HIGHLY INTENSE PULSED NEUTRON SOURCE “NEPTUN” (IBR-3)

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Preface

In the course of one third of centure (since 1984) the IBR-2 reactor has been and still is the most intense high-flux source of thermal neutrons in the world for the investigations on extracted beamlines, providing for the peak density of the neutron flux on the surface of moderators $6{\cdot}10^{15}$ n/cm^2/s and for the time average neutron flux up to 10^{13} n/cm^2/s.[1,2]. However, service life of the IBR-2M is expected to end in 2032 ÷ 2037. Modern science nowadays and especially 20 years after, requires neutron fluxes of one order of magnitude higher. Progress in the technics of spallation neutron sources gave opportunity where the peak fluxes of neutrons approximate to 10^{16} n/cm^2/s, and the average time ones – to 10^{14} n/cm^2/s. Recently performed calculations show that it is hardly possible to radically improve the essential parameters of the IBR-2 type reactor. So, if we look 15 – 20 years ahead we should think about a new neutron source of the fourth generation, after IBR, IBR-30 and IBR-2M.

In the research studies of FLNP specialists [1] it has been shown that pulsed sources of slow neutrons based on the fission reaction (pulsed reactors and pulsed boosters) may be competitive with spallation neutron sources and even significantly (by an order of magnitude) exceed them in peak slow-neutron fluxes using already mastered nuclear technologies. The time-average vector density of the thermal neutron flux can reach ~2 10^{14} n/cm^2/s (in terms of an angle of 2π – the so-called "2π-equivalent flux") at a reactor power of 15-20 MW. A careful comparison of different types of sources has shown that facilities of a pulsed booster type (superbooster) suit the purpose best. The facility considered to be in principally pulsed fast reactor as its predecessors IBR, IBR-30 and IBR-2M but higher power (10-15 MW) and with a reactor core based on fissionable isotope neptunium-237. This causes special features of a new neutron source design.

When being realized, NEPTUN (IBR-3), the successor of the IBR’s, will preserve leading position among world neutron facilities for research on extracted neutron beams such as high current linear proton accelerators. The calculations show that one can expect the peak neutron flux density to be near 10^{17} n/cm^2/s and time averaged thermal neutron flux higher than 10^{14} n/cm^2/s. Duration of pulse 200 ÷ 300 μs is consistent to high degree with experimental needs of neutron spectroscopy physics that use more and more cold moderators and long wave neutrons.

Proposal for the NEPTUN reactor as IBR-3 project version with preliminary calculated technical parameters, preliminary cost estimate of the project and road map of realization are given in the paper.

Why Reactor , not Superbooster?

If compare two modes of pulsed neutron facility based on fission, evidently superbooster mode gives shorter pulses of thermal neutrons 20-30 mks vs 200-300 mks that is peculiar for pulsed reactor. Short pulses seem to be essential especially for neutron spectroscopy with short wavelengh neutrons < 3 angstrems and come up to inelastic scattering experiments with big energy transfer. However, duration of neutron pulses relates to wavelength of neutrons. To thermalize neutrons to, say, 60 K needs about 100 mks but to 30 K (solid methane) - > 150 mks. Therefore, duration of cold neutron pulses is equally long either in superbooster mode or pulsed reactor mode. Up-to the date short pulses of thermal neutrons $20 \div 30$ μs can be rather effectively emulated with long pulses by special technics like Fourier diffractometers or by partition of a long pulse setting off insignificant loss of neutron intensity.

The second as if advantage of superbooster - unsafe operation – appeared to be most probably a myth at close study. A high level of nuclear safety of the superbooster looks evident when comparing the level of criticality of the chain reaction on the stationary research reactor PIK, the pulsed IBR-2M reactor of periodic operation and the IBR-3superbooster, see in Fig. 1.

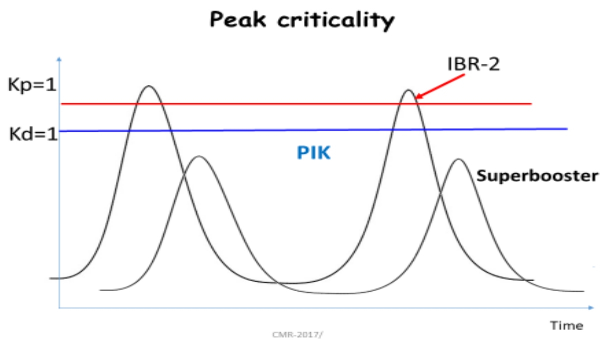
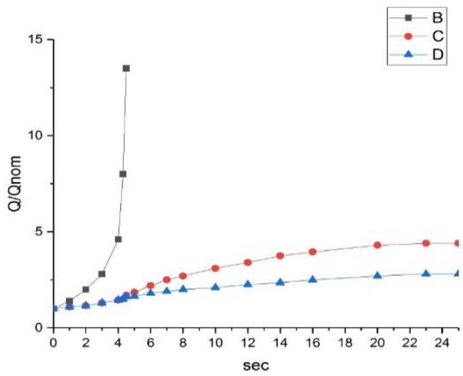


Fig.1. Level of criticality on prompt (k_p) and delayed (k_d) neurtons for some neutron facility

But, level of subcriticality by and large not directly connected to stability and reliability of a facility. Let us see: proton beam current of the accelerator plays leading role in the generation of neutron bursts. A short-term loss of proton pulse leads to a decrease in temperature and, accordingly, to an increase in reactivity. Figure 2 displays magnitudes of abnormal energy release in the first neutron pulse generated by the restored proton beam after loss of beam for several seconds. Each emergency pulse causes long interruption in reactor operation for



restoration of nominal regime. Duty cycle of superbooster will appeared to be well below than 30-40% of pulsed reactor. Operational stability of the accelerator is the key to stable and reliable operation of the superbooster.

Fig2. Excess of nominal pulse energy in superbooster mode of NEPTUN is plotted as a function of duration of proton beam loss for three level of multiplication factor: squares – У=500, circles – У=250, triangles – У=200.

The most distinctive properties of pulsed reactor conception are as following:

- Satisfies in a great degree the world’s best demands for thermal and cold neutron experimental investigations, including condensed matter physics, soft matter physics, biology, fundamental physics, applied neutron research, and so on.
- Feasible configuration & construction, safe operation, not so expensive.
- Follows the evolution and continuity of pulsed neutron facilities of FLNP., Fig.3/

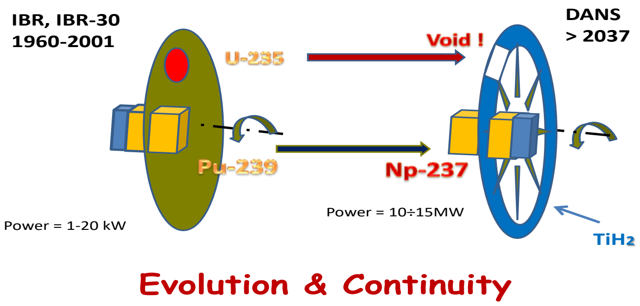


Fig.3

So, we came to clear conclusion – mode of pulsed reactor NEPTUN is preferable than superbooster mode of IBR-3.

NEPTUN - IBR-3 concept

The NEPTUN IBR-3 facility can operate principally in two modes : as periodically pulsed reactor on fast neutrons –the main mode NEPTUN , and as superbooster. In both cases reactor core, reactivity modulator, neutron reflectors and moderators are the same. In the reactor mode of operation it works with no ignition by proton beam.

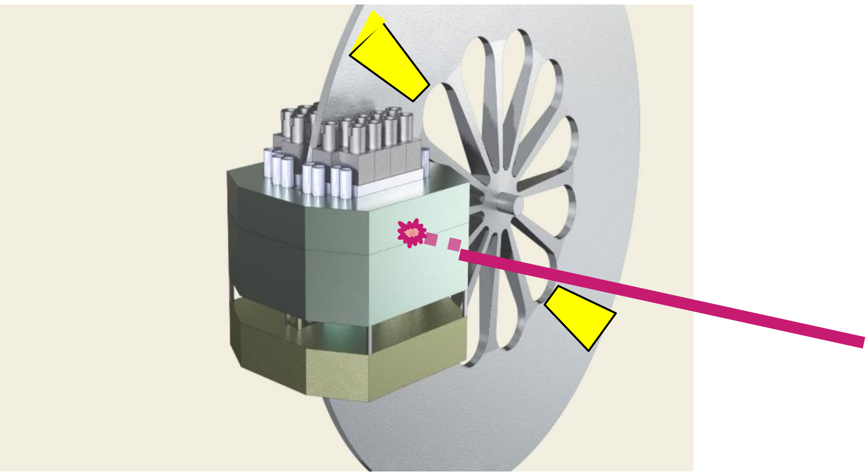


Figure 4. The illustration of the IBR-3 design principle. The yellow sector on the modulator's disk is empty cavity, the rest is titanium hydride. In the superbooster mode pulses of accelerated protons (magenta star) are sent into the core synchronously with the passage of an empty sector through the core.

From here and further description follows only of the pulsed reactor NEPTUN.
The NEPTUN design mainly uses the technical solutions typical for the IBR-2 reactor and the NEPTUN pulsed booster (liquid-metal cooling and reactivity modulator), but at the

same time, innovations have been applied that allow reaching the upper limits of the parameters, namely:

- – as a nuclear fuel, neptunium-237 is used instead of plutonium*);
- – modulation of reactivity is based on the principle of removal of a hydrogen-containing substance from the core (instead of removing the reflector);
- – Slow neutron beams are extracted from moderator coupled with beryllium reflector

Why Neptunium?

The prospect of using neptunium in the multiplying target of a proton accelerator was first reported at the International Seminar on Pulsed Advanced Neutron Sources by scientists from FLNP JINR as early as in 1994.[2].

Neptunium-237 in contrast to conventional nuclear fuels based on U-235 and Pu-239, has a threshold character of the fission cross section, Fig.5. The effective fission threshold about 0.4 MeV is below the fission threshold of U-238, and this makes it possible to create a critical mass of Np-237 [3].

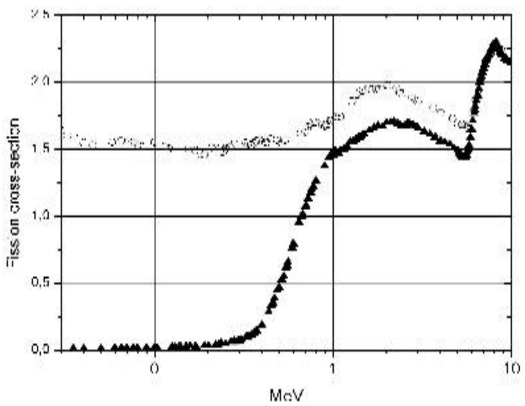


Fig 5. The character of the fission cross section of Np-237 and Pu-239.

There are at least four important positive consequences of using neptunium in the core of a pulsed reactor:

1. First, the lifetime of generation of fast neutrons τ in the neptunium core is much lower than in the plutonium core (9 ns instead of 65 ns at IBR). Duration of fast neutron pulse, initiating by reactivity modulation in supercritical state of nuclear fuel assemble, is proportional $\sim\tau^{1/3}$. Duration of pulse in NEPTUN expected to be shorter than in IBR-2M -150 mks vs 240 mks. Estimation which has been done for a fast pulsed reactor of high power (10-15 MW) loaded with Pu-239 nd modulated with moving reflector , showed duration pulse be as long as 700 mks.

2. The background power of a pulsed source is proportional to the effective fraction of delayed fission neutrons β_{eff}, which in the neptunium zone is expected to be 1.2-1.4 10^{-3} - ~ 1.5 times lower than the same value for plutonium-239.

3. The third consequence of the threshold character of neptunium fission is the possibility of using neutron-moderating materials for the reactivity modulator. In the neptunium core, hydrogen, which is the best neutron moderator, "works" as a neutron absorber, removing them from the core. In this case, the change in reactivity is comparable to the insertion of a fissile material and considerably exceeds the effect from the movement of the reflector.

4. Neptunium nuclear fuel has one more remarkable property: in such a reactor there will be no reduction in the multiplication factor because of neptunium burnup, which is usual for uranium and plutonium reactors. This is explaining by the fact that approximately one neutron out of the three emitted in the fission is captured by a neptunium-237 nucleus, to be followed by β-decay of a neptunium-238 nucleus and formation of a fissile isotope of plutonium:

Np^{237} $\Rightarrow$ neutron capture $\Rightarrow$ Np^{238} β-decay, (2.117 days) $\Rightarrow$ Pu^{238}

The accumulating Pu-238 participates in the fission process along with neptunium, and the neutron multiplication factor in the core practically does not change during NEPTUN service life, Fig.6:

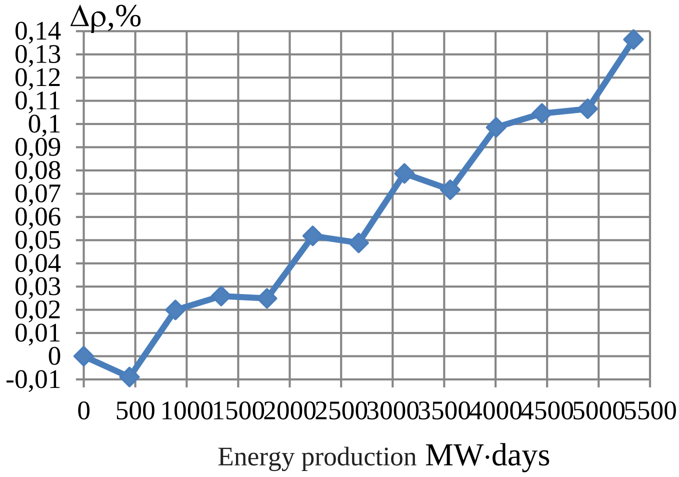


Fig.6. Trend of reactivity due to burn-up of Np-237

How available is neptunium?

^{237}Np is an artificial isotope with a half-life of 2.14×10^6 years and accumulates as a by-product in nuclear power reactors as a result of β-decay of uranium-237 (half-life 6.7 days), which is produced in fast neutron reactors in the (n, 2n) reaction on uranium-238 or by double capture on uranium-235 in thermal neutron reactors. One block of a water-water power reactor produces up to 13 kg of neptunium per year. Neptunium is one of the most significant wastes of atomic energy industry and at the same time – a potential nuclear fuel in compositions with plutonium. Actinide nitrides, and neptunium nitride in particular, have attractive properties for a nuclear fuel – high density and good thermal conductivity. Over the past two decades, properties of neptunium nitride have been rather extensively studied in respect to the problem of radioactive waste transmutation. [4].

Some properties of neptunium nitride are listed in the following table:

	Neptunium nitride at 300 K	Neptunium nitride at 1500 K
Density, *g/cm*^{3}:	13.4	~13
Heat capacity, *J/g/K*	0.20	0.28
Thermal conductivity, *W/m/K*	~13	17,5
Coefficient of thermal expansion (linear), *1/K*	10^{-5}	$1.5\ 10^{-5}$
Modulus of elasticity, *GPa*	140	105

Core and Heat removal

The core is an ensamble of densely-packed fuel elements (FE).The core is placed in two identical stainless steel vessels, between which passes the reactivity modulator rotor, Fig 7.and 7a. Fig 7 represents previous scheme of superbooster IBR-3, Fig 7a – new version of NEPTUN which more acceptable in pulsed reactor mode of operation.

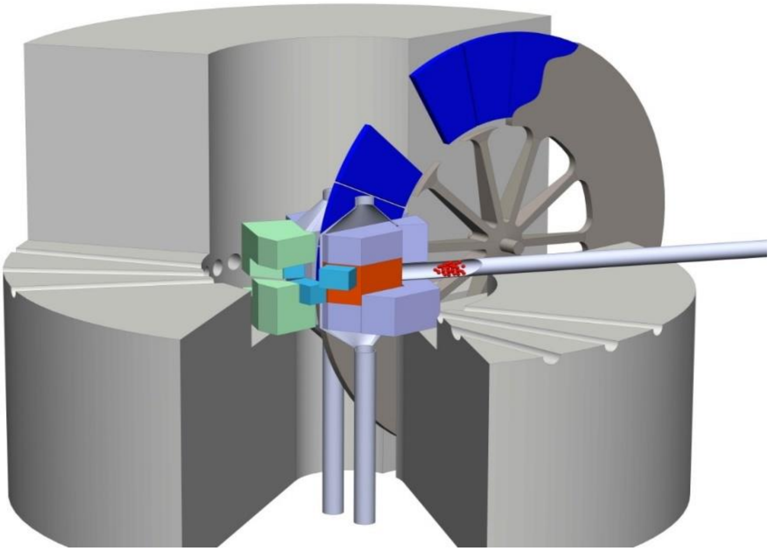


Fig.7. The scheme of IBR-3with a sidelong arrangement of moderators (blue). Moderators are surrounded by a beryllium reflector (green). The reactivity modulator disk (dark blue – titanium hydride sectors) passes between two separate parts of the core surrounded by nickel reflectors (violet). The extracted neutron beams pass through channels in a concrete shield. The cap above the core is the coolant outlet.

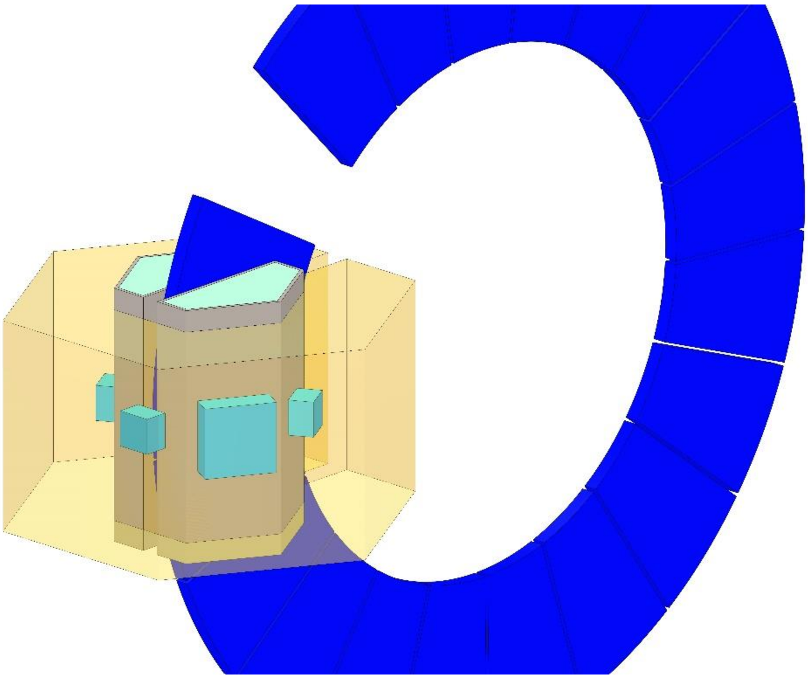


Fig.7a. New approach to NEPTUN composition, the simplified scheme. Moderators (blue) placed on 5 faces of the reactor vessels. They are surrounded by thick beryllium reflector (semitransparent yellow). Neutron beams channels not showed..

The fuel-element column is made of neptunium nitride and placed in a steel cylindrical tube with a gap to compensate for swelling of nitride during the burnup process, which will amount to 10% of the fuel volume at 1500 K (7% burnup of heavy atoms). The gap between the column and the tube is filled with a liquid lead-bismuth alloy. The inner surface of the tube is clad with molybdenum to avoid radiation-induced corrosion.

	FE dimensions (diameter, layer thickness)	Celsius temperature (minimum-maximum)
Sodium coolant	D_{hyd} =3 mm	250 – 450
Steel housing	0.35	270 – 480
Liquid-metal sublayer	0.3	300 – 510
Neptunium nitride	16	650 – 1210

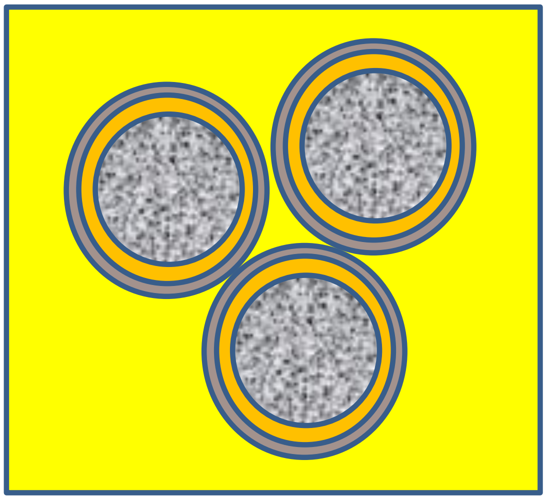


Fig.8. Triangular unit cell for placing fuel elements, pitch 17.6 mm

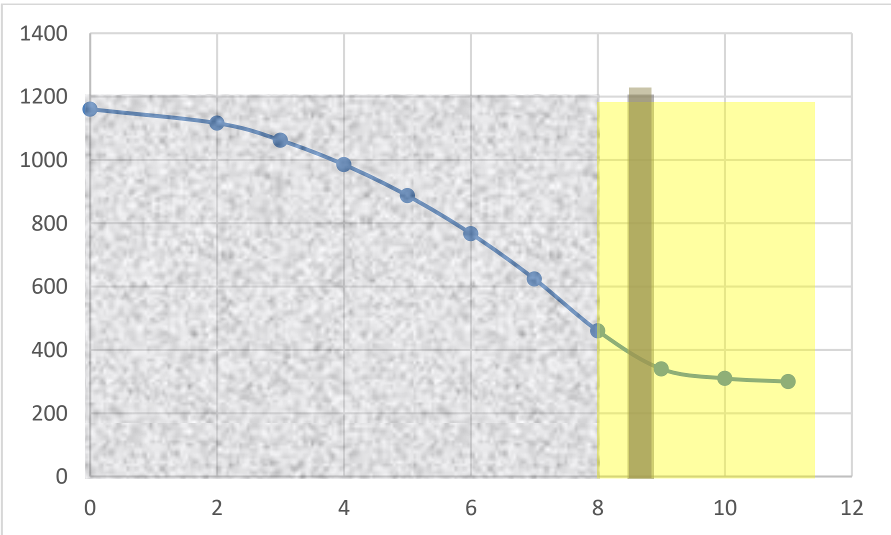


Fig.9. Change in temperature with the radius of fuel element (FE).

The abscissa axis shows the distance from the center of the cylindrical FE column (mm), the ordinate axis – temperature (°C).

To minimize critical loading of the neptunium, geometry of the reactor core is a crude approximation to a sphere. It consists of 3 or 4 sets of fuel rods (FE) with different length of fuel cores. Rough speaking, geometry of the reactor core is a complicated polyhedrons with different shapes of polygons faces from rectangles to trapeziums and hexagons **(see in Fig 10-11).** In order to keep scheme of mounting hardware accustomed and not to disturb flow of coolant, each FE is equal in lengh, notwithstanding length of fuel cores.

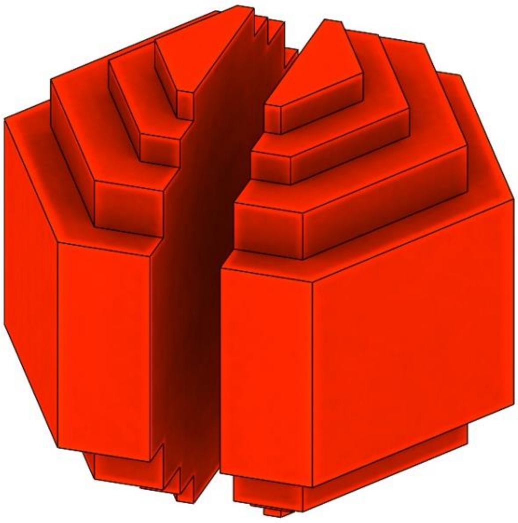


Fig 10. Fuel part of the reactor core – NpN only shown/

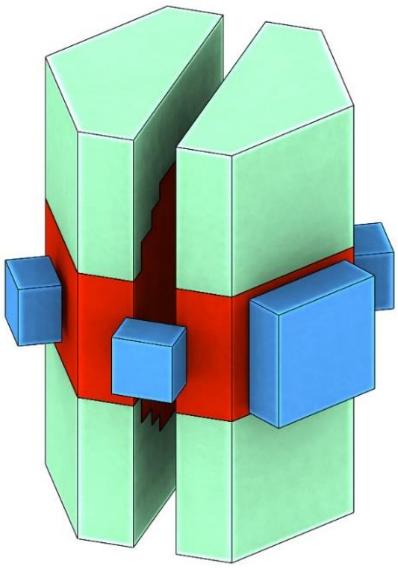


Fig 11. Reactor ensemble of fuel elements (FE) + moderators (with beryllium reflector, reactor vessels and reactivity modulator removed). Red is fuel part of FE, green is nickel reflector part of FE.

. Fuel elements are grouped into blocks of 3,7 or 19 pieces in each, and in order to reduce the size of the core, blocks of FE do not have cases similar to the design of the IBR-30 fuel elements and in contrast to the cassette design as in the case of the IBR-2M reactor.

Heat removal from fuel elements and nickel stationary reflector is done according to the scheme similar to that of the IBR-2 reactor, using liquid sodium (or potassium), which is fed to the vessels of the core from the bottom, The working temperature of sodium of the first loop is 250-450 °C, the coolant flow rate at a power of 10 MW is 180 m^3/h.

. Critical loading of the neptunium reactor at the maximum possible volume fraction of nitride of 72÷73% estimated to be about 450 kg. The volume of the core is about 45 liters.

Reactivity modulator

The main feature of the NEPTUN is the reactivity modulator based on the replacement of a hydrogen-containing substance with a void.

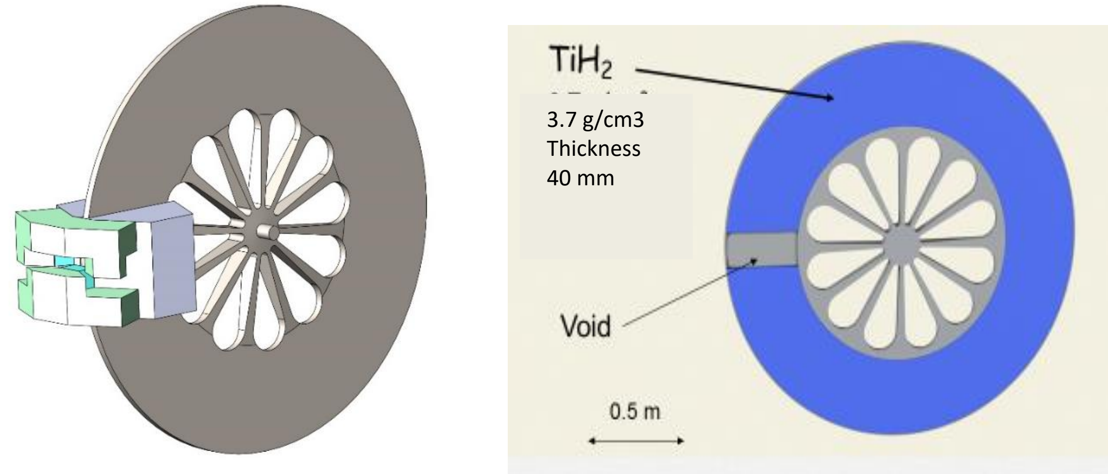


Fig 12. NEPTUN reactivity modulator disk.

The modulator is designed in the form of a rotating disk about 3 m diameter with titanium hydride (density up to 3.7 g/cm^3) shaped as radial sectors along its periphery. One of the sectors is empty; and when this sector enters the region of the reactor core, the neutron multiplication factor increases due to the hardening of the neutron spectrum. The rotation rate of the modulator rotor is 10 revolutions per second.

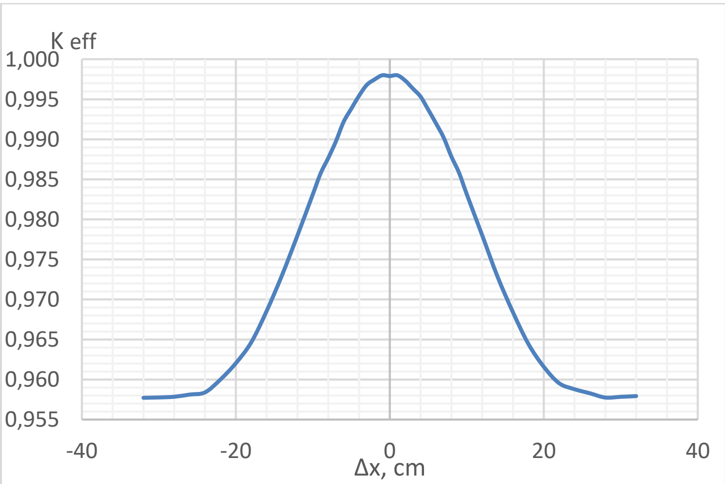


Fig.13. Graph of the modulator reactivity; in the region of ±5 cm from the maximum the reactivity is described by a parabola with a parameter 10^{-4} k_{eff}/cm^2.

The use of such a modulator provides deeper modulation of reactivity than a movable reflector (approximately by a factor of four). The reactor background power will amount to 2-2.5% of its average power instead of 7.5-8% of IBR-2M.

Titanium hydride is a radiation-resistant material, which is well-studied and used in the biological shielding of nuclear power plants . A high hydrogen content in the hydride is maintained up to a temperature of 500 °C. The modulator is air-cooled. The heat load on titanium hydride in the sectors directly adjacent to the empty cavity is rather high - up to 3.5 W/cm^3 at a reactor power of 10 MW. Therefore, to extend the service life of the modulator, the design of the disk allows periodical replacement of sectors with hydride, which during the reactor power pulse appear to be close to the core, with remote sectors.

Moderators

Water moderators adjoint to the five largest faces in median plane of the core which are squares of 25 by 25 cm. This enables to increase thermal and cold neutron fluxes as compared to the previously scheme of NEPTUN published in [5-6] .Most moderators are arranged in wing-type geometry closely coupled with beryllium reflector which enhances thermal neutron flux

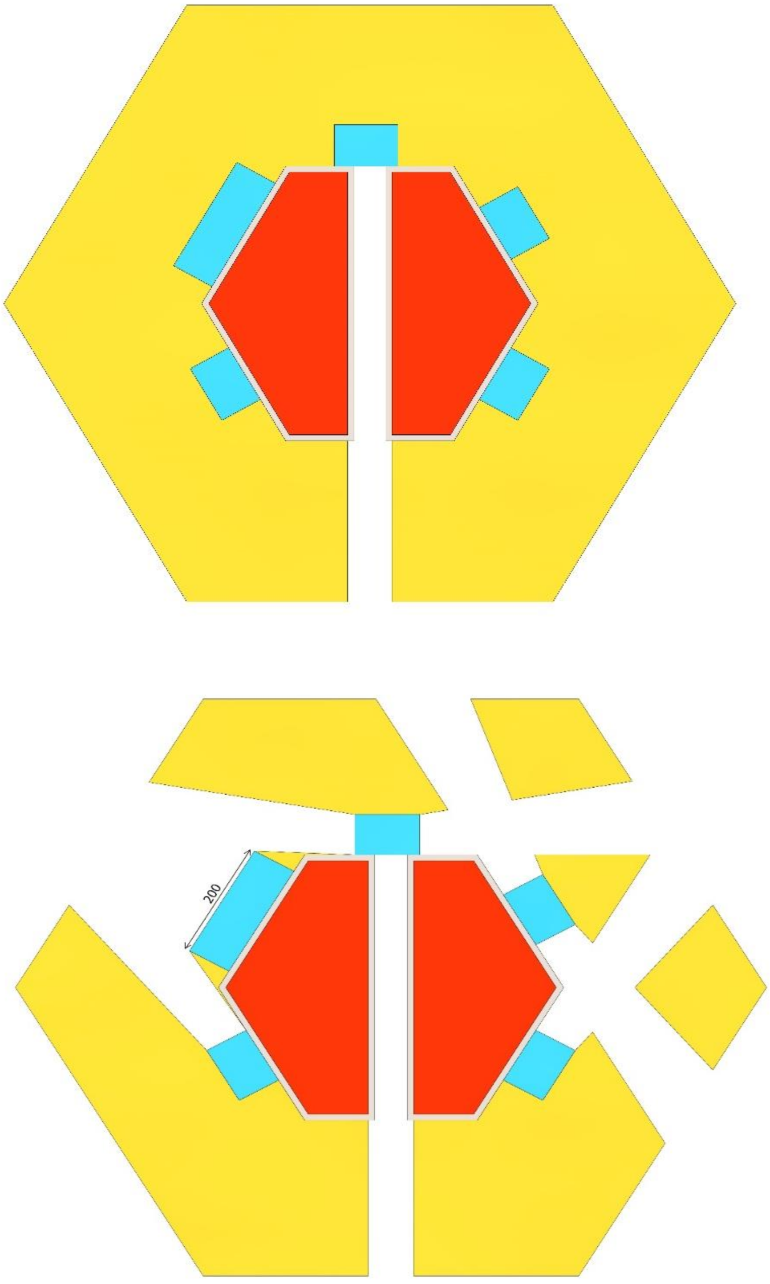


Fig.14. The scheme of arrangement of moderators inside beryllium reflector. Above is a pictiure without neutron channels because there are a lot of schemes for extraction neutrons outsides. From below, one of them is presented ,

This measure reduces the flux of fast neutrons and gamma-rays in the direction of extracted beams about three times as compared to the radial arrangement of moderators at the IBR-2 for the majority of neutron beamlines. Beside wing-type geometry of neutron moderators, the new design of the reactor has usual radial oriented beam like that at IBR-2. Most of wing-type moderators (except one or two) has two working surfaces and can consist, correspondingly, of two different moderating media. Some moderator can be of coupled and grooved type or be decoupled for special application. It is proposed to install five moderators with all beams in one horisontal plane. This configuration of moderators makes it possible to provide 18-21 neutron beamlines of 7 different spectral composition.,

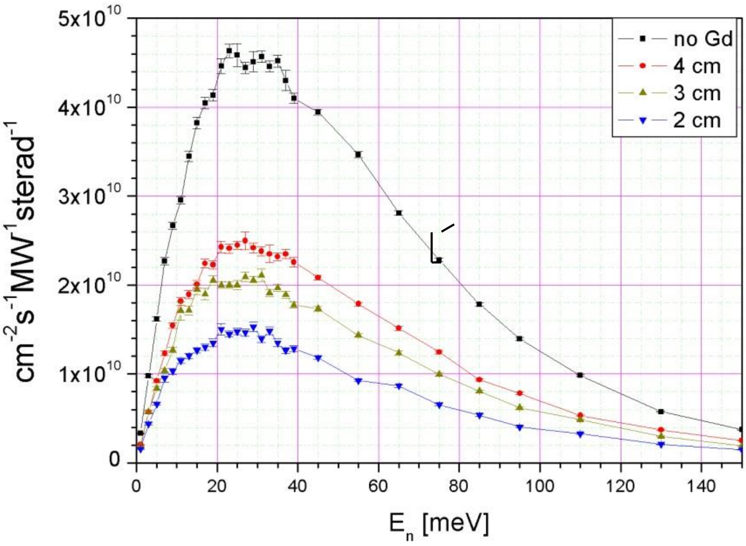


Fig 15. Spectrum of the vector flux of thermal neutrons from the surface of a flat water moderator (of wing type) without gadolinium poisoning (upper curve) and with a gadolinium layer at a distance of 4, 3 and 2 cm from the surface.

Table. Basic parameters of NEPTUN

Thermal neutron flux density, time-average: (depends on position and type of moderator)	$(0.5\div2)\cdot10^{14}$ n cm^{-2} s^{-1}
Peak density of thermal neutron flux:	$(3\div6)\cdot10^{16}$ n cm^{-2} s^{-1}
Half-width of fast/thermal neutron pulse:	150/ 200-300 μs
Pulse repetition rate:	10 Hz
Background power (percentage of the average)	2-2.5%
Number of neutron beamlines	< 22
Number of moderators	5
Thermal power	10 ÷15 MW
Maximum fuel temperature	1500 K
Coolant temperature	250 - 450 °C
Coolant flow rate	up to 180 m^3/h
Reactor service life (in respect to fuel burnup)	20,000-25,000 MW/days
Neptunium nitride loading	~450 kg
Total efficiency of reactivity modulator	~6 % k_{eff}
Prompt neutron generation lifetime	9 ns
Effective fraction of delayed neutrons	1.2 ÷1.4 10^{-3} k_{eff}

Conclusion

Conceptual research of the pulsed neutron source- the superbooster IBR-3, the successer of IBR-2M, was carried out in Frank laboratory of Neutron Physics of JINR in cooperation with the Dollezhal Research and Development Institute of Power Engineering, which performed the engineering design of IBR-2 and IBR-2M reactors.

In result of closer consideration it became evident that operational stability of the facility will depend of stable operation of accelerator. Basing on practice of proton linear accelerators in operation, it is sure that operation of SNS is not reliable in the sense of stable supply target with proton beam. If for nonmultiplying target this is not dramatic, it hardly acceptable for superbooster mode of IBR-3. Besides that, cost of superbooster realization near factor 3 more than NEPTUN.

Essentially, that NEPTUN follows evolution and continuity of pulsed neutron facilities of FLNP.

From all the above, it became apparent and seems reasonable that the new neutron source for JINR should be pulsed reactor with Np-237 as nuclear fuel. Its parameters satisfies in great degree the world's best demands on thermal and cold neutron experimental technics, including condensed matter physics, soft matter physics, biology, fundamental physics, applied neutron research, and so on.

Reactor	– 200 M€
Complex of cold moderators	– 50 M€
Engineering infrastructure	– 100/200 M€
Total:	**350/450 M€**

NEPTUN realization schedule:
Start of the project - 2018
Start of construction – 2027
Power start-up - 2035

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