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NEUTRON PHYSICS

On the Limit of Neutron Fluxes in the Fission-Based Pulsed Neutron Sources

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Abstract—The upper limit of the density of the thermal neutron flux from pulsed sources based on the fission reaction is established. Three types of sources for research on ejected beams are considered: a multiplying target of the proton accelerator (a booster), a booster with the reactivity modulation (a superbooster), and a pulsing reactor. Comparison with other high-flux sources is carried out. The investigation has been performed at the Frank Laboratory of Neutron Physics of JINR.

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INTRODUCTION

In modern science, neutrons are used to study fundamental interactions and symmetries and the structure and properties of atomic nuclei, but they are most widely employed in condensed matter physics, molecular biology, structural chemistry, materials science, and systems of the nondestructive control of bulk materials and industrial products.

The information capacity of studies with neutrons increases with a growth in the intensity of sources. This occurs not only due to the shortened time of experiment conduction, but also because of the new opening opportunities, to which we can refer the improvement of measurement accuracy; the investigation of small objects, complex objects, and objects with small cross sections of scattering; the conduction of experiments with the analysis of neutron polarization before and after scattering; etc. Therefore, aspirations for more intense neutron sources are natural.

The high-flux neutron sources for research on extracted beams [1], both operating now and under construction, have reached the technological limit in a flux density obtained on the source surface. Therefore, the leaders among the continuous-flow reactors—the HFR reactor operating at the Institute Laue–Langevin (Grenoble, France) and the PIK reactor under construction at the Petersburg Nuclear Physics Institute of the National Research Centre "Kurchatov Institute" (Gatchina, Leningrad oblast)—have the time-average flux density of thermal neutrons available for investigations on external beams, $\Phi_{\rm o}^{\rm th}$ = (1.3 and 1.5) × 10^{15} n cm^{-2} s^{-1}, respectively, which actually is the technological limit for reactors of this type.

In creating neutron sources on ejected beams, one trend today is the combination of a proton accelerator and a target made of the heavy metal. The leaders among the operating spallation sources based on proton accelerators—STS (the second target of the SNS facility, Oak Ridge, United States) and JSNS (Ibaraki, Japan)—upon achieving design parameters will yield neutron fluxes on the surface of the external moderator per pulse $\Phi_{\rm p}^{\rm th}$ (5–6) × 10^{15} n cm^{-2} s^{-1}, which is also close to the limit of technological capacities for this type of sources. In the European spallation source ESS under construction (Lund, Sweden) with an accelerator of protons up to the energy of 2.5 GeV and a beam power on the target of 5 MW, the peak flux will be roughly of the same value.

One particular position among the neutron sources in the world is occupied by the pulsed IBR-2 reactor at the Joint Institute for Nuclear Research (JINR, Dubna, Moscow oblast). By a pulsed neutron flux, it is a leader among operating pulsed sources (Table 1). Even after the facilities to be commissioned in 2019–2023 (STS, JSNS, and ESS) achieve design parameters, the Dubna reactor will remain within top three leading sources. However, the time-average density of the flux from the surface of the IBR-2 water moderators, (5–10) × 10^{12} n cm^{-2} s^{-1}, will be substantially lower than the one in the best spallation sources. Additionally, the pulse width of the IBR-2 reactor (around 300 μs) is fixed, whereas at the accelerator-based sources, short (to 20 μs) pulses can be obtained, which provides higher energy resolution in the neutron spectrometry. Calculations performed for the design optimization of the IBR-2 research nuclear facility show that increasing the average power of the

Table 1. High-flux pulsed neutron sources for slow neutron scattering experiments

Country, city	Name, year of creation/modernization	Target power, MW	Neutron flux per pulse, 10^{14} cm^{-2} s^{-1}	Thermal neutron pulse width, μs; frequency, s^{-1}	Time-average neutron flux, 10^{12} cm^{-2} s^{-1}	Number of channels/cold moderators	Stations for neutron scattering				
							diffraction	small angle	reflectometry	inelastic	other
United Kingdom, Chilton	ISIS I, 1985	0.2	10	20–30; 50	1.5	16/2	10	2	3	7	1
	ISIS II, 2009		45	20–30; 5	0.7	13/1	6	4	5	2	2
United States, Los Alamos, Oak Ridge	MLNSC,1985	0.1	7	20–30; 20	0.4	16/2	4	2	3	2	2
	SNS, 2006	1	12	20–50; 60	4	14/1	7	2	3	7	3
	STS, project	0.5	50	50–200, 10	10						
Japan, Ibaraki	JSNS, 2009/plan	1	20/ 65	20–50; 25	10/30	21/1	7	1	2	3	7
China, Dongchuan	CSNS, 2018, plan	0.1	~5	20–50, 25	~1	20					
Russia, Dubna	IBR-2, 1984/2012	2	60	310; 5	10	14/2	6	1	3	2	2
Sweden, Lund	ESS 2019, plan	5	50–75	2800; 14	200–300	16/1 first phase	5	2	2	6	1

reactor and, accordingly, the neutron flux does not seem possible in practice. The issue of increasing neutron flux density in pulsed sources and, first and foremost, the fission-based sources (as is traditional for JINR) is very urgent. All the more so as the resource of the IBR-2 research nuclear facility is defined up to 2032–2035.

In this work, the analysis of possible options of the fission-based high-flux pulsed neutron source for investigations on extracted beams is presented to estimate the possibilities of obtaining the higher neutron flux densities than those currently achieved.

PULSED NEUTRON SOURCES

The history of pulsed neutron sources originated in 1945, with the Manhattan Project, in the context of which the self-quenched pulsed nuclear reactor (or aperiodic pulsed reactor) was created in Los Alamos. Such super-powerful pulsed reactors were created, first and foremost, for defense and were not employed for physical investigations on extracted beams; however, the idea was developed. In 1955, in the town of Obninsk at the Physical Energy Institute, the development of a fundamentally new periodic pulsed reactor—a pulsing reactor—was initiated under the leadership of D.I. Blokhintsev. Prior to this, the pulsed neutron fluxes for nuclear spectroscopy were created with the use of a beam chopper at stationary reactors. The efficiency of using reactors, the power of which was not high in those days, decreased strongly in this case. A pulsing reactor could resolve this problem.

The construction of the IBR pulsing reactor in Dubna began in 1957, and it was commissioned in 1960. It was the world's first reactor in which pulses were generated periodically at a frequency of 5 and 50 Hz due to the rotation of part of the core. With the average reactor power of only 1 kW, a neutron flux was higher than at stationary reactors with a power of 10 MW with a chopper.

One successful operation of the IBR reactor and its modifications (the pulsed booster with an injector–microtron and the IBR-30) stimulated the further development of this trend. In the mid-1960s, several new projects appeared around the world. Of all proposals concerning high-flux pulsing reactors, only the project of the IBR-2 reactor was implemented, which became possible owing to the experience of works with such systems in Dubna and Obninsk. The fundamental IBR-2 distinction from the series of first IBR reactors became the reactivity modulation by the movable reflector, as well as cooling the core by liquid sodium [2].

The IBR-2 pulsed research reactor (formally called the IBR-2 Research Nuclear Facility, abbreviated as IYaU IBR-2) has been functioning at the JINR since 1984. According to established terminology, IBR-2 is a generator of long (around 300 μs), periodic (5 times per second), and intense pulses of thermal and cold neutrons. The neutron beams are used to investigate the spatial and magnetic structures and textures (including biological ones), the dynamics of atoms and molecules, the isotopic composition of substances, and fundamental properties of matter using different techniques with a general title of the "slow neutron scattering method" [3].

The first accelerator-based pulsed source was created in Harwell with the use of a linear electron accelerator in the early 1950s. At the same place in 1959, the idea of a booster was proposed and implemented: a system including the accelerator and the multiplying target, which is a neutron-producing heavy-metal target placed into the subcritical uranium assembly. Photonuclear neutrons initiate a chain reaction in the assembly, which tenfold increases a neutron flux. A chain reaction in the subcritical assembly proceeds only with the operating accelerator; this is a fundamental distinction of this system from a reactor. The Dubna IBR-30 reactor worked in a similar mode of multiplying neutrons from the target of the electron accelerator from 1973 to 2001, but was distinguished from Harwell's variant by the presence of a reactivity modulator allowing the flux to be increased 200-fold. This system is called a *pulse booster*, or a *superbooster*. At present, at the site of the dismantled IBR-30, the new photonuclear resonance-neutron source IREN is created, which is at the stage of development.

Although linear electron accelerators are relatively simple in fabrication, today they are used not enough (due to low efficiency when compared to proton accelerators) and, mainly, for nuclear physics. Boosters also are not widely used. The main problem is the negative public attitude to any systems containing fissile materials. However, the logic of evolution of neutron sources, apparently, will lead to a widespread use of precisely the boosters (superboosters).

Proton accelerators for pulsed neutron sources were brought into use in the early 1970s. At the Argonne Laboratory in Chicago, the ZING-P first pulsed neutron source, based on the neutron-producing target of the pulsing proton beam of the ZGS synchrotron (which was designed for research in particle physics and has become inoperative by that time), was created in 1974 upon an initiative of John M. Carpenter, a founder of the (still acting) regular international forum on pulsed neutron sources ICANS [4]. The first neutron source of the second-generation ISIS, for which a main accelerator was constructed specially, began operations in 1985 at the Rutherford–Appleton Laboratory (Great Britain). Now ISIS is an intense pulsed neutron source most equipped and adapted to research. In 2006 and 2009 the proton neutron sources were accepted into operation in the United States (SNS) and Japan (J-SNS), respectively. Now the mastering of these facilities occurs with gradually reaching the project parameters. These are the highest power and most intense neutron sources of the third generation; to compete with which only the IBR-2 reactor is able. There is no doubt that these sources have good outlook for development.

The listed proton sources of neutrons are referred to a class of pulsed sources with a short width (<50 μs) of the neutron pulse—short-pulse source (SPS). In recent times, the issue of creating a long-pulse (>300 μs) source (LPS) has been discussed very actively. The fact is that the creation of proton accumulators with the energy of a few GeV, required for increasing a neutron flux, is very expensive. Building a powerful linear proton accelerator is much cheaper, but in this case the neutron pulse width increases. The pulse width determines the resolving capacity of the experimental setup: with a standard approach, the shorter the pulse width is, the better the resolution is. However, the development of the experiment technique at the first LPS (the IBR-2 reactor) shows that, in the case of a long pulse, with the use of modern electronics and mathematical software, the neutron pulses with the required duration can be formed, which makes it possible to obtain a resolution at the level of the best SPSs for both elastic and inelastic scattering. However, in this case the neutron flux will be an order of magnitude higher. This experience has been used in constructing LPSs at proton accelerators. A source of this type began operations in 1999 at the linear accelerator of the Institute for Nuclear Research, Russian Academy of Sciences, in Troitsky Administrative Okrug of Moscow.

The highest power LPS-proton neutron source under construction in Sweden (Lund)—European spallation source (ESS)—will have a beam power of 5 MW, i.e., 30 times higher than the power of ISIS [5]. It is proposed to be put in operation in 2019. With an accelerator of protons to the 2.5-GeV energy, an average current of 2 mA, and the nonmultiplying tungsten target, the time-average flux density of thermal neutrons will reach a value of (2–3) × 10^{14} n cm^{-2} s^{-1}, which is, apparently, close to the limit of technical capacity for pulsed neutron sources of any type.

Table 1 presents parameters of high-flux pulsed neutron sources (most cited) used to study condensed media.

Among the merits of pulsed neutron sources based on high-current proton accelerators— spallation neutron sources (SNSs)—are factors such as the absence of nuclear weapon–grade materials, higher radiation safety in comparison to reactors (though the possibility of radiation accident is not excluded in view of the substantial accumulation of radioactive products in the neutron-producing target), and a low neutron background between the pulses. The SNSs also have demerits: a high cost of construction and operation, lower (when compared to reactors) stability and reliability in operation, and a more frequent repeatability of pulses. The last circumstance shortens the range of neutron wavelengths available for investigations using the time-of-flight method.

The IBR-2 reactor, as a neutron source, becomes one of the most intense operating facilities for neutron studies in the world. The averaged flux density of thermal neutrons from the surface of the water moderator reaches 10^{13} n cm^{-2} s^{-1} (the time average for the comb-like moderator), the peak density is 0.6 × 10^{16} n cm^{-2} s^{-1}, and the fluence per pulse amounts to 2 × 10^{12} n cm^{-2}. Each of these values characterizes the efficiency of one or other technique of setting up the neutron experiment. The neutron fluxes at the modern operating pulsed source based on the proton accelerator in Oak Ridge (United States), when reaching project parameters (a proton beam power of 2 MW, from which 0.5 MW will fall on the second target with a high flux density and a long pulse), will be close to the IBR-2 parameters; therefore, these two facilities are of the same class.

The IYaU IBR-2 has an undeniable advantage over SNSs in regards to stability of operation and efficient performance: the cost of reactor operation is at least an order of magnitude lower than the cost of the high-current accelerator. The substantial disadvantage of IBR-2 is the significant neutron background between the pulses (around 8% of the time-average flux).

Nevertheless, the lifetime of any nuclear facility is finite. Due to the wear of metallic and concrete constructions, the decommissioning of IYaU IBR-2 is suggested at around 2032. It should give place to a new neutron source which (obeying the immutable law of progress) will be more efficient and appropriate in terms of increasingly stringent requirements for science and technology, getting rid of disadvantages of the predecessor.

QUALITATIVE ESTIMATION OF ULTIMATE NEUTRON FLUXES IN PULSED FISSION-BASED SOURCES

In sources of significant size, among which are the multiplying targets and pulsed reactors under study, where the migration length of a fission neutron is significantly smaller than the characteristic size of the core target, the thermal neutron flux density in the moderator is determined, mainly, by the volume density of neutron generation in the region adjacent to the moderator rather than by total density. Moreover, the factor of proportionality between fluxes of fast and thermal neutrons will be defined by the specified “target—moderator” geometry and by neutron-physics properties of neighboring media, but by no means by the facility power. Indeed, this follows from the trivial relationship between the volume density of fissions and the neutron flux density in the core:

$$\begin{aligned} Q_{\mathrm{f}}(x) &= \int \Sigma_{\mathrm{f}}(E)\Phi(E,x)\,dE \\ &= \overline{\Sigma_{\mathrm{f}}}\cdot\Phi(x) = W_{\mathrm{sp}}(x)\times 3.1\times 10^{13}\ , \end{aligned} \tag{1}$$

where $\Phi(E,x)$ and $\Phi(x)$ are the differential and total neutron flux densities, n cm^{-2} s^{-1}; Σ_{f} is the macroscopic fission cross section averaged over the energy spectrum; Q_f is the volume density of fissions, fissions per cubic cm per sec; and W_sp is the specific power density, MW/L. All quantities are related to a certain region of the core near the neutron moderator. The thermal neutron flux density on the outer surface of the moderator, which is the most important characteristic of a pulsed source for research on extracted beams, is proportional to the neutron flux density in the core on the boundary with the moderator:

$$\Phi_\mathrm{th}(x) \approx \alpha\Phi(x),$$

where the coefficient α is determined by the "core–moderator" geometry and by the Fermi law of energy distribution of slowing-down neutrons. Depending on the "core–moderator" geometry, $\alpha \approx 0.1–0.2$.

Defining the macroscopic fission cross section in Eq. (1) through the product of the density of a fissile substance in the core γ and the averaged macroscopic fission cross section σ_f, we derive the expression for the thermal neutron flux density:

$$\Phi_\mathrm{th} = \frac{W_\mathrm{sp}(x)}{\gamma \cdot \sigma_\mathrm{f}} \cdot \alpha \cdot 1.23 \times 10^{16}. \quad (2)$$

Here quantity γ is expressed in units of kg/L, while the cross section is in barns. From Eq. (2) the existence of a limit of the thermal neutron flux in pulsed sources is being observed explicitly. Above all, the flux is bounded by the ultimate specific thermal power of the core W_sp. The modern nuclear technology of fast reactors with the ceramic fuel of the type of BR-10, BOR 60, and MBIR [6] makes it possible to remove up to 0.5–1 MW/L (it depends on the core size), while in the resonance-neutron reactor of the type of SM-3 and PIK, the specific power density averaged over the core volume reaches 2 MW/L and, at the core center, up to 5 MW/L. The remaining parameters in Eq. (2) also have its limits determined by the reactor construction. Just so, the nuclear fuel density in the core of the pulsed reactor or booster (γ parameter) cannot be reduced substantially due to adverse effects of thermal shock during the pulsed fuel heating, which is proportional to the specific heat release per 1 kg of the fuel and is inversely proportional to the specific fuel load:

$$\Delta T = \frac{W_\mathrm{sp}(x)}{\gamma \cdot n c_\mathrm{m}}, \quad (3)$$

where n is the pulse repetition rate, while c_m is the mass heat capacity of the fuel, expressed in MJ/kg/K. The rapid heating of the nuclear fuel above the admissible value leads to the premature destructurization of the fuel kernel and/or the fuel cladding damage.

Let us consider qualitatively two practically important cases: fast reactors (or multiplying targets) on plutonium and neptunium and a pulsed resonance-neutron booster.

In fast reactors with plutonium, the fission cross section σ_f remains within the limits of 1.5–2 b in a wide range of neutron energies from 10 keV to 4 MeV. Ultimate values of pulsed heating reach a few hundreds of K in the fast pulsed self-quenching reactors with the metallic fuel at the research centers of Sarov and Snezhinsk [12]; however, for recurring bursts of a periodic reactor, a temperature jump for a short time of the pulse of 200–300 μs, defined by Eq. (3), due to the material fatigue should be roughly an order of magnitude lower. Therefore, experimental and theoretical studies of the thermal shock effect, performed during the creation of IBR-2 [7], allow a substantiated conclusion to be made that heating per pulse of the solid ceramic fuel-rod kernel should be limited by ~50 K. Then, for the nitride fuel (most promising as a nuclear fuel for future pulsed devices), at the pulse frequency $n = 10$ Hz, we derive the following restriction for the ultimate neutron flux:

$$\Phi_\mathrm{th} < \frac{\Delta T n}{\sigma_\mathrm{f}} c_\mathrm{m} \times 0.48 \times 10^{13} \approx (3-6) \times 10^{13}.$$

It is noticeably lower than the limit of the specific power. Calculations show that namely the restrictions due to the admissible heating per pulse set a limit for a flux achievable in the fast plutonium cores, which is equal to (0.6–0.7) × 10^{14} n cm^{-2} s^{-1}, even upon the condition of optimization of the fuel-rod construction.

The resonance-neutron plutonium core of the type of the SM-3 and PIK reactors with the water cooling and cruciform composite fuel rods has certain advantages in the sense of the ultimate flux of thermal neutrons. The advantage is ensured by the fact that the nuclear material is dispersed in the matrix with high thermal conductivity. This provides the opportunity to enhance the pulsed heating of the nuclear fuel several times, i.e., to increase an ultimate value of the term $\frac{W_\mathrm{sp}(x)}{\gamma}$. The high value of the fission cross section in the resonance region (~15 b) is an adverse factor reducing the positive effect, but eventually the core with a power density of around 2 MW/L and with the plutonium load of about 1.5 kg/L will be able to ensure the sufficiently high flux density of (1.5–2) × 10^{14} n cm^{-2} s^{-1} in the pulsed mode at a frequency of 5 Hz (the evaluation is performed on the basis of PIK reactor characteristics [8]).

For a neptunium reactor, due to the threshold behavior of the fission cross section (Fig. 1), its value averaged over the entire spectrum (from ~0.1 to 4 MeV) appears to be noticeably lower than the plutonium cross section (by a factor of 1.5–2). In addition to that, due to the large critical mass of neptunium, the flux limit with respect to a thermal shock is higher than for the plutonium reactor. These factors somewhat increase the ultimate flux of thermal neutrons in the neptunium reactor when compared with the fast plutonium core.

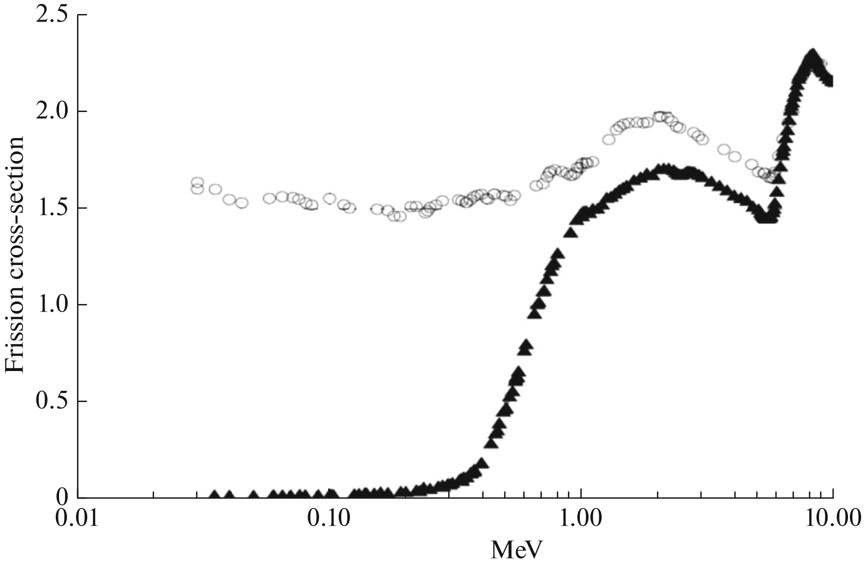

Fig. 1. Microscopic fission cross sections of Pu-239 (open circles) and Np-237. The abscissa axis shows the energy of a neutron that induces a fission, MeV; the ordinate axis presents the miscoscopic cross section in units of 10^{-24} cm^2.

Thus, a level of the thermal neutron flux density on the order of (1–2) × 10^{14} n cm^{-2} s^{-1} in fission-based pulsed sources is the margin of capacities of the nuclear technology of the first half of the 21st century (everywhere in the approach stated above, we are talking about a neutron flux from a flat water moderator with optimal dimensions). This barrier can be cleared and the flux can be roughly an order of magnitude increased in the case of transferring to long-patented apparatus with the circulating molten fuel or to devices of the uranium cycle-pile type [9]. However, this assumption is precarious: the cost of construction, apparently, will be not cheaper than building accelerators with the same capacities. Moreover, the public today is unprepared for similar breakthroughs. At the same time, for a nonfissile tungsten target, a cycle-pile principle is actually implemented in the ESS target station, where a target (circle) consists of 33 tungsten sections.

CONCEPT VARIANTS AND PARAMETERS OF A NOVEL NEUTRON SOURCE OF THE FRANK LABORATORY OF NEUTRON PHYSICS

A selection of the reasonable concept of the novel source depends on several factors of both technical and socioeconomic natures. The authors performed a comparative study of several fundamentally different concepts of a neutron source for the 21st century from the standpoint of neutron parameters adequate for JINR capacities.

The following variants of the source concept were considered in the study:

(1) The nonmultiplying tungsten target of the high-current linear proton accelerator with a beam power of 100 kW (proton energy of 1 GeV, average current of 0.1 mA, burst frequency of 10 Hz, and proton pulse width of 100 μs). The pulse current of protons in this case will reach 0.1 A, which, apparently, can be assumed to be the admissible limit for a single-beam accelerator [10].

(2) The multiplying target of the proton accelerator with the same parameters with plutonium in the core—*booster*. Here the traditional (one-sectional) multiplying target is considered. Recently [11] it has been proposed to use one of the options of two-cascade boosters developed for aperiodic reactor systems [12]. This new trend for periodic beam neutron sources is at the stage of technical development. However, restrictions to a limit of neutron flux for them are the same as for the neutron sources discussed in this work, while the design and physics of processes are more complicated.

(3) The *pulsed booster (superbooster)* is the booster with a reactivity modulator; the core, simultaneously being also a target for protons, is cooled by water, and the plutonium fission occurs using resonance neutrons.

(4) The *pulsed reactor*; a core with neptunium-237 or with plutonium, cooled by molten metal (lead or sodium).

(5) The *superbooster* with the neptunium core (the construction is similar to the design of the pulsed reactor with neptunium).

The use of neptunium demands explanation. The threshold fissile isotope Np-237 has an effective fission threshold of 0.4 MeV, the microscopic fission cross section with a capture of the 1-MeV neutron is 1.5 b (see Fig. 1 for comparative cross sections of plutonium and neptunium). A fission chain reaction is possible on Np-237 in a tight ensemble without mate-

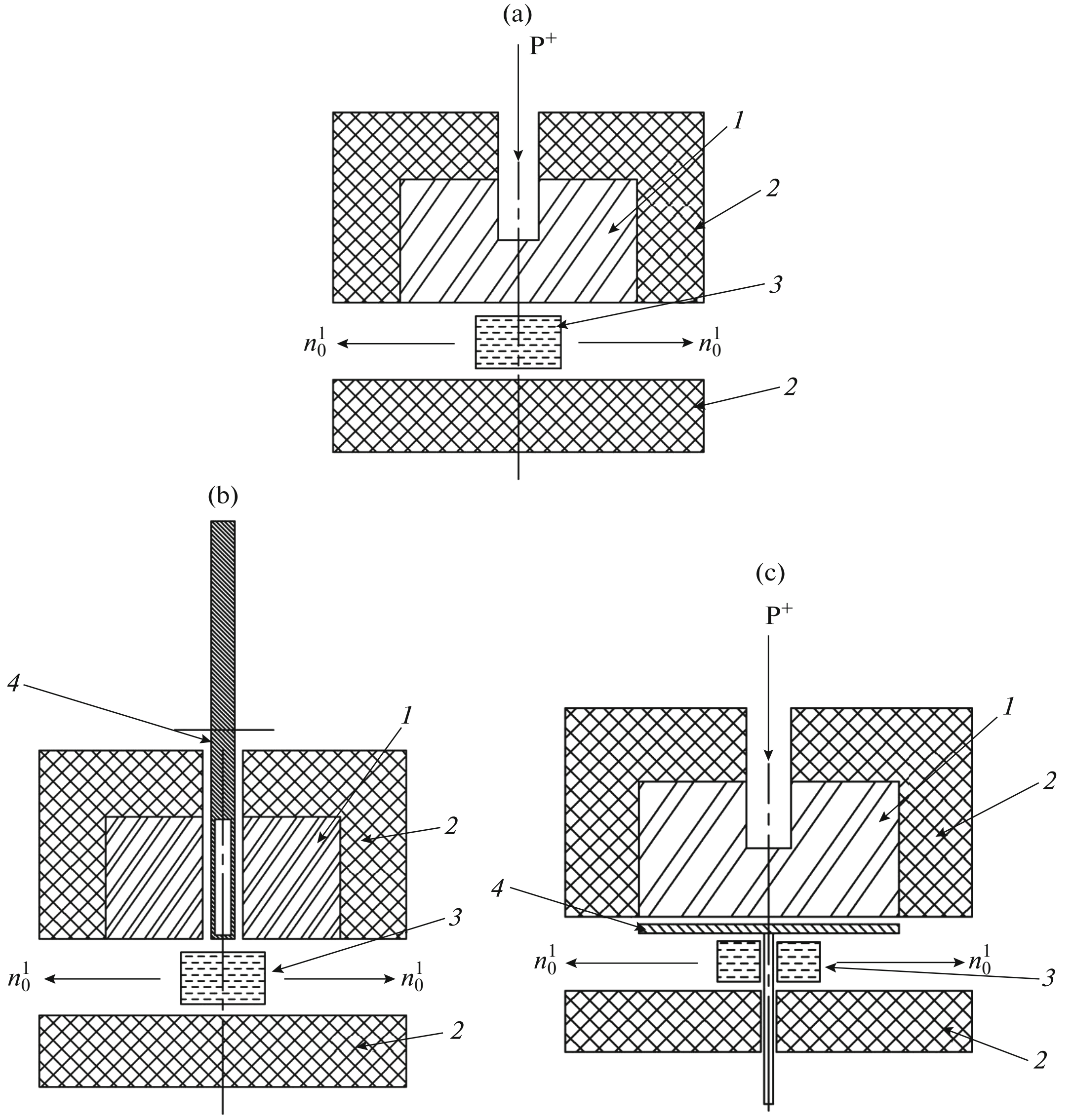

Fig. 2. Calculation schemes of pulsed sources (cylindrical symmetry and vertical section): (a) multiplying target without a reactivity modulator (booster), (b) pulsed reactor with the neptunium core, and (c) multiplying target with a reactivity modulator (pulsed booster). Designation of nodes: (*1*) core target, (*2*) reflector, (*3*) moderator, and (*4*) reactivity modulator.

rials that slow down a speed of neutrons; the critical mass of the sphere made of neptunium metal with the iron reflector is around 39 kg [13]. One of the positive properties of the core with Np-237, arising from its nuclear properties, is the low lifetime τ of the generation of fission prompt neutrons. With the same density of a fissile substance in the core, the τ value for the neptunium core is 7–8 times less than the value for the plutonium core. This ensures a twofold reduction in the neutron pulse width in the mode of the pulsed neptunium reactor (all other things being equal), as well as provides the opportunity for building an intense source with a short pulse of thermal neutrons.

The thermal neutron flux density (2π-equivalent in the direction orthogonal to the surface of the water flat moderator) was evaluated for concept no. 1 in the geometry analogous to the ESS geometry, which was considered as the optimal one [5]. For concept no. 2, the "target–moderator" geometry is given in Fig. 2a. It is conceptually similar to the ESS geometry and ensures a panoramic view of the moderator at an angle of around 90° to the incident flux of fast neutrons, reducing the background, but has a considerably larger volume of the core-target. The same model also was used for concepts nos. 3–5 (Figs. 2b, 2c). The neutron multiplication factor in the core of concept no. 2 is limited by the value 0.96 in accordance with the nuclear safety rules. With the higher value of the multiplication factor, the device is subject to the rules for nuclear reactors, and then the reactivity modulation should be used, i.e., the pulsed booster or the pulsed reactor.

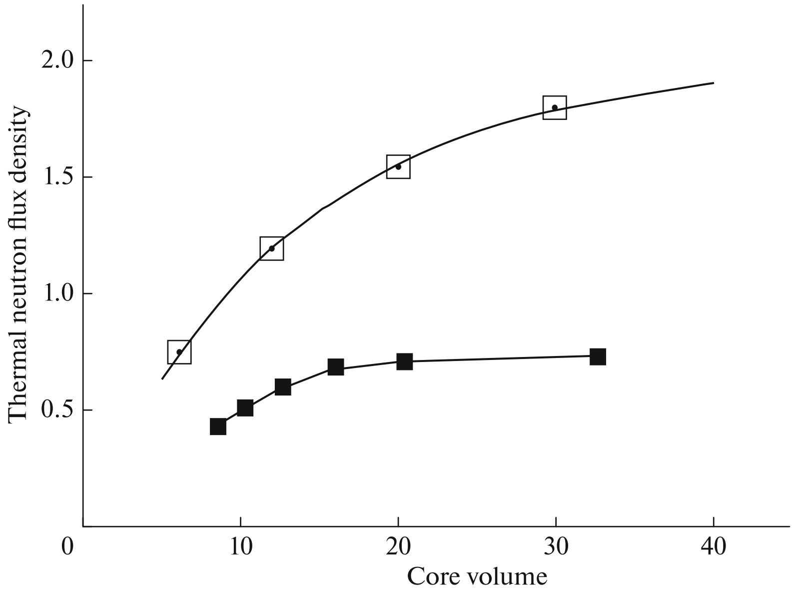

Fig. 3. Calculated flux density of thermal neutrons (in 10^{14} n cm^{-2} s^{-1}) as a function of the core volume (in L) with the given specific power density of 1 MW/L for the fast reactor with the molten metal coolant and nitride fuel (asymptotics of 2×10^{14}, shown with open squares) and for the intermediate plutonium reactor of the type of PIK reactor (black squares).

The neutron-physics computations of the variants were performed using the codes of MCNP-5 and MCNP-X taking into account (apart from neutrons) the proton transport [14]. Thermophysical computations were carried out using the SOLID WORKS software [15], while kinetics and dynamics of a neutron flux were calculated analytically.

Results of the comparative analysis are summarized in Table 2 and in Fig. 3. The saturation of flux density values with core volumes of 20–40 L, obtained by calculations, confirms the above statement on the limit of the thermal neutron flux due to the specific energy release. It can be also noted that coefficient α (of the fast to thermal neutron conversion) in the chosen geometry is closer to 0.1 than to the value of 0.2 accepted in the above analysis.

Values of thermal neutron fluxes indicated in Table 2 are optimal for the relevant facility; neither increase in the core volume nor power enhancement will lead to a growth in the flux or prove admissible due to the lim-

Table 2. Ultimate values of neutron parameters of hypothetical high-flux pulsed sources

	Tungsten	Plutonium	Neptunium
Nonmultiplying target; protons, 1 GeV, 0.1 mA	0.1 /0.7/150 0.1 MW, 0.1%		
Booster; 1 GeV, 0.1 mA		**0.4 /2.5/150** **5 MW, 6%**	
Superbooster; 1 GeV, 0.1 mA		**1.5/4/300*** **30 MW, 6%**	**0.2/2/30**** **15 MW, 3%**
Fast-pulsed reactor		0.7/1/600 10 MW, 7%	**1/3/300** **15 MW, 4%**

In the top row of each cell, (i) the first number is the thermal neutron flux density on the surface of the water flat moderator (2π-equivalent), time-average, in units of 10^{14} n cm^{-2} s^{-1}; (ii) the second number is the peak flux in units of 10^{16} n cm^{-2} s^{-1}; and (iii) the third number is the thermal neutron pulse width in μs. The bottom row of each cell contains the thermal power of the target (booster and reactor) and the background power as a percentage of the total power. Parameters of the linear accelerator are the same everywhere: the proton energy is 1 GeV; the average proton current is 0.1 mA. The peak flux density is indicated for all variants in the accelerator operation mode at the frequency of 10 Hz (except for the pulsed neptunium booster, the frequency in this case can be higher; the data given in the table correspond to a frequency of 30 Hz). For the modes with accelerator, it is connected with the limitation of the pulsed current of protons of a value of 0.1 A, while for the neptunium reactor it is associated with specific features of operation in the pulsed mode.
*Booster with a resonance neutron core.
**Option of the booster with a short pulse of thermal neutrons (“poisoned” moderator, shortened pulse of protons).

Table 3. Comparison of the DANS hypothetical pulsed source of ultimate dimensions with the IBR-2 operating reactor and with the high-intense neutron sources under construction for research on extracted beams

Facility	Moderator type	Peak neutron-beam brightness for neutrons with a wavelength of 1 Å, 10^{14} n cm^{-2} s^{-1} sr^{-1} Å^{-1}	Peak flux density of thermal neutrons, 2π-equivalent, 10^{14} n cm^{-2} s^{-1}	Neutron fluence per pulse, 10^{12} n cm^{-2} sr^{-1}	Time-average flux density of thermal neutrons, 2π-equivalent, 10^{14} n cm^{-2} s^{-1}
IBR-2					
	Comblike	9	58	0.28	0.09
	Comblike, narrow beam of 4.5 cm	12	77	0.37	0.12
J-Park, Japan	Coupled	10	65	0.2	0.3
ESS, Sweden	"Butterfly" type, height of 6 cm	8	50	2.2	2.0
	Height of 3 cm	12	75	3.4	3.0
PIK, RF	Stationary reactor with the D_2O moderator	1.6	10	–	10
DANS*	Comblike	130	800	4	3.0

*DANS is the project of resonance-neutron superbooster with plutonium given in Table 2 (proton energy of 1 GeV, an average proton current of 0.1 mA, a proton pulse width of 100 μs, and a core power of 25–30 MW).

itation of the heat removal or pulsed heating of fuel rods. It should be also noted that the facility parameters given in Table 2 must be assumed to be just preliminary ones; they can only be used for the relative comparison of device variants. Real parameter values may be slightly different in the engineering–physical calculation with allowance for constructive features of each apparatus.

From the analysis of data in Table 2, it can be seen that variants with the multiplying targets and the pulsed reactor are undoubtedly more attractive than the nonmultiplying target. A 4- to 15-fold intensity gain is obtained during the thermal neutron generation. One single common disadvantage of them is the employment of fissile materials.

The variants of multiplying systems in Table 2, which merit a more detailed comparison, are highlighted in bold:

(i) the multiplying plutonium target with a proton accelerator—*booster*;

(ii) the *superbooster* with the resonance-neutron water-cooled plutonium core and with fuel rods of the type of the SM-3 or PIK reactors [8];

(iii) the fast *pulsed reactor* based on neptunium-237;

(iv) the fast *superbooster* based on neptunium-237, with the shortened pulse of the accelerator and with the "poisoned" moderator (the addition of the neutron-absorbing substance into the moderator ensures a reduction in the neutron pulse width).

To the *booster* advantages, the operation in the mode of the largest subcriticality, as well as the higher value of the so-called pulsed source quality (a ratio of the neutron flux to the square of the pulse width) should be referred. Truly speaking, the quality determines a source efficiency for far from all neutron techniques.

Almost an order of magnitude higher quality is provided by the *pulsed booster* based on neptunium-237.

One advantage of the resonance neutron *superbooster* is the high neutron flux, both average and peak fluxes. This variant, apparently, can ensure the largest maximum-achievable flux density of thermal neutrons in the outer moderator of neutrons.

The most important advantage of the *neptunium pulsed reactor* is the operation with no accelerator at all. The cost of construction and operation of this source will be several times cheaper than the cost for the accelerator-based sources.

CONCLUSIONS

The consideration of fundamentally different concepts of the new fission-based neutron source has shown that the ultimate value of the time-average flux density of thermal neutrons on the surface of the flat water moderator can amount to $\sim 1.5 \times 10^{14}$ n cm^{-2} s^{-1} (to 3×10^{14} for a comblike moderator), which is 30 times higher than a flux in the operating IBR-2 reactor (mainly due to the multiple enhancement of the core power). This is a fundamental technological limit for the fission-based pulsed sources, which, by the way, is highly competitive with that of the ESS—today's "beacon" of pulsed sources. A peak flux density of thermal neutrons in any considered variant of the novel source is an order of magnitude higher than all newly commissioned facilities.

We note that, for the conduction of scattering experiments, the main characteristic of the source (apart from the pulse width and frequency) is an average neutron flux, which determines not only the rate of experiment conduction, but also the measurement accuracy in studying small objects and an object with small scattering cross sections, in carrying out the experiments with the analysis of neutron polarization before and after the scattering, etc. By this characteristic, the existing pulsed neutron sources are inferior to stationary reactors. However, as is shown by the analysis of conditions of performing the scattering experiment at the continuous-flow sources and at the pulsed sources, for ideally constructed devices requiring neutron-beam monochromatization, a neutron flux at the stationary source and a peak flux at the pulsed source are equivalent. This means that, even at the existing pulsed sources, conditions for carrying out the experiments can be better than at the stationary reactor. Table 3 presents the main characteristics of the neutron flux, each of which is used in the relevant case.

The variants of the possible novel neutron source considered in the work are not as significantly distinguished between themselves by main neutron parameters: thermal neutron flux, thermal neutron pulse width, background, and the availability of neutron beams for a user. However, each variant has one or another advantage over the others, as well as a disadvantage. A choice is to be made in the future after the detailed analysis of the feasibility, cost, and attractiveness of each facility from the standpoint of users and engineers.

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