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Calculation of neutronic characteristics in different reflector materials with a 15-MWt reactor core using VVR-KN fuel type

Bui Phuong Nam, Huynh Ton Nghiem, Nguyen Nhi Dien and Le Vinh Vinh

Nuclear Research Institute, 01 Nguyen Tu Luc Street, Dalat, Viet Nam
E-mail: nambp.re@dnri.vn

Abstract: VVR-KN is one of the low enriched fuel types intended for a research reactor of a new Centre for Nuclear Energy Science and Technology (CNEST) of Viet Nam. As a part of design orientation for the new research reactor, the calculations of neutronic characteristics in a reactor core reflector using different materials were carried out. The investigated core configuration is a 15-MWt power loaded with VVR-KN fuel assemblies and surrounded by a reflector using beryllium, heavy water or graphite respectively. MCNP5 code together with up-to-date nuclear data libraries were used for these calculations. This paper presents the calculation results of neutron energy spectrum, neutron spatial distribution in the reflector using the above-mentioned materials. Besides, neutronic characteristics calculated for silicon doping irradiation holes in the reflector are also presented and the utilization capabilities of different reflector materials are discussed.

Keywords: *VVR-KN fuel, MCNP5, reflector materials, silicon doping irradiation hole.*

I. INTRODUCTION

Vietnam is planning to build a new research reactor (RR) with an estimated power of about 10-15 MWt for the CNEST in co-operation with Russian Federation (RF). For this purpose, the national research project on design calculation of neutronic characteristics, thermo-hydraulics and safety analysis of the new multi-purpose RR has been carried out. As a part of the research project, this work aims at calculations of neutronic characteristics in a reflector using different materials surrounding the reactor core loaded with Russian VVR-KN fuel type [1].

Materials used for reactor core reflector play an important role in the effective utilization of RRs, as reflectors usually are used for flattening the thermal neutron flux and power distribution, as well as reducing the critical size and fuel mass of the reactor core. In proposed design, a set of three material types including beryllium, heavy water, or graphite were selected to study neutronic characteristics in the reflector.

VVR-KN fuel is a low-enriched fuel manufactured by RF that has been tested in the 6-MWt WWR-K research reactor of Kazakhstan and officially used for this reactor since 2016 in the framework of the conversion project of its core from highly to low enriched fuel [2, 3].

This report presents the calculated results of neutronic characteristics of the reflector using beryllium, heavy water or graphite respectively. In addition, a neutron-specific investigation of an irradiation hole for silicon single-crystal doping, which is one of currently important applications of RRs worldwide, was also conducted and calculated

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results were given. Those results allow to examine the potential of applying neutron fields in different reflective materials. The Monte Carlo code has been used for those calculations [4].

II. CALCULATION METHOD, RESULTS AND DISCUSSION

A. Method and calculation program

VVR-KN fuel

Fig. 1 shows the Russian 19.75% enriched VVR-KN fuel assembly (FA) which consists of two types: the standard one with 1 cylindrical and 7 hexagonal coaxial tubes, and the other with 5 hexagonal coaxial tubes for control rod placement. Table I shows the technical parameters of VVR-KN FAs. The width from the edge to the edge of the outer hexagonal tube is 66.3 mm. The thickness of fuel tube is 1.6 mm, consisting of 0.7-mm UO_2-Al fuel meat and 0.45-mm aluminum cladding on each side. The length of the fuel meat is 600 mm. The total amount of ^{235}U is 248.2 g in the standard FA and 197.6 g in the FA for control rod placement.

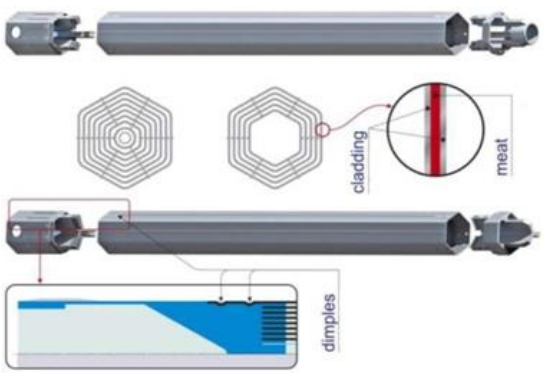
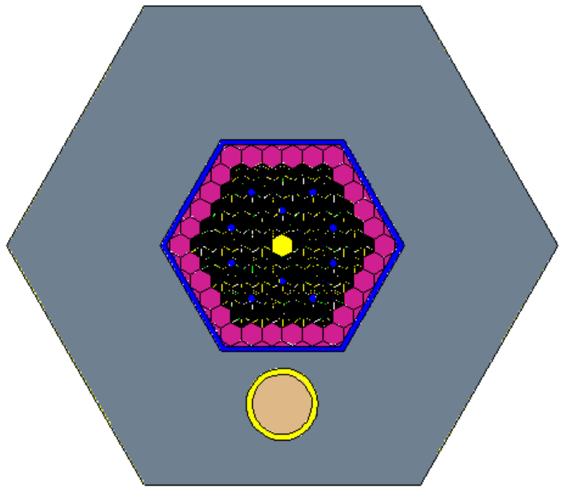


Fig. 1. Two types of VVR-KN FA.

Table I. Technical parameters of VVR-KN FAs.

Parameter	VVR-KN with 5/8 fuel elements
Fuel material	UO_2-Al
Enrichment in U-235, %	19.75
U-235 content in FA, g	197.6/ 248.2
Thickness of fuel tube, mm	1.6
Thickness of fuel meat, mm	0.7
Thickness of cladding, mm	0.45
Width of outer tube, mm	66.3
Length of fuel meat, mm	600



	Water hole at the core center
	FA with control rod
	Standard FA
	Beryllium rod
	Aluminum tank
	Hexagonal reflector
	Silicon doping irradiation hole

Fig 2. The core configuration using VVR-KN fuel.

In this study, the 15-MWt reactor core surrounded by the reflector was modeled according to the geometry of each component including all VVR-KN FAs (50 standard and 10 for control rod placement), a reflective layer by beryllium rods at the core periphery with an average thickness of 6.9 cm, an outer hexagonal reflector with beryllium, heavy water or graphite materials, irradiation holes, etc. Nuclear data is used based on the lasted ENDF-B/7.1 nuclear data library. Fig. 2 shows the cross-section of the reactor core using VVR-KN fuel type.

The hexagonal core with 60-cm height according to the length of fuel meat section, is coverred by 1.5-cm thick aluminum tank. A water hole at the core center is as a neutron trap with the highest thermal neutron flux. Surrounding the FAs are beryllium rods which act as a reflective layer at the core periphery. Outside the aluminum tank, a hexagonal reflector using different reflective materials such as beryllium, heavy water or graphite in which 6- or 8-inch irradiation hole for silicon single-crystal doping is located.

The present work aims at calculating neutron spectrum and spatial neutron distribution in this hexagonal reflector with different reflective materials. In addition, a number of computational results for silicon doping irradiation hole as an example for potential applications of different reflective materials have also been presented.

B. Results

The results of calculating the thermal neutron distribution in the reflector with different materials are shown in Fig. 3. Positions with maximum thermal neutron flux of beryllium, heavy water or graphite reflector are at 37.7 cm, 39.8 cm and 36 cm from the core center and the neutron flux values are of $8.6.10^{13}$, 9.210^{13} and $6.9.10^{13}$ $n.cm^{-2}s^{-1}$, respectively. Fig. 3 also shows that thermal neutron flux in beryllium declines rapidly when away the core with the high non-linear while with heavy water and graphite reflectors, thermal neutron fluxes decrease more slowly and relatively linearly. The main reason is that the thermal neutron absorption cross section in the beryllium reflector is highest, followed by graphite and heavy water ones respectively. Meanwhile the thermal neutron diffusion coefficient in beryllium reflector is lowest, followed by graphite and heavy water ones respectively. This also explains the relative distribution of thermal neutron flux in the reflector in axial direction as shown in Fig. 4.

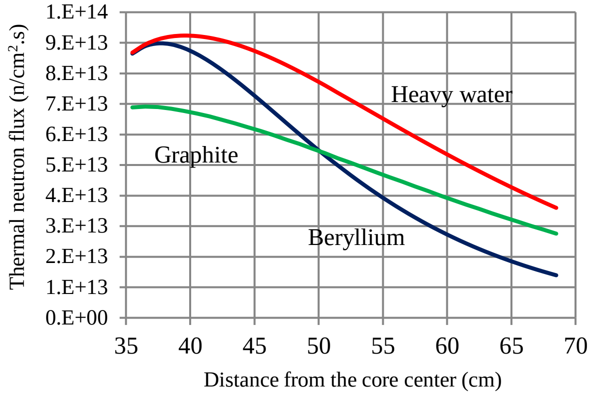


Fig. 3. Thermal neutron distribution in different materials of the reflector.

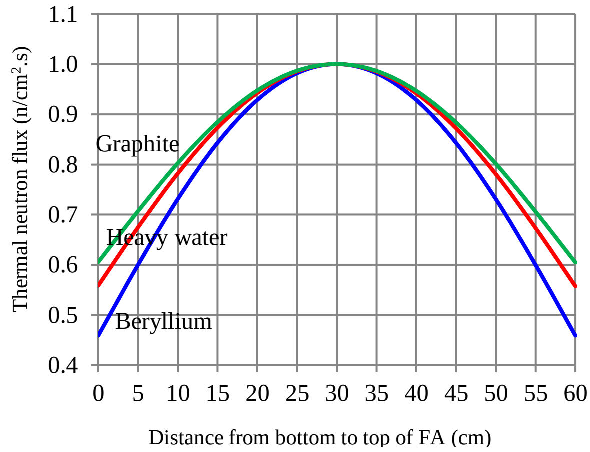


Fig. 4. Relative distribution of thermal neutron flux in different materials of the reflector in axial.

Fig. 5 shows the ratio of thermal to fast neutrons in the above reflective materials, where in the heavy water environment the ratio is highest followed by beryllium and graphite. This is explained by the ability to slow down neutrons in these environments.

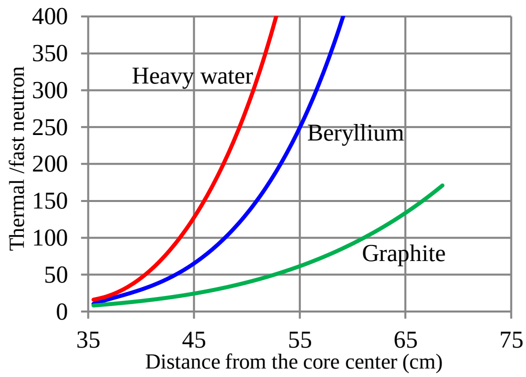


Fig. 5. The ratio of thermal to fast neutron using beryllium, heavy water or graphite reflector.

With applications requiring high thermal neutron flux, in case of using graphite reflector, the ratio of thermal to fast neutrons should be improved by adding a beryllium layer to further slow down neutrons until this ratio is reached as required. **Fig. 6** shows the ratio of thermal to fast neutrons and **Fig. 7** shows the thermal neutron flux distribution in case of adding 6-cm thick beryllium layer to graphite reflector. The calculated results show that the ratio of thermal to fast neutrons and the neutron flux distribution are improved. It means, the thermal neutron flux increases and the neutron flux distribution relatively flattens.

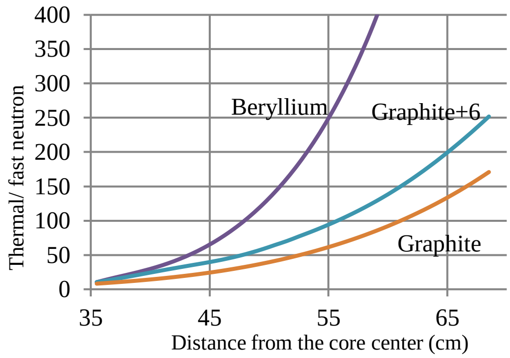


Fig. 6. The ratio of thermal to fast neutrons in case of adding 6-cm thick beryllium layer.

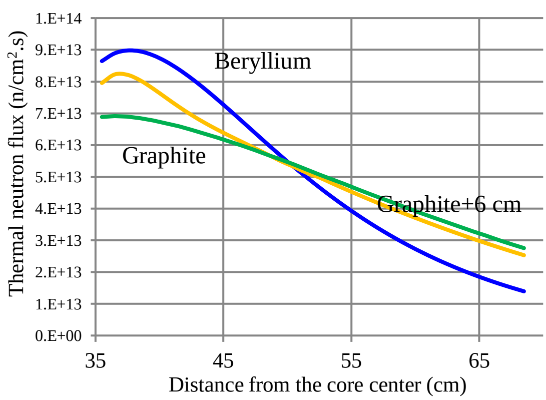


Fig. 7. Thermal neutron distribution in case of adding 6-cm thick beryllium to graphite reflector.

As usual, there are four typical applications of using neutron fields in the reflector of RRs: neutron activation analysis, radioactive isotope production, neutron beam researches and irradiation services. The first two applications may not require high quality of neutron flux, such as flux distribution and stability etc., but just the suitable flux level. Meanwhile the rest requires high neutron flux as well as high quality of neutron flux [7].

With the neutron beam application, neutron guides are used to extract and lead neutron beams outside for material structure study and other basic and applied research purposes. Most neutron beam researches require beam quality with the fast neutron and gamma field are as low as possible. Based on the above results obtained, it was found out that beryllium and heavy water reflectors are suitable for neutron beam application which requires the high thermal neutron flux (see Fig. 3 and Fig. 5). However, heavy water reflector is better than beryllium reflector for neutron beam application due to the thermal neutron flux peak, the ratio of thermal to fast neutrons are higher, and in particular the peak position is far away from the core region that allows to layout experimental devices easier. According to [7], for achieving the best beam quality, most neutron beam tubes in the latest constructed RRs are tangentaligned with the core to minimize the fast neutron and gamma effects.

Among various areas of RR utilization, neutron transmutation dopping of single-crystals silicon (silicon NTD) is a typical application, especially for producing semi-conductor with high quality. This application requires high enough thermal neutron flux to shorten the irradiation time. Since fast neutrons create extended charged lattice defects in a crystal, the fast neutron flux in the irradiation position must be as low as possible [8].

Gamma rays are the major source of heat generation in the ingot, so the gamma field should also be as low as possible, and the ingot must be sufficiently cooled during the irradiation. Specific requirements of high uniformity of neutron field both in radial and in axial directions should be concerned as well [8].

Figs. 3 and 4 show that heavy water reflector is better than beryllium one for silicon doping service. In adition, this application also requires a large enough space and the decretion of flux has shown limited use of beryllium reflectors.

C. Discussion

The results of calculating the neutron specificity for 6- and 8-inch silicon doping irradiation holes are given in Tables I and II, and described in Figs. 8 and 9. The thermal neutron flux in irradiation holes with reflective materials surveyed from $7x10^{12}$ to $3.2x10^{13}$ $n.cm^{-2}s^{-1}$ and the ratio of thermal to fast neutrons from a few tens to a few hundreds were acceptable for this application [9].

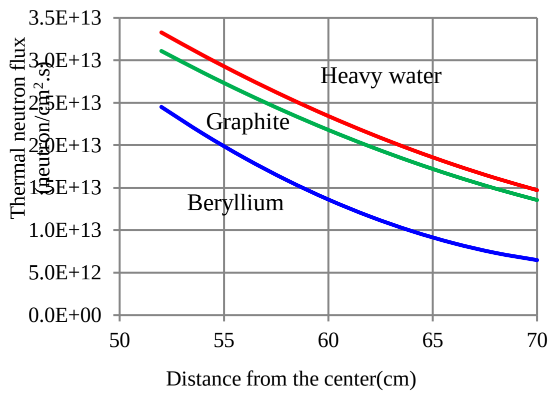


Fig. 8. Thermal neutron flux in 6-inch silicon irradiation hole at different positions in different reflector materials.

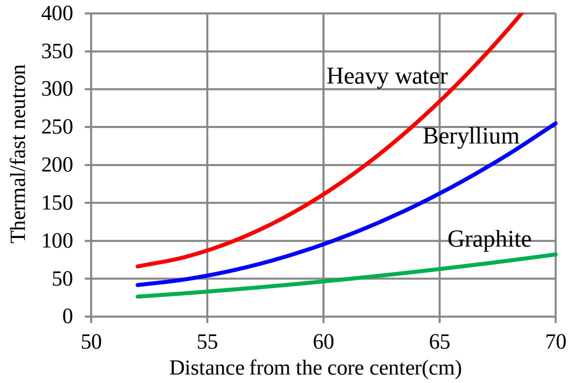


Fig. 9. The ratio of thermal to fast neutron flux at the 6-inch hole for silicon doping.

For single-crystal silicon-doped irradiation application, on the market today the most common sizes are 6 inches and 8 inches (150 mm and 200 mm) that are quite large compared to the reactor reflector size. According to [8], an integral flux value of $6x10^{17}$ $n.cm^{-2}$ is required to produce single crystals with a resistivity of 50 Ω.cm, the common resistivity at market demand. With a flux of $7x10^{12}$ to $3.2x10^{13}$ $n.cm^{-2}s^{-1}$, it takes about from 5 to 24 hours to achieve the above resistivity. According to the purely economic criterion, heavy water is the best reflector, next is graphite and finally beryllium.

Considering the ratio of thermal to fast neutrons, the acceptable value is more than 7, but due to the fast neutron affecting the quality of semiconductor crystals, this number should be as high as possible [8]. The calculated results show that heavy water is the best reflective material for this ratio, followed by beryllium and finally graphite (see Fig. 9). With this criterion, when using graphite for the reflector, it can be improved by adding a beryllium reflector layer as mentioned above.

The homogeneity criterion of resistivity is most important in the doping of silicon single-crystal. The axial uniformity is usually achieved by moving silicon ingots through the neutron field, or by using different materials to smooth the neutron flux distribution along the cavity [8]. The radial uniformity obtains by axial rotation of the silicon ingot. Although silicon crystals are transparent with thermal neutrons, but the decrease of thermal neutrons in the 6-inch ingot is also caused non-uniformity approximately 2%. In addition, the slope and non-linearity of the neutron field also contribute significantly to this inequality. Although the requirement of discrepancy in the radial and axial directions is no more than 5% for 6-inch crystals, but practically some silicon irradiation facilities achieve an unequal approximation in the axial direction of 2.5% [9]. Based on this criterion, the three best reflective materials were examined and the results obtained show that the best is graphite followed by heavy water and the worst is beryllium reflector (see Figs. 3 and 4).

Table II. Neutron flux in 6-inch silicon doping irradiation holes using heavy water, beryllium and graphite reflectors.

Position (cm)	Neutron flux (neutron.cm^{-2}.s^{-1})								
	Heavy water reflector			Beryllium reflector			Graphite reflector		
	Thermal	Epithermal	Fast	Thermal	Epithermal	Fast	Thermal	Epithermal	Fast
53	$3,2.10^{13}$	$4,0.10^{12}$	$4,5.10^{11}$	$2,3.10^{13}$	$3,2.10^{12}$	$5,2.10^{11}$	$3,0.10^{13}$	$7,0.10^{12}$	$1,0.10^{12}$
57	$2,7.10^{13}$	$2,2.10^{12}$	$2,4.10^{11}$	$1,7.10^{13}$	$1,6.10^{12}$	$2,5.10^{11}$	$2,5.10^{13}$	$4,8.10^{12}$	$6,6.10^{11}$
61	$2,2.10^{13}$	$1,2.10^{12}$	$1,2.10^{11}$	$1,3.10^{13}$	$7,3.10^{11}$	$1,2.10^{11}$	$2,1.10^{13}$	$3,4.10^{12}$	$4,2.10^{11}$
65	$1,9.10^{13}$	$6,7.10^{11}$	$6,8.10^{10}$	$9,1.10^{12}$	$3,6.10^{11}$	$6,0.10^{10}$	$1,7.10^{13}$	$2,3.10^{12}$	$2,7.10^{11}$
69	$1,5.10^{13}$	$3,5.10^{11}$	$3,7.10^{10}$	$6,9.10^{12}$	$1,8.10^{11}$	$2,9.10^{10}$	$1,4.10^{13}$	$1,5.10^{12}$	$1,8.10^{11}$

Table III. Neutron flux in 8-inch silicon doping irradiation holes using heavy water, beryllium and graphite reflectors.

Position (cm)	Neutron flux (neutron.cm^{-2}.s^{-1})								
	Heavy water reflector			Beryllium reflector			Graphite reflector		
	Thermal	Epithermal	Fast	Thermal	Epithermal	Fast	Thermal	Epithermal	Fast
56	$2,5.10^{13}$	$3,1.10^{12}$	$3,6.10^{11}$	$1,7.10^{13}$	$2,5.10^{12}$	$4,0.10^{11}$	$2,3.10^{13}$	$5,6.10^{12}$	$8,3.10^{11}$
58	$2,3.10^{13}$	$2,3.10^{12}$	$2,6.10^{11}$	$1,5.10^{13}$	$1,7.10^{12}$	$2,8.10^{11}$	$2,1.10^{13}$	$4,7.10^{12}$	$6,6.10^{11}$
61	$2,0.10^{13}$	$1,5.10^{12}$	$1,6.10^{11}$	$1,2.10^{13}$	$1,0.10^{12}$	$1,6.10^{11}$	$1,8.10^{13}$	$3,5.10^{12}$	$4,7.10^{11}$
64	$1,7.10^{13}$	$9,7.10^{11}$	$9,6.10^{10}$	$9,5.10^{12}$	$6,0.10^{11}$	$9,2.10^{10}$	$1,6.10^{13}$	$2,7.10^{12}$	$3,3.10^{11}$
67	$1,5.10^{13}$	$5,9.10^{11}$	$5,7.10^{10}$	$7,6.10^{12}$	$3,3.10^{11}$	$5,4.10^{10}$	$1,4.10^{13}$	$2,0.10^{12}$	$2,4.10^{11}$

III. CONCLUSIONS

As a part of the national research project on calculation of neutronic characteristics, thermo-hydraulics and safety analysis of research reactor proposed by the Russian Federation for the CNEST of Vietnam, the authors have performed neutron-specific calculations in beryllium, heavy water and graphite reflective materials surrounding a 15-MWt reactor core loaded with VVR-KN FAs and at silicon doping irradiation holes of different reflective materials. The purpose of this work is to review the advantages and disadvantages of reflective materials for typical applications on the research reactor.

The calculated results show that, based on the criteria used on horizontal experimental channels to conduct neutron beams for experiments, heavy water and beryllium reflectors have more advantages than graphite due to the thermal neutron peak is higher, in which, heavy water reflector is better than beryllium one due to the thermal neutron flux peak and the ratio of thermal to fast neutrons are higher.

For neutronic characteristics calculations of 6- and 8-inch silicon doping irradiation holes to make semiconductor, the calculated results show that heavy water and beryllium reflectors bring a higher ratio of thermal to fast neutrons than graphite reflector. However, silicon doping irradiation holes in heavy water and graphite reflectors have more advantages in thermal neutron flux values and particularly about linearity level and slope in thermal neutron distribution. Thus, besides of the outstanding advantages of heavy water reflector, the reflector using both beryllium and graphite to reduce the disadvantages of these two materials should be considered.

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