PWR TO ACCELERATOR DRIVEN SYSTEM (ADS) FUEL CYCLE EMPLOYING DRY PROCESS

Masood Iqbal,[1] **Chang-Joon Jeong** and **Gyu-Hong Roh**
Korea Atomic Energy Research Institute
P.O. Box. 105, Yuseong, Daejeon, 305-600 Korea

Abstract

Direct use of spent pressurised water reactor (PWR) fuel into an accelerator-driven system (ADS) has been studied. Spent fuel from a 1 000 MW PWR with 35 000 MWD/T burn-up was considered. Typical design data of ADS was considered in these calculations. The initial system sub-criticality level and the main physics parameters were investigated. The core calculations were performed using the MCNP and MCNAP codes. For accelerator based neutron source strength and accelerator power estimation, the LAHET computer code was used. It is found that the 19.99wt% enriched uranium fuel combined with spent PWR fuel having ratio of 1:1.2 can make ADS sub-critical level of 0.97.

1. Present address: Pakistan Institute of Science and Technology, P.O. Nilore, Islamabad, Pakistan.

Introduction

A great interest has been displayed world-wide during recent years for accelerator driven sub-critical reactors (ADSR), also called sub-critical reactors on hybrid systems, to produce energy and transmute radioactive waste in a, possibly, cleaner and safer way than at present. Currently, many studies have been performed in this field. [1-4] Recently high energy accelerators appear to be a promising way to incinerate heavy actinides. Sub-critical reactors have to be appreciated in view of the general situation and possible future of power generation by nuclear reactors.

Accelerator-driven systems (ADS), which operate in a sub-critical mode and stay sub-critical, regardless of the beam being on or off, can in principle address the safety issues associated with the criticality. Sub-criticality can also improve the controllability of this nuclear system through a simple electronic control of the accelerator. Sub-criticality provides also substantial flexibility in fuel processing and management. However, a significant development of accelerator technology has to be achieved before a construction of the ADS. The high intensity accelerator with a beam power in the range of 10-100 MW has to be available with the stability, efficiency, reliability, operability and maintainability features never demanded before from accelerator technology.

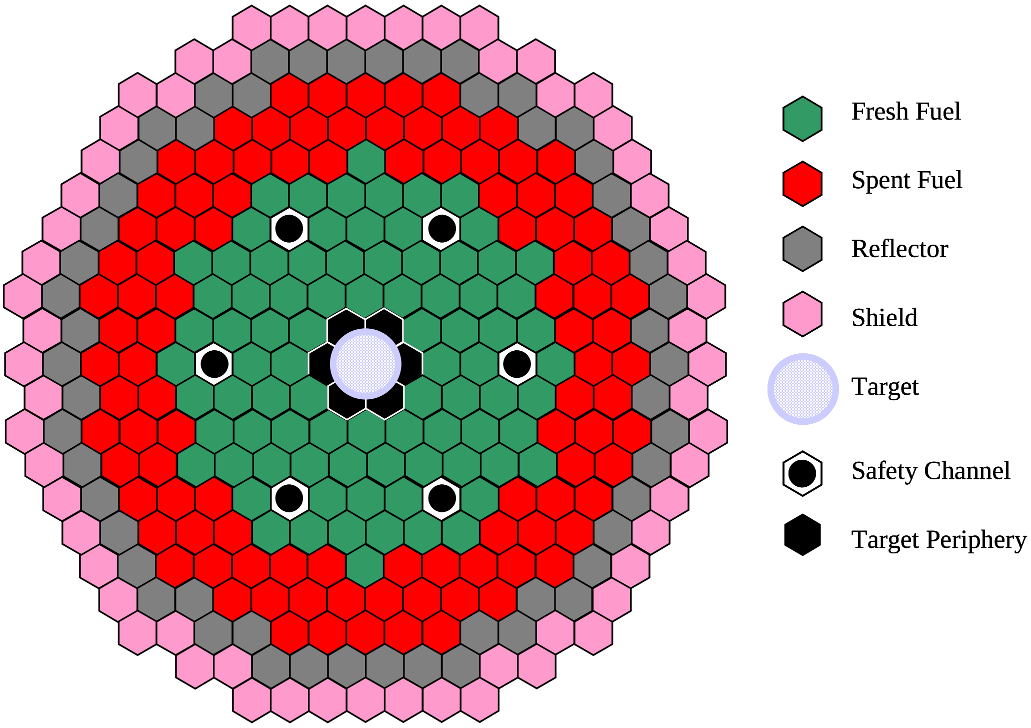
In this study, the spent pressurised water reactor (PWR) fuel is directly used in ADS. Without any reprocessing, an only non-proliferation technique based on a dry fabrication process was employed. To increase the fissile contents, enriched uranium less than 20wt% was mixed to maintain the desired sub-criticality level of 0.97. The main focus of this study is to investigate the fuel cycle in which spent PWR fuel can be used directly in ADS so the minor actinide burning was not considered in this study. The accelerator power with burn-up would be estimated. The neutron spectrum inside the core would also be evaluated.

Modelling of ADS

Reactor core

A hexagonal type of fuel array was considered for the compact core design and to achieve hard neutron energy spectrum by minimising neutron moderation. The reference core consists of 186 hexagonal type fuel assemblies, 54 reflector assemblies, 60 shield assemblies and six emergency safety units. HT-9 is used as cladding material and liquid lead-bismuth as coolant material and a spallation target material. The full core configuration is shown in Figure 1. Fuel is considered as metal fuel combined with 10wt% zirconium. The smear density was taken as ~75%. Fuel assemblies are divided into two zones. One type of fuel is directly form spent PWR fuel after dry fabrication process. Second fuel is of 19.99wt% enriched ^{235}U.

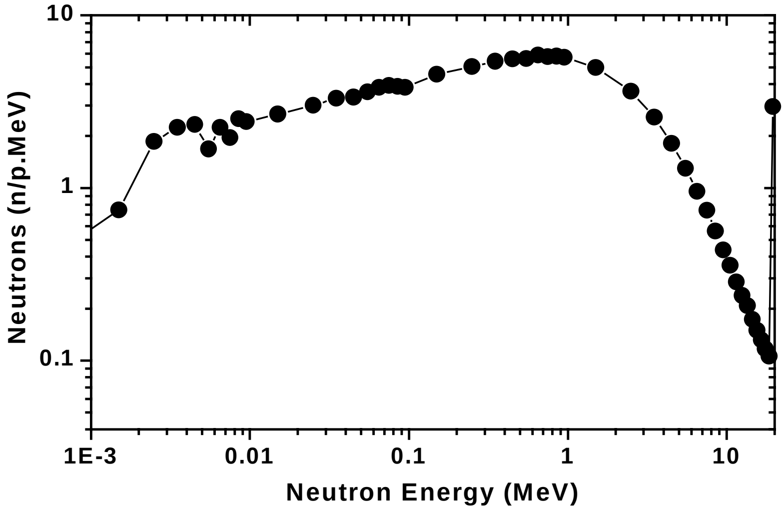
Figure 1. **Full core configuration for ADS**



Spallation target

The difference between ADS and a conventional reactor is the existence of the accelerator beam line and the spallation target region. The spallation target is the most important design parameters, because neutrons generated in the spallation target operate ADS. The physics of spallation is in fact rather complex because of the large range of energies involved and efforts are still going on in various locations to develop models that reproduce all pertinent experimental observations. The spallation process, in contrast to fission, is not an exothermal process: energetic particles are required to derive it. It can, therefore, be triggered in any nucleus, but neutron yield increases with the mass of target nucleus. The particles most commonly used to derive spallation reactions are proton energies around 1 GeV. For this purpose, proton beam of 1 MW (1 GeV, 1 mA) was considered. In these calculations, the same neutron source results were used as Park *et al.* has calculated using the LAHET code. [5-6] The target material is taken as lead-bismuth. The target dimensions are taken as 50 cm in height and in 30 cm diameter. With this combination, 27 neutrons (<100 MeV) are produced per proton, which corresponds to the production rate of 1.7×10^{17} neutron per second in case of 1 mA beam. The energy spectrum from this target material is shown in Figure 2. The peak is around 1 MeV and the average energy is about 7 MeV.

Figure 2. **Neutron energy spectrum from a 1 MW proton beam on lead-bismuth source**



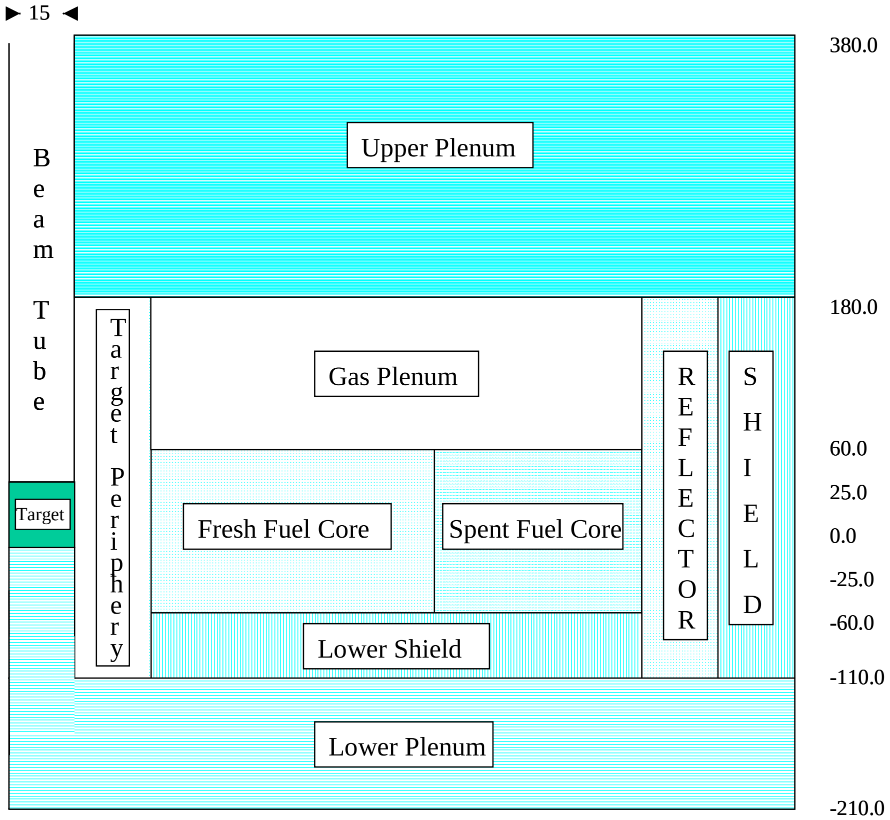
Analysis results

For physics analysis, the MCNP and MCNAP are used. MCNAP is also based on the Monte Carlo theory. It also includes the depletion calculations. The critical and accelerator power calculations were done with both codes and their results compared. The depletion calculations were done using the MCNAP code only. The axial view of the core is depicted in Figure 3. The typical core design data is listed in Table 1. Homogenised material compositions were used per assembly. The core was divided into four regions axially. The cold clean condition was taken.

Table 1. **Typical design parameters of ADS**

Parameter	Value
Assembly	
Ass. Pitch (cm)	19.96
Flow tube outer surface flat-to-flat distance (cm)	19.52
Tube thickness (cm)	0.3556
Tube material	HT-9
Rods per assembly	331
Fresh fuel loading (kg)	7 068
Spent fuel loading (kg)	8 582
Fuel Rod	
Composition (Fuel-Zr)	0.9-0.1
Active core height (cm)	120
Outer diameter (cm)	0.67
Clad material	HT-9
Clad thickness (cm)	0.05
Fuel meat outer diameter (cm)	0.4902
Meat smear density (%TD)	75

Figure 3. **Axial view of the core configuration employed in ADS calculations**



All dimensions are in cm

Fuel composition

Two types of fuel were considered in the designing of the ADS. One fuel is directly from the spent PWR after oxidation reduction process. The second fuel is enriched uranium fuel. These fuels are mixed with natural zirconium to form metallic fuel with ratio of 90:10%. Lead-bismuth was taken as coolant and HT-9 was taken as structural material. In our selection, it was targeted to make the system sub-critical with 0.97 level. With different combinations, the system critical level 0.97 was found with fresh and spent fuel combinations. The fresh fuel loading in this selection is taken as 19.99wt% enriched. The spent fuel requirement for one core is 8.582 tons while fresh fuel loading is 7.068 tons. This requirement of spent fuel is 1/3 of any typical 1 000 MW PWR spent fuel.

Accelerator power

To evaluate the accelerator power for this system, the external neutron source with specification as mentioned earlier, was used in the calculations. In these calculations, it was considered that 27 neutrons (<100 MeV) are produced per proton (1 GeV), which corresponds to the production rate of 1.7×10^{17} neutron per second in case of 1 mA beam. This 1 GeV with 1 mA proton beam presents as 1 MW accelerator power. The accelerator power was calculated after different burn-up steps as well.

Burn-up calculations

For burn-up calculations, MCNAP code was used. First, MCNAP physics calculation results are compared with those of the MCNP. The system K_{eff} with MCNP and MCNAP was 0.96952(0.0004) and 0.96987(0.00041) respectively. The accelerator power calculated from both codes was 10.4 and 10.6 respectively. The energy density per particle calculated from MCNP and MCNAP in 1/12 of the core is shown in Figure 4. It can be seen that the MCNAP slightly underpredicts the energy density than that of MCNP.

Table 2. **Accelerator power requirement and criticality level**

No.	**Burn-up** (days)	$\mathbf{K_{eff}}$	**Accelerator power** (MW)
1	0	0.96987	10.6
2	50	0.96156	12.9
3	100	0.95205	15.7
4	150	0.94442	18.7
5	200	0.93492	21.3
6	250	0.92719	24.2
7	300	0.91935	27.0
8	365	0.90848	31.0

Table 3. **Energy density (KeV/cm^3) in 1/12 of the core**

Location /burn-up	**0** (days)	**50** (days)	**100** (days)	**150** (days)	**200** (days)	**250** (days)	**300** (days)	**365** (days)
[2 0 0]	1.35E+00	1.11E+00	9.10E-01	7.67E-01	6.74E-01	5.91E-01	5.33E-01	4.64E-01
[3 0 0]	1.03E+00	8.41E-01	6.89E-01	5.75E-01	5.01E-01	4.40E-01	3.92E-01	3.39E-01
[5 0 0]	5.68E-01	4.67E-01	3.84E-01	3.22E-01	2.82E-01	2.48E-01	2.20E-01	1.92E-01
[6 0 0]	3.16E-02	2.83E-02	2.50E-02	2.24E-02	2.09E-02	1.97E-02	1.85E-02	1.73E-02
[7 0 0]	1.53E-02	1.37E-02	1.18E-02	1.03E-02	9.63E-03	8.89E-03	8.46E-03	7.70E-03
[1 1 0]	1.44E+00	1.18E+00	9.71E-01	8.22E-01	7.24E-01	6.38E-01	5.77E-01	5.04E-01
[2 1 0]	1.17E+00	9.56E-01	7.81E-01	6.54E-01	5.71E-01	5.00E-01	4.47E-01	3.87E-01
[3 1 0]	8.92E-01	7.25E-01	5.91E-01	4.92E-01	4.30E-01	3.77E-01	3.34E-01	2.90E-01
[4 1 0]	6.57E-01	5.37E-01	4.39E-01	3.68E-01	3.22E-01	2.82E-01	2.51E-01	2.18E-01
[5 1 0]	4.39E-02	3.95E-02	3.49E-02	3.17E-02	2.97E-02	2.80E-02	2.65E-02	2.48E-02
[6 1 0]	1.96E-02	1.74E-02	1.53E-02	1.37E-02	1.27E-02	1.17E-02	1.12E-02	1.03E-02
[2 2 0]	9.60E-01	7.81E-01	6.34E-01	5.29E-01	4.61E-01	4.03E-01	3.58E-01	3.09E-01
[3 2 0]	7.06E-01	5.77E-01	4.69E-01	3.93E-01	3.42E-01	3.00E-01	2.67E-01	2.31E-01
[4 2 0]	5.29E-02	4.74E-02	4.21E-02	3.85E-02	3.60E-02	3.40E-02	3.21E-02	2.99E-02
[5 2 0]	2.37E-02	2.11E-02	1.85E-02	1.68E-02	1.55E-02	1.47E-02	1.38E-02	1.29E-02
[6 2 0]	1.25E-02	1.09E-02	9.46E-03	8.34E-03	7.63E-03	6.99E-03	6.61E-03	6.10E-03
[3 3 0]	4.75E-01	3.91E-01	3.18E-01	2.69E-01	2.35E-01	2.07E-01	1.84E-01	1.59E-01
[4 3 0]	2.82E-02	2.51E-02	2.20E-02	1.98E-02	1.84E-02	1.73E-02	1.63E-02	1.51E-02
[5 3 0]	1.37E-02	1.19E-02	1.04E-02	9.13E-03	8.41E-03	7.84E-03	7.34E-03	6.81E-03
[4 4 0]	1.44E-02	1.26E-02	1.10E-02	9.72E-03	9.00E-03	8.25E-03	7.81E-03	7.12E-03

The sub-criticality level of the system was calculated for one year operation with 1 000 MW reactor power. Also the energy produced by one neutron was calculated to estimate the accelerator power. The system sub-criticality level and accelerator power requirements are listed in Table 2 for each burn-up step. The system K_{eff} and the required accelerator power behaviour with burn-up is shown in Figure 5. Energy density per neutron in each fuel element for 1/12 of the core is listed in Table 3. The radial distribution of the energy density per neutron in one plane is shown in Figure 6

Neutron energy spectrum

Neutron energy spectrum inside the ADS was calculated using MCNP code. The neutron spectrum was averaged over the inner fuel region and outer fuel region separately. Also the full core average neutron spectrum was estimated. The neutron spectrum inside the core is depicted in Figure 7.

Figure 4. **Energy density (KeV/cm^3) in the 1/12 of the core**

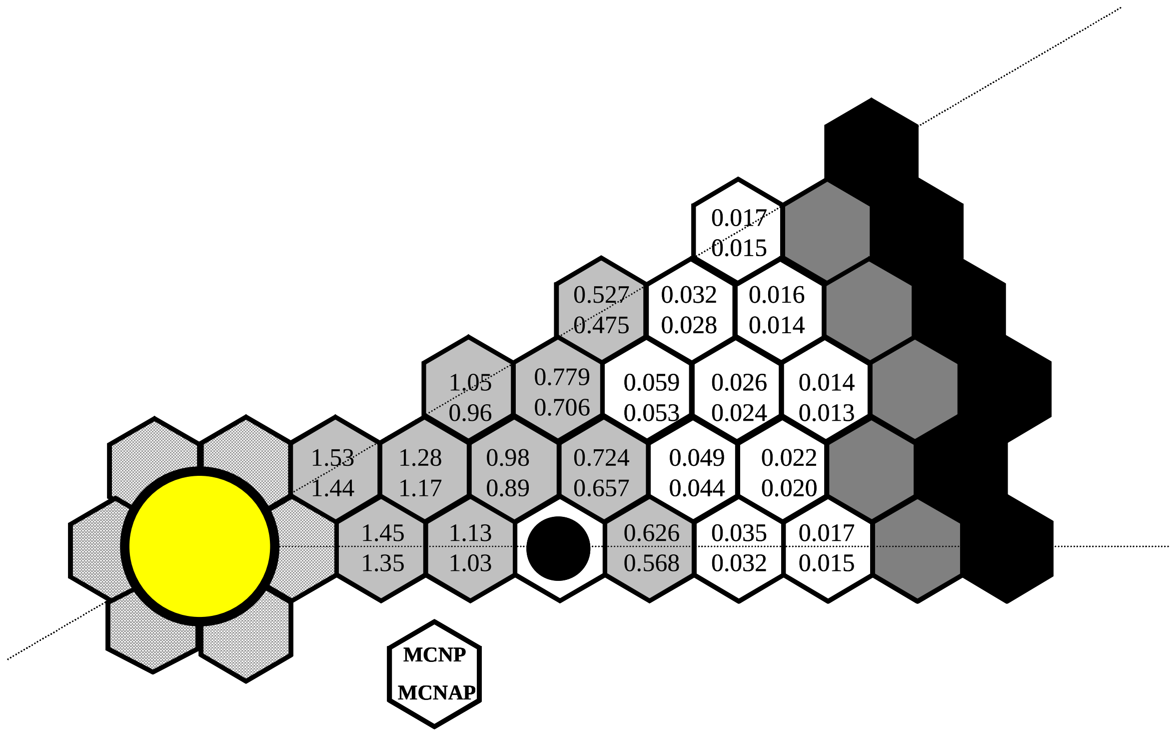


Figure 5. **The behaviour of the system criticality level and the requirement of accelerator power with fuel burn-up**

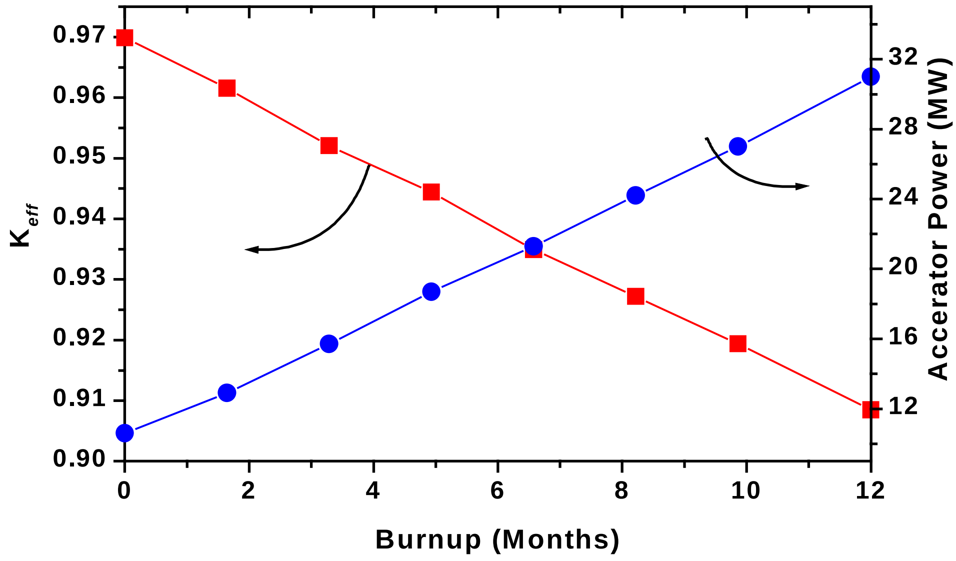


Figure 6. **Radial distribution of energy density per neutron in one plane of the core**

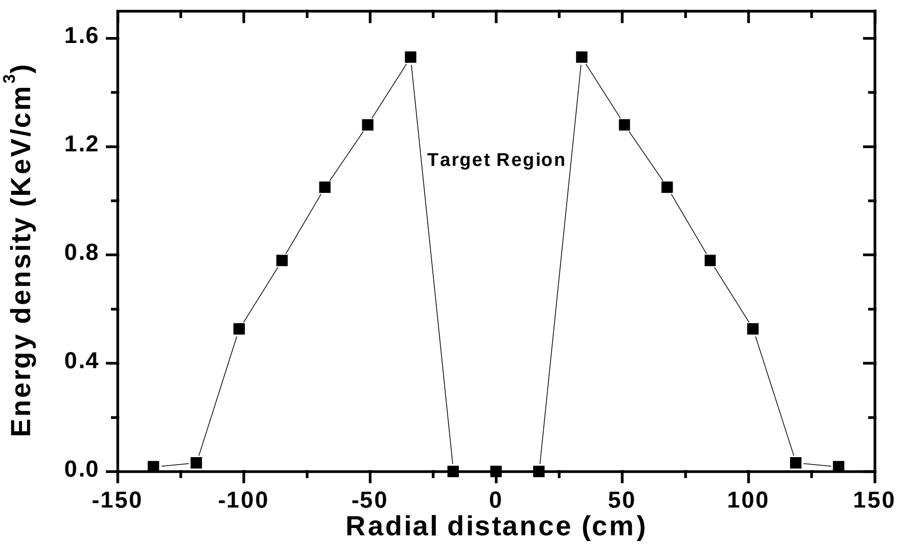
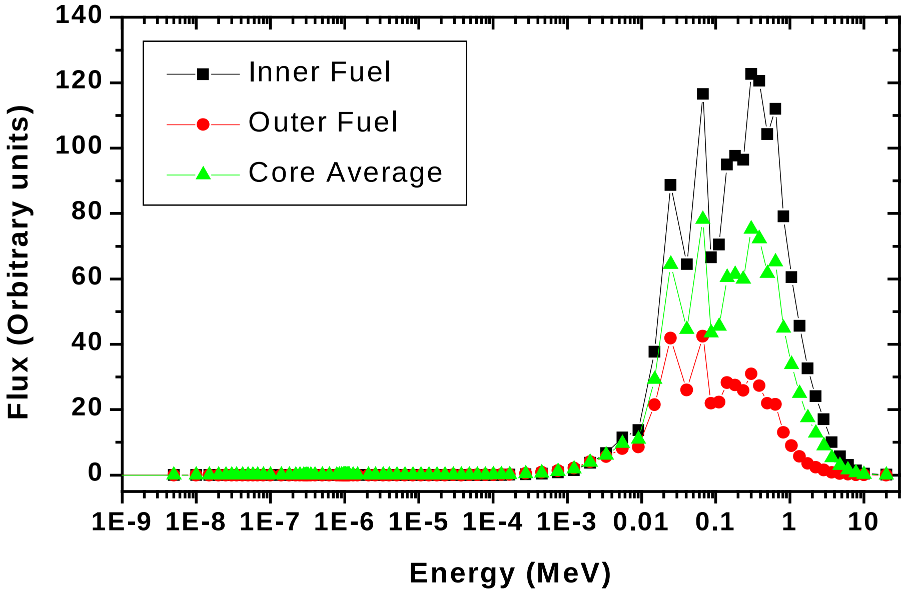


Figure 7. **Neutron energy spectrum in ADS system**



Summary and conclusion

Direct use of spent PWR fuel into an ADS has been studied. The sub-criticality level of 0.97 was achieved after loading a part of the core with enriched uranium fuel. The enrichment and loading of fresh and spent fuel for core was investigated. It was found that fresh fuel of 19.99wt% combined with spent PWR fuel with a ratio of 1:1.2 can make ADS of sub-critical level 0.97. The spent fuel requirement for one core is 8.582 tons while fresh fuel loading is 7.068 tons. This requirement of spent fuel is 1/3 of any typical 1 000 MW PWR spent fuel.

The neutron energy spectrum in the core was also calculated. The neutron spectrum inside core is a fast spectrum. The neutron spectrum in spent fuel is lower as compared to the fresh fuel. It is also because the fresh fuel is inside the core.

The accelerator power was calculated for a system with sub-critical level 0.97. The accelerator power requirement with burn-up was also estimated. The accelerator power calculated by MCNP was 10.4 MW while from MCNAP this value was 10.6 MW.

The burn-up calculations were performed using the computer code MCNAP. The system sub-criticality level and accelerator power was calculated at each burn-up step. These calculations were performed with a step of 50 days. It is found that accelerator power requirement became increased as system sub-criticality level decreased. After one year of operation the accelerator power requirement became 31 MW. This value is very high as compared to the initial requirement. By proper fuel shuffling or fresh fuel loading this value could be optimised.

Acknowledgement

This work has been carried out under the Nuclear Research and Development Programme of the Korea Ministry of science and Technology. Authors also wish to thank Dr. Won-Seok Park, Manager HYPER project KAERI and Dr. Hyun-Chul Lee, for their kind help and technical discussions.

REFERENCES

[1] K. Furukawa *et al.* (1982), *The Combined System of Accelerator Molten-salt Breeder (AMSB) and Molten-salt Converter Reactor (MSCR),* Japan-US Seminar on Thorium Fuel Reactors, NAORA, Japan, October.

[2] C.D. Bowman *et al.* (1992), *Nuclear Energy Generation and Waste Transmutation Using an Accelerator-driven Intense Thermal Neutron Source*, Nucl. Inst. And Meth. A 320 336-367.

[3] F. Venneri, C. Bowman and R. Jameson (1993), *Accelerator-driven Transmutation of Waste (ATW) – A New Method for Reducing the Long-term Radioactivity of Commercial Nuclear Waste*, LA-UR-93-752, Los Alamos Report.

[4] F. Carminati**,** R. Klapisch, J.P. Revol, Ch. Roche, J.A. Rubio, C. Rubbia (1993), *An Energy Amplifier for Cleaner and Inexhaustible Nuclear Energy Production Driven by a Particle Beam Accelerator*, CERN/AT/93-47(ET).

[5] W.S. Park *et al.* (2000), *HYPER (Hybrid Power Extraction Reactor): A System for Clean Nuclear Energy*, Nuclear Engineering Design, 199 155-165.

[6] W.S. Park *et al.* (1999), *TRU Incineration Characteristics of Thermal and Fast Sub-critical Reactors*, Annals of Nucl. Energy, 26 1497-1508.