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The Accelerator Booster Research Reactor - a Useful Tool for Small Laboratories

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1. INTRODUCTION

Investigations of condensed matter by neutron scattering measurements constitute a field of research of growing importance which requires thermal neutron sources of increasingly higher intensity. With the present generation of high flux reactors a limit seems to have been reached of what can be justified economically. For even higher fluxes, pulsed neutron sources in combination with time-of-flight experiments are more suitable because of the substantial reduction in reactor power. Thus, repetitively pulsed reactors will probably be a promising line in the future development of research reactors.

Two versions are possible:

1. The neutron pulse is generated by modulating the reactivity into the prompt super-critical domain.
2. The neutron pulse of an accelerator is multiplied in a so-called booster the reactivity of which is modulated to suppress the background between successive pulses.

However, the successful utilization of this type of reactors must be based on much broader experience in the corresponding experimental techniques and in the problems arising from the reactor plus the experiment.

This can be achieved with facilities less ambitious and expensive than SORA and IBR-2 [1]. In addition, a facility with, e.g., 100 kW can provide a neutron intensity equivalent to a 10^{14} n/cm^{2}s flux of a steady-state reactor and would allow meaningful research contributions. Such a facility can also be installed and operated by small laboratories.

If a LINAC with a neutron intensity of about 2×10^{11} n/s and 100 cycles per second is already available, the most reasonable way is to boost the LINAC by neutron multiplication. For this purpose, the accelerator target is placed in the center of a small fast reactor core whose reactivity is modulated so as to have high multiplication during neutron injection and low multiplication between successive pulses to suppress background. The fast neutrons leaking out from the core are thermalized in hydrogenous moderators located in the reflector surrounding the core. Several beam tubes look at the surface of the moderators. Pulse width and intensity strongly depend on moderator size and material, add moderator optimization is very important.

In Section 2, a typical small booster design is briefly described. It is based on a feasibility study recently made at the Karlsruhe Nuclear Research Center. In Section 3, new experimental and theoretical investigations on the optimization of promising moderators are reported.

2. STUDY OF A 100 kW ACCELERATOR BOOSTER

A feasibility study of a repetitively pulsed fast research reactor with neutron injection has been performed. An artist's view of the design is shown in Figure 1. In the text, numbers in brackets refer to this figure. The design is based on a 60 MeV, 100 mA linear electron accelerator with a pulse length of 7 μsec and 100 sec^{-1} repetition rate. The neutron source strength would be 2.5×10^{16} n/sec and a substantial multiplication is required to get thermal neutron fluxes suitable for condensed matter studies. However, multiplication (M) increases the fast pulse width $l \cdot M$, (where l is the fast neutron lifetime). Figure of merit considerations show that $l \cdot M$ must be smaller than or equal to σ, σ being the variance of thermal neutron emission time distribution. In a practical case, $\sigma = 30\,\mu$sec and $l = 35$ nsec result in $M \leq 850$, but for safety reasons M was limited to 500 or $\rho = -0.002$ below prompt critical. To achieve a signal-to-background ratio of about 10, reactivity is decreased to $-10\,\$$ between the pulses by means of a rotating reflector part (1) similar to the SORA-design. Since, in this case, reactivity modulation only has to reduce the background, a rather simple and very conservative two-armed rotor can be used:

- diameter	128 cm
- frequency	50 rps
- circumferential velocity	2×10^4 cm/sec
- material	TIAC6V4
- reactivity	$0.2\,\Delta k/k$ (=$10\,\$$ for Pu-239)

This relatively slow rotor leads to a time dependent delayed neutron background which peaks when the rotor passes the core, Thus, the overall signal-to-background ratio becomes about 8.5 for plutonium fuel. These characteristics result in a booster power of 100 kW.

The hexagonal reactor core (2) is CO_2-cooled and fueled with PuO_2 pins (3). To keep neutron lifetime and critical mass small, the core is designed as compact as possible. It is surrounded by 6 cm of tungsten (4). Two parts of this reflector can be radially displaced as safety elements (5). Fine control is performed by two rotating rods (6). The LINAC target (7) is located in the center of the core. It consists of helium cooled U-238 shot. The electron beam enters the core from below (8). A cold moderator (parahydrogen) (9) and a moderator at room temperature (H_2O or zirconium hydride) are located close to the core and viewed by six beam tubes (10). The reactor block is shielded by concrete, which leaves enough space around the core accessible from the top for maintenance and easy replacement of components. All parts of the reactor can be exchanged with relatively simple and inexpensive equipment.

Reactor circuits and secondary equipment are located below the experimental floor (11), but enough space is left there for experiments using the LINAC without booster. Then the deflecting magnet (12) is switched off.

Booster Characteristics

Core power	100 kW
critical mass	35 kg Pu-239
active core height	20 cm
core volume	6.8 l
number of fuel pins	162
pin diameter	1.4 cm
pitch-to-diameter ratio	1.05
core coolant	CO_2
coolant inlet velocity	25 m/sec
outlet pressure	5 bar
hot spot temperature	500°C
target power	6 kW
target coolant	helium
coolant velocity in the target	25 m/sec

3. MODERATOR OPTIMIZATION

The moderator of a pulsed reactor must be optimized for high thermal flux and short neutron pulse width. The optimum values depend on the moderating material and the geometry. Therefore, extensive calculations of the leakage flux and the variance of the neutron emission time distribution were performed for various hydrogenous materials. In order to check the calculations measurements were performed on some moderators in cylindrical geometries.

Parahydrogen is of particular interest because of its unique scattering cross section behaviour [2]. Once the neutrons are slowed down below 15 meV, the moderator becomes very transparent. This leads to a high leakage intensity and a short neutron emission time.

3.1 Methods of Calculation

For calculation of the variance of the thermal neutron emission time distribution the first two time moments must be known. As shown by Profio et al. [3], these can be calculated by Laplace transform of the time dependent Boltzmann equation. For moderators whose collision time is comparable with the lifetime, transport theory must be used. In order to account properly for the time-of-flight of the neutrons from all directions, a two-dimensional version of the THERMOS-code in cylindrical geometry has been written which solves the following equations:

$$N^{(0)} = \int_0^\infty N dt = T\left[PN^{(0)} + S\right]$$

$$N^{(1)} = \int_0^\infty tN dt = T\left[PN^{(1)} - \frac{|\mathfrak{r} - \mathfrak{r}'|}{v}\left(PN^{(0)} + S\right)\right]$$

$$N^{(2)} = \int_0^\infty t^2 N dt = T\left[PN^{(2)} - 2\frac{|\mathfrak{r} - \mathfrak{r}'|}{v} PN^{(1)} + \left(\frac{|\mathfrak{r} - \mathfrak{r}'|}{v}\right)^2 \left(PN^{(0)} + S\right)\right]$$

with the transport and collision operators, respectively,

$$TN = \int d\mathfrak{r}' T(\mathfrak{r}, \mathfrak{r}', v) N(\mathfrak{r}', v); \qquad PN = \int dv' P(v, v', \mathfrak{r})\, N(\mathfrak{r}, v').$$

Leakage fluxes perpendicular to the moderator surface and normalized to reactor power were calculated in realistic booster geometry with the two-dimensional multigroup S_N-code SNØW in S_8 approximation [4].

Thermal and epithermal group constants were obtained from THERMOS calculations. For parahydrogen the Young-Koppel scattering kernel was used [5].

3.2 Measurements

Time dependent spectra were measured by the time-of-flight method with a combination of pulsed source and chopper. The time dependence of single energy groups and, hence, the time moments were derived from these spectra. The measurements were performed in a similar way as described in [6 - 8]. To improve the time resolution beyond the chopper half width = 50 s, the time delay between injection of the fast neutron burst and the chopper cut-off time was varied in steps of 5 - 10 μsec.

The experimental arrangement is indicated schematically in Fig. 3. It is similar to the facility described by Reichardt [8]. The 14 MeV source neutrons (pulse width 2 μsec) were moderated by a layer of 10 cm lead and 9 cm graphite in order to soften the incident spectrum. The surface extraction area of the thermal neutrons was about 1.2 cm^2 at half height of the cylinder at a distance of 1.5 cm from the chopper disk.

The moderators investigated were

1) liquid hydrogen with 98% para-H_2 (98%PLH2) at T = 20.4°K
2) liquid hydrogen with 77% para H_2 (77%PLH2) at T = 20.4°K
3) solid methane T = 77°K.

The measured quantities were stationary spectra and the first two time moments. Time moments require integration of the time dependent neutron flux to $t \rightarrow \infty$. This can be done if there is an exponential decay and the decay constant is known. In parahydrogen, no asymptotic decay could be observed. This resulted in uncertainties of the variances of up to 30%. A similar difficulty exists for all moderators in the transient region.

A more detailed description of the measurements and calculations will be published.

4. DISCUSSION OF THE RESULTS

Fig. 2 shows measured leakage spectra of cold moderators compared with water at room temperature. The geometrical arrangement is indicated schematically in Fig. 3. For parahydrogen, the diameter of the container used gives nearly the optimum leakage intensity. For water at room temperature, the container dimensions are much too big. Therefore, a water spectrum is included in the same figure calculated for optimum geometry as indicated in Fig. 6. This spectrum is normalized to give the flux relative to parahydrogen which would exist in the booster.

The calculated and the measured variances for different moderators are shown in Fig. 4. Measurements and two-dimensional THERMOS calculations are in good agreement. In the slowing down region they show the well-known 1/v-behaviour [9]. For energies below 13 meV, where the scattering cross section for parahydrogen is very small, the mean free path becomes comparable to the moderator dimensions. Thus, time-of-flight effects lead to a 1/v behaviour of the variance. This means that in time-of-flight experiments energy resolution below 13 meV is independent of energy. The other moderators show an energy independent variance in the thermal region which is nearly equal to the thermal neutron lifetime.

A series of two-dimensional multigroup S_N-calculations in booster geometry to find the optimum moderator dimensions were performed. For a cylindrical parahydrogen moderator of 30 cm height, as proposed for the booster, the perpendicular leakage flux ϕ for 10 meV neutrons and 1 W booster power is shown in Fig. 5 as a function of the radius of the moderator.

The figure of merit

$$\mathrm{FOM} = \frac{\phi}{(\mathrm{M}\ 1)^2 + \sigma^2}$$

with 1 M = 17.5 sec and σ for 10 meV neutrons has its maximum value at 6 cm radius. Similar optimization studies for liquid water moderators of 30 cm height led to a heterogeneously poisoned arrangement. A 4 x 12 cm slab, with the large side close to the core surface, is subdivided into three 4 x 4 cm cells by two cadmium sleeves. In Fig. 6, the FOM for this water moderator is compared with the FOM of an optimized parahydrogen moderator as a function of energy.

For energies below 15 meV, parahydrogen is superior to water by about a factor of 3.

An improvement seems to be possible by a more skillful parahydrogen arrangement. Future experimental and theoretical work will deal with this question.

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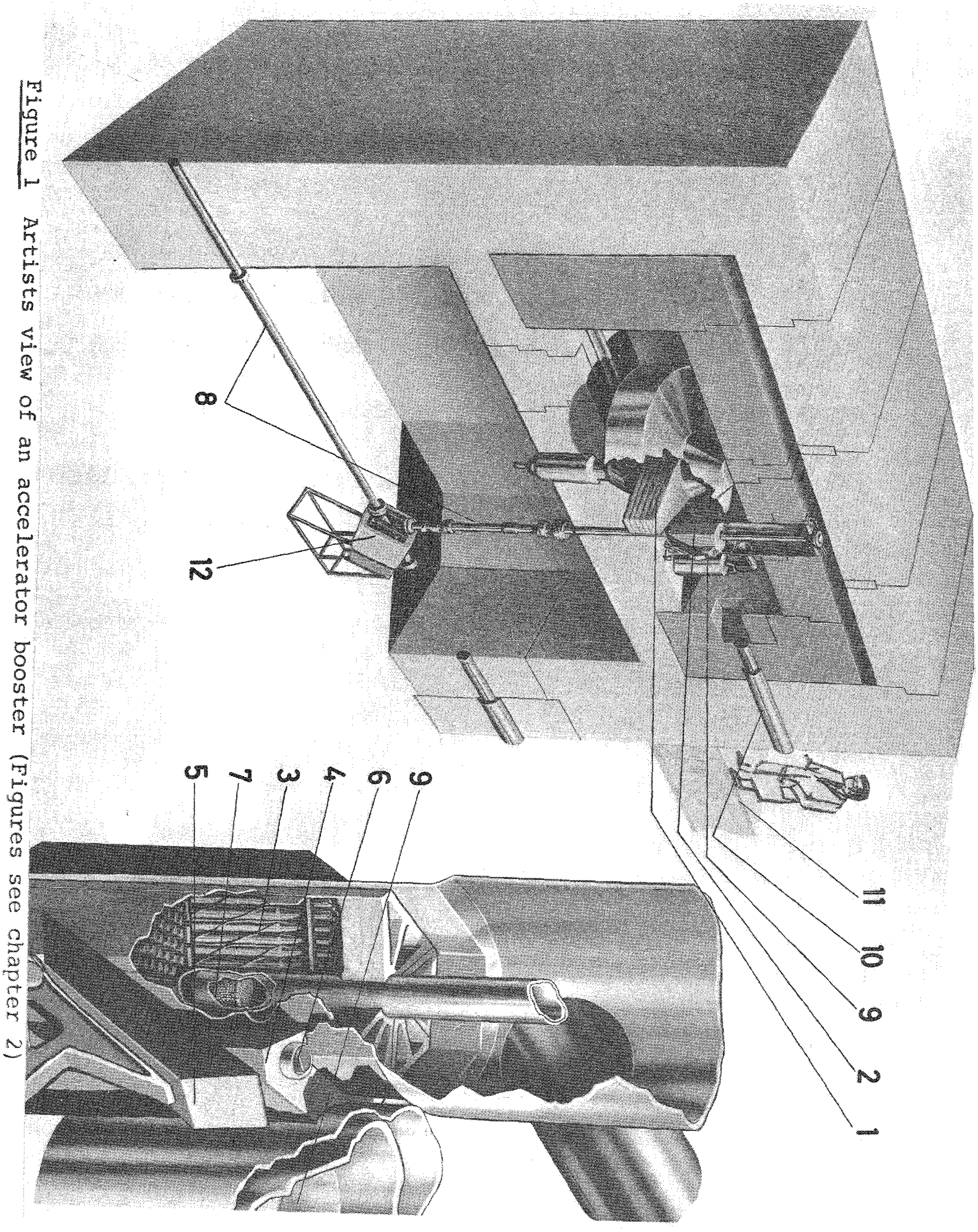

Figure 1 Artists view of an accelerator booster (Figures see chapter 2)

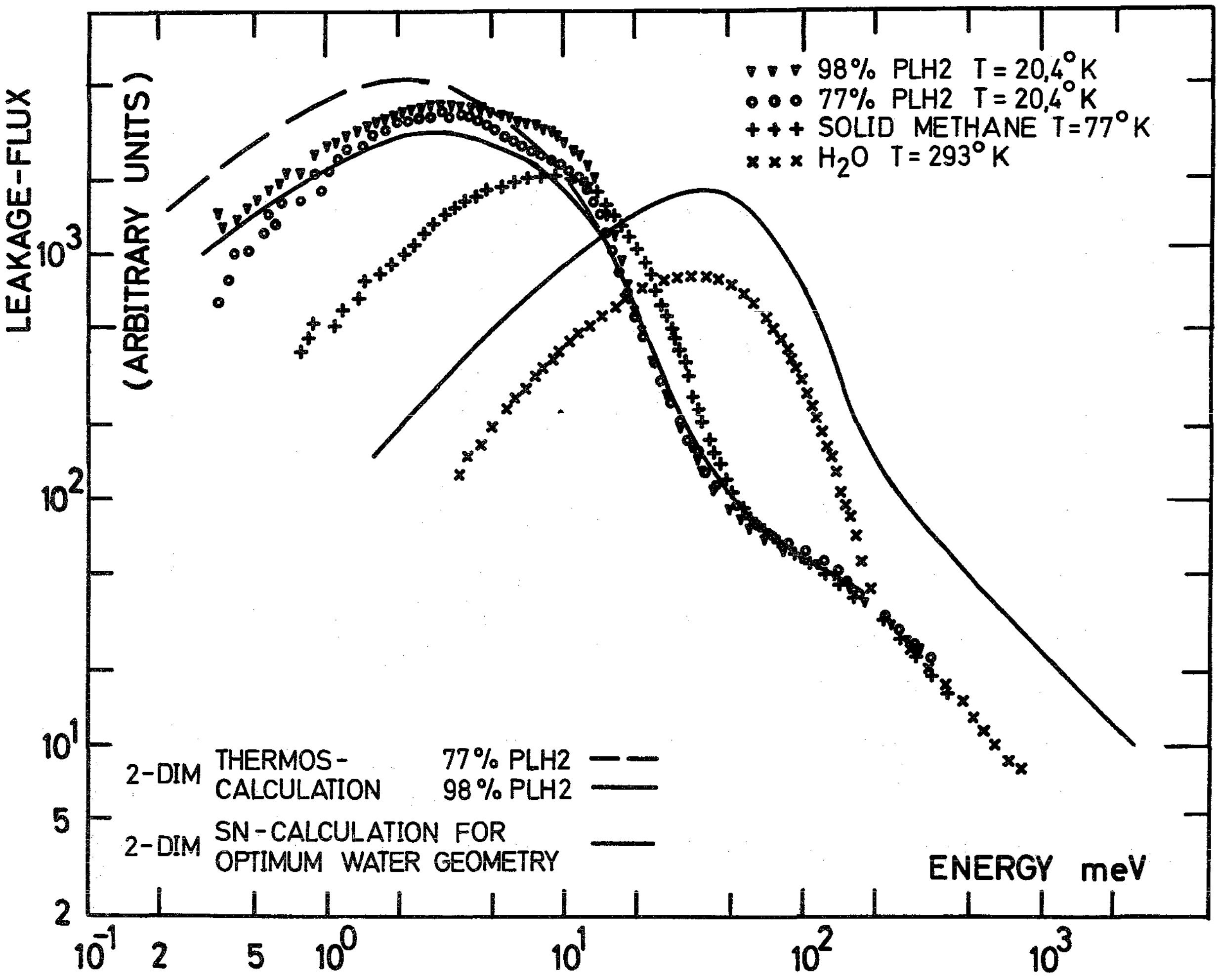

FIG.2 MEASURED NEUTRON LEAKAGE SPECTRA, NORMALIZED TO THE SAME FLUX OF FAST INCIDENT NEUTRONS

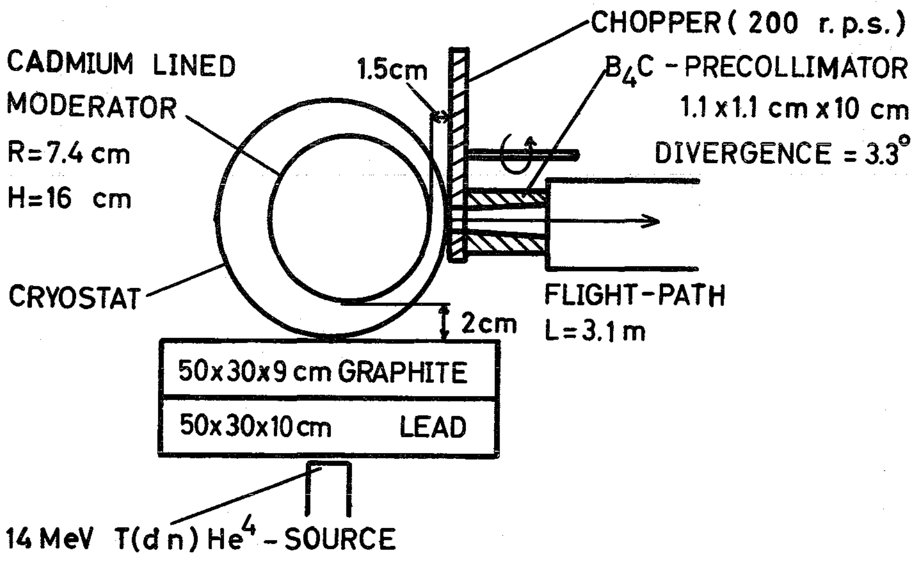

FIG. 3 EXPERIMENTAL ARRANGEMENT

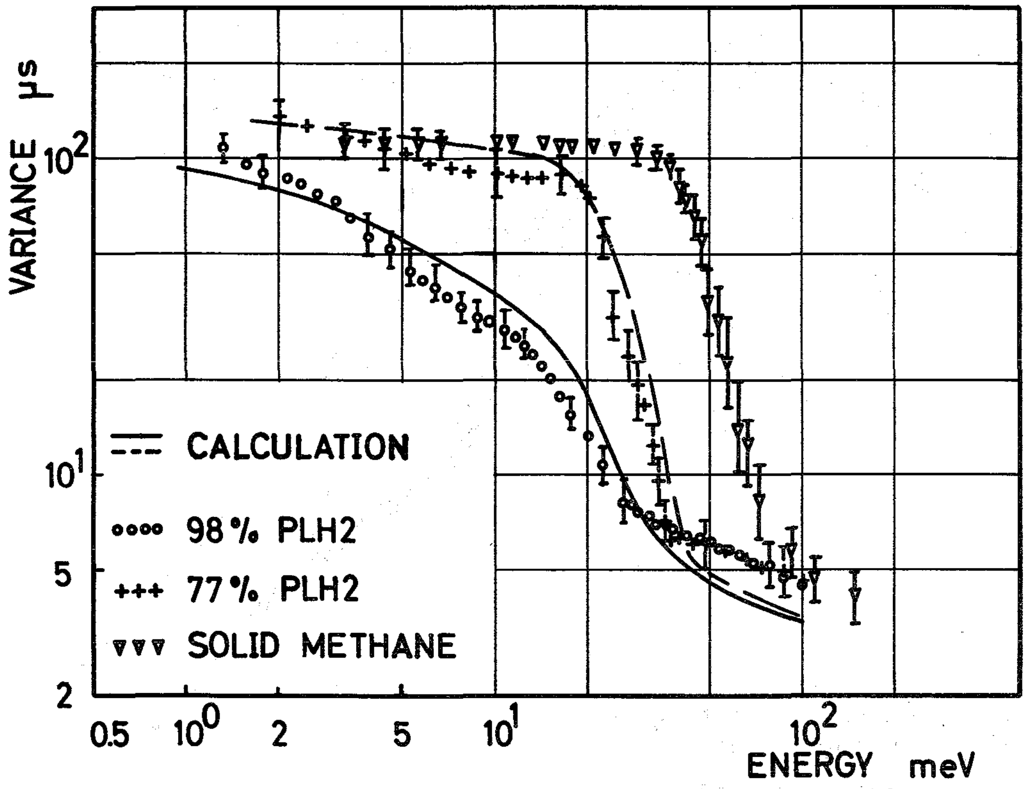

FIG. 4 VARIANCE OF THE THERMAL EMISSION TIME DISTRIBUTION

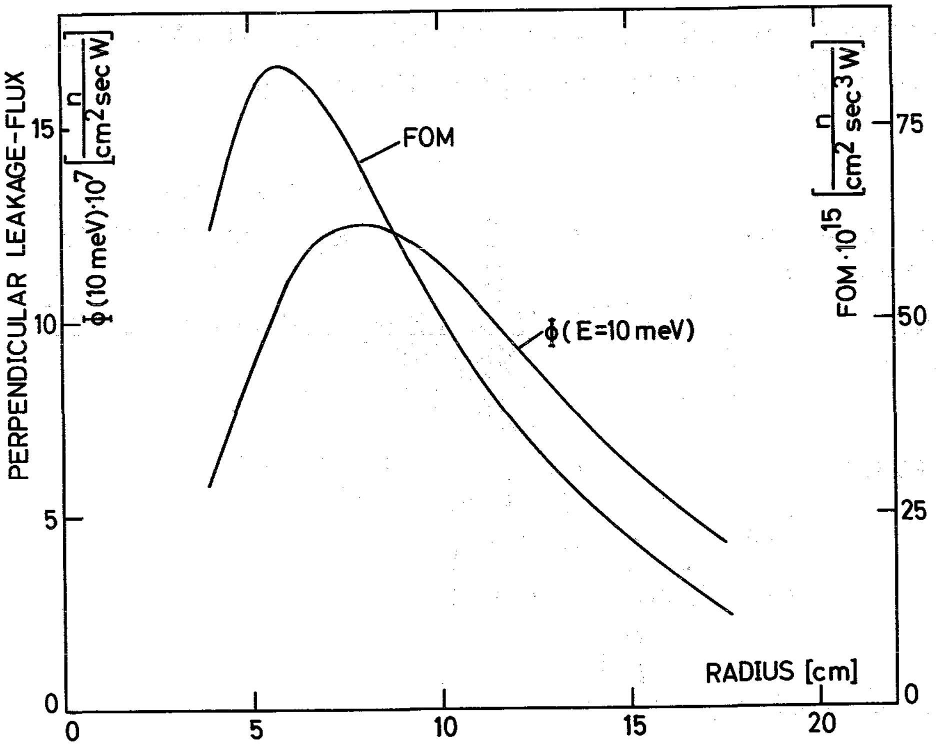

FIG. 5 CALCULATED FLUX AND FOM FOR 10 meV NEUTRONS IN LIQUID PARAHYDROGEN

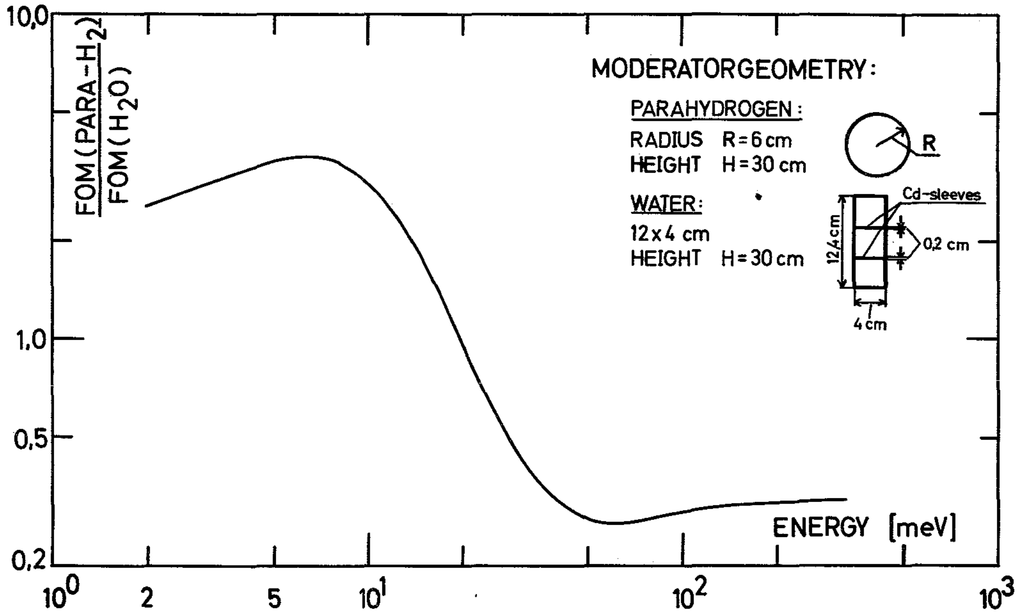

Fig. 6 Comparison of the FOM for parahydrogen and water. The optimum geometry for both moderators is schematically indicated.