ЯДЕРНАЯ ЭНЕРГЕТИКА И ЯДЕРНЫЕ ТЕХНОЛОГИИ

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OPTIMIZATION THE THERMAL MODERATOR FOR PULSED RESEARCH REACTOR NEPTUNE BY SERPENT CODE

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IBR-2M pulsed reactor has the most intense neutron flux around world ~10^{16} n/cm^2·sec at the moderator surface in the peak. It is expected that, IBR-2M reactor will get out of service between 2030–2032. The decision was taken to construct a new pulsed reactor to replace IBR-2M reactor and complement the research capabilities of the high-flux research nuclear reactor PIK in Russian federation. At the moment, serious work is underway in FLNP JINR at Dubna to design the NEPTUNE reactor. The NEPTUNE reactor is the first reactor in the world to use Np-237 as a nuclear fuel, and it is expected that the neutron flux at the moderator surface (at the peak and average neutron flux) will be the highest in the world. This work aims to optimize the thermal (water) moderator for a new pulsed research reactor NEPTUNE in order to maximize the thermal and epi-thermal neutron flux and to adjust the neutron spectrum. As a result, four possible dimensions were proposed to conduct different experiments. And it was suggested to make a chamber which volume and thickness of water can be changed to adjust the neutron spectrum.

Keywords: Neptune, Pulsed reactor, IBR-2, neutron and moderator

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1. INTRODUCTION

At present, neutrons are widely used in the science of everyday, they used in many fields like health, environment, archeology and in physics to investigate nuclear interactions, structure and properties of nuclei, condensed matter including solid states, liquids, polymers, biological systems and chemical reactions. Neutrons are produced in high intensity mainly from reactors (steady state or pulsed) or accelerators, then these neutrons are slowed down to the energy level required to conduct the necessary experiments. Moderators adjacent to the reactor core or next to targets in accelerators are used in order to thermalize fast neutrons.

The most efficient moderators are those materials with light nuclei like hydrogen and hydrogen containing materials, because the fact that neutron loses most of its energy in one collision with proton than other materials [1, 2]. In addition to the scattering reaction, there is also a side reaction takes place in moderator’s material which is the neutron absorption reaction which leads to loss of neutron intensity.

Moderator design task includes optimization of moderator dimensions to achieve the balance between the two interactions to minimize neutron losses, maximize neutron flux and get the needed neutron spectrum in extracted neutron beams.

Pulsed mode of neutron source and high-intensity sources are prospects for increasing the accuracy and reducing the time of experiments that use neutrons as neutron activation analysis, neutron diffraction, reflection and small angle neutron scattering, etc. [3–6].

FLNP at Dubna, Russia aims to replace the current operating reactor IBR-2M with a new high-power fourth generation pulsed reactor NEPTUN by 2030. As an initial step before the practical realization, is designing and optimizing reactor parameters. An extensive numerical calculations using Monte Carlo (MC) simulations have been considered in order to stabilizing the reactor working regime and optimizing neutron parameters [7–9].

This work aims to optimize the thermal (water) moderator of the fourth-generation neutron source in Dubna (reactor NEPTUN) to get the higher possible thermal neutron flux with suitable spectrum in extracted neutron beams [10, 11].

2. MODEL DESCRIPTION

Reactor NEPTUN is a pulsed reactor which will use Np-237 as a nuclear fuel for the first time. It has been proven that critical mass can be formed from Np-237 which can be used as nuclear fuel in nuclear reactors [12–14].

Table 1. Parameters of reactor NEPTUN

Parameter	Value
Average Thermal power, MW	15
Pulse frequency, Hz	10
Fuel, critical mass, kg	NpN, 540
Inlet/outlet coolant temperature (Liquid Na), °C	390/490
Effective delayed neutron fraction	0.0013
Prompt neutron generation time, ns	9
Effective neutron pulse duration, μs	200–240
Background power, % from average power	2.5–3
Fuel rod diameter, mm	17.3
Fuel column height, mm	410
Density of fuel (NpN), gm/cm^3	13.4
Average neutron thermal flux at the surface of water moderator, 10^{14} cm^{-2} s^{-1}	10

Reactor core of planned reactor NEPTUN is divided into two similar parts between them reactivity modulator is rotating. Reactivity modulator is a disk of 3.4 meters diameter and 50 mm thickness divided into sectors and made from stainless steel. These sectors are filled with neutron moderator from TiH_2 and only one empty sector. When empty sector enters the distance between two parts of the core, the pulsed power (and neutron pulse) generates. Around the core there are neutron reflector mainly from Ni with thickness of 30 cm. Inside the reflector there are 4 moderators consists. Moderators consist of thermal moderator from water only to get thermal flux or complex from thermal and cold moderator to get thermal and cold spectrum. Around moderator complexes there are Be reflector of height of 40 cm and thickness of 30 cm to increase the neutron thermal flux in moderator [11, 15–18]. The specifications of reactor NEPTUN are described in table 1. Fig. 1 shows the plan view section and Fig. 2 shows the elevation view of the whole reactor NEPTUNE.

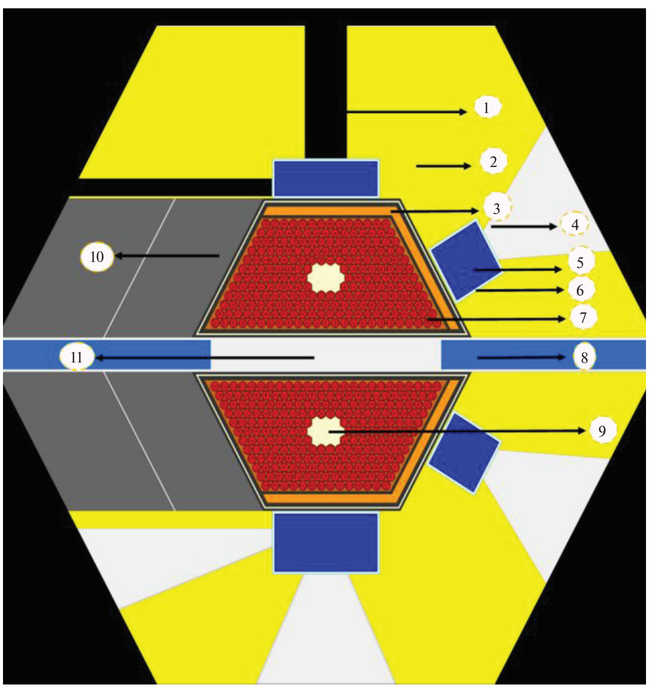

Fig. 1. Plane view of reactor NEPTUNE. 1 – extracted neutron beam, 2 – Be reflector, 3 – Na cooler downcomer, 4 – neutron channel, 5 – water moderator, 6 – Al cover, 7 – fuel rods, 8 – reactivity modulator, 9 – control rod channel, 10 – Ni reflector control rod, 11 – vacuum sector.

3. METHODOLOGY AND CALCULATION TOOLS

Unlike steady state reactors, reactor NEPTUNE is a pulsed type reactor. Where the reactor power increases over nominal power for a very short time and then returned to the nominal power. This performance can be simulated by a three dimensional (3D) continuous energy Monte Carlo neutron transport and burnup code SERPENT-2 by the trans tool. In this paper, which deals only with optimization thermal moderators, it is not concerned with the pulse effect. The SERPENT-2.1.32 code was used to simulate the whole reactor NEPTUNE in order to optimize the thermal moderators [19]. The new energy deposition treatment ability of SERPENT-2 was used and improved the quality and accuracy of the results [20]. Joint Evaluated Fission and Fusion neutron cross section libraries (JEFF 3.3) was used to collect continuous neutron and photon microscopic cross-section data. JEFF3.3 thermal neutron scattering sub-library contains 20 evaluations for 16 materials was used to collect neutron microscopic cross-sections for cold moderator materials. The results present full core runs of 100 million neutron history in criticality source mode to reduce the statistical uncertainty of thermal

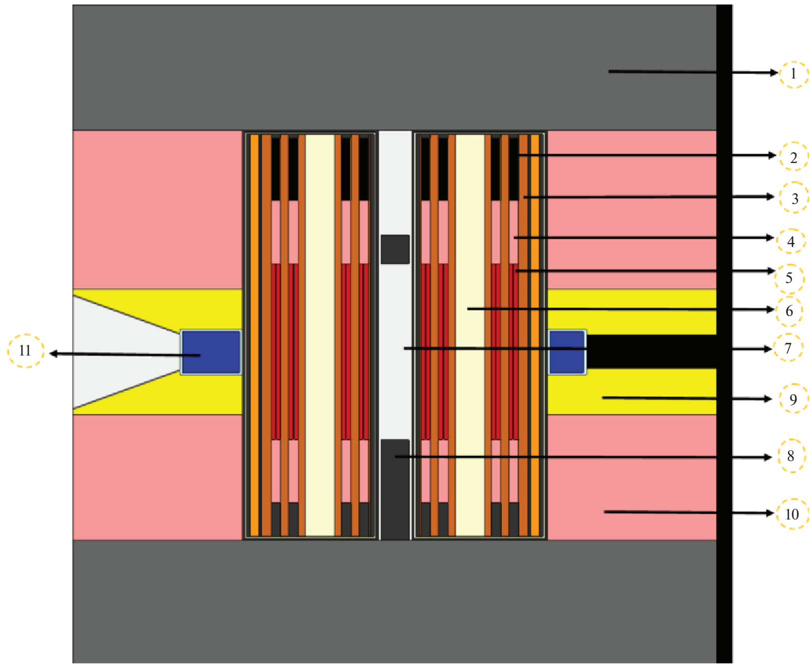

Fig. 2. Elevation view of reactor NEPTUNE. 1 – Stainless steel upper reflector, 2 – fission gas camper, 3 – cooling channels, 4 – inside fuel rod Ni reflector, 5 – NpN fuel column, 6 – control rod channel, 7 – vacuum sector, 8 – reactivity modulator, 9 – Be reflector, 10 – Ni reflector, 11 – water moderator.

flux up to ± 0.01034, in cold neutron flux to ± 0.01769 and in absorbed dose to ± 0.00367.

Around the reactor core there are 4 moderators. The main objective of these moderators is to obtain thermal or cold neutron flux in the extracted neutron beams. Up to the present time, its planned to use one moderator complex provided with cold moderator to get cold neutrons in 4 extracted neutron channels suitable for use in those experiments that need cold neutrons and 3 water moderators to get thermal and epithermal neutrons in extracted beams for other experiments like neutron activation analysis.

In this work, optimization of water moderator complex was done in order to adjust the size of water for new reactor NEPTUNE to obtain the needed neutron spectrum with the maximum possible needed neutron flux.

The optimization was done for only one moderator, and neutron flux from moderator surface was calculated in one channel perpendicular to the moderator surface with a diameter of 4 cm. The new ability of calculating flux or current through a part of surface which is available in SERPENT-2 from version 2.1.32 and on, by using single-bin mesh and cell detector was used to define the integrated flux through the outer surface of moderator and directed to the channel.

First part from this work is dealing with optimization the material of thermal moderator. Therefore, the decision was taken to use ordinary water as a thermal moderator to shift the neutron spectrum towards thermal spectra.

The second part is to optimize the configuration (volume) of water moderator in order to adjust the spectrum and get maximum possible neutron flux.

4. OPTIMIZATION OF WATER MODERATOR

In beams for thermal neutron experiments, water moderator was placed next to reactor core and at the beginning of the channel to shift the fast neutrons from core to thermal spectrum. The water moderator was placed in an aluminum chamber with a thickness of 5 mm see Fig. 3, the dimensions of the water chamber are 20 × 10 × (2–10) cm for width, length and thickness respectively, the change in volume was achieved by changing the thickness from 2 to 10 cm.

The main purpose of this part is to optimize the water volume or water thickness to get the maximum thermal neutron flux in extracted neutron beam.

4.1. Results and discussion of first step

Fig. 4 represents changes in neutron spectrum with change in water thicknesses from 2 to 10 cm in thermal energy range from 10^{-9} to 10^{-6} MeV. The peak neutron flux at thermal point increases with increasing the water thickness. The difference between first three peaks (for curves 2, 3 and 4 cm) is higher than others, which meaning that 4 cm water is enough to shift most neutrons from fast to thermal energy. It can be noted that 4 cm curve also has the highest epi-thermal flux.

In fig. 4, 8 cm water curve has the highest peak around the thermal point (it is superimposed on the

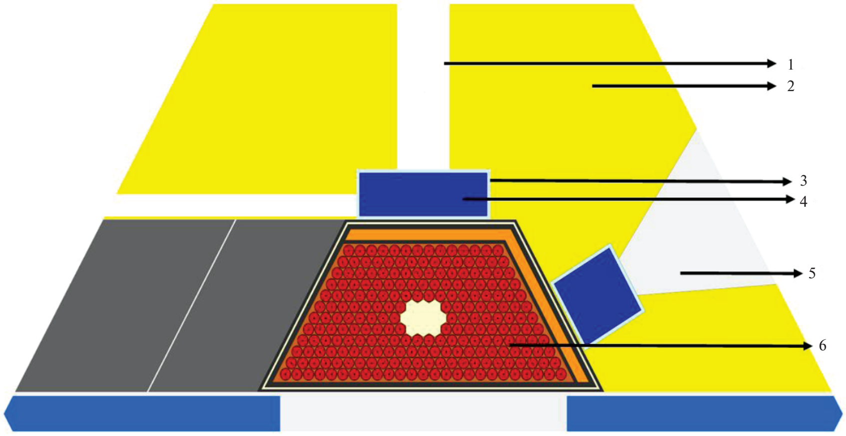

Fig. 3. Cross section for half reactor core, showing water moderator box. 1 — neutron beam. 2 — Be reflector. 3 — water chamber's chamber. 4 — water moderator. 5 — neutron channel. 6 — reactor core.

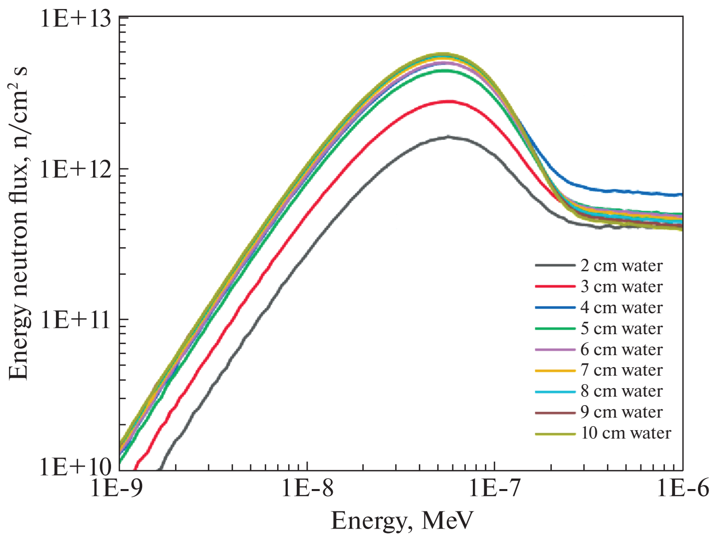

Fig. 4. The neutron flux energy spectrum at different water thicknesses.

curve of 10 cm), this can be explained on the basis of competition between elastic scattering and capture reaction rates as shown in table 2. Table 2 shows that neutron capture reaction rate increases with increasing in the amount of water, while scattering reaction rate reaches its maximum at 8 cm water and the difference between scattering and capture reaction rates reached its maximum value at 8 cm water thickness.

For 5, 6, 7, 8, 9 and 10 cm water, there is almost no significant difference in the scattering and absorbing reaction rates, so we can find the peaks at thermal point almost superimposed on each other.

From fig. 5 it can be concluded that maximum integrated neutron flux can be obtained at water thickness of 5.5 cm.

It can be concluded that from fig. 4, 5 and table 2 that

1) to get the highest thermal flux in extracted neutron beam (within neutron energy interval from 1E-9 to 3E-8 MeV) it is better to choose water thickness of 10 cm regardless of low neutron intensity;

2) to get harder neutron spectrum with good enough thermal flux and high epithermal flux it is better to choose water thickness of 4 cm. This spectrum is more suitable for neutron activation analysis which need more epithermal neutrons;

3) to get high thermal neutron flux with low epithermal flux with high enough intensity (intensity almost the same as for 4 cm water), it is better to choose 8 cm water thickness;

4) optimum choice to obtain the maximum integrated neutron flux with mixed thermal and epithermal neutrons is 5.5 cm water thickness.

5. CONCLUSION

This work contributes to optimize the water moderator to obtain the maximum thermal flux with suitable neutron spectrum. This work also emphasizes the

Table 2. Capture and elastic scattering rates density in water

Water thickness, cm	Capture reaction rate density in water (capture/cm^3 sec), ± statistical uncertainty	Elastic scattering reaction rate density in water (scattering/cm^3 sec), ± statistical uncertainty
1	1.16151E+12 ± 0.00372	4.72607E+14 ± 0.00213
3	1.9329E+12 ± 0.00289	5.91047E+14 ± 0.00198
4	2.53436E+12 ± 0.00256	6.73214E+14 ± 0.00192
5	2.98641E+12 ± 0.00236	7.30634E+14 ± 0.00189
6	3.33822E+12 ± 0.00215	7.73259E+14 ± 0.00178
7	3.56608E+12 ± 0.00213	7.96189E+14 ± 0.00179
8	3.70238E+12 ± 0.00198	8.04989E+14 ± 0.0017
9	3.75776E+12 ± 0.00201	8.01755E+14 ± 0.00176
10	3.76526E+12 ± 0.00188	7.91884E+14 ± 0.00167

SERPENT-2 code ability to analyze complex of moderator for the new research reactor NEPTUNE. The conclusions are listed as follows:

– Four water moderator's volumes have been proposed for water moderator to get the appropriate spectrum for each experiment.

– It would be a good idea to develop a technology to change the size of water moderator chamber in order to adjust the appropriate neutron spectrum for each experiment.

6. FUTURE WORK

The authors intend to compare the effect of different reflector materials on the flux and the reactor parameters like critical mass, fast neutron generation time and effective delayed neutron fraction. Moreover, future work will optimize the cold moderator to get cold neutrons, also will study in deep ortho-hydrogen as a cold moderator.

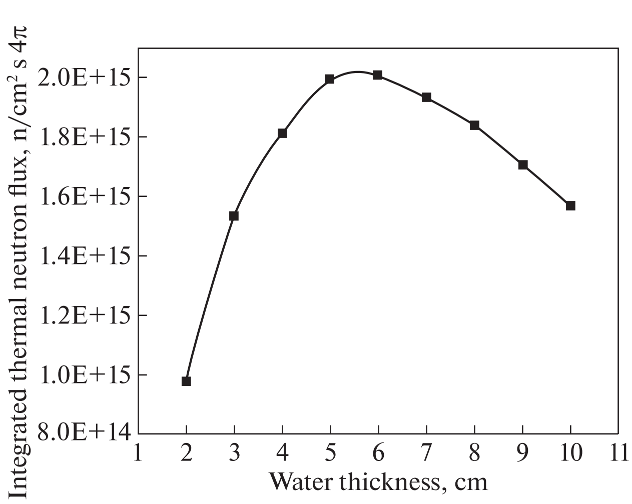

Fig. 5. Integrated neutron flux at different water thicknesses.

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Оптимизация теплового замедлителя импульсного исследовательского реактора НЕПТУН по коду SERPENT

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Импульсный реактор ИБР-2М имеет самый интенсивный в мире поток нейтронов ~ 10^{16} н/см^2·сек на поверхности замедлителя в пике. Ожидается, что реактор ИБР-2М будет выведен из эксплуатации в период с 2030 по 2032 год. Принято решение о строительстве нового импульсного реактора для замены реактора ИБР-2М и дополнения исследовательских возможностей высокопоточного исследовательского ядерного реактора ПИК в Российской Федерации. В настоящее время в ЛНФ ОИЯИ в Дубне ведутся серьезные работы по проектированию реактора НЕПТУН. Реактор НЕПТУН является первым в мире реактором, использующим Np-237 в качестве ядерного топлива, и ожидается, что поток нейтронов на поверхности замедлителя (на пиковом и среднем потоке нейтронов) будет самым высоким в мире. Данная работа направлена на оптимизацию теплового (водяного) замедлителя для нового импульсного исследовательского реактора НЕПТУН с целью получения необходимого спектра нейтронов с максимальным потоком тепловых и надтепловых нейтронов. В результате были предложены четыре возможных варианта размеров камеры замедлителя для проведения различных экспериментов. Было предложено разработать камеру, объем и толщину воды, которые можно было бы менять для корректировки спектра нейтронов.

Ключевые слова: Нептун, импульсный реактор, ИБР-2, нейтрон и замедлитель

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