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Calculation of critical core configurations of a research reactor using MTR, IRT-4M, VVR-KN fuel assemblies

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Abstract: This paper presents calculation results to determine critical core configurations and a minimum number of fuel assemblies (FAs) or uranium mass of a research reactor loaded with three types of FAs such as MTR, IRT-4M and VVR-KN. The MCNP5 code and ENDF/B7.1 library were applied to estimate characteristics parameters of the fuel types and the whole core. Infinitive multiplication factor k_{inf}, neutron flux distribution and neutron spectra of the fuels were calculated. The reactor core configurations with three fuel types were modeled in 3-dimensions, and then the effective multiplication factors k_{eff}, relative radial power distribution of each configuration were also evaluated. From calculation results, twelve fuel loading schemes were chosen based on lowest uranium mass or smallest number of FAs loaded into the core. In addition, two full core configurations using VVR-KN and MTR FAs and consisting of beryllium reflectors, vertical irradiation facilities, horizontal neutron beam ports, etc. have been proposed for further consideration in thermal hydraulic calculations and safety analysis.

Keywords: *Research Reactor, MTR, VVR-KN, IRT-4M, critical core configuration, beryllium reflector, MCNP5 code.*

I. INTRODUCTION

A new research reactor (RR) with multi-purpose and high-power must be designed in conformity with safety requirements as well as effectiveness in its utilization. The selection of reactor type, power level, fuel type and core configuration, technological systems and experimental facilities depends on application purposes. The core design for the 15-MWt Kijang RR (KJRR) using MTR FAs and beryllium reflector was discussed in [1]. This reactor equipped with vertical irradiation facilities but without horizontal neutron beam ports. MTR FAs were also used for the core design and initial criticality calculations of the 5-MWt Jordan Research and Test Reactor (JRTR) using heavy water as the neutron reflector of the core [2, 3]. The VVR-KN FAs were used in the core design calculation for conversion of the 10-MWt WWR-K RR from highly enriched uranium (HEU) to low enriched uranium (LEU) [4]. In this reactor, light water and beryllium have been used as the neutron moderator and reflector, respectively.

Vietnam has a plan to construct a high-flux multi-purpose RR for the Centre for Nuclear Energy Science and Technology (CNEST), so study on the conceptual design of a new 10-MWt RR has recently been carried out under a national research project framework.

In this work, MCNP5 radiation transport code [5] was used to determine characteristics parameters including neutron fluxes, neutron spectra and infinitive multiplication factor of

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the FAs. The whole core calculations were conducted to estimate effective multiplication factors and neutron flux distribution or relative power distribution. The reactor core structures with beryllium reflector, horizontal neutron beam tubes, vertical irradiation positions, etc. were fully modeled and calculated at steady state condition and room temperature (~ 20^0C).

MCNP5 code and ENDF/B7.1 library were already validated for the Dalat Research Reactor (DRR) using 92 LEU VVR-M2 FAs for design and start-up calculation. The calculation results showed good agreement with experimental data during start-up of the DRR with total LEU fuel [6, 7].

The effective multiplication factors and the number of loaded FAs or uranium mass of each critical core configuration were determined. The commercial MTR, Russian IRT-4M and VVR-KN fuel types are LEU fuels with 19.75% of ^{235}U. Some core configurations were chosen for the first criticality based on the minimum number of FAs or the mass of uranium loaded into the reactor core.

II. METHOD AND CALCULATION MODELS

MCNP5 code is a general purpose, continuous energy, generalized geometry, time dependent and coupled neutron/ photon/ electron Monte Carlo transport code [5]. The neutron energy regime is from 10^{-11} to 20 MeV for all isotopes and up to 150 MeV for some isotopes. The capability to calculate k_{eff} eigenvalues for fissile systems is also a standard feature of the code.

Three types of FAs (MTR, IRT-4M and VVR-KN) and 12 core configurations were modeled in detail using the MCNP5 code and the nuclear data library ENDF/B7.1. Neutron thermal scattering data S(α, β) with energy under 4 eV for light water, beryllium and graphite at room temperature were used for steady state conditions.

Specifications (geometry and materials) of the three FA types are listed in Table I and their cross section views are shown in Fig. 1. The FAs were modeled with exact geometry in 3D models with reflective boundary [2, 3, 4].

Table I. Specifications of the three FA types

Parameter	MTR	IRT-4M		VVR-KN	
Number of fuel elements (FE) in each fuel assembly (FA)	21	6	8	5	8
Fuel shape	Plate	Square	1 cylindrical 7 square	Hexagonal	1 cylindrical 7 hexagonal
Thickness of FE, mm	1.27	1.60		1.60	
Fuel meat	0.51	0.70		0.70	
Fuel cladding	0.38	0.45		0.45	
Length of fuel meat, mm	640	600		600	
Fuel composition	U_3Si_2-Al	UO_2-Al		UO_2-Al	
Enrichment of ^{235}U, %	19.75	19.75		19.75	
Mass of ^{235}U in each FA, g	403.5; 336.3 218.6; 159.7	263.8	300	197.6	248.2
Fuel density, g/cm^3	4.8; 4.0 2.6; 1.9	4.97		2.8	
Nuclear concentration, 10^{24} atom/cm^3	5.201E-02	1.052E-02		5.961E-02	
^{234}U	9.884E-06	2.468E-05		1.581E-05	
^{235}U	2.429E-03	2.515E-03		1.417E-03	

^{238}U Aluminum Oxygen Silicon	9.736E-03 3.161E-02 - 8.221E-03	1.007E-02 6.741E-02 2.521E-02 -	5.669E-03 3.830E-02 1.420E-02 -
Fuel cladding	Al (SAV1)	Al (SAV-1)	Al (SAV-1)

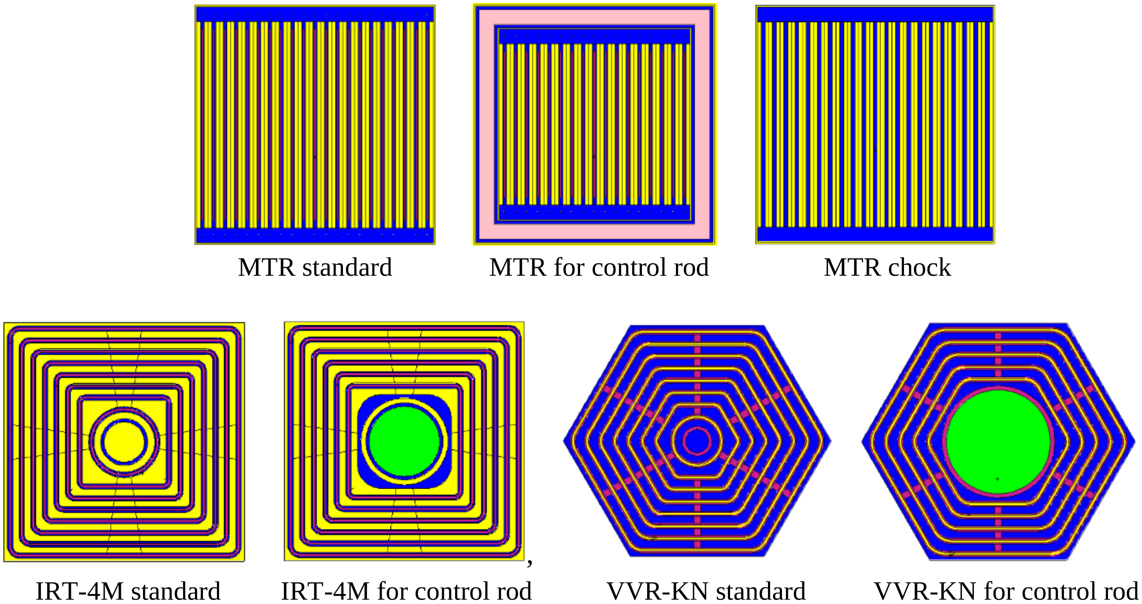


Fig. 1. MTR, IRT-4M and VVR-KN standard FAs and FAs for control rods, respectively.

A. Initial core configuration

All FAs were modeled in true geometry at radial and axial direction, and reflected boundary condition was applied. The IRT-4M with 6 tubes and VVR-KN with 5 tubes are FAs for control rods, which were modeled with a water ring at the center.

At initial core configuration, step by step each FA was loaded around center of the core and made a symmetry shape until the reactor reached criticality in case with or without a neutron trap at the reactor core center. The top and bottom of all FAs were modeled with homogeneity of materials including water and aluminum.

An arrangement of FAs in the reactor core was mainly in light water media and the core has one or two layers of berrylium reflector located outermost of the core. Each berrylium rod of the reflector has the same dimension of FA. In this work, only two cores with MTR and VVR-KN fuels were fully structured for further study on thermal hydraulics and safety analysis.

B. Calculation results and discussions

1. Infinitive multiplication factor

Table II presents the calculation results of infinitive multiplication factors of 3 FA types with different uranium densities in MTR fuel and different number of fuel tubes/ elements in IRT-4M and VVR-KN FAs. KCODE card and initial spatial distribution of fission points with KSRC card in MCNP5 code were applied for all calculation cases. In order to get a standard deviation smaller than 0.008%, total 2.0×10^5 particles were used in the criticality calculations for fuels.

Table II. Calculation results of infinitive multiplication factor k_{inf}.

Fuel assembly		k_{inf}
MTR fuel density (g/cm^3)	4.8	1.64599 ± 0.00007
	4.8 (Cd)	1.43014 ± 0.00007
	4.0	1.62327 ± 0.00007
	2.6	1.54662 ± 0.00006
	1.9	1.46579 ± 0.00006
IRT-4M fuel	6 tubes	1.63229 ± 0.00007
	8 tubes	1.64837 ± 0.00007
VVR-KN fuel	5 tubes	1.61735 ± 0.00008
	8 tubes	1.65153 ± 0.00008

2. Relative radial thermal neutron flux distribution

Fig. 2 shows the obtained results of the radial thermal neutron flux distribution in relative unit of the three FA types from fuel assembly's center to outside. The present work only calculates the neutron flux distribution on fuel layers.

The energy of thermal neutron in the calculation has value from 10^{-11} to 6.25×10^{-7} MeV. Basically, thermal neutron flux is highest at the moderator region and lowest at the center of fuel meat. Therefore, the optimal determination of the fuel volume relative to the moderator volume depends on a number of factors including the uranium enrichment, neutron spectrum and flux distribution or reactor power. In addition, the efficiency of the fuel rods and fuel assemblies in the core is changed correspondingly to the reactor operation time.

The radial neutron flux peaking factors of the three FA types are shown in Table III with different distance of each fuel element. IRT-4M with 6 tubes (IRT-6T) and VVR-KN with 5 tubes (VVR-5T) have 2 and 3 light water rings, respectively.

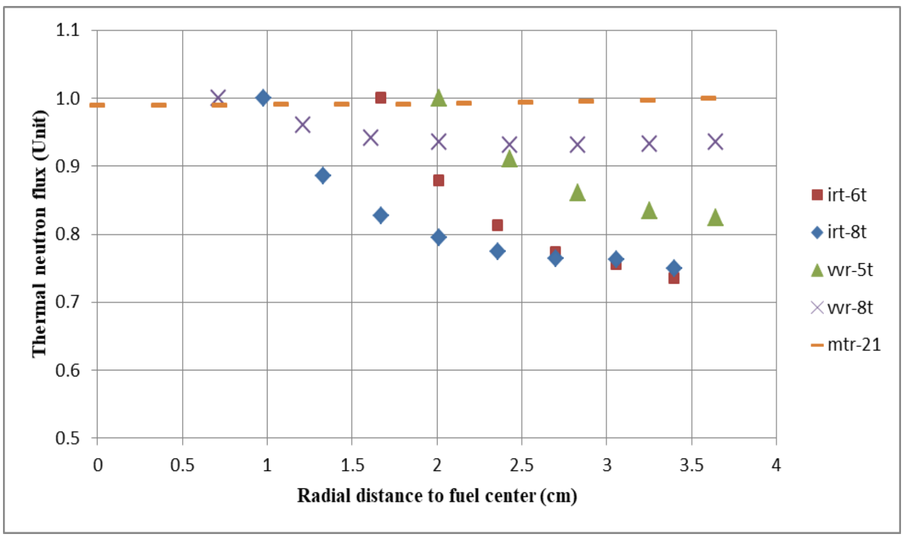


Fig. 2. The relative radial thermal neutron flux distribution of MTR, IRT-4M and VVR-KN FAs.
(IRT-6T and IRT-8T are IRT-4M with 6 and 8 tubes, respectively; VVR-5T and VVR-8T are VVR-KN with 5 and 8 tubes, respectively; MRT-21 is MTR fuel with 21 plates)

Table III shows that maximum relative thermal neutron flux peaking factors of k_{inf} are 1.360, 1.212 and 1.010 for IRT-6T, VVR-5T and MTR fuels, respectively.

Table III. Radial flux peaking factors of the three FA types.

Radius (cm)	VVR-8T	VVR-5T
0.71	1.057	-
1.21	1.015	-
1.61	0.996	-
2.01	0.988	1.129
2.43	0.985	1.028
2.83	0.984	0.971
3.25	0.986	0.941
3.64	0.988	0.931
Max./Min. (*)	**1.074**	**1.212**
Radius (cm)	**IRT-8T**	**IRT-6T**
0.98	1.220	-
1.33	1.080	-
1.67	1.009	1.211
2.01	0.969	1.065
2.36	0.945	0.984
2.70	0.933	0.936
3.06	0.930	0.915
3.40	0.915	0.890
Max./ Min. (*)	**1.334**	**1.360**

Radius (cm)	MTR (4.8 g/cm^3)
0	0.990
0.36	0.990
0.72	0.990
1.08	0.991
1.44	0.991
1.80	0.992
2.16	0.992
2.52	0.993
2.88	0.995
3.24	0.997
3.60	1.000
Max./ Min. (*)	**1.010**

(*) Maximum relative thermal neutron flux peaking factors of k_{inf}. It means the ratio of maximum/ minimum radial flux peaking factor of each FA type.

3. Neutron spectrum

Neutron spectra of the standard FAs are shown in Fig. 3. It can be seen that in full range of energy from 10^{-11} to 10 MeV with 108 neutron energy groups, the difference of neutron spectrum results from data library is insignificant. Difference of maximum peaks in thermal energy range between the 3 FA types is about 5% and the highest value is of MTR fuel. In epi-thermal and fast energy range, the difference between the 3 FA types is insignificant.

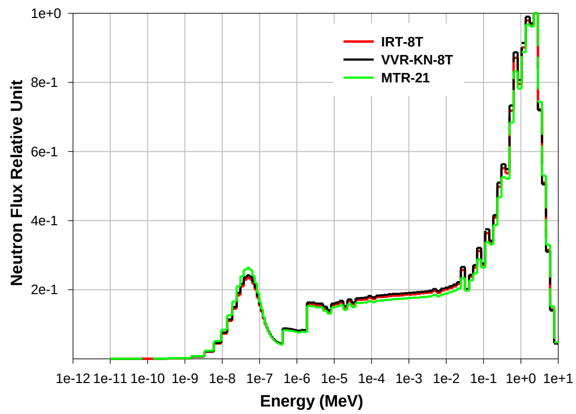


Fig. 3. Neutron spectra of MTR, IRT-4M and VVR-KN FAs.

4. Effective multiplication factors

a) Critical configuration using MTR FAs

Fig. 4 and Fig. 5 show the horizontal cross section of the reactor core. The core model by MCNP5 includes not only a beryllium reflector but also a light water pool tank. The core shape is of 7×9 rectangular grid cells (58.16 cm width and 69.64 cm length) with its active height of 64.0 cm and beryllium reflector with thickness of about 7 cm.

First case: the initial core is configured using FAs with 4 different densities of 1.9, 2.6, 4.0 and 4.8 g/cm^3. The core is of with and without the central neutron trap.

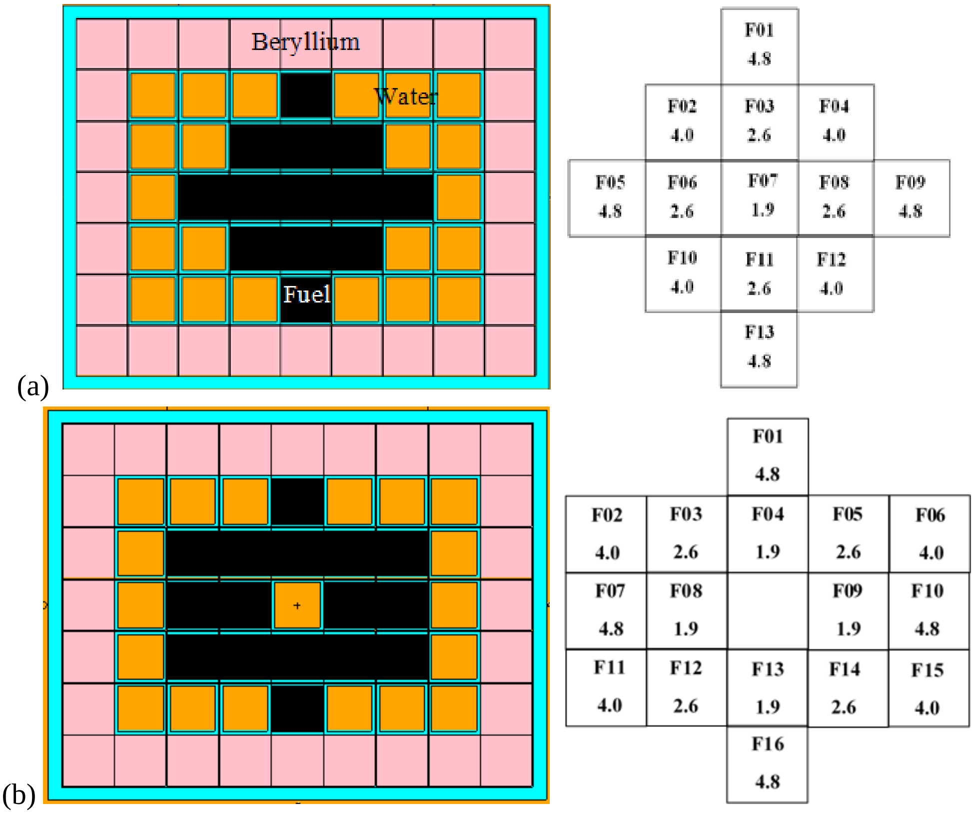


Fig. 4. Core configurations contain 13 (a) and 14 (b) MTR FAs with different density.

Since the FAs for the initial core have different densities, hence they have different uranium content, the configuration will be chosen for the first criticality based on the following criteria:

- The minimum number of FAs loaded into the core.

- The minimum mass of uranium loaded into the core.

- The uniformity of the FAs distribution in the core.

Second case: the initial core is configured using FAs with density of 4.8 g/cm^3. The core is without the central neutron trap. Cadmium wires with a radius of 0.02 cm were mounted at each end of each fuel plate as burnable poison to control the reactor reactivity.

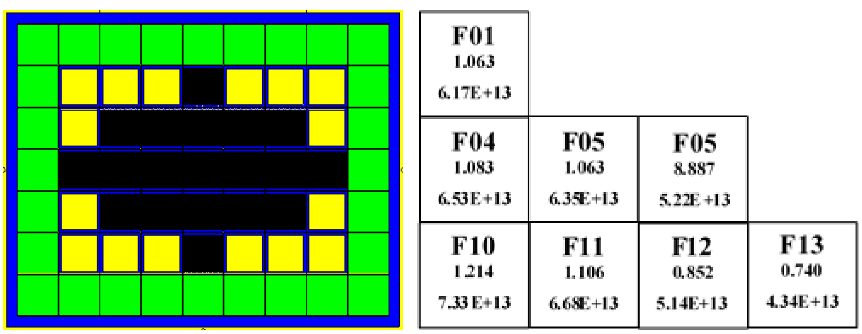


Fig. 5. Core configuration with 19 MTR FAs (left) and relative power distribution, average thermal neutron flux in ¼ core (right).

b) Critical configuration using IRT-4M Fas

The core is composed of 8×10 lattices (60.0 cm × 74.98 cm) with its active length of 60.0 cm and surrounded by the beryllium reflector (Fig. 6).

c) Critical configuration using VVR-KN FAs

The core is a cylindrical shape with its active length of 60.0 cm and surrounded by the beryllium reflector (Fig.7).

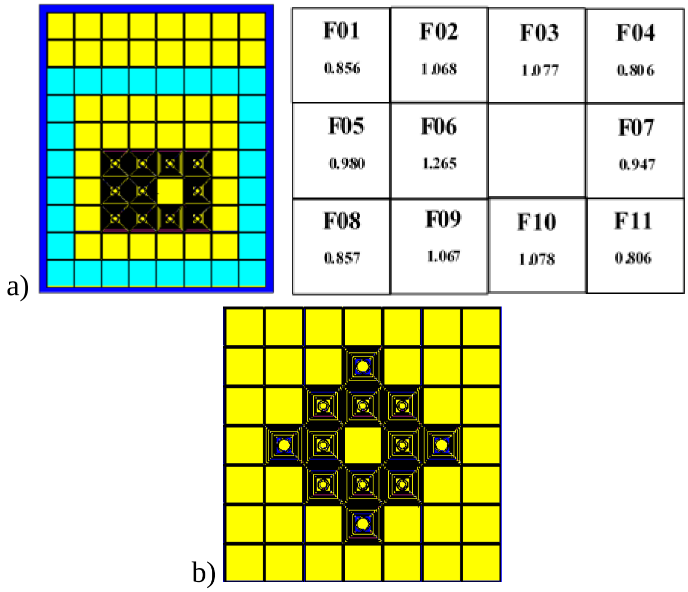


Fig. 6. Core configuration contains 11 IRT-8T FAs, power distribution (a) and 12 IRT-4M FAs (4 IRT-6T for control rod and 8 standard IRT-8T FAs) (b), and relative power distribution (right).

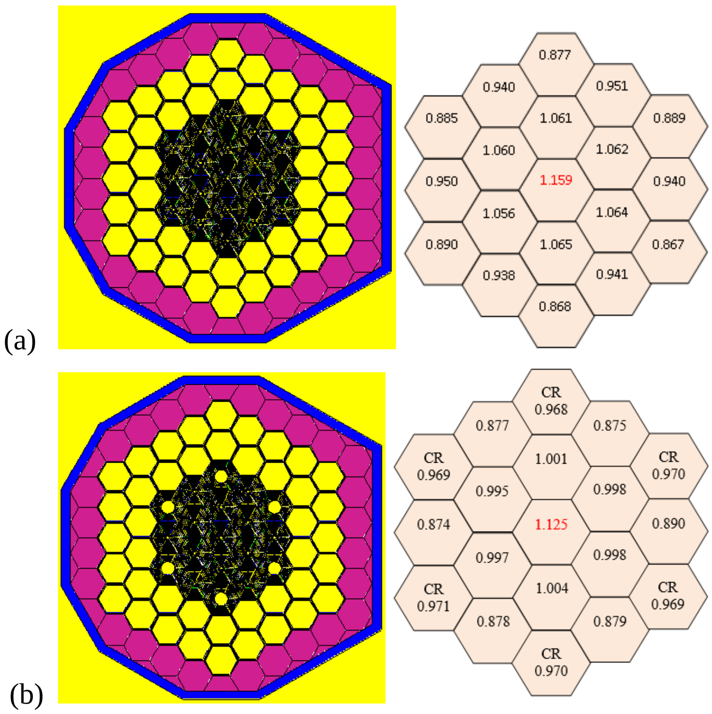
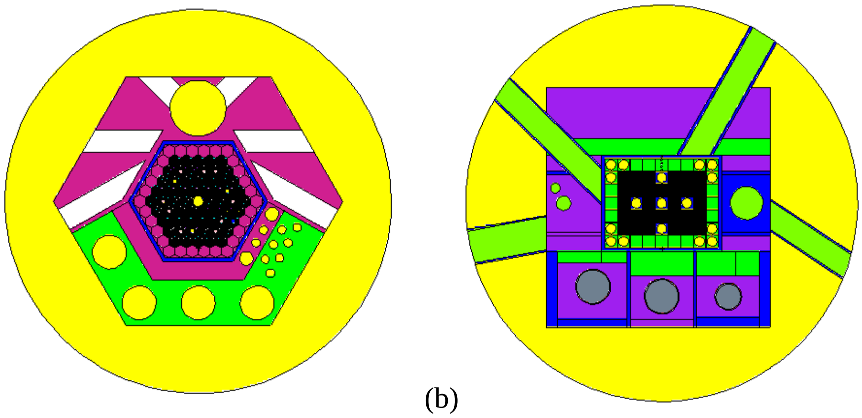


Fig. 7. Core configuration contains 19 VVR-KN FAs of 8 tubes (a) and 13 VVR-KN FAs of 8 tubes, 6 VVR-KN FAs of 5 tubes (b), and relative power distribution (right).



(a) (b)

Fig. 8. Proposed core configurations using VVK-KN fuel (a) and MTR fuel (b).

In case of the core configuration using VVR-KN FAs shown in Fig. 8 (a), a total of 19 vertical irradiation holes including 4 holes for silicon neutron transmutation doping (NTD), 15 holes for radioisotope production (RI), neutron activation alalysis (NAA), etc. and 6 tangential horizontal beam tubes (4 thermal and 2 cold neutron beam ports) are arranged. And in case of the core configuration using MTR FAs shown in Fig. 8 (b), a total of 23 vertical irradiation holes (3 holes for silicon NTD with 6- and 8-inch diameter ingots, 20 other holes for RI, NAA, etc.) and 4 horizontal beam tubes (3 for thermal and 1 for cold neutron) are arranged.

Table IV. Calculation results of effective multiplication factor of 12 core configurations.

No.	**Type of FAs**	**Fuel density, g/cm^3**	**Number of FAs**	**k_{eff}**	**Mass of U^{235}, g**
1	MTR 21 plates	4.8; 4.0; 2.6; 1.9	13	1.00296 ± 0.00007	3993.2
2		4.8; 4.0; 2.6; 1.9	16	0.99874 ± 0.00008	4472.4
3		4.8 (Cd)	19	1.00718 ± 0.00007	7667.0
4	IRT-4M 6/8 tubes	4.97	0/11 (*)	0.99978 ± 0.00010	3300.0
5			4/8	1.00675 ± 0.00011	3600.0
6			6 (B_4C)/14	1.00505 ± 0.00011	5790.0
7			6 (B_4C)/10	1.00067 ± 0.00011	4211.4
8			4 (B_4C)/12	1.00160 ± 0.00010	4811.4
9	VVR-KN 5/8 tubes	2.8	0/19	0.99545 ± 0.00012	4799.4
10			6/13	0.99511 ± 0.00011	4495.2
11			6 (B_4C)/30 (**)	1.00505 ± 0.00011	8789.4
12			6 (B_4C)/30 (**)	1.00067 ± 0.00011	8789.4

(*) *Number of FA for control rod/ Number of standard FA.*

(**) *Different control rod positions in the reactor core.*

The differences between the suggested configurations are shown in Table IV based on the minimum number of FAs or uranium mass. This table also shows that the core configuration No. 4 using IRT-8T fuel has the lowest number of FAs to reach criticality which is 11 standard FAs only, and the highest number of FAs is the core configurations No. 11 and 12 using VVK-KN fuel which consist of 6 FAs for control rod and 30 standard FAs.

III. CONCLUSIONS

Criticality calculations for critical core configurations of the reactor using MTR, IRT-4M and VVR-KN fuel types with beryllium reflector were performed. Maximum relative thermal neutron flux peaking factors of k_{inf} are 1.360, 1.212 and 1.010 for IRT-6T, VVR-5T and MTR fuels, respectively.

Neutron spectra of standard FAs of the three fuel types were also calculated in full range of energy from 10^{-11} to 10 MeV. The obtained results showed that the difference at thermal energy range between the fuel types is about 5% and the highest value is of MTR fuel. In epi-thermal and fast energy range, the difference between the the fuel types is insignificant.

Based on calculation results, twelve fuel loading schemes were chosen. The differences between these configurations are based on the number of FAs, the uranium mass and the uniformity of FA distribution. The calculated results indicated that the core loaded with the IRT-8T fuel reaches criticality with 11 standard FAs and without FA for control rod which has the smallest number of FA compared to other fuel types. In addition, two full core configurations using VVR-KN and MTR FAs and surrounding with beryllium reflectors were proposed for further conceptual design of the 10-MWt high-flux multi-purpose research reactor of CNEST. These cores equipped with vertical irradiation facilities and horizontal neutron beam ports which are arranged to meet the required utilizations and applications for Vietnam in long-term strategy.

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