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MULTIPLYING TARGET FOR A HIGH-INTENSITY SPALLATION NEUTRON SOURCE

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ABSTRACT

The possible design of an intensive pulsed neutron source for time-of-flight experiments is considered. Its major characteristics are expected to be: peak and average slow neutron flux density on the moderator surface up to 10^{17} and 10^{14} n/cm^{2}s respectively, neutron pulse duration about 30 μs and pulse repetition rate 25 pps. This level of performance is achieved due to using a multiplying target driven with the proton beam of the Moscow meson factory.

1. Introduction

Wide use of the neutron time-of-flight methods in nuclear and solid-state physics has stimulated development of high-flux research reactors and high-intensity neutron sources based on the pulsed reactors [1] and, more recently, proton accelerators [2,3]. At present, among the facilities actively used in physical experiments we can list the pulsed reactors IBR-30 and IBR-2 (with the average power 30 kW and 2 MW respectively) in Russia [4] as well as neutron sources driven with medium-energy proton beams - LANSCE (LANL, USA), IPNS (ANL, USA), ISIS (RAL, UK) and KENS (KEK, Japan) [2,3].

Several projects of the next-generation pulsed neutron sources are being developed in the US (LANL, ANL, ORNL) and in Europe (ESS - European Spallation Source). Typical design decisions are as follows: pulsed proton accelerator with energy up to 2.5 GeV and beam power up to 5 MW, targets made of Ta or W, light water and liquid hydrogen moderators.

Keywords: Fissile target, Thermal shock, Liquid metal coolant

At INR RAS, the construction of the intense pulsed neutron source IN-06 is near completion now. It has the water-cooled target made of natural uranium silicide [5] and is driven with the 600 MeV proton beam of the linac of the Moscow meson factory transformed by the compressor ring into a sequence of 0.4 μs proton pulses [6].

Fast subcritical assemblies with the multiplication factor about 20 ($K_{eff} < 0.95$) are of certain interest as the targets for pulsed neutron sources. A multiplying target with limited multiplication substantially reduces required proton pulse intensity, while preserving a short enough (1-2 μs) neutron pulse and relatively low inter-pulse background. The desire to keep the latter value as low as possible makes Pu^{239} and U^{233} having low delayed neutron fraction more attractive.

At present, the INR in collaboration with IPE (Obninsk), JINR (Dubna), ARSRIEP (Arzamas), Bochvar's Institute of Inorganic Materials and EDBMB (Nizhny Novgorod) is developing the design of the high-intensity pulsed neutron source RIN-10 with the peak and average slow neutron flux density about 10^{17} and 10^{14} n/cm^2s.

To achieve this goal we suppose to upgrade the existing proton accelerator of the Moscow meson factory and employ a fissile target with the multiplication of ~20.

2. Proton accelerator

As a first step to achieve the desired level of neutron source performance it is supposed to upgrade the accelerator: to rise proton energy from 600 to 700 MeV by adding one more section to its main part and to increase duration of the beam macro pulse to 350 μs against the present 100 μs, leaving the pulse current at the design level (50 mA). At present, experiments are conducted with the pulse current up to 20 mA and proton energy up to 420 MeV (the final section of the accelerator's main part is not used due to lack of clystrons).

3. Storage ring

To transform the time structure of the proton beam without affecting its average intensity it is supposed to use a storage ring with the charge-exchange injection and single-turn ejection that is constructed now for the pulsed neutron source IN-06 [6]. After injecting one macro pulse of beam current, accumulated protons are ejected onto the neutron target. Evaluations made show that it is possible to store and eject ~10^{14} protons per pulse at the repetition rate up to 50 pps [7]. That is quite adequate for our purpose, so no upgrading is required.

4. Multiplying target RIN-10

As a neutron-producing target, the fast subcritical assembly with uranium nitride fuel and liquid gallium coolant, having $K_{eff} < 0.95$, is used.

As a prototype for the multiplying target, we have chosen the fast research reactor BR-5 successfully operating at the Institute of Physical Energy (Obninsk) since 1958, in the startup and physical research of which one of the authors participated [8]. This reactor can use either oxide, carbide or nitride fuel, it has the sodium core cooling and large air-cooled Ni reflector.

The most important difference between the reactor BR-5 and the target of RIN-10 is that the latter should operate in the pulsed mode. The possibility of creating a target of this kind depends mainly on the long-term fatigue strength of fuel element cladding under thermal shocks caused by repetitive power pulses. Other differences are less significant.

Using the nitride fuel with high thermal conductivity allows us to keep the fuel temperature under 1000 K, reducing diffusion of fission products out of crystalline lattice. This feature as well as using U instead of Pu^{239} and low-temperature gallium coolant should be treated as advantages from the standpoint of ensuring environmental safety.

Liquid gallium, which has the melting point 302 K and boiling point 2250 K, does not interact with water and oxygen and is low-aggressive to stainless steel at low temperatures, allows us to choose relatively simple and, as a consequence, reliable design of the coolant circuit. It is supposed that the first loop will contain gallium with forced circulation by electromagnetic pumps; the second loop - demineralised water transferring heat to air.

Neutron capture in Ga^{71} results in production of Ga^{72} having half-life period 14.12 hr and emitting hard γ-radiation (2.2 MeV). No isotopes with longer half-life are produced in interactions of fission neutrons with Ga. But the spallation process induced by primary protons results in production of Ga^{67} with half-life of 77.9 hr and relatively soft γ-radiation (< 388 keV). This isotope is the most unpleasant for service systems, so to minimize the volume of Ga under proton irradiation a special inner tungsten target with low gallium volume fraction is used. Other, non-gallium, radioactive nuclides can be removed by selective absorption in the cooling system.

The above-mentioned considerations led us to the following target design (Fig. 1).

The proton beam is injected through an inclined ion guide into the inner tungsten target consisting of tightly packed metal tungsten rods cooled with gallium flow. Injecting protons through the target corner reduces possibility of coolant loss in case of window failure due to radiation damage or burning by the collapsed beam. At the same time, it enables fuel reloading without disassemblying the beam transport system. The beam window is cooled by gallium.

The target core consists of hexagonal fuel element assemblies. Fuel elements are in the form of tubes made of cold-deformed stainless steel (4C-68XD of 316 steel class) with 6 mm diameter and 0.3 mm thick wall. Tubes are filled with U or Pu nitride with density 11.5 g/cm^3 packed under vibration. The lower tip of the fuel element is short, while the upper part of the tube contains Ni with 1 mm diameter and 200 mm long gas volume. The target core dimensions are ∅300×300 mm, fuel element are distantiated with wire. Coolant flows through both halves of the core in turn. Average heating of coolant at velocity 3 m/s is about 70 K.

The target and moderators are surrounded with the large (∅1300×1300 mm^3) air-cooled Ni reflector. It has several tangential horizontal and vertical channels 150 mm in diameter used for replacement and maintenance of moderators and neutron guides. Lower movable part of reflector serves as a safety and reactivity control. The target core is decoupled from the reflector and moderators with a boron-containing layer.

Moderators assemblies are inserted into the reflector through vertical channels. It is supposed that two light-water and two liquid-hydrogen moderators will be installed. Each moderator is provided with 6 tangential neutron guides, so, in total, the neutron source will have 24 neutron beams.

The major characteristics of the neutron source for three possible fuel compositions are given in Table 1.

Table 1. Target characteristics for various fuel compositions.

Fissile isotope	U^{233}	U^{235}	Pu^{239}
Fuel density, g/cm^3	11.5	13.5	11.5
Prompt neutron lifetime, ns	70	57	65
Average slow neutron flux density (25 pps), n/cm^{2}s	$7.6 \cdot 10^{13}$	$7.3 \cdot 10^{13}$	$8.1 \cdot 10^{13}$
Peak slow neutron flux density, n/cm^{2}s	$8.6 \cdot 10^{16}$	$8.5 \cdot 10^{16}$	$8.8 \cdot 10^{16}$
Coolant volume fraction, %	52	33	55
Fuel temperature rise per pulse, °C	32	20	30
Thermal power, MW	8.8	9.1	7.6

Neutronic characteristics of the target have been evaluated using the Monte Carlo neutron transport code NeuMC with the total yield, spatial and energy distribution of primary neutrons calculated with the SHIELD code [9].

As it was mentioned above, the possibility to create this target is determined by fatigue strength of fuel element cladding under thermal shock conditions. Unfortunately, up to now there is no experimental information about fuel element behaviour under short (~1 μs) power pulses. Evaluations of few- and many-cycle fatigue made under assumption that the fuel element undergoes about 10 oscillations per power pulse give for 5 mm diameter fuel elements clad with 4C-68XD steel the values of permissible number of power pulses and average lifetime presented in Table 2. Rather steep dependence of lifetime upon the temperature rise per pulse demands for detailed calculation of fatigue strength of fuel elements as well as for an experimental investigation of their behaviour.

Table 2. Fuel element lifetime.

Temp. rise per pulse, °C	Permissible number of pulses	Lifetime, yr
30	$3 \cdot 10^{10}$	25.4
40	$2.5 \cdot 10^{8}$	0.13
50	$5 \cdot 10^{6}$	0.002

The major characteristics of the RIN-10 target in comparison with other pulsed neutron sources are given in Table 3.

Table 3. Comparative performance of the RIN-10 neutron source.

Neutron source	IN-0.6	RIN-10	ESS
Proton energy, GeV	0.6	0.7	1.3
Beam current, mA	0.2	0.4	3.8
Repetition rate, pps	50	25	50
Neutron generation rate, n/s	$1.7 \cdot 10^{16}$	$5 \cdot 10^{17}$	$6 \cdot 10^{17}$
Average slow neutron flux density, n/cm^2s	$2.0 \cdot 10^{12}$	$8 \cdot 10^{13}$	$6.3 \cdot 10^{13}$
Peak slow neutron flux density, n/cm^2s	$1.2 \cdot 10^{15}$	$8.6 \cdot 10^{16}$	$4.2 \cdot 10^{16}$
Thermal power, MW	0.12	7.6 - 9.2	6.3

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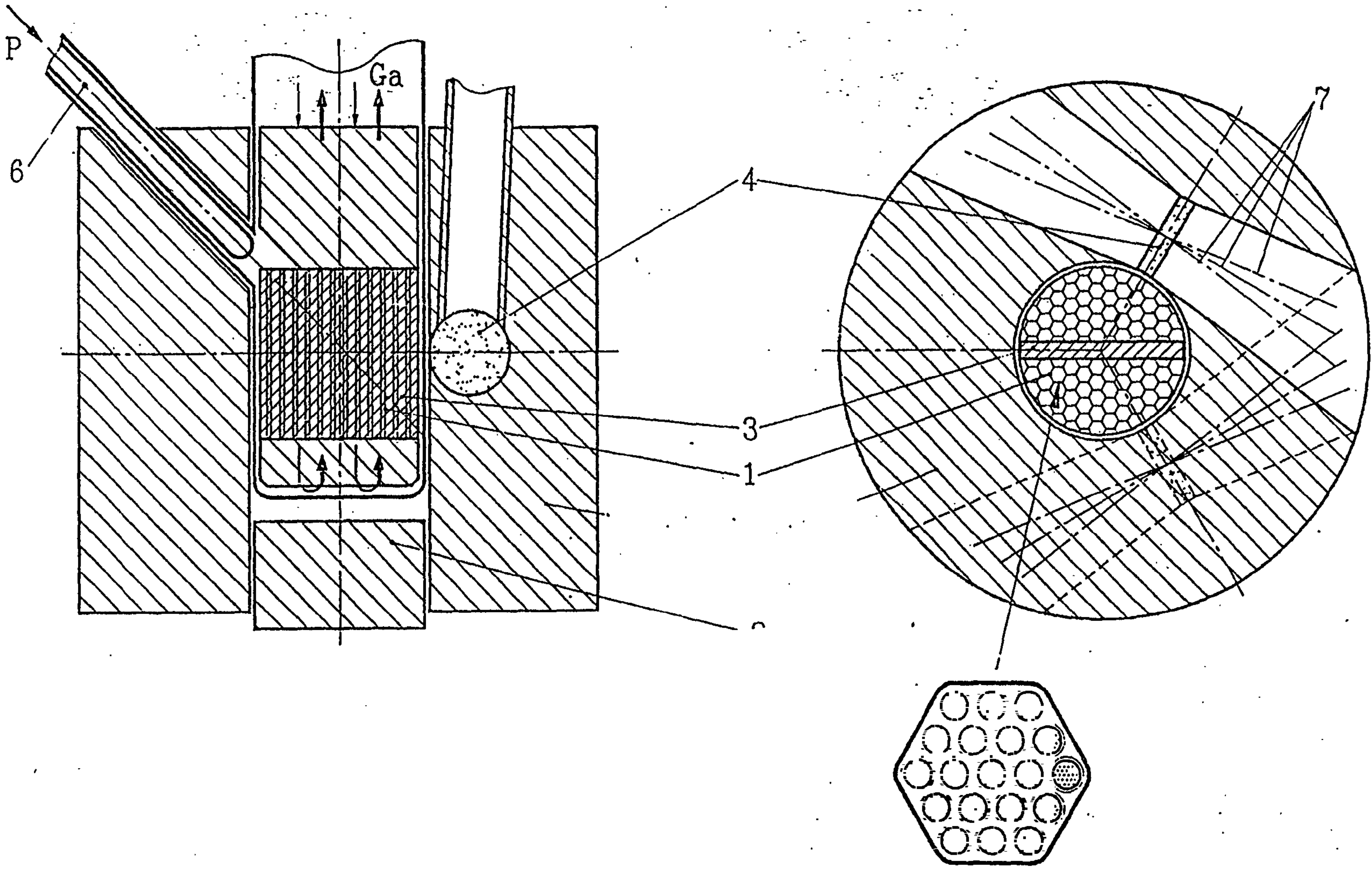

Figure 1. The layout of the RIN-10 neutron source.