CONCEPTUAL NEUTRONIC DESIGN OF AN ADVANCED HANARO REACTOR USING THE U3SI2 AND U-MO FUEL

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ABSTRACT

Korea Atomic Energy Research Institute (KAERI) is developing an Advanced HANARO Reactor (AHR) based on the HANARO experiences through its design to operation stages. AHR will be a 20 MW multi-purpose research reactor and loaded with the HANARO fuel assemblies of rod type. It uses U_3Si_2 dispersion fuel with a uranium density of 4.0 gU/cm^3 as the reference fuel. HANARO is optionally considering a core conversion by using high density U-Mo fuel of up to 6.0 gU/cm^3. This paper compares the neutronic characteristics of 4.0 gU/cm^3 U_3Si_2 fuel and up to 6.0 gU/cm^3 U-Mo fuels at the AHR core, which are under an irradiation test at HANARO. The compared parameters are the linear heat generation rate, control rod worth, cycle length and neutron flux.

1. Introduction

Since its first criticality in 1995, the HANARO research reactor has been operated successfully and the number of users and utilizations has been increased rapidly. The demand for its utilization is expected to exceed the capability of HANARO in the near future. It is necessary to prepare in advance for the future demand and improve the experiences obtained from the design to operation stages of HANARO. Therefore, based on the HANARO experiences, the development of an Advanced HANARO Reactor (AHR) was launched in 2003 [1]. Various concepts for the reactor core and structure, and other systems have been studied. The preliminary concept of the development will continue until 2006. This paper presents the conceptual core from the viewpoint of the reactor physics, which is described in section 2 in detail.

We are considering a core conversion of HANARO for an enhanced utilization. The demand for the irradiation holes in the high neutron flux region is already exceeding the capability of HANARO. The irradiation holes such as CT, IR1&2, OR3~6 in Fig. 1 are in the high neutron flux region and are cooled by a forced convection. As IR1 will be occupied by the fuel test loop this year, the demand for the other irradiation holes will be more intense. So a core conversion is necessary for an enhanced utilization, in which some fuel channels such as OR1,2,7,8 will change to serve as irradiation holes [2].

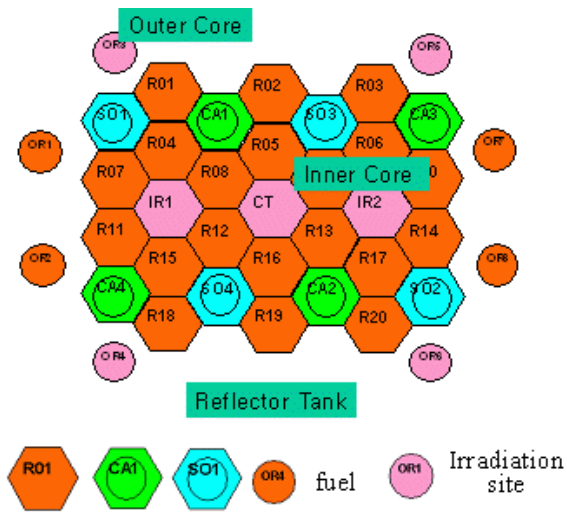

Fig. 1. The core layout of HANARO

The development of nuclear fuel is crucial to the core conversion and the reactor design of a new reactor with a higher performance. The current HANARO fuel is in the form of U_3Si dispersed in the Al matrix with a loading density of 3.15 gU/cm^3. High density fuel is required for compensating for the reduction of the fuel assembly during the core conversion. U-Mo fuel with a high uranium density has been developed for the core conversion of HANARO like other countries. Previous study showed that when a high density U-Mo is used in HANARO, additional irradiation sites are possible with an increased cycle length [2]. As the qualification of U-Mo fuel is delayed, U_3Si_2 fuel of 4.0 gU/cm^3 was selected as a reference fuel in the core design of AHR and it is being irradiated with other U-Mo fuels [3]. As the problem of the U-Mo fuel is being solved, it is time to study the core design of AHR by using U-Mo fuel. We expect that a dispersion fuel with large grain particles and/or a multi-core fuel will show a better performance [3]. Dispersion fuel of a 4.5 gU/cm^3 density and a multi-core fuel of 4 cores are being developed. As the multi-core fuel has up to 4 cores of 2.0 mm in diameter in the aluminum matrix, the multi-core fuel can be equivalent to a dispersion fuel of a 3.0, 4.5, 6.0 gU/cm^3 density. This paper compares the neutronic characteristics of 4.0 gU/cm^3 U_3Si_2 fuel and up to 6.0 gU/cm^3 U-Mo fuels in the core design of AHR.

2. Physics Design of AHR

We are considering a 20 MW multi-purpose reactor with a high performance. The basic design principles are as follows:

. Multi-purpose research reactor with a medium power,
. Adaptation of the HANARO concepts,
. High neutron flux,
. High safety and economics aspects,

. Improvement of the operability and maintainability, and
. Sufficient space and expandability of the facility.

The core design will satisfy the basic design principles while achieving a high neutron flux which is most important in a research reactor. Although the reactor physics design of AHR using the current HANARO fuel could give us a higher neutron flux, the uranium density is too low to obtain a high discharge burnup. The AHR requires a higher uranium density fuel for a higher performance without an economical loss. Two types of fuel assemblies comprising of a hexagonal and a circular fuel assembly will be used at the AHR core, as with HANARO.

The core configuration should be optimized according to its purpose. As AHR is a multi-purpose research reactor, the flux level should be high both at the core and reflector regions. A multi-purpose research reactor in general provides at least one irradiation hole at the core region, in which the fast neutron flux can be high. Reactor core should be as compact as possible to obtain a high neutron flux at the reflector region. The sites of the Control Absorber Rods (CARs) are restricted by the cooling method and the position of the control driving units. An upward forced convection cooling system will be applied to AHR. The CARs are located at the periphery of the core. The number of fuel channels should be optimized for the reactor power. Various options for the reactor core have been studied and the core model in Fig. 2 was selected as the reference.

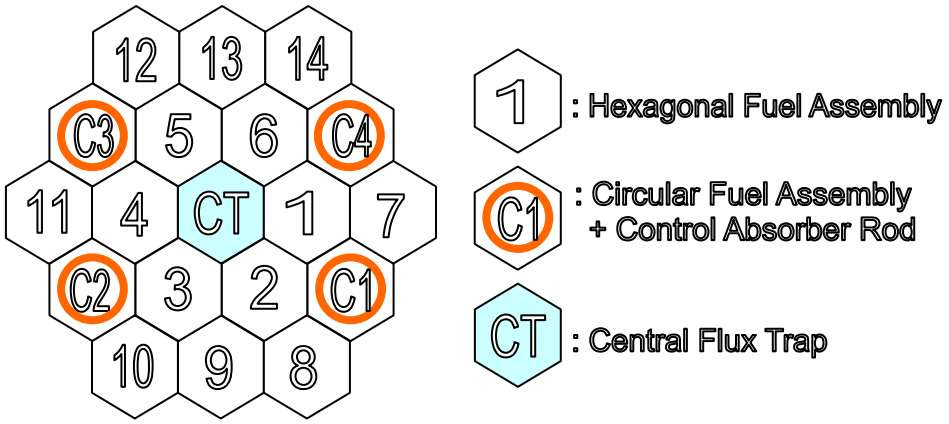

Fig. 2. The core layout of AHR

14 channels are loaded by the hexagonal fuel assemblies, and four channels are loaded by the circular fuel assemblies, and one channel is devoted to the Central flux Trap (CT). The core reactivity is controlled by four CARs made of hafnium which are used as the first shutdown system. The secondary independent shutdown system will be a heavy water drainage system. The number of vertical irradiation holes and horizontal beam tubes at the reflector region will be determined later. The reactivity effect by the irradiation holes is only considered at this design stage. The nominal fission power of AHR is 20 MW and the other design characteristics are similar to HANARO.

Most of the parameters were calculated by using the MCNP [4] code. HELIOS [5] was used for the burnup calculations, in which the 2-dimensional full core model was used. The

maximum unperturbed thermal neutron flux levels (<0.625eV) at the core and reflector regions are estimated to be about 5.03E+14 & 4.36E+14 n/cm^2/sec, respectively. The thermal neutron flux distribution is shown in Fig. 3. The fast neutron flux (>1.0MeV) in the central flux trap is estimated to be about 1.67E+14 n/cm^2/sec.

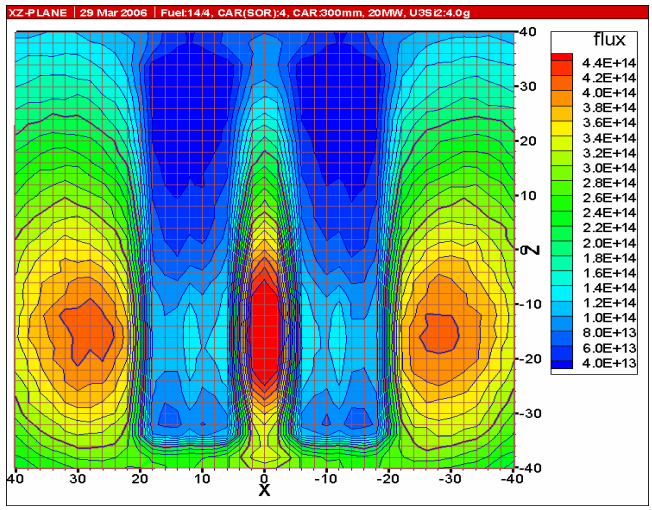

Fig. 3. Thermal neutron flux profile (xy-plane)

The partially inserted CARs cause the maximum Linear Heat Generation Rate (LHGR) to become larger. The peak powers were evaluated for all CARs insertion depths. At the Beginning Of Cycle (BOC), the maximum LHGR was estimated to be 118.6 kW/m and the total peaking factor was 2.54. The flux levels and the peaking factor were estimated for a fresh core. In the equilibrium core, the flux levels become higher and thus the peaking factor will become lower.

A core excess reactivity of up to 102 mk will be provided at the BOC to compensate for the xenon, temperature, power, xenon override, fuel burnup and experimental irradiation loads. This excess reactivity is obtained by loading two new hexagonal fuel assemblies or one hexagonal fuel assembly plus two circular fuel assemblies. The core excess reactivity at the End of Cycle (EOC) will be above 30 mk, in which each 15 mk is reserved for a xenon override and a typical target loading. The total reactivity worth of CARs is about 212 mk and it meets the shutdown margin at the BOC of the equilibrium core. It is estimated that the reactor can operate at 20 MW without a refueling for 31 days. The moving span of the CARs is shorter than that of HANARO. The average burnup values in the equilibrium core at BOC and EOC were about 28 and 35%U-235, respectively. The average discharge burnup of the fuel assemblies is about 58%U-235.

3. Comparison of the U_3Si_2 and U-Mo fuel

Physics analysis for a comparison of the U_3Si_2 and U-Mo fuel will be limited to the fuels currently being tested in HANARO. Analyzed fuels will be 4.0 gU/cm^3 U_3Si_2, 4.5 gU/cm^3

U7Mo and 6.0 gU/cm^3 U7Mo. The compared physics parameters are the distributions of the LHGR, CAR worth, cycle length and neutron flux.

Total 576 fuel rods of a standard type will be used in the current design of AHR, which results in the core uranium loading of 51.1 kgU. The number of fuel rods is equivalent to the number of fuel rods in HANARO after a core conversion from the view point of the thermal-hydraulics. HANARO uses two types of fuel rods to obtain a more uniform power distribution in the fuel assembly. If AHR has a large power peak, the reduced rod as HANARO or other remedies will be used. As U-Mo fuel has enough density for a high discharge burnup, the combination case of 4.5 gU/cm^3 and 6.0 gU/cm^3 fuel could be an option for flattening the power distribution. Table 1 shows the core characteristics of the reference and U-Mo cores such as the core uranium loading, maximum LHGR, CAR worth, etc.

Table 1. Core characteristics of reference and U-Mo cores

Core (Fuel spec.)	Core U loading [kg] (Ratio)	Max. LHGR [kW/m]	k_{eff} (All Rod Out) CAR worth [mk]	Cycle length [days]	Average discharge burnup [%U-235]
Reference (4.0 gU/cm^3, U_3Si_2)	51.1 (1.00)	118.6	1.26931 183.5	31	57.7
Core A (4.5 gU/cm^3, U7Mo)	57.5 (1.12)	118.8	1.26745 179.8	34	56.4
Core B (6.0/4.5 gU/cm^3, U7Mo)	66.6 (1.30)	115.3	1.27346 174.0	40	56.9
Core C (6.0 gU/cm^3, U7Mo)	76.6 (1.50)	124.2	1.28742 165.4	50	61.6

The cycle length and discharge burnup are estimated at the same refueling condition as the reference. Core A is similar to the reference with 4.0 gU/cm^3 U_3Si_2 fuel except for the cycle length. The use of Mo instead of Si requires a further uranium loading of 12% for the same excess reactivity. The increased neutron absorption by the usage of Mo and further uranium loading decreases the CAR worth. The change of the CAR worth is less than 10% at the uranium loading increase of 50%. The increase of the cycle length is proportional to the amount of uranium loading. The maximum LHGRs except for Core C are below 120 kW/m, which is selected as the physics design limit of the LHGR at the current design stage. A reduction of maximum LHGR is required for Core C.

The neutron flux distributions are compared at the fresh core state. The flux at the bare core without the irradiation facilities are calculated in 2x2x2 cm rectangular mesh size. As the thermal/fast flux in the CT are calculated at its center, the average thermal flux within the CT is lower and the average fast flux is higher. The flux at the core with the irradiation

facilities are calculated at each irradiation hole. The CARs are located at an estimated average position during the reactor operation. Table 2 shows the maximum neutron flux in the CT and the reflector region.

Table 2. Maximum neutron flux [n/cm^2/sec] in the CT and reflector region
(Core models without the irradiation facilities)

Region \ Core	Reference	Core A	Core B	Core C
CT, fast flux (>1.0MeV)	1.67E+14	1.56E+14	1.52E+14	1.50E+14
CT, thermal flux (<0.625eV)	5.03E+14	4.65E+14	4.54E+14	4.27E+14
Reflector, thermal flux (<0.625eV)	4.36E+14	4.40E+14	4.29E+14	4.31E+14

Although the design of the irradiation facilities such as the vertical holes and the beam tubes is very important, their arrangement will not be fixed at an early stage. At the current design stage, it is important to obtain a core model to provide a high and broad flux at the reflector tank. This requirement is fulfilled by a compact core design, which requires a large reactivity load. The reactivity load of 20 mk in the AHR design is reserved for the facilities. When the same facilities as HANARO are arranged at the reflector thank, the reactivity effect in the AHR core is 18.5 mk. HANARO spends only 13.9 mk for its facilities. The neutron flux at the important facilities of the reference and U-Mo cores are compared in Table 3. For the comparison of Table 3, the irradiation holes at a forced convection area are loaded with dummy fuel assemblies and the other holes are filled with light water. The neutron fluxes are the averaged values from -35.0 to +35.0 cm from the axial core center. The neutron fluxes of the U-Mo cores are lower as the results of Table 2.

Table 3. Comparison of the neutron fluxes [n/cm^2/sec] at the irradiation facilities

Irradiation facilities \ Core		Reference	Core A	Core B	Core C
		Thermal/Fast flux (<0.625eV)/(>1.0MeV)	Difference (%)	Difference (%)	Difference (%)
Vertical holes (Forced convecion)	OR3	2.25E+14/3.02E+12	-1.4/+5.9	-2.4/+2.5	-3.8/+0.7
	OR4	2.18E+14/3.22E+12	-2.0/+2.1	-3.8/-4.1	-4.9/-2.0
	OR5	2.15E+14/3.03E+12	-1.8/+1.6	-2.3/+7.1	-3.6/+5.3
	OR6	2.33E+14/3.01E+12	-1.3/+8.7	-2.7/-0.3	-3.7/+13.8
	Average	- / -	-1.6/+4.6	-2.8/+1.3	-4.0/+4.5
Vertical holes (Natural convection)	IP4	2.53E+13/ -	-2.7/ -	-3.2/ -	-6.0/ -
	IP5	5.31E+13/ -	-1.4/ -	-1.7/ -	-4.1/ -
	IR11	8.06E+13/ -	-1.8/ -	-3.3/ -	-5.1/ -
	IR15	9.86E+13/ -	-0.4/ -	-2.8/ -	-3.1/ -
	NTD1	1.87E+13/ -	-1.4/ -	-2.0/ -	-3.4/ -
	NTD2	2.03E+13/ -	-0.5/ -	-2.4/ -	-3.7/ -
	NAA1	2.53E+13/ -	-2.3/ -	-2.4/ -	-3.5/ -
	NAA3	1.16E+14/ -	-2.8/ -	-2.4/ -	-4.8/ -
	HTS	5.23E+13/ -	-2.3/ -	-2.4/ -	-4.2/ -
	Average	- / -	-1.7/ -	-2.5/ -	-4.0/ -
Beam tubes	ST1	1.51E+14/ -	-1.4/ -	-2.3/ -	-4.0/ -
	ST2	1.90E+14/ -	-2.3/ -	-1.9/ -	-5.3/ -
	ST3	2.28E+14/ -	-0.9/ -	-2.0/ -	-4.7/ -
	ST4	1.70E+14/ -	-1.1/ -	-1.2/ -	-4.2/ -
	NR	3.09E+13/ -	-0.6/ -	-3.8/ -	-6.5/ -
	IR	2.51E+14/ -	-1.5/ -	-3.4/ -	-4.9/ -
	CN	5.85E+13/ -	-2.4/ -	-3.5/ -	-5.3/ -
	Average	- / -	-1.5/ -	-2.6/ -	-5.2/ -

4. Concluding Remarks

Based on the experiences of HANARO's construction and operation, we succeeded in obtaining a conceptual core with a high performance. This conceptual core provides a high fast and thermal flux at the experimental sites. The high discharge burnup will provide us with a high economic benefit. The U-Mo cores are favorable for a longer cycle core. The reference core could be replaced by the core with U-Mo fuel without a significant loss of the flux performance. The core design is based on proven technology through HANARO in principle. As we adopt a high density fuel for AHR, we should qualify the 4.0 gU/cm^3 U_3Si_2-Al fuel or up to 6.0 gU/cm^3 U7Mo fuel. As the considered fuels for AHR will be used for a core conversion of HANARO, the fuel will naturally be demonstrated in HANARO.

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