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Fuel Cycle Performance Evaluation of the Pressure-Tube Type Light Water Cooled High-Conversion Reactor

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Abstract

A design concept of pressure-tube type light water cooled reactor (HCPLWR) core was proposed as a thermal high-conversion reactor using a thorium based once-through cycle strategy. In the previous work, a design feasibility in fuel cycle economics and nuclear safety were confirmed. In this work, HCPLWR was evaluated in the aspects of proliferation resistance, transmutation capability and radioactive toxicity. Evaluation was done by a direct comparison of indices with PWR, CANDU and Radkowsky Thorium Fuel(RTF). Conversion ratio was measured by fissile inventory ratio and fissile gain. Proliferation resistance of plutonium composition from spent seed and blanket fuels was measured by bare critical mass, spontaneous neutron source rate, and thermal heat generation rate. For the evaluation of long-lived minor actinide transmutation was measured by a new parameter, effective fission half-life. Evaluation of radioactive toxicity was done by a new index.

Two-dimensional calculation for the assembly-wise unit module showed each parameter values. Even though conversion capability of HCPLWR was higher than one of RTF, it was concluded that current HCPLWR design was not favorable than RTF. Design optimization is required for the future work.

1. Introduction

A nuclear design concept for high-conversion pressure-tube type LWR (HCPLWR) was proposed as an advanced thermal reactor concept [1]. The design objective of this core was to make PWR have some favorable features under the restriction of once-through fuel cycle option. Those were better fuel cycle economy, higher proliferation resistance, better environmental benefits in spent fuel disposal and increased reactor safety. This design concept was evolved out of previous works.

The first one is a concept of light water cooled PHWR [2]. A feasibility of a pressure-tube type light water cooled reactor was shown in that work. Compared to the pressure vessel reactor, the use of pressure tube might give some benefits. First of all, fuel bundles can be reloaded in continuous mode just like as in CANDU, which will bring higher reactor availability. Secondly, much more reactivity control devices and core monitoring devices can be arranged within a space between pressure tubes in core, which leads eventually to on-line monitoring and maintenance capability. Thirdly, coolant flow rate for each fuel channels can be controlled when it is needed because every fuel channels are separated from each other. This feature is essential for the seed and blanket core concept where power generation densities from seed fuels are much higher than those from blanket fuels.

The second one is a concept of high conversion PWR using thoria blanket fuel [3]. In this concept, a design modification of Radkowsky Thorium Fuel (RTF) concept [4] was done for the practical application of once-through thorium fuel cycle option. The use of thorium-based seed and blanket concept gave acceptable fuel cycle economics in LWR with additional benefits in proliferation resistance and production rate of long-lived minor actinides.

HCPLWR concept of this work was expected to have most of all favorable features from two design concepts mentioned above. However, fuel cycle performance of this concept was checked only for the high-conversion, i.e. fuel cycle economics, at the previous work [1]. The other aspects of design feasibility such as proliferation resistance, minor actinide transmutation, radioactive toxicity needed to be evaluated. In the following sections, HCPLWR was compared with other options with some performance indices.

2. Design Concept of HCPLWR

The core of high-conversion pressure-tube light water cooled reactor (HCPLWR) has the same configuration as one of the CANDU except that it has dry calandria tank and thorium based seed and blanket fuel bundles. Therefore, geometry and material of pressure tubes are same with CANDU. Coolant circulating in the tubes, however, is chosen to be light water instead of heavy water. Fuel bundles are designed to be hexagonal lattice array in order to be tightly pitched for the high conversion. Just like as RTR (or RTF) [5], thorium blanket fuel bundles are to be loaded at the separate region, (here, at the different pressure tubes) from driver channels. Seed bundles should be reloaded annually, whereas blanket bundles should be kept more than 10 years. The complexity of reloading operation requirement can be solved without problem in a pressure-tube type reactor.

Enrichment level of uranium both in seed and blanket should be high up to 20 w/o in RTR. In case of the optimized design, U-235 enrichment of U-15%Zr seed fuel could be much less than RTR, as of 13.5 w/o. The choice of blanket fuel material was pyro-carbon coated particle fuels which have been used for MHTGR. This particle fuel has high mechanical integrity at extremely high burn-up state. 259 biso-carbon-coated particles (209 ThO_2 fertile particles with 50 UCO fertile particles) were designed to be packed into a PWR fuel pellet shape graphite matrix. In this choice, the enrichment level of U-235 in UCO was 5 w/o. Detail description of HCPLWR can be found in the previous work. [1]

There was no flexibility in optimization of seed/blanket volume ratio in a core. The channel ratio of seed to blanket was found to be 1/3 as shown in Fig.1. The size of blanket pins was a little larger than the one of seed fuel pins. Fig. 2 shows a cross-sectional view of a unit channel consisting of 3 blanket channels and one seed channels.

3. Fuel Cycle Performance Indices

In this section, various aspects of HCPLWR concept were measured by performance indices and compared with PWR, CANDU and Radkowsky Thorium Fuel. For the exact comparisons, specific power density was adjusted for each reactor type to the reference power generation of 900 GWD. All calculation was done by 2-dimensional HELIOS calculation for a unit assembly module instead of 3-dimensional whole core.

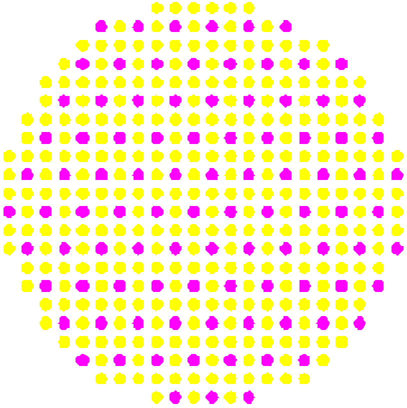

Figure 1. Cross Sectional View of Reactor Core

(Seed/Blanket Channels within a Vacant Calandria)

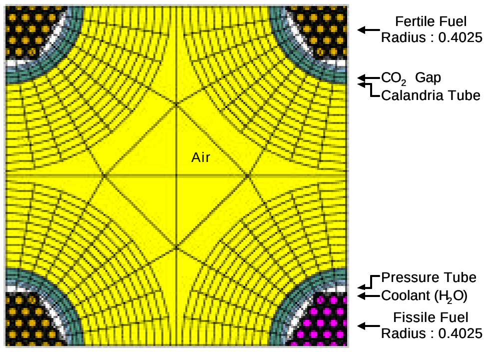

Figure 2. The Unit Module of the Optimized Seed/Blanket Channels

(Node Configuration for HELIOS calculation)

3.1 Conversion Index

Fissile production rate in a blanket fuel is largely different from in a seed fuel in a seed/blanket core depending on core arrangement, flux spectrum, and material compositions. Value of conversion ratio changes by a large ratio through the cycle depended on both fissile production rate and burnout rate. As a conversion index, fissile inventory ratio (FIR) and fissile gain (FG) were measured as an overall performance indices. The following tables showed the differences among reactor concepts. Compared with RTR, HCPLWR showed much higher conversion capability under the once-through cycle option.

Table.1 FIR and Fissile Gain

INDEX	PWR	CANDU	RTR-Seed	RTR-blanket	HCPLWR seed	HCPLWR Blanket
FIR	0.35	0.72	0.21	1.37	0.67	1.96
Fissile Gain(%)	-64.61	-28.18	-78.65	37.46	-33.15	96.05

Table.2 Comparisons of BCM, SNS and TG

INDEX	Weapon grade	PWR grade	CANDU grade	RTR-seed grade	RTR-blanket grade	HCPLWR-seed grade	HCPLWR-blanket grade
BCM (kg)	10.39	14.50	12.78	14.26	15.45	10.89	13.66
Ratio to WG	1	1.4	1.2	1.3	1.5	1.0	1.3
SNS $(\text{kg-sec})^{-1}$	5.35×10^4	4.16×10^5	2.61×10^5	5.27×10^5	7.90×10^5	1.31×10^5	6.36×10^5
Ratio to WG	1	7.8	4.9	9.8	14.8	2.4	11.9
TG (watt/kg)	2.22	12.58	3.76	41.68	72.66	10.31	69.36
Ratio to WG	1	5.7	1.7	18.8	32.7	4.6	31.2

3.2 Proliferation Resistance Index

One of the major benefits of thorium based cycle is the non-proliferation potential of spent fuel. Quality of spent fuel composition can be measured by the following three parameters [6]. Bare critical mass (BCM), a required mass to make material critical is dependent on the plutonium isotope vector. BCM values were evaluated by MCNP-4/B. Calculated BCM from HCPLWR was not favorable compared with RTR. The amount of plutonium fissile in spent fuel, however, is much less in HCPLWR than in RTR.

Another parameter for proliferation resistance is a spontaneous fission source (SNS) rate from reprocessed plutonium. SNS from HCPLWR seed is not larger than RTR, that is less favorable in proliferation attribute. Thermal heat generation (TG) is a measure of alpha-decay heating per critical mass. TG from HCPLWR seed is much less than RTR, which means that it is much unfavorable than RTR.

3.3 Transmutation Index

It is not simple to measure the transmutation characteristics of minor actinides within a fuel. They are transformed into fissile by the neutron capture and decay. Np-237 is transformed into Pu-239 by a single path of neutron capture, whereas Am-241 has two paths to fissile. In a thermal reactor, high capture cross sections of Np-237 and Am-241 lead to Pu-239 and Am-242m which have high fission cross sections and are destroyed with high possibility [7]. It is seen that minor actinides are incinerated by fission after transmuting through the decay chains.

$$^{237}\mathrm{Np} \xrightarrow{(n,?)} {}^{238}\mathrm{Np} \xrightarrow{ß^-} {}^{238}\mathrm{Pu} \xrightarrow{(n,?)} {}^{239}\mathrm{Pu}$$

$$\mathrm{Am} \xrightarrow{\quad} \mathrm{Am}$$

$$\mathrm{Am} \xrightarrow{\quad} \mathrm{Am} \xrightarrow{} \mathrm{Cm} \xrightarrow{} \mathrm{Pu} \xrightarrow{\quad} \mathrm{Pu}$$

This performance can be measured by a simple parameter definition. Effective fission half-life (EFHL) of a certain isotope represents its fission loss potential by itself and daughters those were transmuted by capture and decay [8]. Table 3 shows EFHL of three major long-lived minor actinides.

$$s_f + \sum_f f_j s_? \frac{}{s_t^j} + \sum_k \lambda_i \frac{}{s_t^k} \qquad (1)$$

where
i = mother isotope,
j = daughter isotope generated by neutron capture,
k = daughter isotope generated by decay,
f_j = transmutation branching ratio of path from i to j,
σ_f = fission cross-section,
σ_γ = capture cross-section,
l_i = decay constant of isotope i to k

Table.3 Effective Fission Half-Life

NUCLIDE	PWR	CANDU	RTR-seed	RTR-blanket	HCPLWR-seed	HCPLWR-blanket
Np-237	2.32	1.79	3.18	2.94	4.36	1.36
Am-241	0.72	0.48	0.97	0.87	1.88	0.45
Cm-244	4.60	9.64	6.11	5.87	5.97	3.10

We can find that EFHL of blanket is generally shorter than that of seed in Table 3. This is because the neutron spectrum of blanket is softer than that of seed. For an effective transmutation of minor actinides such as Np, Am, Cm by capture reactions in thermal reactors, the softer neutron spectrum is appropriate because of high capture cross sections in thermal energy range.

The production rate of higher actinides, such as Cm-245 and Cm-246, from Am-243 and Cm-244 under the soft neutron spectrum is smaller than that under the hardened neutron spectrum. Therefore, the use of thermal reactor can lead to the accumulation of heavier actinides such as Cm and Cf.

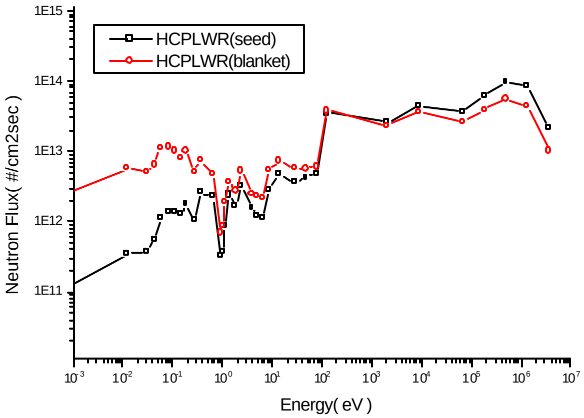

Fig.3 Neutron spectrum in HCPLWR

3.4 Radio-toxicity Index

Radio-toxicity of actinides largely vary with time. It is not easy to compare the time-dependent variations of each isotopes existing in a reactor volume. Therefore, a new index of time-independent value is required for the evaluation of overall radio-toxicity level in spent fuels. Integration on time is one of the methods to derive this time-independent index [9]. Integration is done to the total radio-toxicity for any time intervals (i.e. t=0 to 1x10^3 years, or 1x10^3 to 1x10^6 years) to obtain time-integrated values. When the time interval is from 0 to 1x10^3 years, integrated index is a short-term radio-toxicity index, I_S. This is defined as,

$$I_S = \int_0^{1\times10^3 y} A(t)dt \qquad (2)$$

This I_S provides the total radio-toxicity during the radioactive nuclides will be confined in a vitrified waste. As another time interval, we set the time interval from 1x10^3 to 1x10^6 years for estimating long-term radio-toxicity index, I_L.

$$I_L = \int_{1\times10^3 y}^{1\times10^6 y} A(t)dt \qquad (3)$$

I_L shows the total radio-toxicity during the time until which minor actinides and its daughters become stable. Figure 4 shows the total radio-toxicity of reactors. The radio-toxicity is calculated for minor actinides which have larger mass numbers than 92 and have long half-lives. Radio-toxicities of blankets are relatively higher than those of seeds, because isotopes such as U-232, U-233, U-234 produced from thorium chain played high radioactive level attributes from $1x10^3$ to $1x10^6$ years.

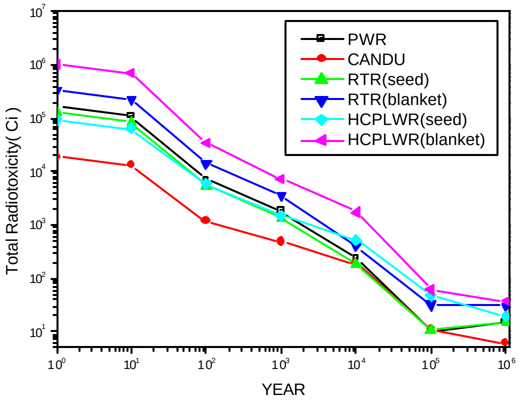

Fig.4 Total Radio-Toxicity Variation

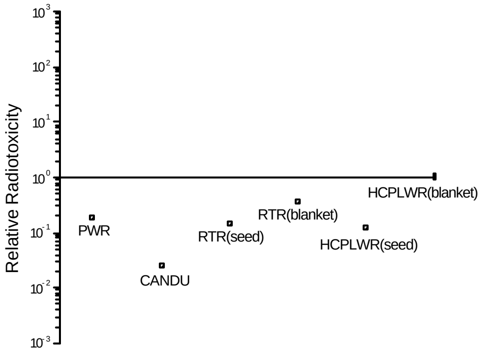

Fig. 5 Short-term Time-Integral Radio-Toxicity

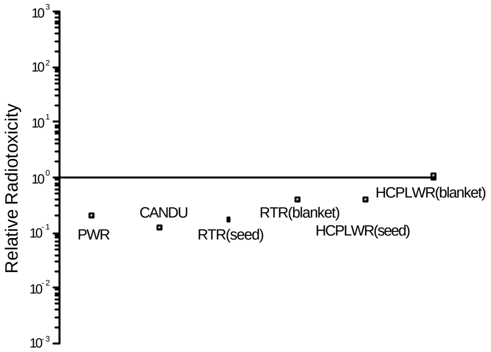

Fig.6 Long-term Time-Integral Radio-Toxicity

4. Conclusion

A proposed design of HCPLWR showed high conversion characteristics, whereas proliferation resistance was not favorable compared with RTR. However, it is expected to be almost comparable to RTR because total amount of spent seed fuel is less than RTR. A simple measure of LLMA transmutation capability showed that HCPLWR is a little favorable than RTR. Therefore, it is concluded that HCPLWR is a potential option of high conversion LWR core based on fuel cycle performance. The other favorable features expected from pressure-tube type core are summarized as the followings. On-power fuel reloading capability gives flexibility in reloading strategies and high plant availability. The use of a dry calandria concept gives two good points - additional reactor scram capability as a design diversity and a long-term cooling reservoir when a proper water flooding system is designed for dry tank. The vacant space between pressure tubes gives a chance to put any reactivity control devices and monitoring devices. A nuclear safety aspect was checked to be acceptable by all negative temperature feedback coefficients. Compared with RTR design option, separated pressure-tube coolant system gives a freedom of coolant flow rate control between seed and blanket channels. This feature can mitigate a large ratio of power sharing between seed and blanket, which is a current issue in RTF application in PWR.

HCPLWR design concept was optimized only for the high conversion capability in the previous work. In this study, it is found that design optimization is required to make spent fuel more proliferation resistant. Performance indices used in this study is not exact parameters. Development and validation of new fuel cycle performance indices should be followed for the reliable design optimization in R&D activities of future reactor concept.

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