THE EFFECTIVENESS OF FAST AND THERMAL SPECTRUM FOR TRU INCINERATION IN SUBCRITICAL SYSTEM

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Abstract

An investigation to compare the relative effectiveness of fast neutron with thermal neutron in a subcritical system has been performed. Accelerator driven thermal and fast neutron systems are modelled on a CANDU reactor and a typical LMR with Pb-Bi coolant, respectively. TRU mixed with Thorium was selected as a fuel in both systems. The ratio of TRU to Thorium is adjusted to make the system subcriticality about 0.97 and the system output power is set to be 1000 MW_{th}. The thermal system was found to have unacceptable beam fluctuation and power peaking variations. The characteristics of thermal neutron are believed not to allow the employment of solid fuel concept in a thermal neutron subcritical system. In addition, the sensitiveness of thermal neutron to the concentration of TRU and fission products is believed to inevitably require on-line refuelling for reducing the beam power fluctuation. From the overall comparison, a fast neutron is concluded to be much better for the operation of the subcritical system.

Introduction

Korea Atomic Energy Research Institute (KAERI) is performing the project to develop an accelerator driven transmutation system, «HYPER (Hybrid Power Extraction Reactor)». As the first step to decide the neutronic characteristics of the HYPER system, a neutron energy spectrum study was performed. Many studies already have been done to decide which neutron spectrum is better for the transmutation. [1,2] However, as most of them were conducted on a theoretical basis, a more realistic investigation has been performed in this study. Two different types of an accelerator driven systems were developed. The thermal neutron system was developed using CANDU design values and the fast neutron system was constructed using typical LMR design data. Pb-Bi was adopted as a coolant for the fast system instead of sodium.[3] TRU mixed with thorium was used as fuel for both systems.

An optimum neutron energy spectrum would be something that minimises or maximises the following objective function,

$$F(\chi) = f(w_a a(\chi), w_b b(\chi), w_c c(\chi), ...) \qquad (1)$$

where,

- χ : neutron energy spectrum
- w : weighting factor for the parameter
- a, b, c, .. : system parameters.

In general, the system parameters to be considered for the determination of the neutron energy spectrum are; 1) transmutation capability, 2) system safety (reactivity coefficient, power shape control), 3) neutron economy, 4) TRU inventory, 5) total heavy metal inventory to be processed, 6) a required accelerator beam power, 7) toxicity variation, etc. The neutron energy spectrum effects on the TRU incineration were analysed based on individual parameters rather than the system performance index expressed in Eq. (1).

System model description

The basic core geometrical specifications for the thermal and fast systems were derived from a CANDU reactor [4] and a typical LMR [5], respectively. The proton energy was assumed to be 1.0 GeV and the beam powers were adjusted to produce 1 000 MWth system power. The composition of TRU was that of spent fuel being depleted up to 33 000 MWD/MTU and having 10 years cooling time. Table 1 shows the weight fraction of each nuclide in TRU.

Table 1.**Nuclide fraction in TRU**

Nuclide	W. Fraction
^{237}Np	0.046
^{238}Pu	0.014
^{239}Pu	0.521
^{240}Pu	0.237
^{241}Pu	0.077
^{242}Pu	0.045
^{241}Am	0.050
^{243}Am	0.008
^{244}Cm	0.002

Thermal Neutron Subcritical System

As it is in the CANDU system, the oxide form was employed as a fuel type for the subcritical thermal neutron system. Thorium was mixed with TRU for the fabrication of the fuel rod (mechanical strength) and for the minimisation of the reactivity swing as the TRU burns up. The geometrical specifications of a fuel rod and unit assembly in radial direction are described in Figure 1, 2, respectively. Total 37 Fuel rods are positioned on concentric circles of which the diameters are 2.9769 cm, 5.7506 cm, and 8.6614 cm.

Figure 1. **Fuel rod for thermal system**

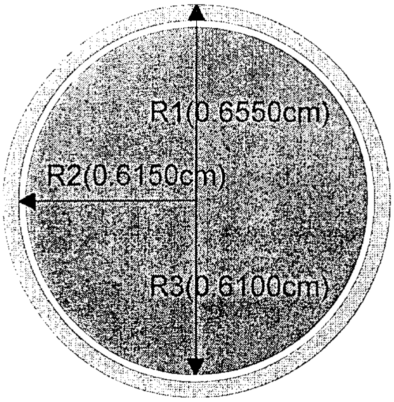
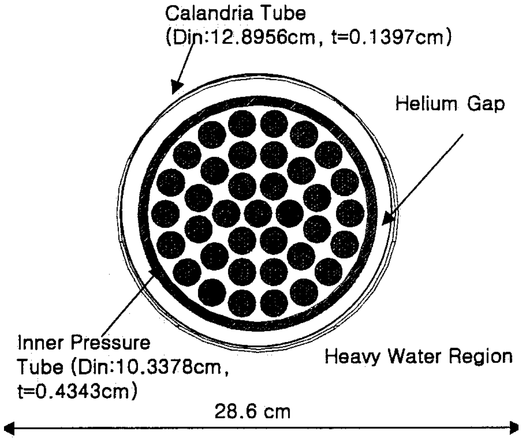


Figure 2. **Unit assembly for thermal system**



The core size was determined from the following conditions and assumptions;

1. Average linear power density of the fuel rod is 24kW/m.
2. Total core shape should be a type of square cylinder.
3. Spallation target region should be placed in the centre with about 1 m diameter.

The number of assemblies required was found to be 244 and the active core height was assumed to be 5 m. The composition of nuclides in the fuel meat was adjusted to make system subcriticality ~0.97 in eigenmode calculation at BOL condition. The fuel composition was determined to be (Th(98.4%)-TRU(1.16%))O_2. The major design parameters are described in Table 2.

Fast neutron subcritical system

The basic design parameters for a fuel rod were obtained from the design values of a typical liquid metal reactor. Fuel rods are arrayed in a triangular shape. Figure 3 shows the array of fuel rods and their geometrical specifications. HT-9 was selected for the cladding and the fuel form was determined to be a solid metal. The assembly consists of 331 fuel rods and its specifications are in Figure 4.

Lead bismuth (44.5Pb-55.5Bi) was employed to remove heat from the system. The reason for the selection of Pb-Bi as a coolant is that Pb-Bi can be used also for the spallation target. The spallation region was placed in the core centre. The reflector assemblies with the size of the fuel assembly and the Pb-Bi filled were loaded around the periphery of the active core region. The shield assemblies were placed in the outer most region of the core.

Figure 3. **Rod array for fast system**

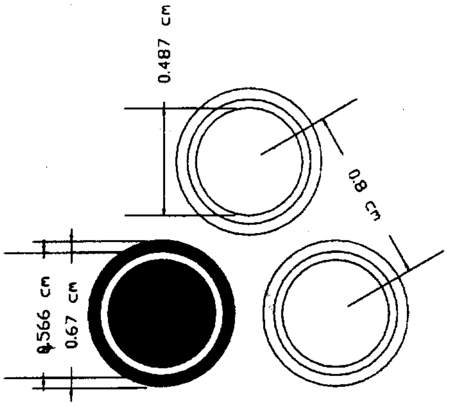
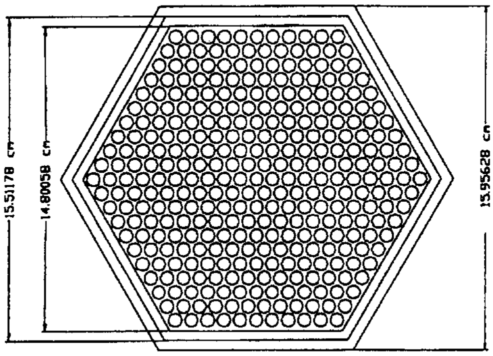


Figure 4. **Assembly for fast system**



For improvements in core safety, most of the fast neutron systems have a core height of 1~1.5 m. In this study, core height was assumed to be 1.0m. Core average linear power density was 16 kW/m which is a very common value in metal fuel.[4] Based on these limitations and using the condition of total core output, the core size was determined. The system was found to have 180 fuel assemblies. Fuel chemical composition was xTh-yTRU-0.1Zr. The sum of x and y was set to be 0.9 and they were adjusted to make the system subcriticality 0.97 in eigenmode calculations at BOL condition. From the calculations, x and y were determined to be 0.72 and 0.18, respectively. Table 2 shows the design parameters of the fast neutron system.

Table 2. **Design parameters of fast and thermal systems**

System Parameter	Fast System	Thermal System
Fuel Rod Design Parameter		
– Fuel Type	Th(0.72-TRU(0.18)-Zr(0.1)	(Th(0.984)-TRU(0.016))O$_2$
– Cladding Material	HT-9	Zr
– Fuel Meat Diameter (cm)	.4887	1.22
– Clad Outer Dimater (cm)	0.67	1.31
– Cladding Thickness	0.052	0.045
Fuel Assembly		
– Array Type	Triangular	Concentric
– Pitch-to-Diameter Ration	1.194	–
– Lattice Pitch (cm)	15.9563	28.6
– No. of Fuel Rods	331	37
Core		
– Power (MWth)	1 000	1 000
– Subcriticality (Eigenmode)	0.97	0.97
– Coolant	Pb-Bi	Heavy Water
– No. of Assembly	180	244
– Active Height (cm)	1.0	5
– Effective Radius (cm)	151.58	252

Target system

The targets for both of the thermal and fast systems were assumed to be Pb-Bi and have cylindrical shapes with the height of 50 cm and the radius of 15 cm. A proton with the energy of 1 GeV was found to produce 26.1 neutrons when it has spallation reactions with Pb-Bi.

Calculational results and discussion

The MONO (Monte-carlo Origen coupling) system was developed for HYPER system analysis at KAERI. The basic logic flow of MONO is very similar to that of other Monte Carlo depletion codes. The thermal and fast systems were loaded uniformly with the fuel assemblies described in section 2.

Figure 5 shows the variation of system multiplication factors as TRU burns up. Both spectrum systems were adjusted to have eigenvalue ~0.97 at zero burnup. However, the multiplication factor of the fast neutron system is larger from the beginning. The build-up of fission products explains the sharp drop of multiplication at the first burnup step. Because of a large absorption cross-section of fission products in thermal energy, the fluctuation of multiplication factors in the thermal system is much more severe than in the fast system. Figure 6 shows the variation of beam power to keep the system power 1 000 MWth. The fast system is believed to have higher multiplication than the thermal system for the same K_{eff} (eigenvalue) condition. In addition, the fluctuation of beam current required to keep the system power constant is supposed to be unacceptable for the thermal system.

Figure 5. **Multiplication factor vs burnup**

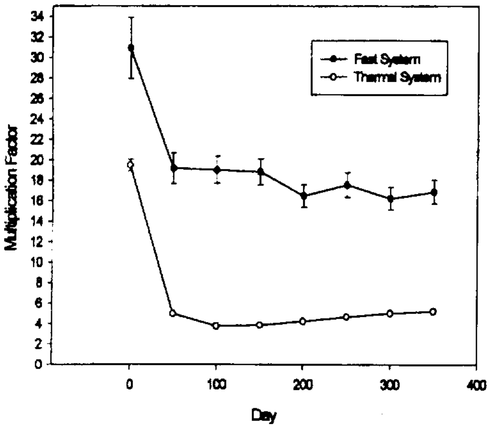


Figure 6. **Beam current fluctuation vs burnup**

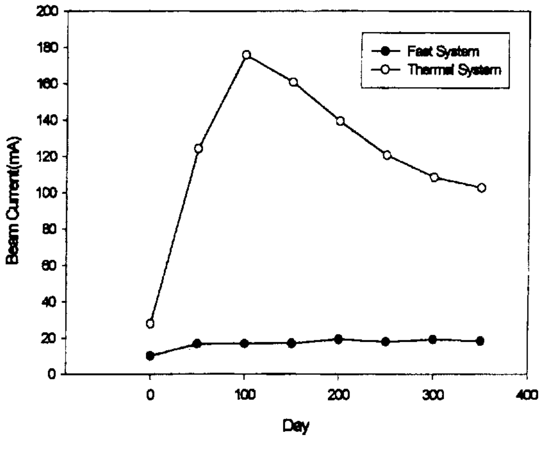


Figure 7 shows the variation of TRU inventory in the system. As expected, the inventory of the thermal system is about 1/3 of the fast system. From the figure, the thermal and fast systems incinerate about 207.13 and 318.01 kg of TRU a year, respectively. U-233 makes a contribution to that difference. U-233 build-up rates are shown in Figure 8. Both systems have almost the same amount of U-233 after one year operation. However, the total amount of U-233 produced in the thermal system is considerably different from that of the fast system. In order to produce 1 000 MW for a year, approximately 360 kg of fissile material has to be consumed. Thus, about 160 kg and 40 kg of U-233 are supposed to be depleted in the thermal and fast systems, respectively. Figure 9 shows the relative toxic variations in the system as a function of TRU burnup. As expected, the thermal system has a higher capture-to-fission ratio and makes TRU more toxic.(higher actinide)

Figure 7. **TRU inventory variation vs burnup**

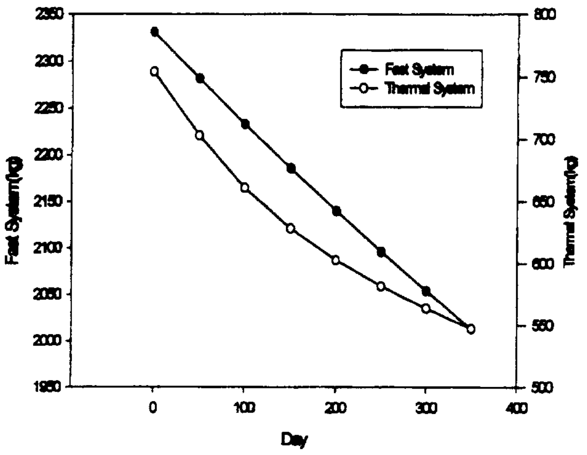


Figure 8. **The amount of ^{233}U produced**

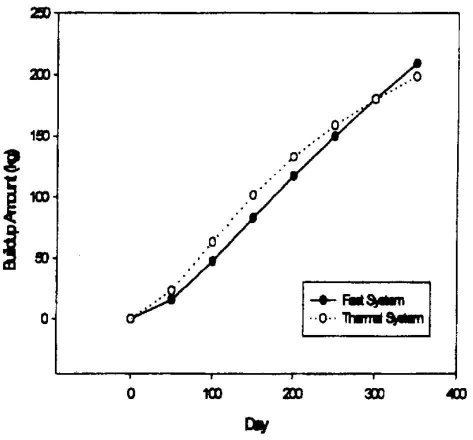


Figure 9. **Relative radioactive ingestion hazard variation**

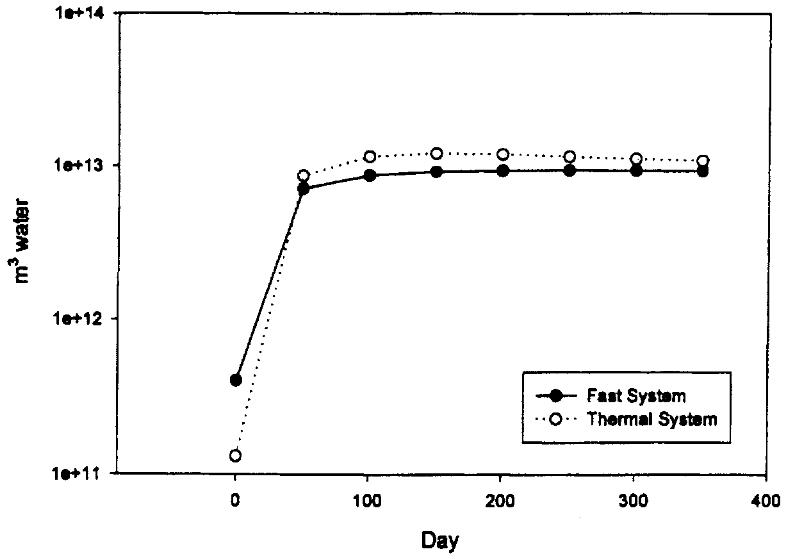


Figure 10 and 11 show the relative assembly power variations versus TRU burnup for fast and thermal systems, respectively. The radial power shape of the fast system is not perturbed considerably as TRU burns up. On the other hand, the burnup of TRU shows a totally different trend in the thermal system. The build-up of fission product prevents the spallation neutrons from being propagated to outer regions of the system. Thus, the power peaking of the thermal system becomes something unacceptably high.

Figure 10. **Relative assembly power variation in fast system**

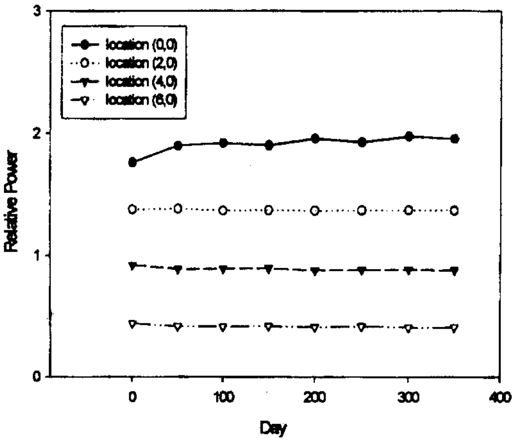
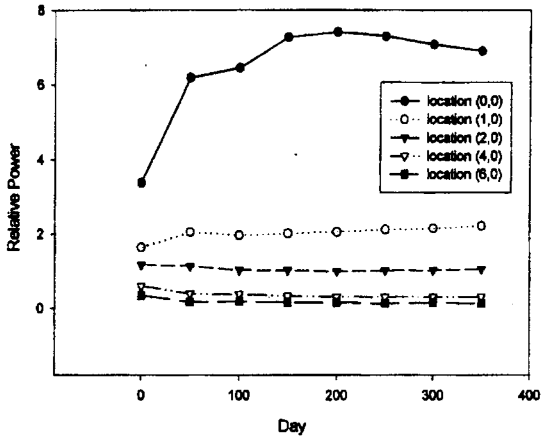


Figure 11. **Relative assembly power variation in thermal system**



Summary and conclusion

A type of system comparison study was performed to investigate which neutron system is more effective for the incineration of TRU. Table 3 shows the results of the comparison.

Table 3. **System performance parameters for TRU incineration**

Parameters	Thermal System		Fast System	
Multiplication Factor	19.469	(BOC)	30.905	(BOC)
	5.216	(EOC)	16.880	(EOC)
Beam Fluctuation (Max/Min)	6.28		1.89	
Transmutation Capability	207.13 kg		318.01 kg	
– TRU(BOC)	754.3 kg	(BOC)	2 331 kg	(BOC)
– TRU(EOC)	547.2 kg	(EOC)	2 012.99 kg	(EOC)
Power Peaking	3.39	(BOC)	1.76	(BOC)
	6.91	(EOC)	1.96	(EOC)
Toxic Variation	1.3×10^{11} m^3 water	(BOC)	4.0×10^{11} m^3 water	(BOC)
	1.1×10^{13} m^3 water	(EOC)	9.3×10^{12} m^3 water	(EOC)

Unacceptable beam fluctuation and power peaking variations of the thermal system come from the characteristics of the thermal neutron. In general, TRU and fission products have larger neutron fission/absorption cross-section in thermal energy than high energy. Therefore, a small change of TRU or fission product concentration disturbs the system multiplication or power shape considerably. Especially, this kind of phenomena becomes much more severe in a subcritical system because large absorption cross-section localises the influence of the external neutron. Figure 11 shows such localisation. As TRU burns up, the radial power shape is skewed to the central region of the system. Zoning of TRU fuel could lessen these kinds of power peaking problems. However, the characteristics of the thermal neutron would not allow the employment of a solid fuel concept in a thermal neutron subcritical system. In addition, the sensitiveness of thermal neutron subcritical system to the concentration of TRU and fission products is believed to inevitably require on-line refuelling for reducing the beam power fluctuation.

From the overall comparison, a fast neutron is concluded to be much better for the operation of the subcritical system.

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