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Conceptual Nuclear Design of a 20 MW Multipurpose Research Reactor

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Abstract: This paper presents some of studied results of a pre-feasibility project on a new research reactor for Vietnam. In this work, two conceptual nuclear designs of 20 MW multi-purpose research reactor have been done. The reference reactor is the light water cooled and heavy water reflected open-tank-in-pool type reactor. The reactor model is based on the experiences from the operation and utilization of the HANARO. Two fuel types, rod and flat plate, with dispersed U_3Si_2-Al fuel meat are used in this study for comparison purpose. Analyses for the nuclear design parameters such as the neutron flux, power distribution, reactivity coefficients, control rod worth, etc. have been done and the equilibrium cores have been established to meet the requirements of nuclear safety and performance.

Keywords: *HANARO, AHR, MTR, MCNP, MVP, HELIOS, dispersed U_3Si_2-Al, open-tank-in-pool, equilibrium core, BOC, EOC, shutdown margin*.

I. INTRODUCTION

Research reactor has been widely utilized in various fields such as industry, engineering, medicine, life science, environment, etc., and now its application fields are gradually being expanded together with the development of its technology. The utilization of a research reactor is related to the necessary and essential technologies of information technology, nano-technology, biotechnology, environmental technology and space technology. Hence, R&D in the area of research reactor utilizations has a large effect on the growth of a national industry.

Vietnam has a plan to construct a high performance multipurpose research reactor (MRR) to satisfy increasing utilization demands. So, the pre-feasibility studies to build a new MRR have been set [1,2]. The Korea Atomic Energy Research Institute (KAERI) has considerable experience in the research reactor technology through the design, construction, operation and utilization of the High-flux Advanced Neutron Application Reactor (HANARO) of 30 MWth. Therefore, in the framework of the joint study on the pre-feasibility of MRR with KAERI, a model of Advance HANARO Reactor (abbreviated as AHR) has been developed to meet the requirements for use in the future [3,4]. Based on the model of AHR, a similar reactor model with plate fuel type MTR (abbreviated as MTR) has been also developed for the purpose of comparison between the two fuel types.

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II. NUCLEAR DESIGN REQUIREMENTS

A. General

A research reactor should be designed in conformity with user's requirements. The reactor type, power, and core configuration, systems and the installed experimental facilities depend on the application purposes and on the construction and operation costs as well. Hence, a flexible design is an indispensable feature when considering a future expansion of its experimental facilities.

The major basic principles to develop models of the conceptual design are as follows.

1) Multipurpose research reactor with a medium power

2) High ratio of flux to power

3) High Safety and Economics

4) Sufficient spaces and expandability of the facility for various experiments

Fundamentally, a research reactor should be designed to achieve the established safety objectives such as the IAEA standards. The nuclear design requirements for the AHR and MTR are considered in two parts, functional and performance requirements.

B. Funtional Requirements

The functional requirements aim to ensure the safety of the reactor and ready to operate in all conditions.

1) The power coefficient and temperature and void coefficients of the reactivity should be negative for all operational and accident conditions.

2) The shutdown margin should be at least 10 mk (1mk = $\Delta k/k \times 1/1000$) regardless of any changes in the reactor condition.

3) The second reactor shutdown system should be prepared to improve the reactor safety and its shutdown margin should be at least 10 mk for all relevant design basis fault sequences.

4) The excess reactivity should be at least 10 mk at the end of cycle for conducting experiments and 15 mk for the Xe override.

C. Performance requirements

The performance requirements aim to ensure meeting the requirements of use and high economic efficiency.

1) The neutron flux variation at the irradiation sites and the nose of the beam tubes should be stable with a 5% variation regardless of a loading or unloading of samples.

2) The axial neutron flux gradient in the reflector region should be within ±20% over a length of 50 cm.

3) The maximum fast and thermal neutron fluxes at an irradiation site inside the core should be greater than $1.3\text{x}10^{14}$ and $4.0\text{x}10^{14}$ n/cm^2-s, respectively. The maximum thermal neutron flux at the reflector region should be greater than $4.0\text{x}10^{14}$ n/cm^2-s.

4) The maximum local power peaking factor should be less than 3.0.

5) The average discharge burn-up of the fuel assembly should be higher than 50% of the initial fissile heavy material, U-235.

6) The reactor operating cycle should be longer than 30 days.

III. CORE CONCEPT

The basic concepts of the reactor are the light water cooled and moderated, heavy water reflected, open-tank-in-pool type research reactor and 20 MW power cores loaded with two typical geometric kinds of fuel elements as rod or flat plate.

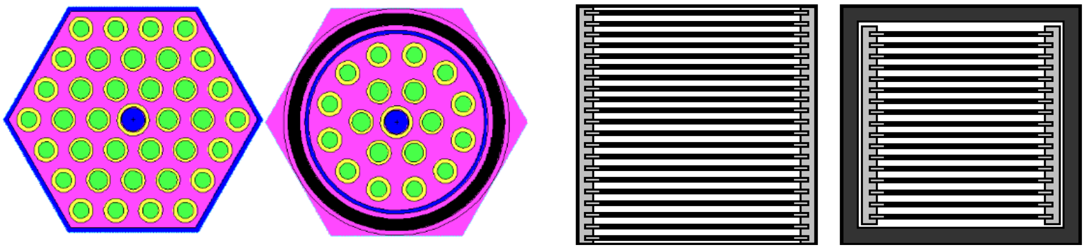
A. Fuel

Fuels selected for the design are commercial or commercial available. The fuel meat is fabricated by a dispersion of high density U_3Si_2 particles into pure Al with its uranium enrichment 19.75 wt%. Two kinds of fuel assemblies in the core are standard fuel assembly and control fuel assembly (including control rods inside fuel assembly). Some specifications of the fuel elements and assemblies are listed in Table I and their cross sectional views are showed in Figure 1.

Table I. Specifications of the fuel element and assembly

Fuel element		
Meat content	66.0w/%U, 5.2w/%Si, 28.8w/%Al	72.8w/%U, 6.0w/%Si, 21.2w/%Al
Fuel length (mm)	700.0	700.0
Fuel diameter/width×thickness (mm)	6.35/5.49 (In/Out)	64.0/51.4x0.61 (S/C)*
Fuel density (g/cm^3)	6.06	6.6
Cladding thickness (mm)	0.76/1.19 (In/Out)	0.37/0.445 (In/Out)
Cladding material	Al	Al
Fuel assembly		
Shape	Hexagonal	Square
Element number	36/18 (S/C)	21/17 (S/C)

** S/C: Standard fuel assembly / Control fuel assembly*



a) AHR standard b) AHR Control c) MTR standard d) MTR control

Fig. 1. Cross sectional view of AHR and MTR standard and control fuel assemblies

B. Core Arrangement

The core has 23 lattices that consist of fourteen standard assemblies, four control assemblies and three in-core irradiation sites. The heavy water reflector tank of 200 cm in diameter and 120 cm in height surrounds the core. The reactor regulating system shares control rods with the reactor protection system. Fig. 2 shows the horizontal cross sectional view of the AHR and MTR cores. Some specifications of the cores are listed in Table II.

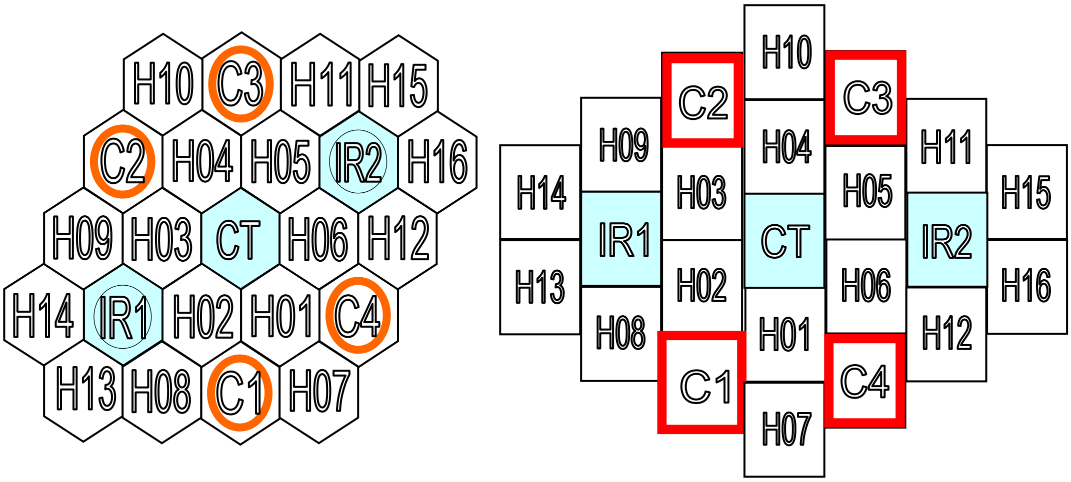


Fig. 2. The horizontal cross sectional view of the AHR and MTR cores

Table II. The specifications of the cores

Reactor type	AHR	MTR
Core volume (cm^3)	1199.5 x 70	1527.7 x 70
Fuel assembly Number	16 S + 4 C	16 S + 4 C
Control rod Number	4	4
Absorber material	Hf	Hf
Total weight U-235 (kg)	9,87	10,12
In-core irradiation sites	3	3

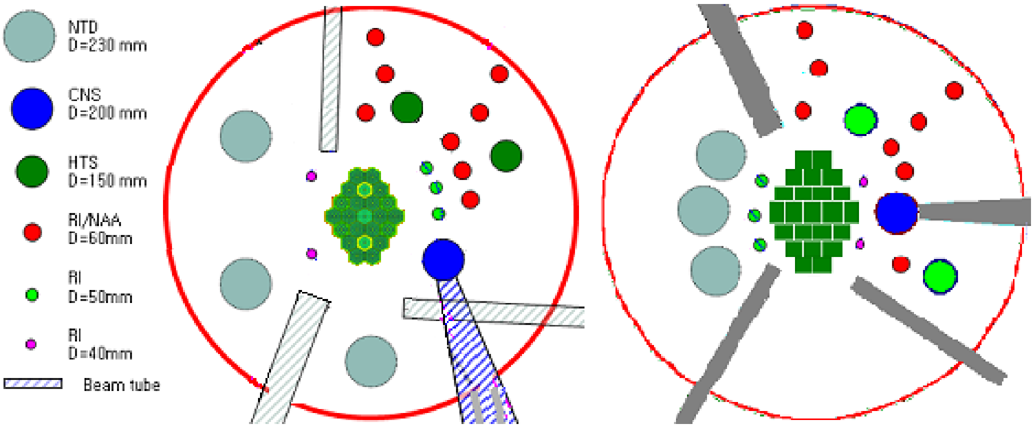


Fig. 3. The layout of the experimental sites of the AHR and MTR

IV. NUCLEAR ANALYSIS

To confirm that the conceptual cores satisfy the functional and performance requirements, nuclear analyses are performed for fresh core and equilibrium core with several code systems such as MCNP [5], MVP [6], HELIOS [7], etc.

A. Fresh Core

The basic analysis of the core characteristics was performed for the fresh core with and without irradiation facilities.

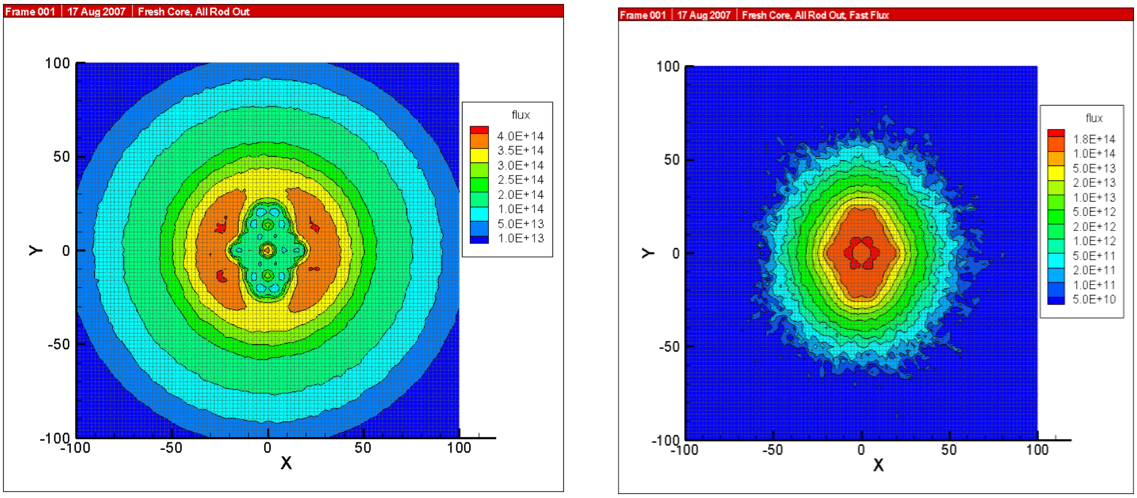
The core configuration should be designed to meet the functional and performance requirements. The neutron flux at the in-core irradiation sites and the reflector region of the cores without irradiation facilities was calculated by the MCNPX code [8] using a mesh tally. On the other hand, the power distribution, the reactivity of the core and the reactivity worth of control rods were also assessed to meet the requirements. Two core configurations with one and three in-core irradiation sites were proposed. Although the first configuration (with one irradiation site) is better in the fuel saving point of view, the configuration with three in-core irradiation sites was selected to meet predicted utilization of in-core irradiation in the future.

As the ultimate goal of a research reactor is its utilization, the irradiation facilities should be designed in conformity with the user's requirements. The required irradiation facilities should be located at proper positions to maximize neutron utilization and minimize reactivity effect. Based on the neutron flux distribution of the reflector region, the arrangement by their purposes has been studied to achieve the objectives above. Their reactivity worth is considered as a priority because of the influence to the reactor core. Various layouts of the irradiation facilities were proposed, and one of them was selected. To evaluate the stability of neutron flux at the irradiation sites, their neutron fluxes were calculated when the control rods are located at 300 mm and fully withdrawn.

The reactivity effect by the irradiation facilities was estimated to be 20.2 mk and 28.9 mk and the total control rods worth 182.4 mk and 217.7 mk for AHR and MTR, respectively. Table III shows the neutron fluxes at the irradiation facilities. Figure 4 presents the thermal and fast neutron distribution of the AHR fresh core.

Table III. Neutron fluxes at the experimental sites

	Neutron flux [n/cm2/sec](Thermal<0.625eV, Fast>1.0MeV)							
	AHR				MTR			
	Maximum		Average		Maximum		Average	
	Thermal	Fast	Thermal	Fast	Thermal	Fast	Thermal	Fast
CT	4.46E+14	1.46E+14	3.04E+14	9.80E+13	4.01E+14	1.13E+14	2.87E+14	8.06E+13
IR1	3.21E+14	1.18E+14	2.23E+14	8.29E+13	3.37E+14	9.31E+13	2.49E+14	6.76E+13
IR2	3.16E+14	1.20E+14	2.23E+14	8.26E+13	3.33E+14	9.16E+13	2.46E+14	6.65E+13
CNS	8.71E+13	1.15E+12	7.01E+13	8.76E+11	8.49E+13	1.69E+12	6.48E+13	1.24E+12
ST1	1.37E+14	1.96E+12	-	-	1.40E+14	3.23E+12	-	-
ST2	2.40E+14	3.47E+12	-	-	1.79E+14	1.01E+13	-	-
NR	1.28E+14	3.20E+11	-	-	1.28E+14	1.32E+12	-	-
NTD1	4.74E+13	1.13E+11	4.31E+13	8.12E+10	4.93E+13	4.19E+11	4.26E+13	3.19E+11
NTD2	4.63E+13	9.91E+10	4.24E+13	7.60E+10	5.29E+13	4.84E+11	4.57E+13	3.56E+11
NTD3	5.16E+13	2.43E+11	4.70E+13	2.04E+11	4.64E+13	5.21E+11	3.93E+13	3.78E+11
HTS1	6.96E+13	3.42E+11	5.96E+13	2.71E+11	7.02E+13	6.30E+11	5.79E+13	5.03E+11
HTS2	2.23E+13	2.07E+10	1.93E+13	1.39E+10	2.25E+13	2.81E+10	1.97E+13	2.29E+10
NAA1	1.39E+14	4.96E+11	1.20E+14	3.88E+11	1.22E+14	8.15E+11	1.05E+14	6.27E+11
NAA2	4.11E+13	-	3.59E+13	-	4.00E+13	-	3.55E+13	-
NAA3	1.74E+13	-	1.52E+13	-	1.53E+13	-	1.35E+13	-
RI1	3.53E+14	1.47E+13	2.60E+14	9.05E+12	2.31E+14	1.49E+13	1.69E+14	9.28E+12
RI2	3.44E+14	1.42E+13	2.57E+14	8.91E+12	2.18E+14	1.47E+13	1.58E+14	9.13E+12
RI3	2.46E+14	4.03E+12	1.85E+14	2.54E+12	2.10E+14	1.53E+13	1.58E+14	9.56E+12
RI4	2.48E+14	4.23E+12	1.86E+14	2.82E+12	2.03E+14	1.45E+13	1.52E+14	8.92E+12
RI5	2.24E+14	3.12E+12	1.67E+14	2.10E+12	2.15E+14	1.55E+13	1.58E+14	9.51E+12



a) Thermal Neutron Flux

b) Fast Neutron Flux

Fig. 4. Neutron flux profile at the AHR fresh core

B. Equilibrium Core

An equilibrium core is dependent on an operation strategy, so there may be various equilibrium cores according to a reactor operating strategy. In this report, an equilibrium core is proposed and analyzed to meet the established design requirements.

Fuel Management

A candidate model for an equilibrium core can be easily obtained by considering target discharge burnup, cycle length and excess reactivities at begin of cycle (BOC) and end of cycle (EOC). There are many candidate models according to the number of reloaded fuel assemblies and the loading pattern. The equilibrium cores with 2 or 3 fuel assemblies reloaded for an operation cycle (the 9-batch or 6-batch core) are assessed. The 9-batch cores show a high discharge burnup and a good fuel economy, but the cycle lengths are less than 30 days. They look proper for a low utilization condition of the reactor. The 6-batch cores with a cycle length greater than 30 days are suitable for the design requirements, so they are selected for evaluating in detail. In the 6-batch core, three of the standard fuel assemblies or two of the standard fuel assemblies and two of the control fuel assemblies are replaced for an operation cycle, so the whole core will be replaced for 6 cycles according to the loading strategy. There are many loading patterns that they depend on the fuel management strategy. The loading pattern showed in Table IV is evaluated in detail.

Table IV. Loading location of the fuel assemblies for 6-batch cores

Cycle	Assembly Number (standard+control)	Loading Location	
		AHR	MTR
1	2+2	H14,H16,C1,C3	H9,H12,C1,C3
2	3+0	H8,H10,H12	H14,H15,H7 (move H14,H15,H7 to H2,H4,H6)

3	3+0	H7,H9,H11	H13,H10,H16 (move H13,H10,H16 to H3,H5,H1)
4	2+2	H13,H15,C2,C4	H8,H11,C2,C4
5	3+0	H2,H4,H6	H14,H15,H7 (move H14,H15,H7 to H2,H4,H6)
6	3+0	H1,H3,H5	H13,H10,H16 (move H13,H10,H16 to H3,H5,H1)

Once a cycle length and a loading pattern are determined, an equilibrium core is obtained by numerical iterations. The initial core is loaded with the new FAs then the burnup calculations are iterated by the loading pattern until the parameters of burnup and reactivity are stable over 6 cycles. Table V presents the calculated results of the average burnup and reactivity of 6 cycles for different cycle lengths. From these results, it can be concluded that the 36 days cycle for AHR and 34 days cycle for MTR meet the performance requirements.

Table V. Burnup and reactivity of the equilibirum cores

Reactor type	AHR			MTR		
Cycle Length (days)	35	36	37	33	34	35
Average Burnup (%U-235)						
- BOC	23.43	24.02	24.61	22.38	23.04	23.70
- EOC	31.82	32.65	33.47	29.08	29.94	30.81
- Discharge	50.35	51.77	53.18	48.65	49.91	51.17
Reactivity (mk)						
- BOC (no Xe)	111.9	109.9	107.8	87.8	85.8	83.6
- Fuel Depletion	37.5	38.7	39.9	15.1	16.7	18.3
- Xenon Buildup	38.1	38.1	38.0	36.2	36.3	36.3
- Power Defect	3.0	3.0	3.0	3.0	3.0	3.0
- EOC (eq. Xe)	33.4	30.1	26.9	33.5	29.8	26.0
- Shutdown Margin	15.0	17.1	19.6	22.2	24.2	26.4

Power Distribution

The power distribution is strongly dependent on the positions of the control rods and it was checked for all possible positions at 5 cm intervals. The largest maximum linear power of the equilibrium cores was observed at a 300 mm position of the control rods. The power distribution for the equilibrium cores of 6 cycles at a 300 mm position of the control rods was calculated. Table VI shows maximum total peaking factors for the 6 cycles equilibrium cores and Table VII shows the power distributions and peaking factors at the cycle that total peaking factor reaches the maximum value. The maximum local power peaking factor for AHR and MTR are 2.56 and 2.79 respectively.

Table VI. Maximum total peaking factor for the equilibrium cycles

Reactor type	Parameter	Cycle					
		1	2	3	4	5	6
AHR	Position of FA	H02	C2	H01	H03	C3	H04
	Fq(peaking factor)	2.47	2.56	2.5	2.46	2.56	2.49
MTR	Vị trí FA	H09	H04	H01	H11	H04	H01
	Fq	2.69	2.77	2.74	2.76	2.76	2.79

Table VII. Power distribution and peaking factor for equilibrium cores
(cycle 5 for AHR, cycle 6 for MTR)

Location	AHR		MTR	
	Total Power (kW)	Fq	Total Power (kW)	Fq
H01	1117	1.93	1167	2.79
H02	1061	1.72	1158	1.82
H03	1314	2.21	1229	1.96
H04	897	1.58	1092	2.51
H05	1064	1.73	1223	2.02
H06	1305	2.18	1143	1.82
H07	811	1.38	1033	2.12
H08	1071	1.64	1179	2.21
H09	1329	2.37	985	1.67
H10	1063	1.76	1066	2.31
H11	1088	1.65	1213	2.26
H12	1298	2.29	987	1.66
H13	1224	1.78	1137	2.01
H14	991	1.4	1093	1.91
H15	1184	1.57	1170	2.05
H16	1050	1.42	1174	1.96
C1	577	2.44	445	1.28
C2	491	2.04	527	1.55
C3	589	2.56	449	1.29
C4	476	1.95	531	1.56

Reactivity Coefficients

To affirm the inherent safety, the reactivity coefficients should be determined. They include temperature coefficients of fuel, light water and heavy water. Physical changes of water due to a temperature change could be considered in two ways: one is a density change, and the other is a cross section change for a nuclear reaction. There are the gaps of the flow tubes for AHR. The light water in the fuel region is to cool the fuel assemblies, and so called a ‘coolant’ and the light water in the gaps of the flow tubes is called a ‘moderator’. Nuclear characteristics of these two light water regions are somewhat different, and a heat transfer between them is small. Therefore, their temperature variations following a power change are also different, thus the respective temperature coefficients were computed separately. The effect of a spectrum hardening of neutrons following a temperature increase for heavy water is so small that it can be negligible. Table VIII presents the result of temperature and void coefficients. From this result, they are negative (except temperature coefficient of moderator. where almost of arriving neutrons are slowed down) and meet the functional requirements. The temperature variation of moderator is so small, therefore its contribution to power coefficient is small.

Table VIII. Reactivity coefficients of temperature and void

Parameter	AHR	MTR
Fuel temperature coefficient (mk/K)	<-0.002	<-0.02
Light water temperature coefficient (mk/K)		
- Coolant	-0.059	-0.11
- Moderator	0.06	
Light water void coefficient (mk/%)		
0 - 5 %	-1.23	-1.79
5 - 10 %	-1.37	-1.97
10 - 20 %	-1.48	-2.25
Heavy water void coefficient (mk/%)		
0 - 5 %	-1.26	-0.79

V. CONCLUDING REMARKS

From the functional and performance requirements, two reactor models AHR and MTR were proposed and investigated. The reference reactors are the light water cooled and moderated, heavy water reflected and open-tank-in-pool type research reactors with a 20 MW power.

The maximum fast and thermal neutron flux in the core region are greater than 1.0×10^{14} n/cm^{2}s and 4.0×10^{14} n/cm^{2}s, respectively. In the reflector region, the thermal neutron peak occurs about 28 cm far from the core center and the maximum flux is estimated to be 4.0×10^{14} n/cm^{2}s.

For the equilibrium cores, the cycle length is greater than 30 days, the whole core will be replaced for 6 cycles, and the assembly average discharge burnup is greater than 50%. For the proposed fuel management scheme, the maximum peaking factor Fq is less than 3. The shutdown margins by the 1st and 2nd shutdown systems are greater than 10 mk and the temperature coefficients are negative showed the inherent safety feature. The parameters for utilization and for the safety aspects of the reactor respectively meet the performance and functional requirements.

The comparison of cores loaded with 2 different fuel types, AHR and MTR, shows that the AHR fuel type core has a little longer operation cycle and higher discharge burn up as a result. In the safety point of view, the MTR core has an advantage because of shutdown margin, temperature and coolant void coefficients are higher compared to those of AHR core.

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