CONSIDERATION
OF LH_2 AND LD_2 COLD NEUTRON SOURCES
IN HEAVY WATER REACTOR REFLECTOR

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Abstract

The reactor power, the required CNS dimensions and power of the cryogenic equipment define the CNS type with maximized cold neutron production. Cold neutron fluxes from liquid hydrogen (LH_2) and liquid deuterium (LD_2) cold neutron sources (CNS) are analyzed. Different CNS volumes, presents and absence of reentrant holes inside the CNS, different adjustment of beam tube and containment are considered.

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Introduction

To make decision about which type of the CNS to use in specified conditions, it is needed to perform general consideration and comparison of candidates for CNS. Development of the CNS has a long history and a lot of information has been accumulated [1]. This information and independent consideration for specified case can help to solve the problem of the choice.

Main requirement is to maximize the cold neutron flux production. In this work the attempt will be made to compare the liquid hydrogen (LH_2) and deuterium (LD_2) CNS.

Instruments and Initial condisions.

To perform analysis the Monte Carlo [2] algorithm with modifications [3] is used. The cross sections (XS) are operated with [4]. Cross section of the liquid hydrogen and deuterium moderators are taken from [5].

Initial conditions for the task are the next .

- Reactor type and its power are defined. In our case it is the reactor with the compact core and large heavy water (D_2O) reflector. The CNS is placed in reflector.
- Only liquid hydrogen and deuterium moderators for cold neutron production are to be considered.
- Total heat load (Q_{tot}) allowed for the CNS is defined.
- The neutron guides adjusted to the CNS define the surface of the neutron luminosity.

The sketch of the reactor and the CNS position are given on Fig.1.

We will analyze the next items.

- Value of the cold neutron flux generated with different CNS types.
- Position of the CNS in accordance of the total heat load allowed for the CNS.

Reactor fluxes and CNS position.

Unperturbated neutron (thermal, epithermal and fest) and gamma fluxes inside a heavy water reflector are shown at Fig.2a. The total heat loads deposited in point detectors from hydrogen, deuterium and aluminum are shown at Fig.2b and inlude heating due to fast neutron slowing down and due to gamma rays. The choice of the CNS position in the reflector can be made in the next ways.

- In the minimum of the total heat release (60-100cm from core vessel). Total heat load in the CNS is minimized.
- In the maximum thermal flux (about 12-15cm from core vessel). In this case the CNS will produce the largest number of cold neutrons
- Intermediate position.

Liquid moderator cross-sections and the CNS shape

The LD_2 and LH_2 are given on Fig.3. In this work the LH2 is composed from 50% of ortho and 50% of para-hydrogen. The LD_2 is composed from 98% of ortho and 2% of para deuterium. The cross section energy dependence of liquid hydrogen and deuterium are quite different.

- The LD_2 XS for thermal neutron is about 0.2 cm^{-1}. To have a effective cooling of the thermal neutrons the LD_2 dimension has to be a few free paths, let's say 3-5. It means that dimension of the LD_2 is 15-25 cm and the volume is up to 25 liters.
- The mean free path of cold neutron in LD_2 is about 3.5 cm. It is preferable to extract the cold neutrons from depth of about of 3 mean free paths or from 10 cm. It means that CNS with LD_2 moderator can have the cavity.
- The LH_2 XS for thermal neutron is about 1.2 cm^{-1}. The 3-5 mean free paths is 2.4-4 cm. It defines the thickness of the hydrogen layer.
- The mean free path of cold neutron in LH_2 is less than 1 cm. It means that it is possible to take the cold neutrons from the CNS surface.
- The absorption cross section for hydrogen is much higher then for deuterium or heavy water. It means that the total volume of the LH_2 in D_2O has to be minimized.

Different structure of the cross sections leads to quite different shapes of the CNS with LD_2 and LH_2 moderators. The sketches of the cold neutron sources are presented on Fig.4 and Fig.5.(It should be noticed that in our work the LH_2 CNS has one window in the direction of the beam. At Fig.5 the cavity is not shown.)

Comparison of the LD_2 and LH_2 CNS

At the first step let's consider the moderators of spherical shape and different volumes. The sketch is shown at Fig.6b.

- Thermal flux on the surface of the spherical moderator volume is the same for all spheres
- Thermal spectrum has maxwellian shape at 300K
- Gain factor is the ratio of the outgoing flux from LD_2 or LH_2 to the outgoing flux from D_2O or the ratio of cold flux in the LD_2 center to the cold flux in the D_2O center.
- Pure moderators are considered: 50%/50%(ortho) LH_2 and 98%/2%(para) LD_2

It is seen the next.

- Only from some volumes the LD_2 becomes better then LH_2 (Fig.6a and 6b). Small CNS of about a few hundred cubic centimeters is preferable to make with the LH_2. Large CNS of about 5-10 liters or greater are preferable to make with the LD_2 moderator (see Fig.6a). Gain factor for outgoing cold and very cold neutrons for LD_2 is higher then for the LH_2 (Fig.6a and 6b).
- In case of the LD_2 moderator the gain factor in the center of the CNS is much higher that gain for the flux on the CNS surface. It means that cavity can increase the cold neutron emittion.

- Gain factor for LH_2 CNS is practically constant except for small volumes (a few hundred cm^3). The reason is that the cold neutrons are generated in the LH_2 layer of 2-4cm and do not feel the inner part of the CNS. It is possible to remove the CNS inner part at all and does not change the outgoing flux.

At the second step let's consider more realistic situation with real materials and feedbacks. The sketch of the geometry is shown at Fig.7.

- The model has all components (metallic walls and beam tube) to consider correctly the changes in the neutron fluxes in the CNS (consideration with feedbacks). The sketches of the cold neutron sources are presented on Fig.4 and Fig.5
- This assembly is placed in large volume of the heavy water. Inside heavy water there is maxwellian thermal neutron flux generated with the constant surface source far from CNS position. Temperature of the heavy water and neutron spectrum is 300K.
- In table 1 the total volumes and weights of moderator and aluminum shall (where moderator is placed) are given.

Results of the fluxes and spectra calculations are shown at Fig.8 and in table 2.

- It is seen from Fig.8 and table 2 that emitted cold neutron flux from the LD_2 CNS is greater than emitted cold neutron flux from the LH_2 CNS.
- Temperature of emitted cold neutron spectrum from the LD_2 CNS is lower than the temperature of emitted cold neutron spectrum from the LH_2 CNS.
- Effect of the cavity is different for different LD_2 volumes. For 10 l CNS the increase of outgoing flux is only by factor of 1.05. For 20-30 l CNS the increase of outgoing flux is by factor of 1.12-1.13
- It is seen from table 2, that the effect of removing of the heavy water gap between the CNS containment and beam bottom will increase the cold neutron emittion by 1.2 times.
- Changing of the pure orthodeuterium to mixture of 50%ortho and 50%para deuterium decreases flux by 1.09 times.

Using the information from table 1 and fluxes from Fig. 2a let's estimate the heat loads in the CNS. The heat load includes the next components:

- Heat loads due to fast neutron slowing down.
- Heat loads due to gamma rays from the reactor core.
- Heat loads due to beta particles and gamma rays from n-gamma reaction in aluminum

The heat loads are shown at Fig.9a as thick lines. At this figure (Fig.9a) the cold neutron flux emitted from the LD_2 CNS of different volumes are estimated and shown as thin lines. For estimation the thermal flux from Fig.2a and the information from the table 2 are used.

From the Fig.9a it is possible to construct the dependency of the outgoing cold neutron flux from the CNS volume and to use the heat load deposition as a parameter. Results are shown at Fig.9b (the effect of cavity is not taken into account).

- For total heat load of (0.05-0.1) kW/MW the change of the CN flux outgoing from the CNS volume is quite slow.
- Increase of the CN flux outgoing from the CNS is not same as increase of total deposited heat load. For example, increasing of the total deposited heat load for 20 l LD_2 CNS by factor 8 (from 50 W/MW to 400 W/MW) will increase of the CN flux by factor 2.
- The effect of the cavity is higher for larger LD_2 volume. It is preferable to use the CNS with larger volume, for example, to use 20 l instead 10 l. Position of the CNS will be different, of course, to have the same Q_{tot}.

At the third step we perform direct calculation of the LH_2 and LD_2 sources. In reality it is needed to perform the real scale calculation because a) increasing the moderator volume leads to increasing of the constructive materials which have much higher absorption cross sections then heavy water or LD_2 and b) neutron fluxes vary with distances.

Initial conditions for the task are the next .

- Reactor type is defined. It is the reactor with the compact core and large heavy water (D_2O) reflector.
- Total heat load allowed for the CNS is about 0.1 kW/MW from all sources (neutron slowing down, gamma from core and neutron-gamma reactions in constructive materials, beta radiation).
- The CNS surface of the neutron luminosity is 3 dm^2. Total volumes of the LD_2 and LH_2 are 10 l and 2.8 l respectively.

The sketches of the cold neutron sources are presented on Fig.4 and Fig.5. Details are given in tables 3 and 4.

Position of the LH2 CNS for these conditions is practically in the thermal neutron flux maximum in the D_2O reflector. Total specific heat load is presented in table 3 and is equal to 0.095kW/MW. To move it close to the core will not increase the CN flux. Increasing of the moderator volume will not increase the CN flux. Total heat load will grow rapidly in both cases. It can be said that the position are optimal and the CN flux cannot be improved.

Position of the LD_2 CNS is at 5 cm further from the core than LH_2 CNS. Total heat load for LD_2 CNS is given in table 4 and is equal to 0.111 kW/MW. To move it close to the core will increase the CN flux. Increasing of the moderator volume will increase the CN flux. Total heat load will grow rapidly in both cases. It can be said that the total heat load allowed for the LD_2 CNS of about 0.1 kW/MW is not sufficient. Increasing this parameter will increase the CN flux.

Comparison of the LH_2 and the LD_2 CNS is given in the table 5 and at Fig.10. In table the ratio of the fluxes normalized on reactor power are given. It is seen that in the case of the LD_2 CNS, the fluxes are higher and the spectrum temperature is lower than in the case of the LH_2 CNS. Temperature is defined as the maximum temperature of the maxwellian fitting of the neutron spectrum.

To continue the analysis, consider absolute values of the reactor power at 20 MW. For example, this is power of the FRM-II reactor. Many research reactor works at similar level of the power. Specific heat load of 0.1 kW/MW corresponds to 2kW of total head load. Modern cryogenic machine is able to remove up to 4-6 kW. In our previous consideration this increase is useless for the LH_2 CNS, but important for LD_2 CNS. It is possible to increase LD_2 volume up to two times and install 20 l instead of 10 l. It increases the CN flux up to 1.26 times in accordance with table 2.

Finally the LD_2 CNS will produce up to about 1,4 times more of the cold neutrons for the experiments than the LH_2 CNS.

Conclusions

- The value of the reactor power, the value of the total heat load allowed for the CNS and surface of luminosity (the CNS volume) define the type of the cold neutron source.
- For 20 MW reseach reactor and for 4 kW of allowed total heat load deposition in the CNS and 3 dm^2 surface of luminosity the LD_2 CNS will produce up to 1.4 times than the LH_2 CNS.

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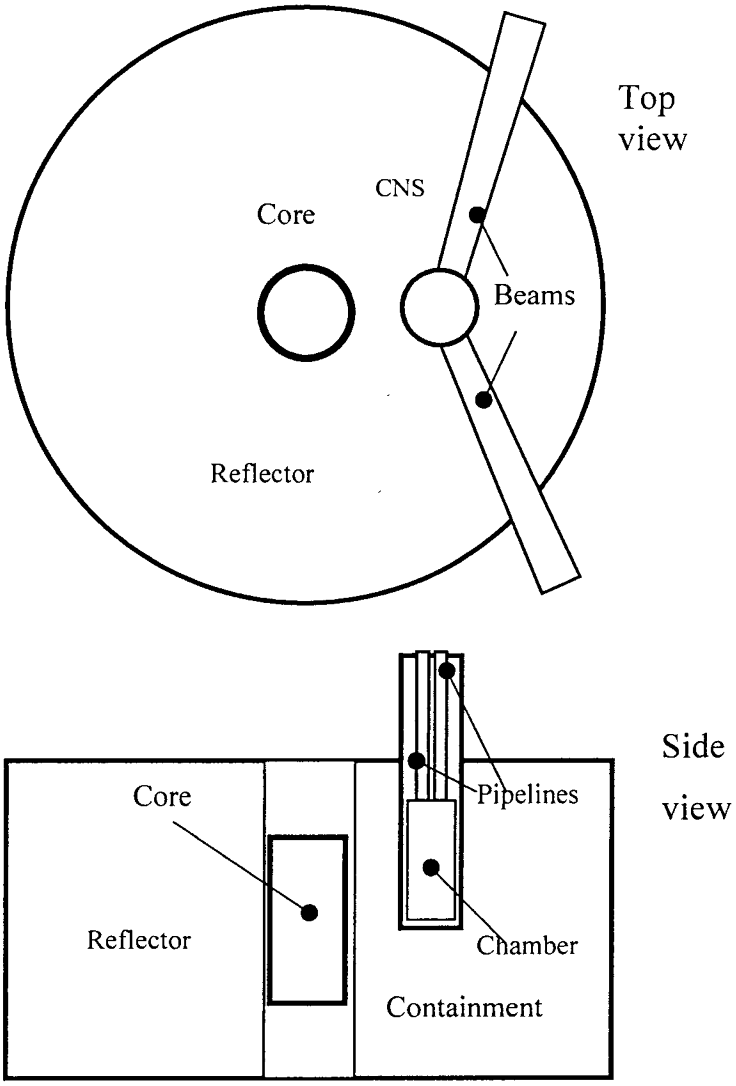

Fig.1. Schematic view of the geometric model

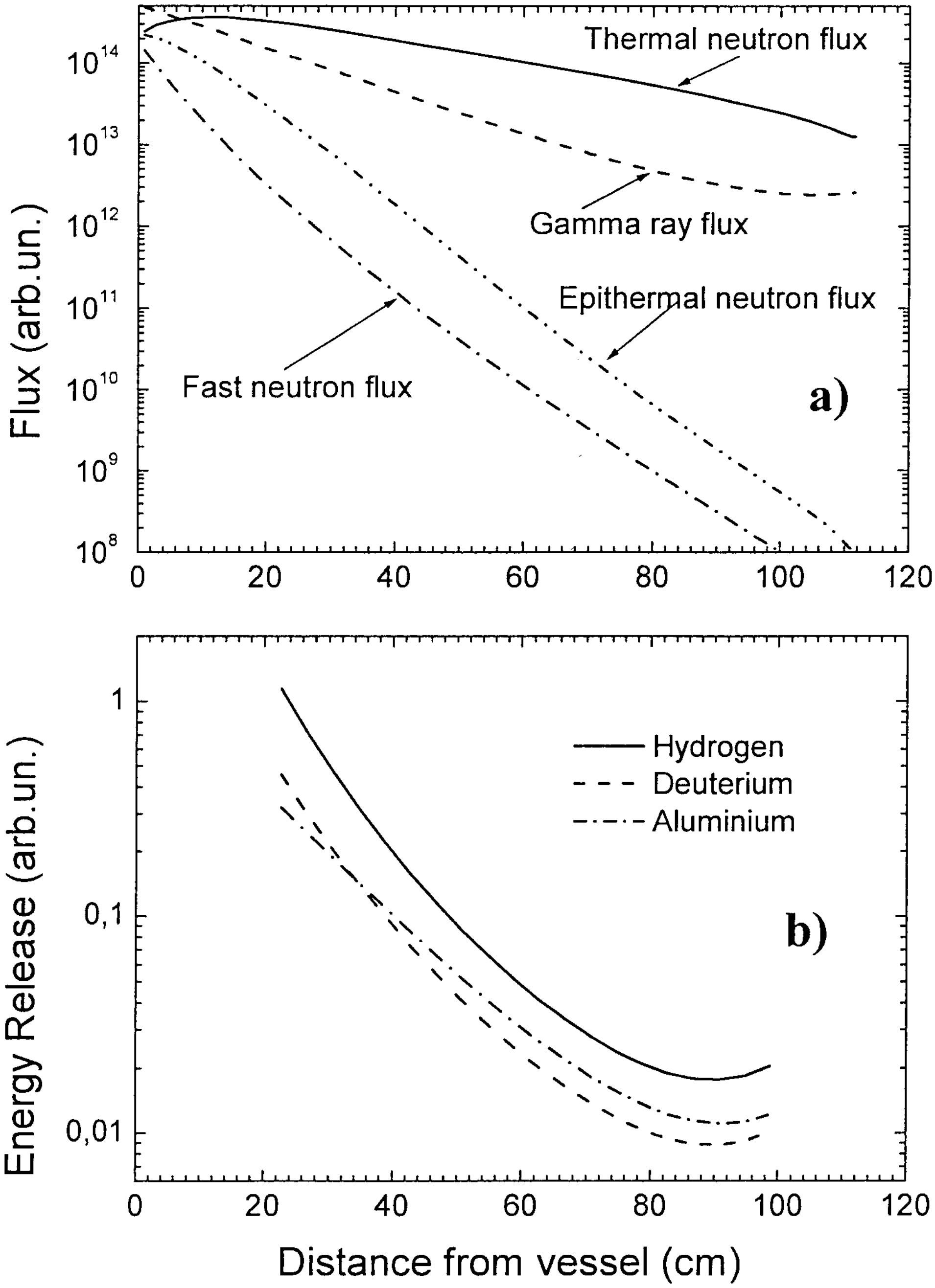

Fig.2. Fluxes in the heavy water reactor reflector (a) and total energy release in point detectors in heavy water reflector (b)

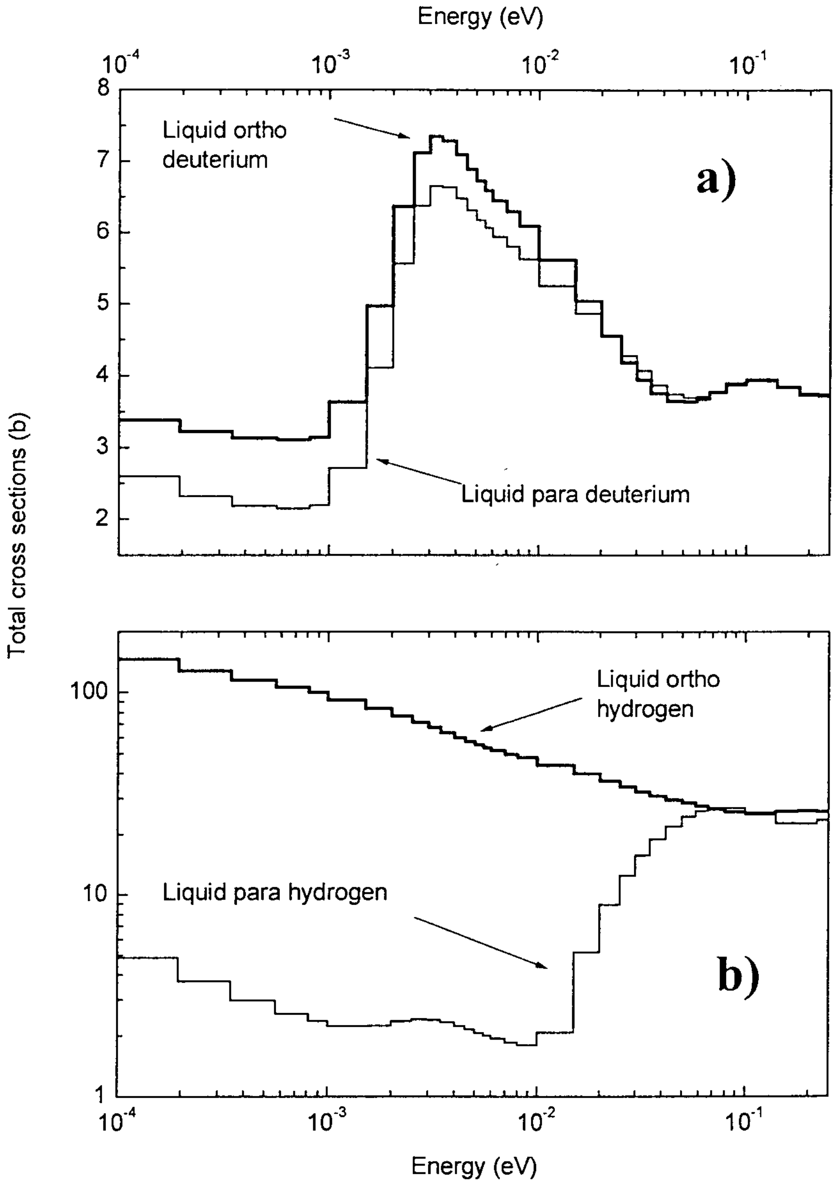

Fig.3. Deuterium (a) and hydrogen (b) total cross sections [5]

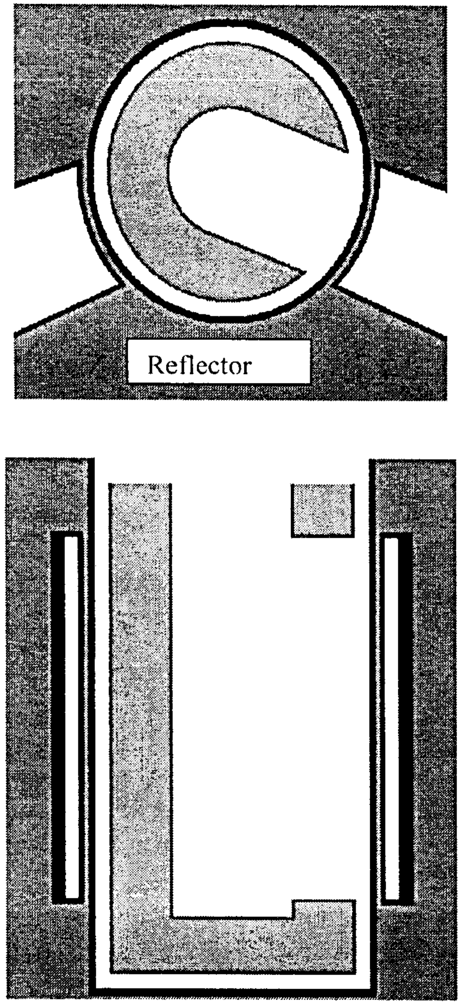

Fig.4. Hydrogen CNS
(horisontal and vertical slises)

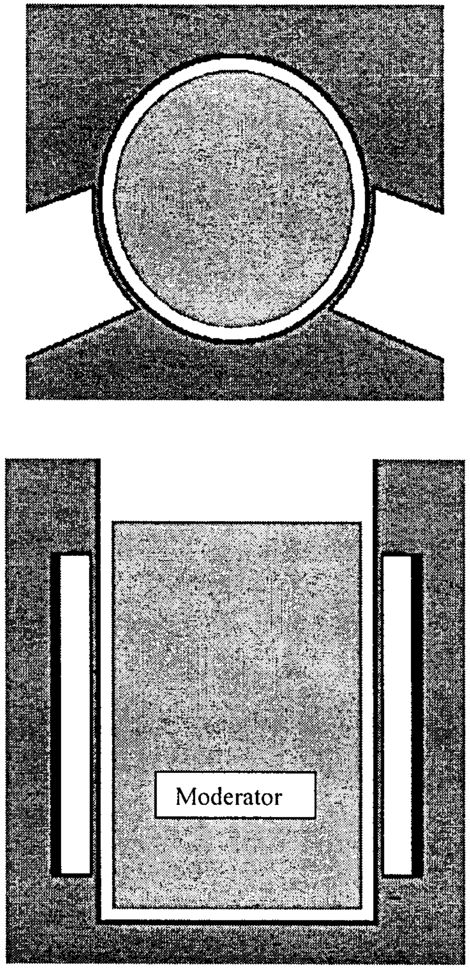

Fig.5. Deuterium CNS
(horisontal and vertical slises)

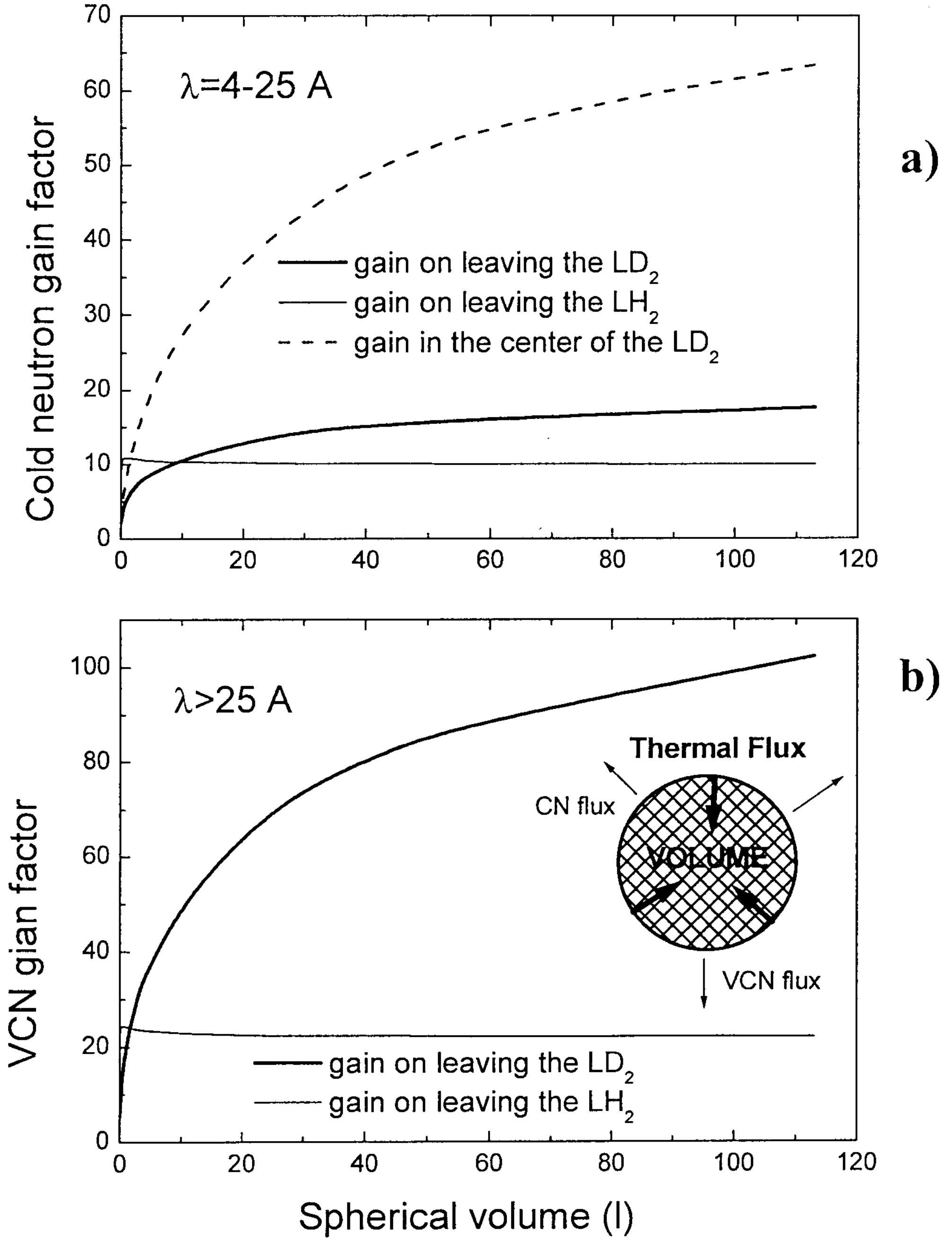

Fig.6. Ideal gain factors for the LD_2 and LH_2 CNS

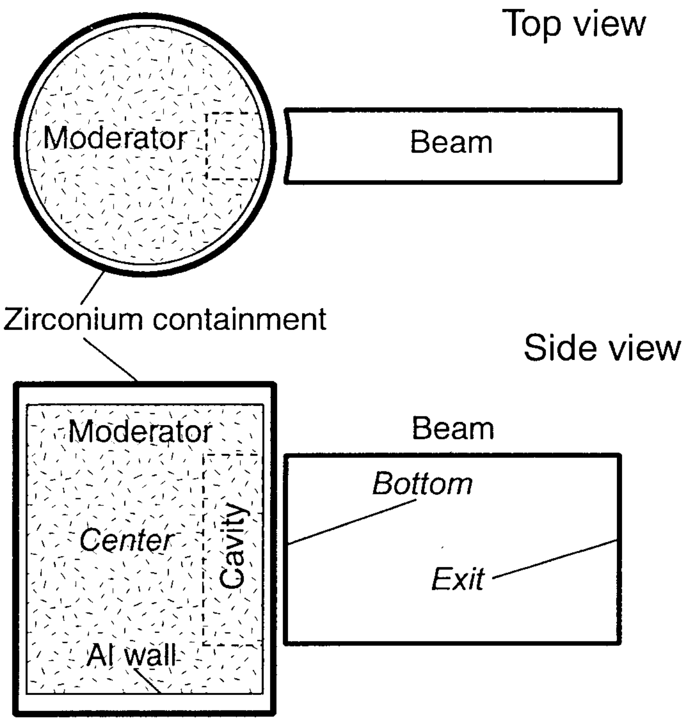

Fig.7. CNS geometry for investigation of CNS efficiency

Table1.Cold neutron source parameters

N/N	Moderator	Moderator volume (l)	Moderator mass (g)	Aluminum shell mass (g)
1	hydrogen	2.8	224	1050
2	deuterium	4.3	610	820
3	deuterium	10	1650	1400
4	deuterium	20	3300	2200
5	deuterium	30	4950	2880

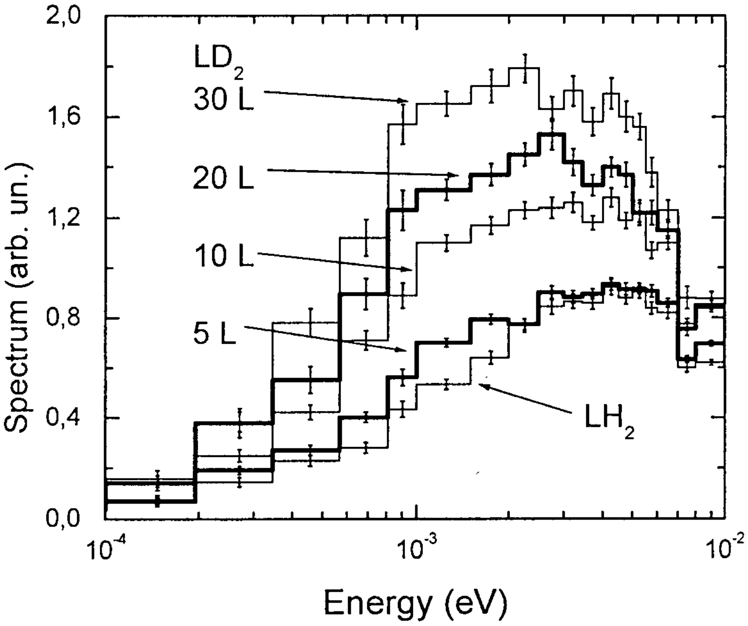

Fig.8.Neutron spectra at beam bottom

Table2. Cold neutron fluxes for different sources placed in heavy water

	Center	25 cm from beam bottom
	Arb.un.	Arb.un.
H_2 source 2.8 l	0.43 (0.6)	0.70 (2.3)
D_2 source 4.3 l	0.66 (0.4)	0.79 (1.8)
D_2 source 10 l	**1.00 (0.4)**	**1.00 (2.1)**
-, with cavity	0.92 (0.4)	1.05 (2.0)
-, w/o water between containment and beam bottom	1.00 (0.4)	1.20 (1.8)
-, 50%para+50%ortho deuterium	0.86 (0.4)	0.92 (2.0)
D_2 source 20 l	1.28 (0.5)	1.13 (2.4)
-, with cavity	1.17 (0.5)	1.26 (2.3)
D_2 source 30 l	1.40 (0.5)	1.24 (2.6)
-, with cavity	1.28 (0.5)	1.40 (2.3)

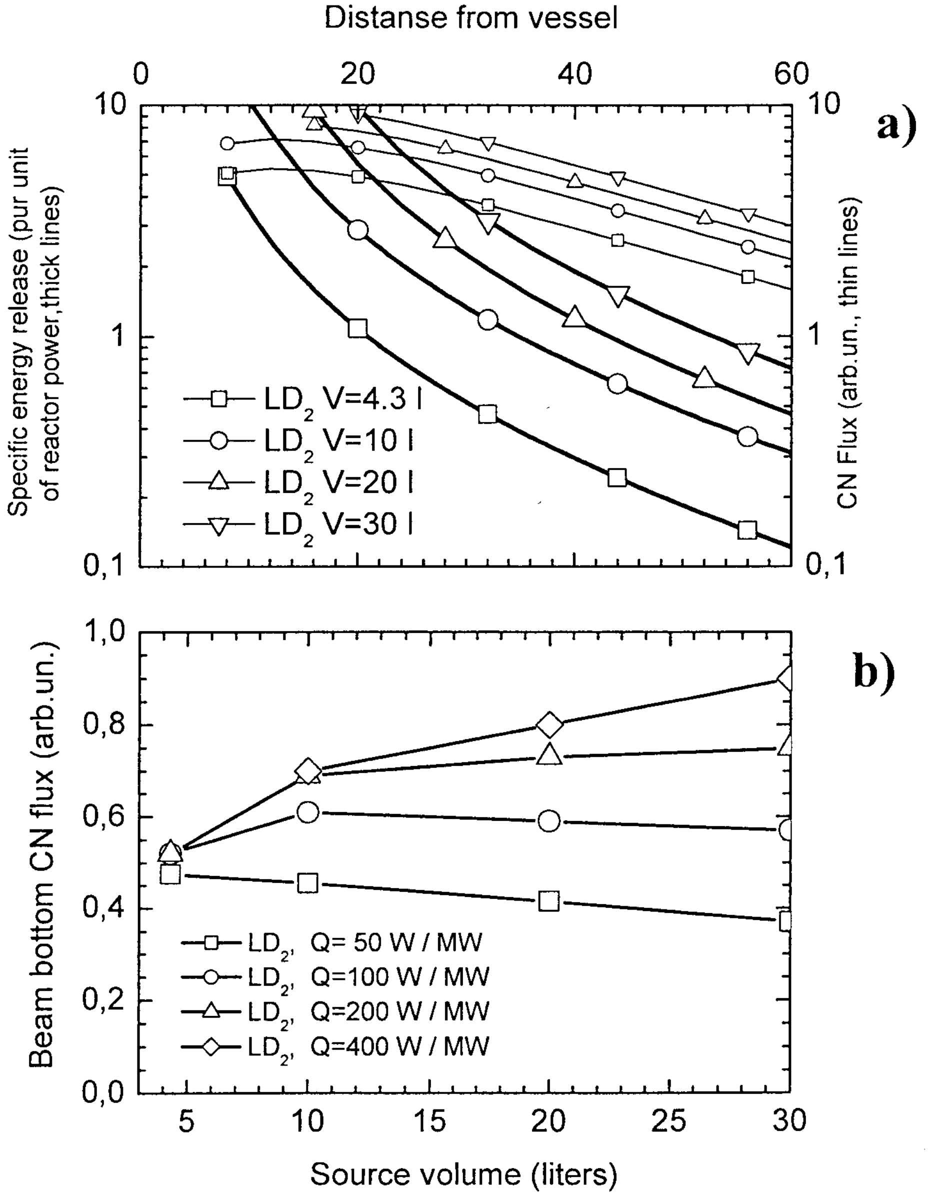

Fig.5. CNS investigation (cavity effects are not taken into account)

Table 3. Heat load in the LH_2 CNS

Position	Weight	Q_{total}
	g	W/MW
Chamber	1042	52.8
Pipelines	619	15.3
Hydrogen in chamber	198	23.6
Hydrogen in pipelines	65	3.2
Total		94.9

Table 4. Heat load in the LD_2 CNS

Position	Weight g	Q_{total} W/MW
Chamber	1419	54.9
Pipelines	543	9.2
Deuterium in chamber	1650	45.4
Deuterium in pipelines	117	1.5
Total		111

Table 5. Cold neutron fluxes comparison

	Cold flux ratio LD_2/LH_2 for E<10meV	Neutron temperature for LD_2 CNS	Neutron temperature for LH_2 CNS
Guide entrance in the right beam tube	1.08	31.4±0.9°K	40±1°K
Guide entrance in the left beam tube	1.13	31.4±0.9°K	42±1°K
Inside moderator	2.2	27.3±0.5°K	35±1°K

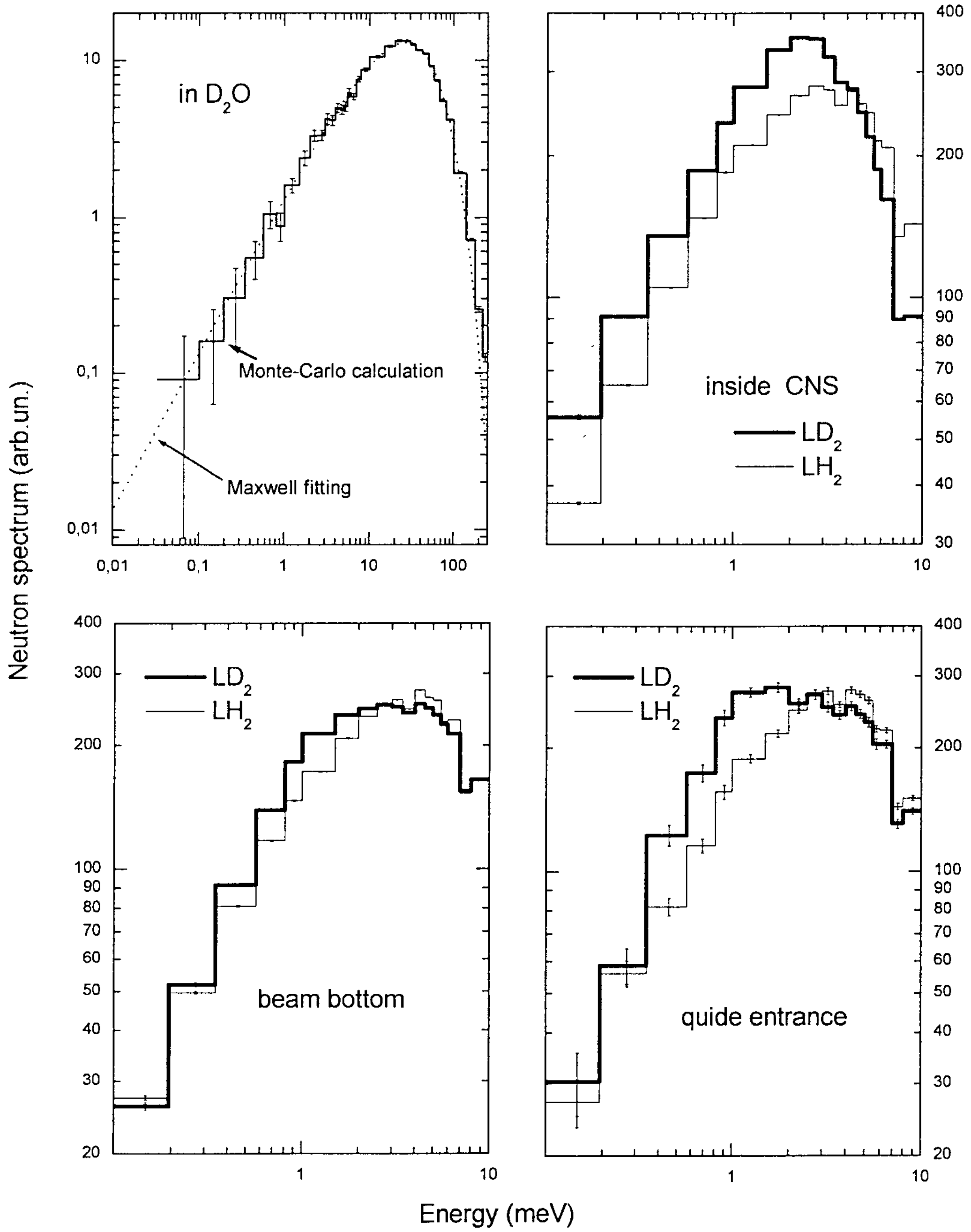

Fig.10. Neutron spectra in LD_2 and LH_2 CNS. Spectra inside CNS, at beam bottom and quide entrance are normalized to unity.

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