CONCEPTUAL NUCLEAR DESIGN OF TWO MODELS OF RESEARCH REACTOR PROPOSED FOR VIETNAM

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ABSTRCT: The joint study on the development of a new research reactor model for Vietnam was done. The KAERI (Korea Atomic Energy Research Institute) experts and DNRI (Dalat Nuclear Research Institute) researchers developed an advanced HANARO reactor (AHR), a 20-MW open-tank-in-pool type reactor, upward cooled and moderated by light water, reflected by heavy water and rod type fuel assemblies used. Based on the AHR model, a MTR reactor with plate fuel assemblies was developed.

Computer codes named MCNP and MVP/BURN were used. Major analyses have been done for the relevant nuclear design parameters such as the neutron flux and power distributions, reactivity coefficients, control rod worth, etc. in both with clean, unperturbed core and equilibrium core condition.

In case of AHR model, calculation results using MVP/BURN and MCNP codes were compared with the results using HELIOS and MCNP codes by KAERI experts and they are in a good agreement.

1. Introduction

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

The major basic principles to develop a reference model of AHR and MTR reactors are as follows:

1) Multipurpose research reactor with a medium power
2) Application of the HANARO concepts
3) High ratio of flux to power
4) High Safety and Economics
5) Sufficient spaces and expandability of the facility for various experiments.

The detailed nuclear design requirements for the AHR and MTR are considered in two parts, functional and performance requirements. The functional requirements are:

1) The overall power coefficient of the reactivity shall be negative for all operational and accident conditions.

2) Temperature and void coefficients of the reactivity associated with the fuel and core shall be negative for all operational states and accidents conditions.

3) The shutdown margin should be at least 1% Δk/k regardless of any changes in the reactor condition, by taking into account the worst set of reactivity effects from

experiments and irradiations, and with the most reactive control assembly stuck in its most reactive position.

4) The second reactor shutdown system should be prepared to improve the reactor safety and its shutdown reactivity margin should be at least 1% Δk/k for shutting down the reactor for all relevant design basis fault sequences.

5) The excess reactivity for conducting experiments should be at least 10 mk at the EOC of the reactor.

6) A reactivity of 15 mk for the Xe override should be reserved.

7) The shutdown system should maintain the reactor in a sub-critical condition.

Performance requirements are as below:

1) The maximum unperturbed thermal neutron flux at an irradiation site inside the core and reflector region should be greater than $4.0x10^{14}$ and $4.0x10^{14}$ n/cm^2.s, respectively. The maximum unperturbed fast neutron flux at an irradiation site inside the core should be $1.3x10^{14}$ n/cm^2.s.

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

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

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

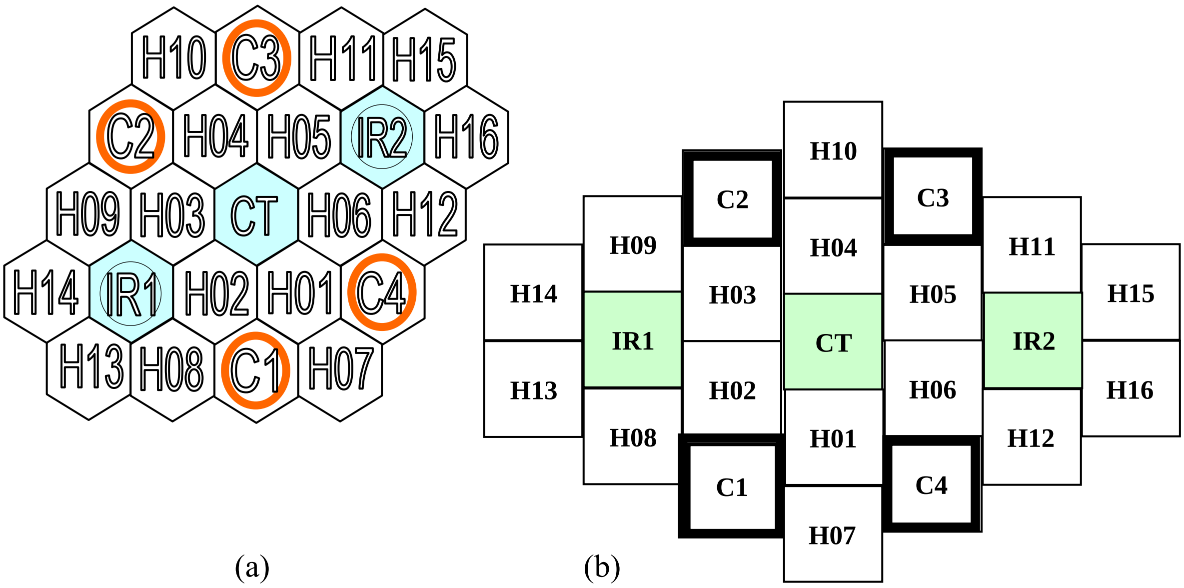
5) The axial neutron flux gradient in the reflector region should be within ±20% over a length of 50 cm.

2. Structure of the proposed reactors

The reactor core is composed of 23 hexagonal lattices (4.48 cm in side) for AHR and square lattices (8.15 cm in side) for MTR, and their active length is 70 cm. The heavy water reflector tank of 200 cm in diameter and 120 cm in height surrounds the core. The nominal core consists of 16 standard fuel assemblies, 4 control fuel assemblies and 3 in-core irradiation sites. 4 control rods are used for both reactor control system and reactor protection system. The active volumes are 1199.5 x 70 cm^3 for AHR and 1527.7 x 70 cm^3 for MTR, the amount of U-235 is 9,87 kg for AHR and 10,12 kg for MTR. Figure 1a and Figure 1b show a horizontal cross sectional view of the AHR and MTR cores, respectively. Table 1 summarizes the main characteristics of the AHR and MTR cores.

Table 1: Main characteristics of the AHR and MTR core

No.	Characteristics	AHR reactor	MTR reactor
1	Core volume, cm^3	1199.5 x 70	1527.7 x 70
2	Number of fuel assemblies	16 + 4	16 + 4
3	Number of control rods	4	4
4	Absorb material of CR	Hf	Hf
5	Amount of U-235, kg	9,87	10,12



(a) (b)

Fig. 1: Cross section view of the AHR core (a) and MTR core (b)

Fuel assemblies of AHR are similar of HANARO reactor in geometry, but with higher Uranium density. Fuel assemblies of MTR are similar of OPAL reactor, but with longer length. Fuel type is U_3Si_2-Al with enrichment of 19.75 % U^{235}.

For AHR, 2 kinds of fuel assemblies are used. A standard fuel assembly is composed of 36 fuel rods and loaded into the hexagonal flow tubes. A control fuel assembly consists of 18 fuel rods and is loaded into the cylindrical flow tubes. Control and shut-off rods of a tubular type are inserted into or withdrawn from the core by moving the surrounding cylindrical flow tubes up and down.

For MTR, 2 kinds of fuel assemblies are used, standard and following control rod fuel assemblies. Each fuel assembly has 8 cm x 8 cm in square section for standard and 6.8 cm x 6.8 cm for following control rod fuel assemblies, and more than 1 m in length. In each fuel assembly there are 21 fuel plates for standard and 17 fuel plates for following control rod fuel assemblies. The Cd wires with 0.04 cm in diameter are sticked on two edges of each fuel assembly as burnable poisoning material for reactivity control.

A Control Absorber Rod (CAR) is a hollow cylinder type with 0.4 cm thickness for AHR and a square cylinder type with a 0.5 cm thickness for MTR. They are made of natural Hf with a 70 cm in length. In a case of AHR, CAR moves up and down while embracing an 18-elements fuel assembly and in a case of MTR, CAR is connected above following fuel assembly in aluminum square cylinder type with a 2.95 cm thickness. When CAR moves up, following fuel assembly moves up to fill up the place of CAR went out.

The concept of using control rods sharing for both the Reactor Protection System (RPS) and the Reactivity Control System (RCS) is adopted. Even with this common control rods concept, the RPS and RCS are independently separated from each other in terms of an instrumentation and control.

The heavy water reflector tank provides 4 tangential beam tubes and a total of 18 vertical irradiation holes with different diameters. Thus 10 holes are selected for a radioisotope production (RI), 3 holes for a neutron activation analysis (NAA), 2 holes for hydraulic transfer system (HTS), 3 holes for a neutron transmutation doping (NTD). There are 4 beam tubes, including 2 for thermal neutron, 1 for cold neutron (CN) and 1 for neutron radiography (NR).

I. 3. Results of calculation and nuclear analysis

For AHR, MVP/BURN and MCNP computer codes were used. Calculation results were compared with the results of KAERI experts using HELIOS and MCNP codes and in a good agreement. It shows that MVP/BURN and MCNP codes are suitable for reactor design calculation. For MTR, only MVP/BURN and MCNP codes were used. The analysis results are described for both a fresh core and an equilibrium core. A fresh core is a core loaded with all new fuels which can not be configured practically. An equilibrium core is dependant on the choice of the reactor owner, and it can be configured differently according to its operation policy.

3.1. Fresh core

Neutron flux distribution. The neutron fluxes were calculated for an unperturbed clean core by the MCNPX code using a mesh tally. The neutron flux is grouped into fast and thermal groups, whose cut-off energies for each of them are above 1MeV and below 0.625eV, respectively. The position of the peak thermal flux in the reflector is predicted to be about 28 cm from the core center, and the fast flux reduces exponentially from the core.

Reactivity of control rods and reactivity effect of irradiation facilities. The calculation results shown in Table 2. The total control rods worth is 178.5 mk and 182.4 mk for AHR and 217.3 mk and 217.7 mk for MTR with and without irradiation facilities in the reflector, respectively. Reactivity effect of irradiation facilities are about 20.2 mk for AHR and 28.9 mk for MTR in case of control rods withdrawn.

Table 2: Reactivity of irradiation facilities and control rods

Reactor type	**Irradiation facility**	**Position of CAR**	**k-eff**	**Reactivity (mk)**	
				CAR	Irradiation facilities
AHR	Non	Full out	1.2570	178.5	20.2
		Full in	1.0266		
	Yes	Full out	1.2259	182.4	
		Full in	1.0019		
MTR	Non	Full out	1.1296	217.3	28.9
		Full in	0.9070		
	Yes	Full out	1.0939	217.7	
		Full in	0.8835		

Neutron flux distribution at irradiation facilities. Table 3 shows that the neutron fluxes at irradiation holes of AHR and MTR are satisfied with application purposes.

Table 3: Neutron flux at irradiation holes

Position	**AHR reactor**				**MTR reactor**			
	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

Power distribution and power peaking factors. Table 4 shows the maximum power peaking factors and linear power following the control rods position of AHR. Such values at position of 300 mm are 2.33 and 96.5 kW/m, respectively. In case of MTR, such values at position of 300 mm are 2.82 and 187.7 kW/m, respectively.

Table 4: Maximum peaking factors and maximum linear power of AHR

Position of control rods (mm)	**Maximum peaking factors (Fq)**	**Maximum linear power (kW/m)**
550	2.02	83.8
500	2.10	87.1
450	2.14	88.8
400	2.26	93.6

350	2.29	94.9
300	2.33	96.5
250	2.28	94.4
0	2.04	84.5

Table 5 shows the power distribution and peaking factors for each fuel assembly with the control rods position at 300 mm. Results show that maximum peaking factors of MTR are even still less than 3.0 but relatively high as 2.82.

Table 5: Power distribution and peaking factors (position of control rods at 300 mm)

Position	AHR reactor			MTR reactor			
	Power	Fr	Fq	Power	Fr	Fq	*
H01	1085	0.98	2.11	1086	1.04	2.80	2.37
H02	1188	1.07	2.13	1117	1.07	1.94	1.89
H03	1193	1.07	2.13	1118	1.07	1.95	1.89
H04	1101	0.99	2.12	1089	1.04	2.82	2.37
H05	1194	1.07	2.16	1129	1.08	1.98	1.91
H06	1193	1.07	2.15	1125	1.08	1.96	1.90
H07	988	0.89	1.90	940	0.90	2.16	1.84
H08	1090	0.98	2.00	1089	1.04	2.35	1.97
H09	1130	1.02	2.10	1088	1.04	2.37	1.99
H10	1054	0.95	2.05	945	0.90	2.20	1.87
H11	1127	1.01	2.03	1125	1.08	2.42	2.04
H12	1099	0.99	1.98	1100	1.05	2.39	2.01
H13	1103	0.99	1.79	1024	0.98	1.87	1.60
H14	1137	1.02	1.83	1017	0.97	1.86	1.60
H15	1136	1.02	1.78	1076	1.03	2.03	1.74
H16	1120	1.01	1.83	1057	1.01	1.82	1.59
C1	506	0.91	2.16	714	0.84	2.04	1.80
C2	524	0.94	2.33	714	0.84	2.04	1.81
C3	520	0.94	2.30	729	0.86	2.10	1.85
C4	510	0.92	2.23	717	0.85	2.03	1.80

Reactivity Coefficients. An isothermal temperature coefficient can be defined as a reactivity effect by the temperature and density changes of all the reactor components such as its coolant, reflector, fuel, etc. In this calculation, it was calculated for temperature changes at every 5 degree in the range of 20 to 50 degree. Table 6 shows the isothermal temperature coefficient. From Table 6, a power defect of -3.0 mk should be considered for AHR and -6.0 mk for MTR.

Table 6: Isothermal temperature coefficient

Temperature [°C]	**H_2O density [gm/cc]**	**D_2O density [gm/cc]**	**Reactivity defect [mk]**		**Coefficient [mk/°C]**	
			AHR	MTR	AHR	MTR
20	0.9983	1.1053	0	0		
25	0.9971	1.1045	-0.2893	-0.8715	-0.0579	-0.1743
30	0.9957	1.1033	-0.6361	-1.7882	-0.0694	-0.1833
35	0.9940	1.1017	-1.0421	-2.7322	-0.0812	-0.1888
40	0.9923	1.1000	-1.5089	-3.7200	-0.0934	-0.1976
45	0.9902	1.0979	-2.0381	-4.7665	-0.1058	-0.2093
50	0.9880	1.0957	-2.6315	-5.8550	-0.1187	-0.2177

Prediction of excess reactivity of the equilibrium core. The reactivity for the equilibrium core should be evaluated to meet the reactivity requirements for an equilibrium core. The expected excess reactivity to compensate the effects for fuel burnup, power defect, Xe accumulation, Xe override and irradiation targets at the beginning of a cycle in an equilibrium state is presented in Table 7. The maximum excess reactivity at the beginning of a cycle (BOC) is expected to be 113 mk for AHR and 93 mk for MTR.

Table 7: Reactivity demands for an equilibrium core

Items	**Excess reactivity (mk)**	
	AHR reactor	MTR reactor
Fuel burnup	35~40	15~20
Power and temperature defect	3	6
Xe accumulation	35~40	33~38
Xe override	15	15
Irradiation targets	5~15	5~15
Total	93~113	74-94

3.2. Equilibrium Core

Fuel management. A candidate model for an equilibrium core can be easily obtained by considering a target discharge burnup, a cycle length and an excess reactivity at a BOC and an EOC. There may be many candidate models according to the number of reloaded fuel assemblies and the loading pattern.

Table 8: Burnup and reactivity for the equilibrium cores of AHR

Parameter	**6-batch core (day)**			**9-batch core (day)**		
Cycle (day)	36	37	38	26	27	28
Average Burnup (%U-235)						
- BOC	24.1	24.6	25.2	26.8	27.7	28.5
- EOC	32.7	33.5	34.3	33.0	34.2	35.2
- Discharge	51.9	53.2	54.6	55.4	57.4	59.2
Reactivity (mk)						
- BOC (eq. Xe)	69.43	67.72	65.80	60.55	57.57	54.77
- EOC (eq. Xe)	29.43	26.72	23.30	28.29	23.60	19.58

Burnups and reactivities of an equilibrium core. Table 9 shows the results of burnups and reactivities with different cycles. It shows that the 36-day cycle for AHR and 34-day cycle for MTR are satisfied with the purpose that average burnup of discharged fuel assemblies are more than 50%, using reactivity is about 30 mk and the working cycle is more than 30 days.

Table 9: Burnups and reactivities of an equilibrium core with different cycles

Parameter	**AHR reactor**			**MTR reactor**		
Cycle (day)	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
Excess 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	36.2	36.3	36.3
- Power coefficient	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. Power distributions for the equilibrium core of 6 cycles were evaluated and shown in Table 10. The maximum total peaking factor Fq of AHR was 2.56. This value is higher than of fresh core as of 2.33. For MTR this value was 2.79 and 2.82, respectively.

Table 10: Maximum peaking factors of the equilibrium cores

Reactor type	**Parameters**	**Cycle**					
		1	2	3	4	5	6
AHR	FA position	H02	C2	H01	H03	C3	H04
	Fq	2.47	2.56	2.50	2.46	2.56	2.49
MTR	FA position	H09	H04	H01	H11	H04	H01
	Fq	2.69	2.77	2.74	2.76	2.76	2.79

Reactivity Coefficients.

+ The fuel temperature coefficient is estimated as being negative and about -0.002 mk/K and -0.001 mk/K for AHR and MTR, respectively. However, this effect is so small that it can be negligible.

+ The coolant temperature coefficient is negative in the temperature range from 293 to 400K and about 0.059mk/K and 0.11 mk/K for AHR and MTR, respectively.

+ The void coefficients for the coolant are negative and about 1.23, 1.37 and 1.48 mk/% for the ranges of 0~5%, 5~10% and 10~20%, respectively for AHR. For MTR, these coefficients are negative and about 1.79, 1.97 and 2.25 mk/% for the ranges of 0~5%, 5~10% and 10~20%, respectively

+ The temperature coefficient for the heavy water due to a density decrease is negative and about 1.26 and 0.79 mk/% in the range of 0~5% for AHR and MTR, respectively. Table 11 summarizes the above-mentioned values.

Table 11: Temperature coefficients

Parameter	**AHR reactor**	**MTR reactor**
Fuel temperature coefficient (mk/K)	<-0.002	<-0.001
Light water temperature coefficient (mk/K)		
- Coolant	-0.059	-0.11
- Moderator	0.060	
Density coefficient for light water (mk/%)		
0 - 5 %	-1.23	-1.79
5 - 10 %	-1.37	-1.97
10 - 20 %	-1.48	-2.25
Density coefficient for heavy water (mk/%)		
0 - 5 %	-1.26	-0.79

4. Conclusion

Major analyses have been done for the relevant nuclear design parameters such as the neutron flux and power distributions, reactivity coefficients, control rod worth, etc. using MCNP, MVP/BURN codes.

For a clean, unperturbed core condition such that the fuels are all fresh and there are no irradiation holes in the reflector region, the fast neutron flux ($E_n \geq 1.0$ MeV) reaches more than 1.0×10^{14} n/cm^{2}s and the maximum thermal neutron flux ($E_n \leq 0.625$ eV) reaches more than 4.0×10^{14} n/cm^{2}s in the core region. In the reflector region, the thermal neutron peak occurs about 28 cm far from the core center and the maximum thermal neutron flux is estimated to be 4.0×10^{14} n/cm^{2}s.

The cycle length was estimated more than 30 days long with a refueling scheme for 6-cycle equilibrium core. The excess reactivities at a BOC and an EOC are satisfied to user's requirements. The assembly average discharge burnup is more than 50% of initial U-235 loading. For the proposed fuel management scheme, the maximum peaking factor Fq was calculated less than 3.0. The shutdown margins by the 1st and 2nd shutdown systems were estimated more than 1%. Both the isothermal temperature coefficient and the power coefficient were negative, so the AHR and MTR cores are characterized as being inherently safe.

It was shown that AHR model is better than MTR model in the economic aspect, but the inherent safety of MTR model is higher than of AHR model.

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