic system involving both uranium and thorium fuel cycle is described. In Chapter 3 the performance of the proposed symbiotic system is discussed. Chapter 4 gives the concluding remarks.

2. Proposed Symbiotic System

Based on the observation on the above mentioned conditions (Chapter 1) of developed and developing countries, in this study, we propose a symbiotic system consisting of (Figure 1):

(1) A large-sized (typically 3000 MWth), sodium-cooled, metallic fuel, fast breeder reactor (FBR), for producing electricity and providing surplus of fissile material, which is operated inside a nuclear park in a developed countries (or a proper internationally controlled area), which is accompanied by nuclear fuel cycle facilities such as separation, storage and fabrication facilities. As will be discussed in the following subsection, the FBR is designed to have a high breeding ratio so that excessive neutrons can be used for both breeding the fissile Pu and producing fissile ^{233}U.

(2) A number of small-sized (typical power range of 30 to 300 MWth) long life, thermal, satellite reactors operated under thorium fuel cycle, shipped to and deployed in a user country. No on-site refueling, reprocessing, etc. are expected to be conducted in the deployed site. After stop of the operation, the reactor (core) is replaced by a new one, and the old one is shipped back to the nuclear park for reprocessing. As for these satellite reactors, small-sized, long life pressurized water reactors (PWR) and block-type high temperature gas-cooled reactors (HTGR) are considered.

Detail discussion on each type of reactor considered in the system is given below.

2.1 Large-Sized Sodium-Cooled, Metallic Fuel, Fast Breeder Reactor

For the FBR design, we adopt the present fast reactor technology, i.e. sodium coolant and metallic fuel are selected. Main parameters of the design are shown in Table 1.

Table 1. Main design parameters of large-sized fast breeder reactor

Power (MWth)	3000
Fuel	(U or Th)$Zr^{10\%}$
Clad	Ferritic stainless steel
Coolant	Sodium
Pellet power density (W/cm^3)	280
Pellet diameter (cm)	0.709
Heavy metal inventory (ton)	137

Metallic fuel is selected because it provides higher breeding ratios than oxide fuel of the sodium cooled FBR [9]. Sodium is a good coolant material since it provides higher heat removal capability, in comparison with other liquid metals, considering simple thermal reactor characteristics such as the required pumping power and convective heat transfer coefficients.

To pursue high production rate of ^{233}U fissile material from the FBR, we propose an innovative core design as the following. In a conventional FBR, it is common that the FBR consists of core and blanket regions. Core region is typically located in inner side and fueled by enriched uranium/plutonium, while blanket region is typically located in outer side and usually fueled by natural uranium. In the present study, we introduce a uranium and thorium mixture core. Uranium and thorium fuel pins are arranged in the core without any blanket surrounding it. Uranium pins are responsible to maintain the FBR criticality by mainly producing ^{239}Pu from ^{238}U while thorium pins are mainly used for producing ^{233}U fissile material. There are several advantages of this mixture core design such as: (1) it provides higher flux level in the thorium pins so that a higher fissile production rate can be achieved, (2) it has more negative Doppler coefficients and less positive coolant void reactivity coefficients, and (3) it is more proliferation resistant than the conventional core, because thorium pins in blanket region of conventional FBR core are easier to be taken out from the core. On the other hand, there are challenges of this mixture core to be resolved in the future such as: (1) the core criticality become worse because neutron leakage increases due to the disappearance of blanket, and (2) lower core power density which implies higher fuel inventories.

2.2 Small-Sized, Long-Life Pressurized Water Reactors

The small-sized, long-life PWRs are based on the established PWR technology. Main parameters of the design are shown in Table 2. As already mentioned, since we pursue a long life reactor without on-site refueling, we select thorium fuel and once-through fuel cycle. The characteristic of long core life time is attributed to the high conversion ratio due to the high η–value of ^{233}U. In addition, by using thorium fuel, the reactors can be designed to have a negative moderator temperature and coolant void coefficients over the whole reactor life even with low moderator to fuel ratio (MFR).

The fuel pin cell parameters shown in the table are partly derived from the Shippingport reactor design [10]. There are three types of pin cell in the Shippingport core and blanket regions with distinct pin diameters. We chose pin diameter of 14.5 mm which corresponds to the Shippingport regular blanket pins since our preliminary study showed that this pin diameter provided the highest conversion ratio for wide range of ^{233}U enrichment and MFR. Parametric investigation was performed on the MFR and discharge fuel burnup to achieve an optimum design of the reactors.

Table 2. Main design parameters of small-sized, long-life, pressurized water reactor with thorium cycle.

Power (MWth)	30 to 300
Fuel	$(^{233}U, ^{232}Th)O_2$
Clad	Zircaloy-4
Coolant	H_2O
Moderator fraction ratio (MFR)	0.3 to 2.0
Pellet power density (W/cm^3)	45
Pellet diameter (cm)	1.31
Heavy metal inventory (ton)	6.2 to 62
Burnup (GWd/t)	20 to 60

2.3 Small-Sized, Long-Life High Temperature Gas-Cooled Reactors

The small-sized, long-life, high temperature gas-cooled reactors are based on the established prismatic/block type HTGR technologies combined with an innovative burn-up strategy, CANDLE (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy producing reactor) [11]. Main parameters of the design are shown in Table 3.

Table 3. Main design parameters of small-sized, long life, CANDLE HTGR with thorium fuel cycle

Power (MWth)	30
Fuel type	Block type (HTTR) TRISO coated fuel particle
Kernel	$(^{233}U, ^{232}Th)O_2$
Enrichment (%)	6.5 to 15 %
Packing fraction (%)	30.0
Fuel compact inner diameter (cm)	1.0
Fuel compact outer diameter (cm)	2.6
Coolant hole inner diameter (cm)	3.4
Coolant hole outer diameter (cm)	4.1

TRISO coated fuel particles adopted in the design allow a high burn-up level under high temperature environment while maintaining the excellent performance of fission products confinement. The use of thorium fuel under CANDLE burnup strategy provides high discharge fuel burnup and long core life. As will be shown below, CANDLE burnup strategy also provides a simpler and safer reactor operation which is one of the basic requirements of SMR.

Detail discussion on CANDLE burnup strategy is given elsewhere [12], however, it is worthily to state the following general merits of the strategy:

(1) Burnup reactivity control mechanism is not required, because the excess burnup reactivity becomes zero.
(2) Reactor characteristics (e.g. power peaking, reactivity coefficients) do not change with burnup. Estimation of core condition is very easy and reliable. Therefore, the reactor operation is simple.
(3) The reactor core height is proportional to a reactor core life. Therefore, the design of a long life reactor core is easier.
(4) Infinite multiplication of fresh fuel after the second core is less than unity. The risk for criticality accident is small. The transportation and storage of fresh fuels become safer.

The initial fuel is constructed with ^{233}U, thorium oxides mixed with gadolinium (Gd) burnable poison; the mixture is placed in the kernels of TRISO-coated fuel particles. The burnable poison concentration is adjusted to diminish much faster than fissile material (^{233}U) during burnup, so that the fuel composition can achieve the requirement for the CANDLE burnup strategy.

3. Performance of the Symbiotic System

A detail discussion on the optimization of each component of the symbiotic system and the overall performance of the symbiotic system is given by [13]. Here, we just give the summary results as shown in Table 4.

For a symbiotic system which consists of a large-size, sodium-cooled, metallic fuel FBR and small-sized, long life, CANDLE thorium HTGRs and FBR discharge fuel burnup of 100 GWd/t (which is closed to present FBR discharge fuel burnup level), one FBR can support 14 HTGRs with thermal power of 30 MWth and enrichment range of 6.5% to 15%, and the power production ratio of about 0.14. For a symbiotic system with small-sized, thorium PWRs (thermal power of 300 MWth and discharged burnup of 60 GWd/t), one FBR can support 2.7 PWRs, and the power production ratio is about 0.27.

Table 4. Performance of the proposed symbiotic system (FBR power and burnup equal to 3000 MWth and 100 GWd/t, respectively)

Parameters	HTGR	PWR
Power (MWth)	30	30 to 300
Enrichment (%)	6.5 to 15	3.07 to 5.1
Burnup (GWd/t)	62 to 137	20 to 60
Core lifetime (year)	19 to 39	10 to 31
Fissile inventory ratio	0.25 to 0.55	0.67 to 0.55 *)
Support factor	14	2.7 to 16.3 *)
Energy production ratio	0.14	0.16 to 0.27 *)

*) *At MFR and burnup cases of 1.0 and 60 GWd/t, respectively*

4. Concluding Remarks

This study concluded that, the proposed symbiotic system is feasible to be realized from the neutronics and mass balance point of view. The system is sustainable: (1) the large fast breeder reactor is a self-sustained, only supplied by natural uranium and thorium, and its excessive fissile material (^{233}U) can be discharged to support the satellite reactors, and (2) the small-sized satellite reactors' fissile fresh-fuels are fully provided by the large fast breeder reactor. Power production ratio between small and large reactors of 0.14 to 0.27 can be achieved.

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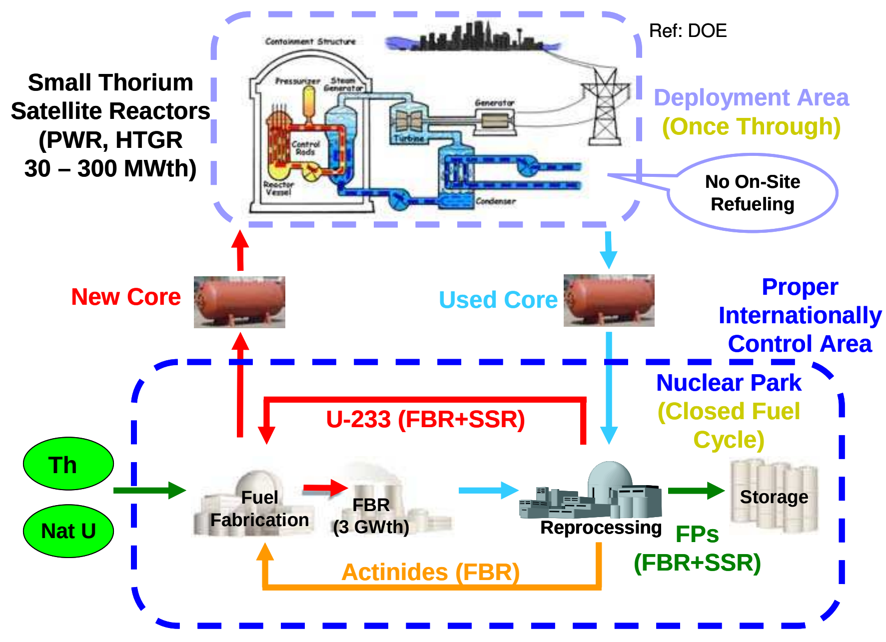

Figure 1. Symbiotic system of a large-sized, sodium-cooled, metallic fuel fast breeder reactor with small-sized, long life thorium satellite reactor