HYDROGEN AND DEUTERIUM COLD AND ULTRACOLD NEUTRON SOURCES AT THE PNPI RESEARCH REACTOR IN GATCHINA

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Abstract

St. Petersburg Nuclear Physics Institute (PNPI) is located in Gatchina, Russia, has a 16 MW WWR-M reactor. The reactor has been operating since 1959 and since the middle of the 1970s the cold and ultracold neutron production has been in progress there. As intended, this program has increased substantially the experimental capabilities of the reactor as an instrument for fundamental physics research. It has allowed us to make progress in the investigations which require an extremely high neutron beam intensity such as the search for neutron electric dipole moment, neutron lifetime and correlation constants measurements, the search for P-odd effects in interactions with cold neutrons and so on.

Having started with a simple cold beryllium UCN converter, we went on to use the most efficient moderators such as liquid hydrogen and deuterium, recently solid deuterium. Some new approaches were developed in designing cold sources, which resulted in our medium power reactor becoming competitive with high flux reactors.

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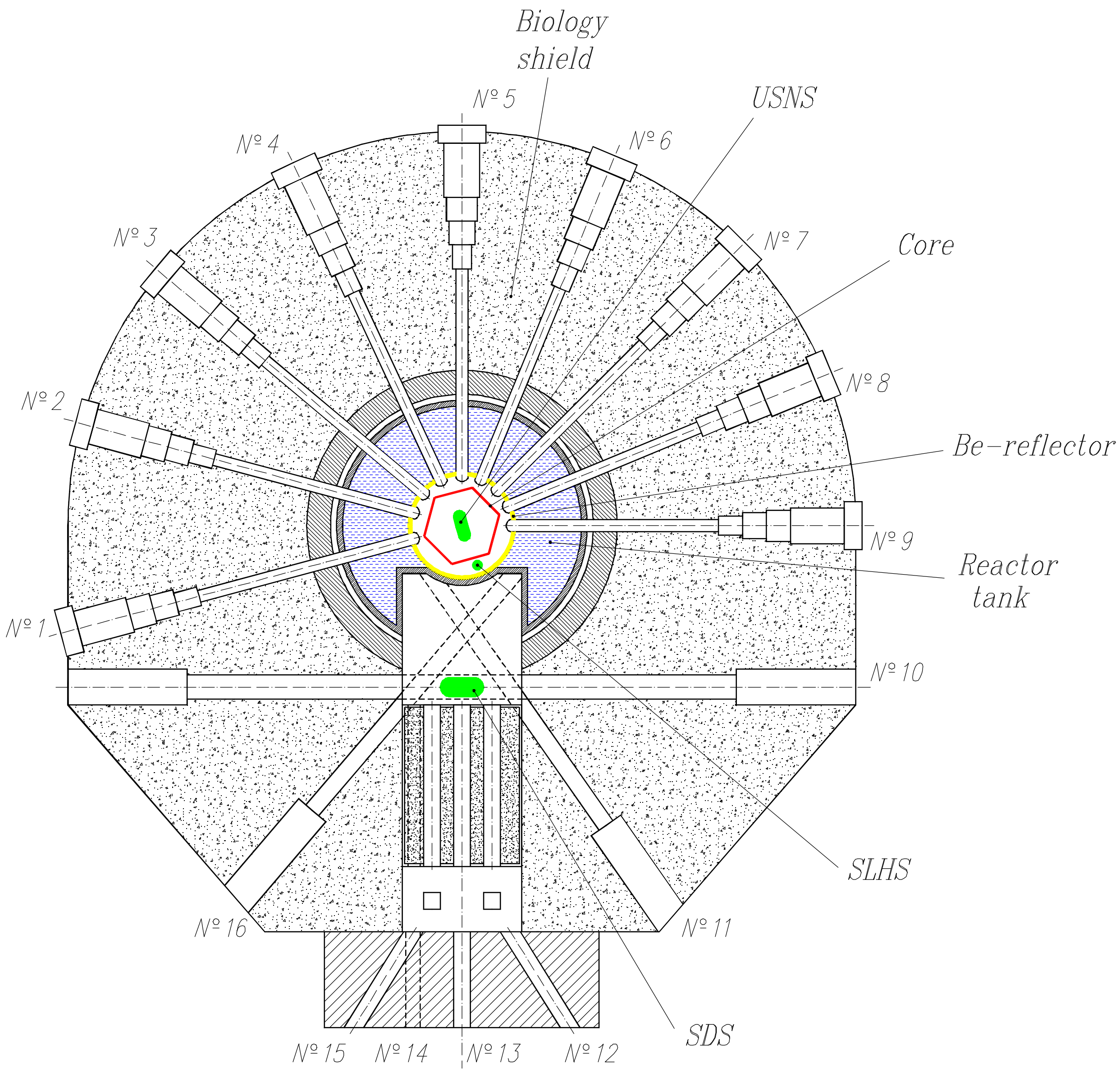


Fig 1. Plan View of WWR-M reactor

Parameters	Value
Maximum power level	18 MW
Minimum fuel cycle length	6-12 days
Active fuel high	600 mm
Active fuel region volume	100-150 l
U^{235} loading	8.5 kg
Horizontal experimental channel	17
Vertical experimental channel	3

Plan view of reactor WWR-M with located cold and ultracold neutron sources in different position is shown on the Fig 1.
SLHS –small liquid hydrogen source; USNS – universal neutron source; SDS – solid deuterium source.

Small Liquid Hydrogen Source

Provided that the moderator volume is not large and the heating is not high, the simplest technique is a direct cooling of the moderator chamber by means of a cold helium circulation. This principle was used in the first hydrogen ultracold neutron source at the WWR-M reactor [1]. The source was placed at the Be-reflector where the perturbed neutron flux was 6.10^{13}n /cm^{2}s for thermal neutrons and 8.10^{12}n/ cm^{2}s for neutrons with energy E>1 MeV. The specific nuclear heating was 8 W/g for hydrogen and 0.3 W/g for the chamber material. The chamber contained 150 cm3 of liquid hydrogen and the total nuclear heating was 300W. The chamber was made like a heat exchanger that allowed us to keep liquid hydrogen subcooled up to a reactor power of 12 MW. However, at 18 MW just 15% of vapor was in the chamber. This ultracold neutron source gave a gain factor of about 30 and 4.10^4n /s of UCN flux integrated up to the velocity 7 m/s. It was operating from 1980 to 1985 producing, at the time, the highest UCN intensity in the world.

Assembly of the small hydrogen source is shown on Fig 2. Probably the maximum capability of the method of direct cooling was demonstrated in that case. It certainly could be recommended for application as the simplest and the most efficient way of heat removal, when the radiation heating is not very high.

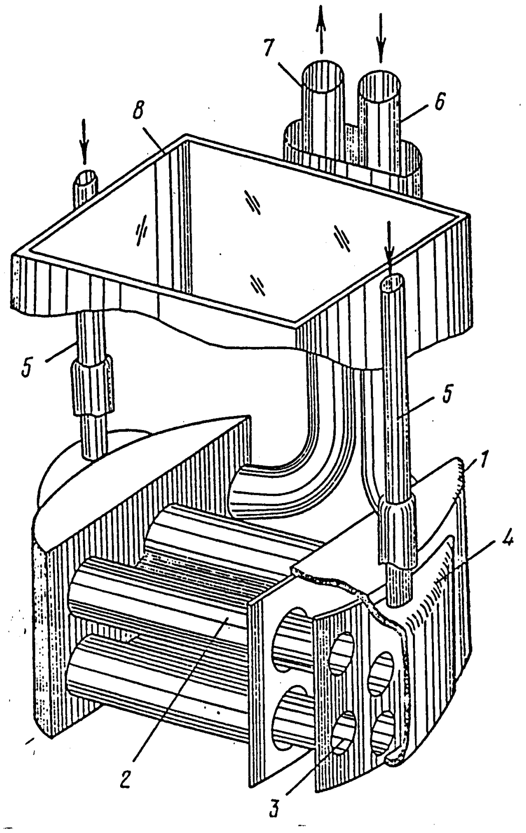


Fig 2. 1 - helium collector; 2 -helium jacket; 3 - tubes with moderator; 4- hydrogen collector; 5 - hydrogen input tubes; 6 - helium input tube 7 - helium output tube; 8 -neutron guide

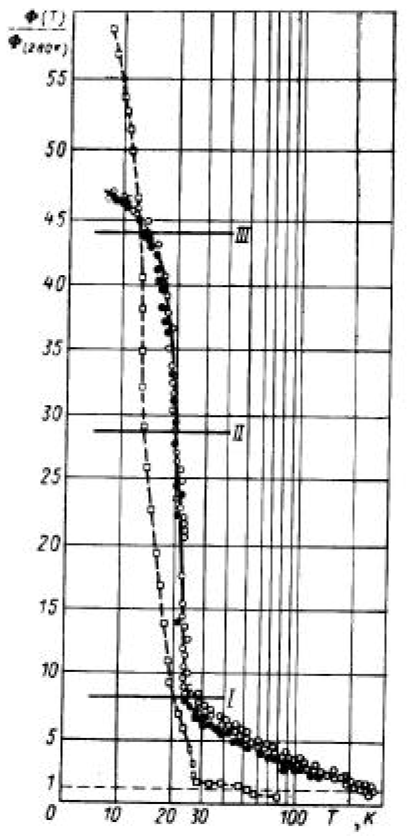


Fig 3. Temperature dependence of the yield of ultra cold neutrons for different state of hydrogen.

Temperature dependence of yield of ultracold neutrons is presented on Fig 3. White points in Fig 3 are obtained in process of cooling of hydrogen and black points in process of heating of hydrogen. Area 1 is corresponded to gaseous state of hydrogen; area 1-2 is concerned to process of liquefaction of hydrogen; 2-3 cooling of liquid hydrogen and the area of 3 for solid hydrogen.

Universal Subcooled Neutron Source

To obtain the maximum of cold neutron intensity at the WWR-M reactor, we had to place a large hydrogen source into the center of the reactor core. In this case, the extremely high specific heating required a high power method of heat removal. It was found that the best way would be a natural circulation of subcooled liquid hydrogen between the chamber and the external heat exchanger. This method is known as a thermosiphon, but it has not been used regularly with subcooled liquids before. It can maintain the moderator in the chamber a few degrees below the boiling point at the highest reactor power.

This new neutron source has been operating at the WWR-M reactor since 1986 [2]. It is a universal source since it produces both ultracold and polarized cold neutrons. The chamber with the moderator is placed inside the flux trap in the center of the reactor core where the flux is (1.5-2).10^{14} n /cm^2s for thermal neutrons and 2.10^{13} n /cm^2s for neutrons with energy E> 1 MeV The chamber, made of zircalloy, has a volume of 1 liter. The specific nuclear heating was 18-20 W/g for hydrogen and 0.7 W/g for zircalloy. The total nuclear heating with 100 percent hydrogen was 2.8 kW. The liquid mixture of 40 percent of hydrogen and 60 percent of deuterium is used as the moderator. In this case the total nuclear heating is 1.8 kW.

A layout of the source at the reactor and the neutron data obtained are presented in the Fig 4,5,6,7. The neutron characteristics for cold neutrons (see Fig 6) are practically the same for both 100% hydrogen and hydrogen 40% + deuterium 60% moderators. The detailed studies of hydrogen-deuterium mixtures have been carried out in special experiment.

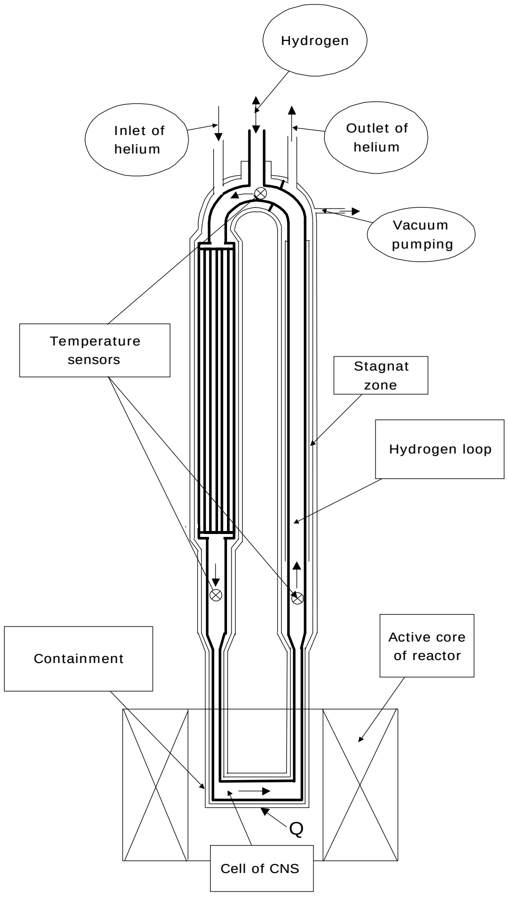


Fig 4. Subcooled liquid hydrogen thermosiphon.

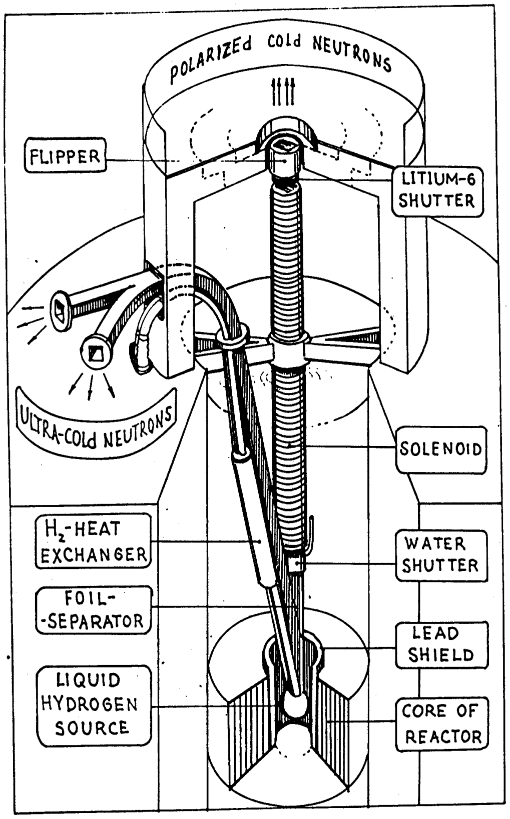
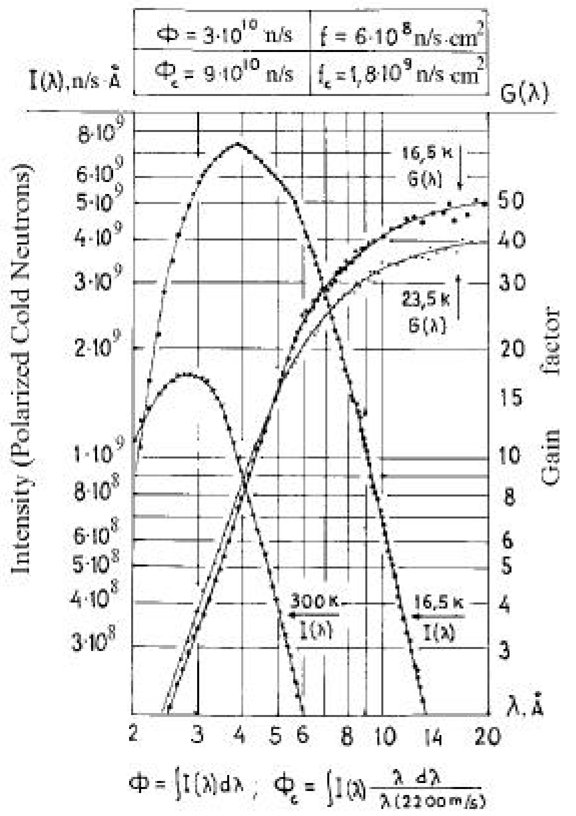


Fig 5. Schematic diagram of the universal liquid hydrogen source.



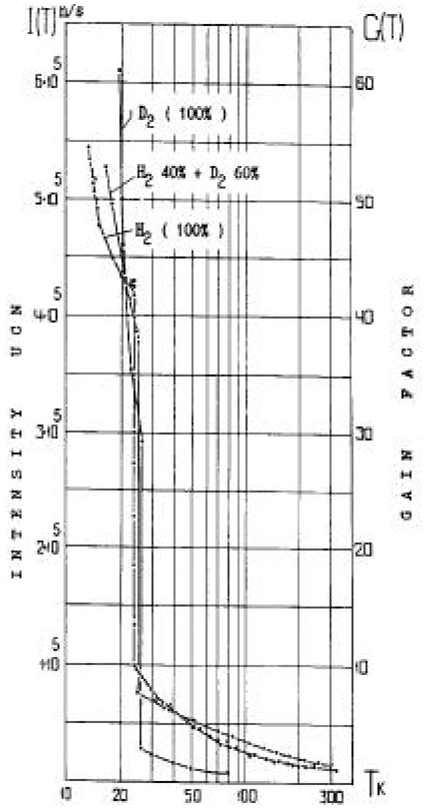


Fig 6. Spectra of the neutron fluxes and the gain factor for polarised beam of cold neutrons.

Fig 7. Temperature dependence of the yield of ultra cold neutrons for different moderators.

An attractive feature of the source is that the thermosiphon circuit is placed entirely in the cold helium flow, the hydrogen being surrounded by two walls with helium between them and then by vacuum containment. Such an approach to the source design improves heat transfer, allows independent operation of the reactor and of the source and substantially increases the reliability of the construction and the hydrogen safety.

Solid Deuterium Source

The experimental results of ultra cold neutron (UCN) production by means of solid deuterium source (SDS) at WWR-M reactor are considered in [3]. A gain factor of UCN yield from solid deuterium at 13-14K to UCN yield from gaseous deuterium at 300K is 1230 and 550 at solid deuterium temperature 18.7K (triple point).

A layout of the source is shown in Fig 9. The source chamber (diameter 150 mm, length 300 mm with two elliptical domes) is made from zirconium alloy. It has volume 6 l (Fig 9). The chamber has double walls (2x0.5 mm) with flowing cold helium between them from cryogenic refrigerator (capacity 150W at 4.5K). At cooling the deuterium from a tank (volume 6 m3) supplies the chamber. The deuterium is condensed and come to a solid state in the chamber.

The relative gain factors for neutrons with different wavelengths are shown in Fig 10 and Fig 11.

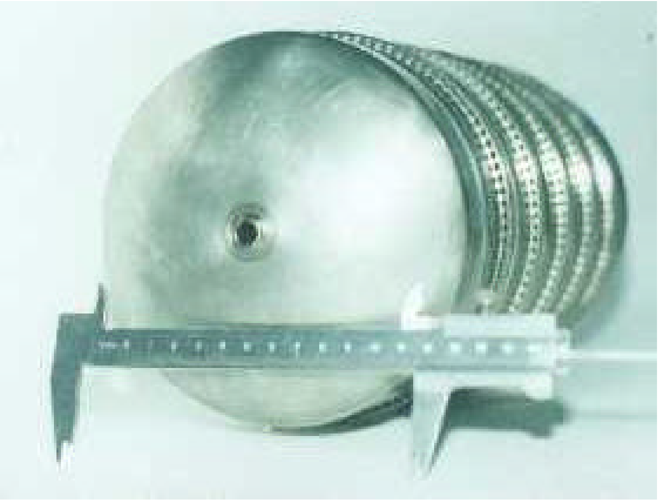


Fig 8. The cell for solid deuterium source.

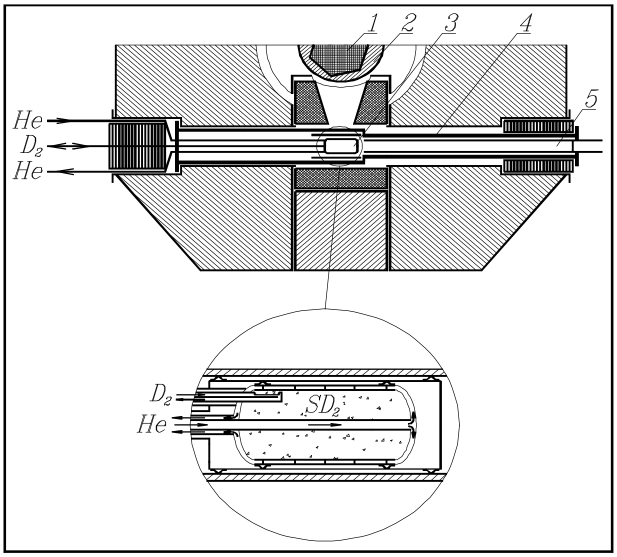


Fig 9. Arrangement of the solid deuterium source in the reactor.

1.Chamber with solid deuterium; 2.Reactor core; 3.Berillium reflector; 4.Vacuum container; 5.UCN guide

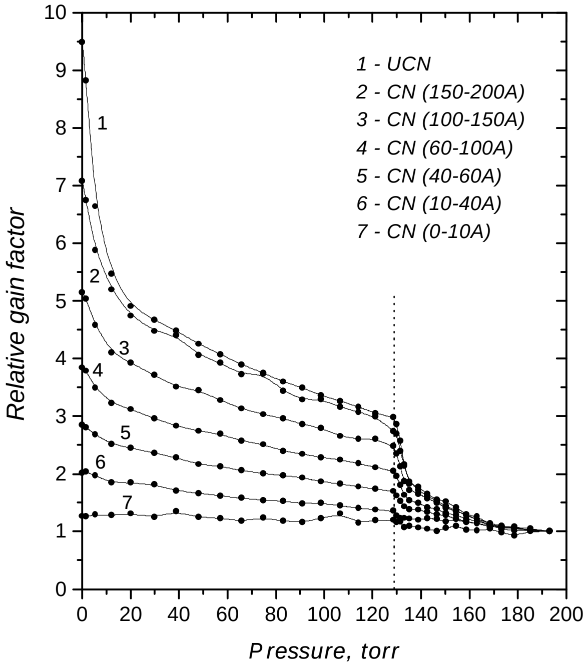


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Fig 10. The relative gain factor for neutrons with different wavelengths as a function of the pressure in the system.

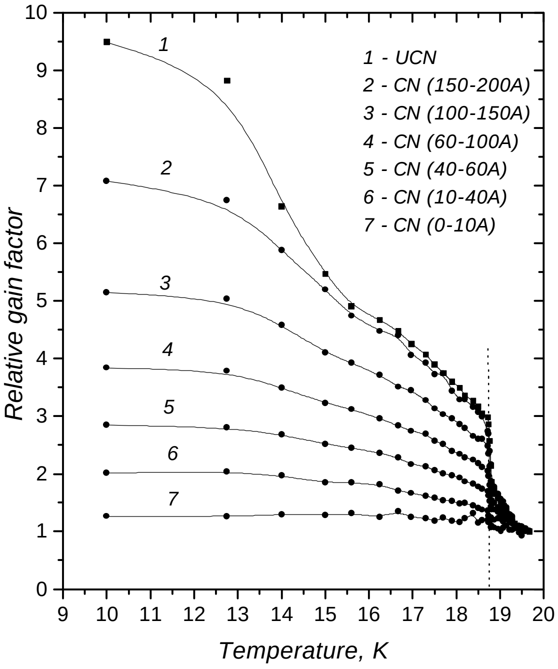

Fig 11. The relative gain factor for neutrons with different wavelengths as a function of the temperature.

A special technical solution is necessary to decrease the deuterium temperature lower 10-12K. The problem is a loss of a thermal contact between cold chamber wall and the solid deuterium because of a deuterium volume decreases at cooling. A cooling is possible at some torrs of a vapor pressure. For example, at 12K the saturated vapor pressure is 0.75 torr, but at 10K - only $5x10^{-2}$ torr. A possible technical solution is to place a spiral tube on inner chamber wall to achieve a good thermal contact. However, at first step we did experiments with a simple design. The second step will be with the same design, but with deuterium containing some helium quantity for heat exchange. Only third step will include more complicated chamber design if it will be necessary.

Next step of investigation is decreasing of the source temperature down to 6-7K with aim to study capability of increasing of UCN yield. It is necessary to note, that at 6-7K the heat conductivity of the solid ortho-deuterium increases in order of value. It makes better the source capacity to heat load. The result of investigation can be used for new projects of solid deuterium sources at high flux reactors with heavy water reflectors. A heavy water is a good shield from high-energy neutrons and gamma rays. That allows having a low level of heat load at high flux of thermal neutrons (reactor PIK, Gatchina, reactor ILL, Grenoble). Another possibility is using of solid deuterium sources at neutron spallation sources, where the relation of heat load to neutron flux is better than one for reactors. For example, the solid deuterium source for UCN production is planning to be installed at 1MW spallation source in Los Alamos (USA).

The main parameters of all sources are presented in the table.

TABLE OF PARAMETERS

PARAMETER	VALUE		
	SLHS	USNS	SDS
Moderator substance	Hydrogen	Mixture 40% H_2 60% D_2	Deuterium
Thermal neutrons flux at 18 MW $n \cdot cm^{-2} \cdot sec^{-1}$	$6*10^{13}$	$2.0*10^{14}$	$1.7*10^{12}$
CN UCN $n \cdot cm^{-2} \cdot sec^{-1}$	 $1*10^{3}$	$6*10^{8}$ $6*10^{3}$	Gain 1230
Moderator chamber volume, *l*	0.15	1(6)	6
Heat load on construction material, *W*	100	800	40
Heat load in moderator, *W*	84	1000	40
Total heat load with losses, *W*	300	2000	90
Available capacity of cryogenic refrigerator, *W*	500	4000	150
Temperature level, K	20	20	5
Hydrogen tank volume, m^3	0.16	5	6
Pressure, warmed up, *MPa*	0.25	0.25	~ 0.1
Pressure, cooled down, *MPa*	0.15	0,15	High vacuum
Helium flow rate, *g/sec*	16	100	10
Oxygen impurity, *volume %*	$3.4 x10^{-4}$		
Nitrogen impurity, *volume %*	$2 x10^{-2}$		

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