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Conceptual study of cold-neutron source in China Advanced Research Reactor

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Abstract

The fundamental design of the cold-neutron source (CNS) to be installed in the China Advanced Research Reactor (CARR) was prepared. The principal design criterion of the fundamental CNS design is the maximum increase of cold-neutron flux considering nuclear heating to be removed and safety problem. All nuclear calculations were performed with MCNP (version 4A) computer code using a complete 3D model of a reactor core and CNS except a horizontal cold-neutron channel. The nuclear heating, integral cold- and thermal-neutron flux and cold-neutron gain factor were evaluated for all options. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: CARR; Cold-neutron source; Nuclear heating; MCNP

1. Brief introduction of China Advanced Research Reactor

The China Advanced Research Reactor (CARR) is a high-flux and multipurpose reactor, cooled and moderated by light water and reflected by heavy water. This reactor is of inverse neutron trap design and of tank-in-pool type with a power of 60 MW. Its maximum thermal-neutron flux reaches $1.0 \times 10^{15}\,n/cm^2/s$ at the central position when the central fuel assembly is replaced by an experimental channel. The peak flux in a heavy-water reflector is about $8.0 \times 10^{14}\,n/cm^2/s$, where the high-intensity neutrons are available for scientific and engineering fields.

A large fraction of fast neutrons leaks out from the cylindrical tube, because the reactor has a rather compact core that poses a low slowing down ability for fast neutrons. Then, the thermal-neutron peak occurs in a heavy-water reflector because of its good quality of slowing down ability and very small absorption.

The reactor has a quite pure thermal-neutron spectrum and much more space available for arranging many vertical and horizontal channels. There are nine horizontal beam channels, 17 vertical irradiation channels, one vertical cold-neutron source (CNS) channel and one vertical hot-neutron source channel in the heavy-water reflector (see Fig. 1).

The main applications of the CARR are listed as follows: to provide high neutron flux for neutron scattering experiments; to produce many kinds of useful radioisotopes; material irradiation; other applications such as NTD, NAA and neutron radiography and so on.

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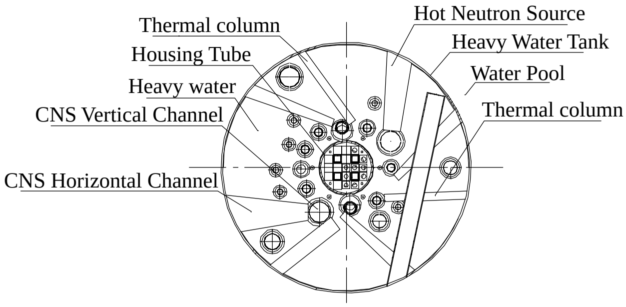

Fig. 1. The core layout of the CARR.

2. Conceptual design of CNS

The vertical CNS channel in the CARR was located at the position where the thermal-neutron flux is of peak value. The distance between the center of the CNS moderator cell and the reactor core center is 46 cm. The level of the horizontal cold-neutron beam tube is 10 cm lower than the axial center of the reactor core. This beam tube feeds two neutron guide tubes leading cold neutrons into the experimental hall.

The goal of the CNS conceptual design was to optimize the cold-neutron flux with wavelength longer than 2 Å under the condition of suitable nuclear heating. The more the nuclear heating, the larger the power of refrigerator and the higher the construction and operation cost. In order to reduce the cost, it is necessary to maximize the cold-neutron flux while the nuclear heating should be minimized.

There are two important selections that should be considered in detail. Firstly, what kind of material should be used as a cold moderator among LH_2, LD_2, and a mixture of LH_2/LD_2. Secondly, what kind of shape should be used in a moderator cell, namely an elliptical sphere, a cylinder and a cylindrical annulus with a void hollow inside and so on.

In order to get conceptual information on the CNS, we investigated two cases to evaluate nuclear heat load, cold- and thermal-neutron flux and cold-neutron gain factor. One of them is the case for which an elliptical sphere moderator cell is filled by liquid hydrogen with different thicknesses, and the other the cylindrical annulus moderator cell in which the outer shell is filled with liquid hydrogen of variable thickness and the inner shell is void.

3. Modeling the reactor and CNS in MCNP

All neutronic calculations were performed using MCNP (version 4A), which is a general-purpose Monte Carlo code coupled with neutron and gamma rays, developed at the Los Alamos National Laboratory (LANL). This code has cross-sections as a function of continuous energy and thermal scattering kernels for various materials used in a CNS. The ENDF/B-V-based cross-sections provided by the LANL are used for all materials.

3.1. The model of reactor core

This reactor core contains 11 kg ^{235}U. The core height is 850 mm with the MTR-type fuel assembly, for which an U_3Si_2–Al dispersion type fuel meat with 19.75 wt% enriched silicide uranium is used. The reactor core-housing container is made from an aluminum cylinder of $\varnothing 479 \times 12$ mm and takes a role as a pressure boundary. There are 21 lattice cells in the reactor core, among which 17 standard fuel assemblies, three shim control rods follower fuel assemblies, one regulating rod follower fuel assembly are incorporated. Aluminum lump is filled into the space between the core and the housing container. The outer wall of the core-housing container serves also as the inner wall of the heavy-water reflector tank. The outer diameter of the heavy-water tank is 2.2 m. The outer diameter of a vertical CNS channel is 19 cm and the inner diameter is 18 cm. The inner diameter of the nose position of the horizontal cold-neutron beam channel is 15 cm.

The complete 3D MCNP model for the reactor core and vertical CNS channel, etc. has been worked out. Other facilities like vertical and horizontal channels are neglected. Because the structural design of the horizontal cold-neutron beam channel is now not fixed, we fill temporarily helium gas in the space where the horizontal channel occupies. So, we could only optimize the flux in a moderator cell. The neutron spectrum at the exit of a beam tube will be roughly the same with that in the moderator cell although the intensity is different.

3.2. The different variants of CNS

The two cases, the elliptical sphere moderator cell and a cylindrical annulus type one with void inside, were considered. The former looks like a flat canteen, which is filled by 50% ortho-H_2 and 50% para-H_2 with normal density. The material of the moderator cell is zircaloy, whose thickness is 0.5 mm. A typical dimension is 12 cm width, 20 cm height and 4.6 cm depth in a beam direction. We investigated the influence of the depths, 4, 3.5 cm and so on, on the cold-neutron flux. The center axis of the elliptical sphere in the depth direction is on the center axis of the horizontal cold-neutron beam channel.

The outer shell of the cylindrical annulus moderator cell has liquid hydrogen and the inner shell is a void. The hydrogen vapor is in an upper part of the outer shell and a mixture of vapor and liquid at the boiling temperature in the lower part. The void fraction of the mixture is estimated to be 20%. The wall thickness of the outer shell is 0.65 mm and that of the inner shell is 0.5 mm. The outer diameter of the outer shell is 15 cm and the thickness of liquid hydrogen in the outer shell is considered to be typically 15 mm, but 18, 20 and 12 mm cases are also considered. The outer diameter of the inner shell is determined from the liquid hydrogen thickness in the outer shell. The height of hydrogen vapor in the outer shell is 40 mm and that of mixture is 160 mm. The center of the mixture in a vertical direction is at the same level with the center of the horizontal cold-neutron beam channel. The ratio of the para- to ortho-hydrogen is considered to be 1:1 because para-hydrogen is not built up during operation in the usual CNS using liquid hydrogen as a moderator [1] and the concentration of para-H_2 depends on the radiation level [2].

4. Nuclear heat load calculations

The calculating method of nuclear heating and the origin of nuclear heating are described in detail by Gaubatz [3]. It includes nuclear heating by neutrons, prompt gamma rays, delayed fission product gamma rays, beta particles from ^{28}Al, and delayed gamma rays from ^{28}Al. The nuclear heating of zircaloy is similar to that of aluminum. The total nuclear heating in the CNS is evaluated by adding up the following items: the heating of a moderator cell (labeled as A), the heating of moderator (LH_2) in a moderator cell (labeled as B), the heating of the moderator transfer tube (labeled as C) and the heating of moderator (LH_2) in the moderator transfer tube (labeled as D).

We classify all options into three cases: Case 1: an elliptical sphere moderator cell with 50% ortho-H_2 and 50% para-H_2. Case 2: a cylindrical annulus moderator cell with 50% ortho-H_2 and 50% para-H_2, and Case 3: a cylindrical annulus moderator cell with 100% para-H_2. The calculated nuclear heat loads for various options of the CNS are listed in Table 1 at which for saving MCNP calculating time, both A and B, C and D have been merged into one in cases 2 and 3.

Table 1
Total heat load in watts for various options of the CNS in CARR

Items	Shape	Options	A	B	C	D	Sum
Case 1	Elliptical sphere	Width = 4.6 cm	1088.0	375.4	1259.3	234.7	2957.4
		Width = 4.0 cm	980.5	219.1	1247.7	231.6	2678.9
		Width = 3.5 cm	470.7	128.6	1453.6	268.7	2321.6
Case 2	Cylinder	LH_2 thickness = 12 mm	1332.6		499.6		1832.2
		LH_2 thickness = 15 mm	1402.7		512.3		1915.0
		LH_2 thickness = 18 mm	1464.8		506.4		1971.2
		LH_2 thickness = 20 mm	1526.6		379.7		1906.4
Case 3	Cylinder	LH_2 thickness = 15 mm	1264.8		476.0		1740.8

Table 2
Integral cold and thermal neutron flux for various options of the CNS in CARR

Items	Shape	Options	Cold flux (n/s/cm^2) $0 \leqslant E_n \leqslant 4.5$ meV	Thermal flux (n/s/cm^2) 4.5 meV $\leqslant E_n \leqslant 0.625$ eV
Case 1	Elliptical sphere	Width = 4.6 cm	3.56e + 14 ± 1.4%	1.46e + 14 ± 2.65%
		Width = 4.0 cm	2.99e + 14 ± 0.44%	1.30e + 14 ± 0.47%
		Width = 3.5 cm	3.30e + 14 ± 0.42%	2.73e + 14 ± 0.44%
Case 2	Cylinder	LH_2 thickness = 12 mm	4.05e + 14 ± 0.63%	1.56e + 14 ± 0.61%
		LH_2 thickness = 15 mm	4.13e + 14 ± 0.89%	1.38e + 14 ± 0.87%
		LH_2 thickness = 18 mm	4.31e + 14 ± 0.58%	1.27e + 14 ± 0.57%
		LH_2 thickness = 20 mm	4.67e + 14 ± 0.54%	1.29e + 14 ± 0.54%
Case 3	Cylinder	LH_2 thickness = 15 mm	3.56e + 14 ± 0.70%	1.20e + 14 ± 0.67%

5. Cold/thermal-neutron flux and cold-neutron gain factor in the moderator cell

The cold- and the thermal-neutron flux in a moderator cell were calculated for the nominal power of 60 MW. Cold-neutron fluxes with energies $E_n \leqslant 4.5$ meV or wavelengths $\lambda_n \geqslant 4$ Å and thermal-neutron fluxes with energies lower than the cadmium limit at $E_n \leqslant 0.625$ eV in the moderator cell were averaged over the whole liquid hydrogen volume.

The cold-neutron gain factor is defined as the ratio "average cold-neutron flux in the cold moderator/average cold neutron flux in the warm moderator" [1]. The warm moderator is D_2O at 300 K filling in the volume of the moderator cell.

The integral cold- and thermal-neutron flux in the moderator cell are listed in Table 2. The gain factor as a function of a neutron wavelength is shown in Fig. 2.

However, we have some problems to be solved and in the later calculations these problems will become clear:

(a) Why the ratio of nuclear heating produced by the neutron to that by the gamma ray (0.54:1) is so different in case of zircaloy from the result of HANARO case (0.12:1) although the ratio in case of aluminum is reasonable. The heating contribution from neutron collision is very large when zircaloy is used as moderator cell material. With further examination, we found the neutron collision heating by thermal neutron $E_n \leqslant 0.625$ eV contribute more than 90% of total neutron collision heating. These results are shown in Table 3.

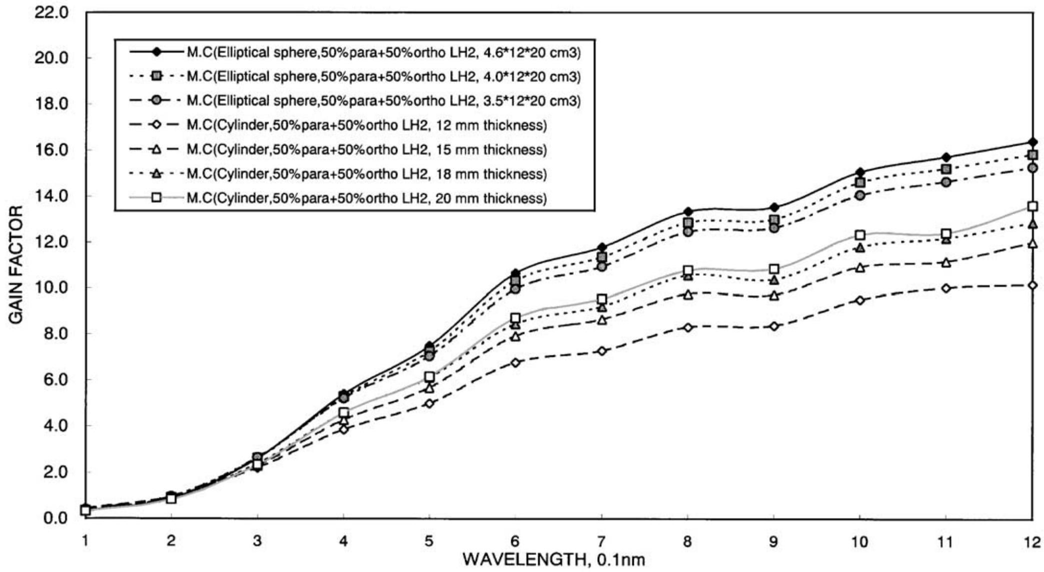

Fig. 2. The gain factor with respect to wavelength.

Table 3
Percent of neutron collision heating and flux in the CNS

Neutron energy	Zircaloy		Aluminum	
	Heating	Neutron flux	Heating	Neutron flux
$0 \leqslant E_n \leqslant 0.625$ eV	93.3%	86.0%	0.1%	88.5%
0.625 eV $\leqslant E_n \leqslant 5.53$ keV	4.3%	10.3%	0.1%	8.6%
5.53 keV $\leqslant E_n \leqslant 0.821$ MeV	0.6%	2.7%	23.8%	2.1%
0.821 MeV $\leqslant E_n \leqslant 20$ MeV	1.8%	1.0%	76.0%	0.8%

(b) We need to optimize the CNS performance from a point of view of cold-neutron flux and nuclear heating considering the heat removal system.

6. Conclusions

Conclusions can be drawn from the conceptual design of the CNS for the CARR:

(a) The total nuclear heating should be limited below 3 kW taking account of the cost and a cooling system.

(b) The cylindrical annulus moderator cell with a void inner shell is better than the elliptical sphere type one from standpoints of the cold-neutron flux and gain factor. This is because the effect of neutron absorption by the thicker liquid hydrogen layer is larger in case of the elliptical-shape moderator cell than the cylindrical annulus one.

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