Proceedings of the Korean Nuclear Society Spring Meeting
Kwangju, Korea, May 1997

Design Analysis of a Thorium Fueled Reactor with Seed-Blanket Assembly Configuration

Kyung Taek Lee and Nam Zin Cho

Korea Advanced Institute of Science and Technology
Department of Nuclear Engineering
373-1 Kusong-dong, Yusong-gu
Taejon, Korea 305-701

Abstract

Recently, thorium is receiving increasing attention as an important fertile material for the expanding nuclear power programs around the world[1]*. The superior nuclear and physical properties of thorium-based fuels could lead to very low fuel cycle cost and make thorium reactors economically attractive. In addition, the use of thorium in reactors would permit more efficient utilization of low cost uranium reserves and reduction of nuclear wastes. In this work, the nuclear characteristics of a new type of thorium fueled reactor (Radkowsky Thorium Reactor) consisting of seed-blanket assemblies are addressed and compared with those of typical assemblies of a PWR (CE type). Also, an assessment on several advantages of thorium fueled reactors is provided. All these results are based on the HELIOS code*[2] *calculation.*

I. Introduction

Current interest in thorium reactors throughout the world stems largely from the fact that ^{233}U produced by neutron capture in thorium is a more valuable fuel for thermal reactors than the plutonium that results from capture in ^{238}U. Fig. 1 shows these two types of conversion. Because of the high net neutron yield (η) of ^{233}U in thermal reactors relative to either ^{239}Pu or ^{235}U, the thorium-^{233}U fuel system has higher conversion ratios and longer fuel life than ^{238}U-based fuel system. Thorium reactors, therefore, are expected for long-term purposes to lower fuel costs than many typical uranium converters. In particular, due to its high η value, some of the advanced thorium reactors are able to breed enough ^{233}U to sustain self-recycle without supplementary feed of enriched material.

The favorable neutronic properties of ^{233}U not only help in reducing fuel cycle cost but also lead to more efficient utilization of low-cost uranium reserves which necessarily form the basis of all nuclear power systems that exploit only fission chain reactions. Thus the introduction of thorium converters into nuclear power systems can delay the exhaustion of low-cost ore and at least provide additional time required for the development of commercially competitive breeders.

Thorium reactors have an additional advantage in nonproliferation. This effect is arised mainly from two factors. First, because of its isotopic composition, an attempt to separate ^{233}U from ^{238}U, ^{236}U, and ^{234}U isotopes will also remove the fissile ^{235}U from the resulting enriched stream. Therefore, separation of ^{233}U from other nuclides is very difficult. Second, the contamination of the recycle material by a hard gamma-emitter (^{208}Tl), originating in the ^{232}U chain, will require that the reprocessing facility be remotely operated. Consequently, the thorium reactor provides an inherently enhanced proliferation resistance in comparison with a standard LWR cycle of current technology.

Recently, Radkowsky proposed a new type of thorium reactor consisting of seed-blanket fuel assemblies. In this work, this type of seed-blanket thorium-based fuel assembly is studied and compared with a standard LWR assembly (CE type).

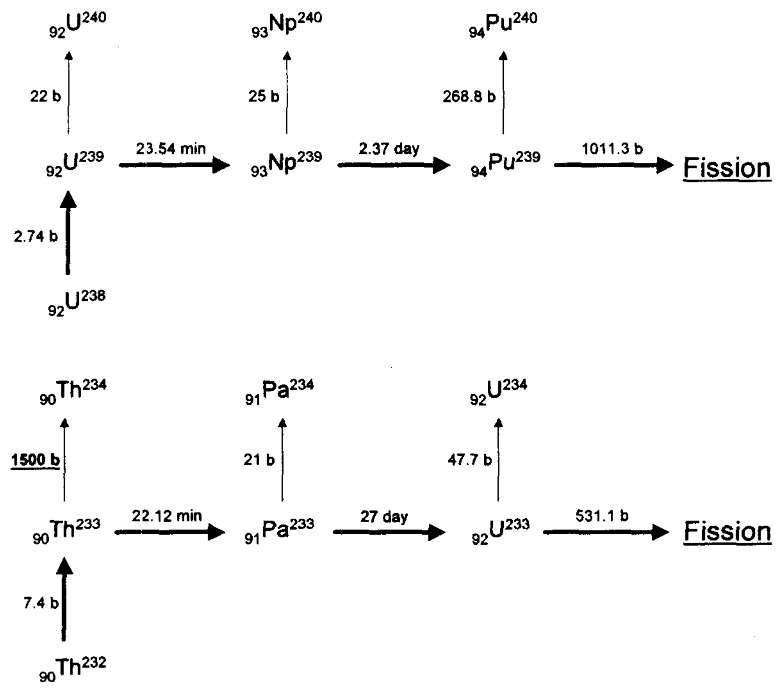


Fig. 1. Two types of conversion process.

II. Radkowsky Thorium Reactor (RTR)

The Radkowsky Thorium Power Corporation (RTPC) advocates a novel fuel cycle for pressurized water reactors - Radkowsky Thorium Reactor (RTR) core concept. The main objective of the RTR development is based on two major concerns of the existing nuclear power industry : the storage and permanent disposal of the spent nuclear fuel and the proliferation danger associated with the current nuclear fuel cycle.

The main idea of the RTR concept is to separate spatially the ^{232}Th part of the fuel and fissile driver part of the core. This separation allows separate fuel management schemes for the thorium part of the core (a subcritical "blanket") and fissile part of the core (a supercritical "seed"). Also, proper control of region-wise burnup can be done by separated fuel management. The design objectives of the blanket are efficient generation and proper fissioning of the ^{233}U isotope, while the design objective of the seed is to supply excessive neutrons, which are parasitically absorbed by ^{232}Th in the blanket in a most economic way, i.e., with minimal investment of the natural uranium. To compensate low initial excessive reactivity and parasitic capture of neutrons, RTR takes up a soluble boron free reactivity control system. Removing soluble boron during the power production cycle, we may simplify the CVCS and obtain corresponding capital cost savings. But extensive use of burnable absorbers is required in the seed region to reduce reactivity control requirement.

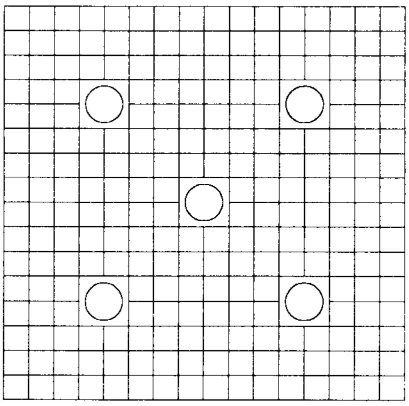
The main design solution is based on a seed-blanket unit (SBU) assembly geometry. By using SBU, we can achieve full compatibility with existing pressurized water reactors (PWRs). Compared with existing PWRs, except for the use of SBU, RTR has almost the same hardware components and most of the concepts included in RTR are based on existing and proven technology. Figure 2 shows typical PWR and RTR fuel assemblies.

Compared with Pu build-up in the U chain, ^{233}U build-up is quite slow, reaching saturation at burnup of 40 GWD/MT. The difficulties in fuel reprocessing make it impossible to adopt a recycling fuel management. Because of these factors, thorium based fuel should be burned further up to a burnup of at least 70~80 GWD/MT, corresponding to 8~9 full power years.

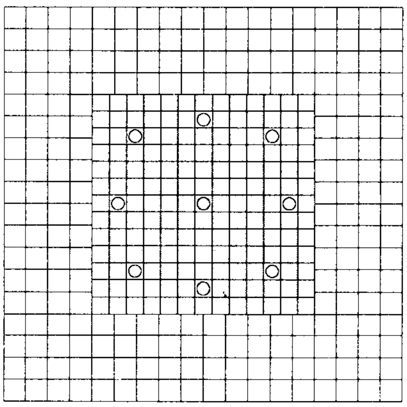
Important design features of RTR are as follows :

- Heterogeneous, seed-blanket assembly geometry,
- Separate fuel management schemes for seed and blanket,
- In-core seed fuel management - three batch scheme, annual cycle,
- In-core blanket fuel management - single batch, nine to ten year cycle,
- Seed fuel : U/Zr metal alloy, 20% enriched U,
- Blanket fuel : (ThO_2 + UO_2) mixture, less than 20% enriched U,
- Seed fuel design is based on the fuel technology of the Naval Propulsion Reactor of Russian Federation Design.

In addition to the general advantages of the thorium cycle, RTR claims to have additional advantages. The most attractive advantage of RTR is to reduce the amount of the spent nuclear fuel. The RTR core and cycle design reduce significantly the spent fuel discharge. The reduced weight and volume of the spent fuel result in reduction of the on-site spent fuel storage requirement. The comparison of the toxic nuclides inventory in RTR and LWR spent fuel shows that toxicity of RTR spent fuel is relatively lower than that of PWR spent fuel, due mainly to smaller inventory of the actinides. Other merit of RTR is proliferation resistance as already mentioned. Due to the use of uranium and thorium mixture as a blanket material, proliferation potential of ^{233}U can be negligible. The plutonium discharged from RTR is not adequate to make weapons.



(a) CE type Assembly



(b) RTR type SBU

Fig. 2. CE type assembly and SBU geometry.

Ⅲ. Assembly Calculations

To assess the characteristics and properties of RTR, assembly calculations were performed using HELIOS, a transport theory calculation code. The transport method of HELIOS is called the CCCP method, because it is based on current coupling and collision probabilities[2]. The system calculated is made up of space elements that are coupled by interface currents with each other and with the boundaries, and the properties of each space element, its responses to sources and in-currents, are obtained from collision probabilities. In this method, the flux in a given energy group and region i is given as follows :

$$\phi_i = \sum_{j=1}^{J} X_{ij} Q_j + \sum_{s=1}^{S} Y_{is} j_s^- , \quad (1)$$

where ϕ_i = the neutron flux in region i, integrated over its volume V_i,

Q_i = the volume-integrated neutrons source in region i,

j_s^- = the surface and sector-integrated in-current in the sectors, i.e., the fraction of the total in-current through the peripheral segment containing s that enters in this sector,

X_{ij} = the source-response flux, i.e., the volume-integrated flux in region i due to one particle born uniformly and isotropically in region j,

Y_{is} = the current-response flux, i.e., the volume-integrated flux in region i due to one particle entering the space element in sector s as an in-current caused by an isotropic flux.

By evaluating terms included in equation (1), the flux can be calculated for given energy group and region. Using this calculated flux, the flux for the entire system is obtained by the current coupling method.

In this paper, a typical CE type assembly and an RTR assembly (SBU) are assessed by 34-group HELIOS calculations. The design parameters for each assembly are given in Table Ⅰ. To par the rated power of each assembly, power per unit heavy metal for CE-assembly and SBU is set to 40 W/g and 50 W/g, respectively. In the case of SBU, refueling of the seed region is considered by restart option in the HELIOS code and burnup calculation is performed up to 88000 MWD/MT to estimate the ^{233}U and plutonium buildup for the entire fuel cycle. Fuel of the seed region is $U\text{-}ZrH_{1.6}$[3], which has been used for the nuclear propulsion system, with 25 wt% uranium and 20 wt% enrichment of ^{235}U. Fuel of the blanket region is (UO_2+ThO_2) mixture with 8.8 wt% uranium and 20wt% enrichment of ^{235}U. For simplicity, calculated states are assumed to be the same with those of a typical PWR.

Table Ⅰ. Design Parameters of CE and RTR Assemblies

	CE-Assembly	RTR-SBU
Assembly type	16×16	18×18 (13×13 seed)
Assembly pitch	20.6 cm	20.6 cm
Pin pitch	1.2875 cm	Seed 0.8803 cm Bket 1.1444 cm
Material	UO_2 (3.3 wt%)	Seed $U\text{-}ZrH_{1.6}$ Bket UO_2 + ThO_2
Fuel OD	0.84 cm	Seed 0.5741cm Bket 0.7466 cm
Clad OD	0.96 cm	Seed 0.6564 cm Bket 0.8534 cm
Number of waterholes	5	9
Initial mass of U loaded	1152.852 g/cm	161.914 g/cm
Rated power of assembly	4.61162E+04 W	4.66487E+04 W

IV. Results and Conclusions

From the results of HELIOS calculations, we find typical trend and some advantages of RTR. Compared with CE assembly, while SBU has quite different local properties, its overall properties are very similar to those of CE assembly. In contrast to the MOX loaded core, RTR has almost the same neutron spectrum with the UO_2 core. Thus if local control is done by proper operation, many existing and proven technology can be applied to the design process of RTR. The basic nuclear data at BOC of CE type and SBU are summarized in Table Ⅱ. Fig. 3 shows the criticality as a function of effective full power day (EFPD). The rapid changes correspond to the assembly refueling for CE type and the seed refueling for SBU.

Fig. 4 shows actinide buildup. For the same EFPD, actinide buildup in SBU is about 25% of the CE assembly case. The required mass of uranium is reduced by about 18%. In Fig. 5, mass of ^{233}U in the blanket region of SBU is given. As expected, it reached saturation after a sufficiently long time. So long-term fuel cycle is required for full utilization of fissile conversion. Fig. 6 shows the flux profiles in CE assembly and SBU along a symmetry axis.

From the results of these preliminary assessments, we find that RTR is one of the most effective reactors among the various reactor types which have been proposed. Although some technical problems still remain, i.e., extensive use of burnable absorbers and development of new control rod drive mechanism, RTR may contribute in a major way to solving the two main problems of light water nuclear technology, which are possible diversion of the fuel for weapons and the storage of the spent fuel.

Table Ⅱ. Two Group Data for CE Assembly and SBU

	CE-Assembly		RTR-SBU	
	Fast	Thermal	Fast	Thermal
D	1.39920	0.40919	1.36811	0.35251
Σ_a	9.1721E-03	8.1383E-02	8.4781E-03	8.6124E-02
$\nu\Sigma_f$	6.8029E-03	1.3970E-01	4.8051E-03	1.3092E-01
Σ_r	1.4937E-02	0.0	1.9850E-02	0.0

References

1. IAEA, *Utilization of thorium in power reactor*, Report of a Panel held in Vienna (1966).
2. SCANDPOWER A/S, *HELIOS Methods*, HELIOS Documentation Rev. No 2 (1995).
3. M.T. Simnad, "The U-ZrHx Alloy : its properties and use in Triga fuel," *Nuclear Engineering and Design*, **64**, 403-422 (1981).

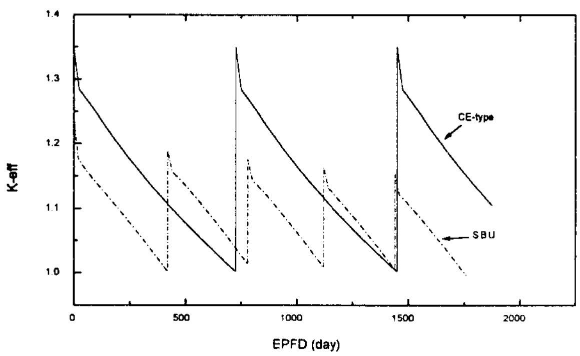
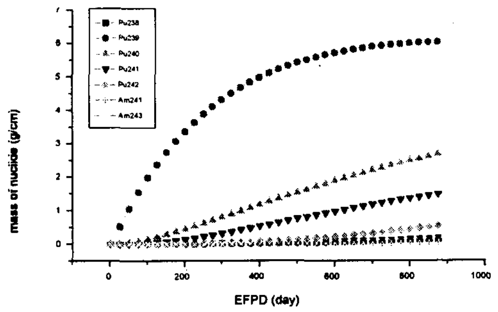
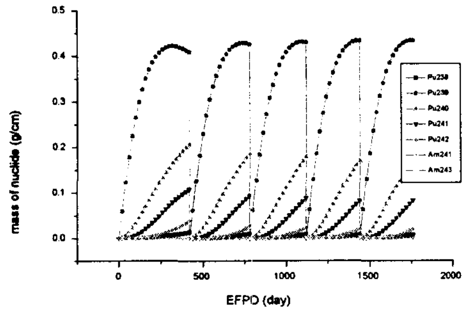


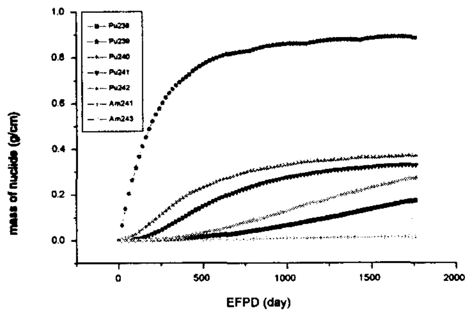
Fig. 3. Criticality of CE assembly and SBU.



(a) CE-type assembly



(b) SBU-seed region



(c) SBU-blanket region

Fig. 4. Actinide buildup in CE assembly and SBU.

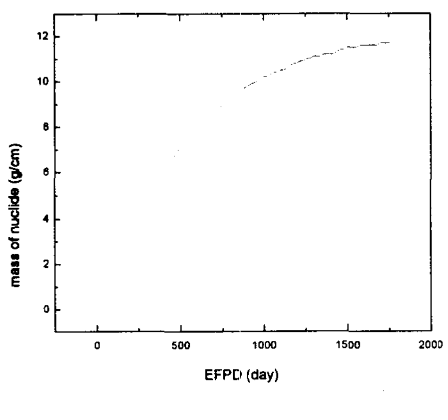


Fig. 5. Behavior of ^{233}U builup.

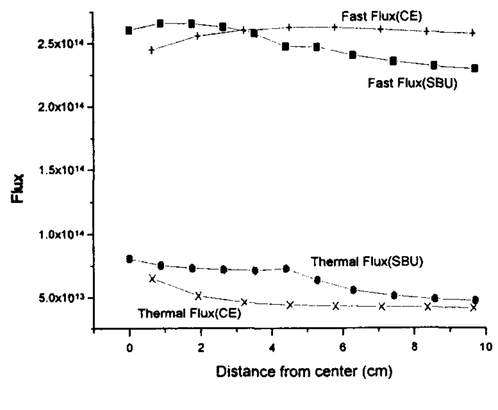


Fig. 6. Flux distributions along a symmetry axis in CE assembly and SBU.