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Beam Facility for Neutron Half-Life Measurement
at the Research Establishment Risö

by

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Abstract

A beam facility has been constructed at the Risö DR 3 reactor for use in the measurement of the neutron half-life. This report summarizes the technical design considerations pertinent to the facility and the physical equipment used to obtain a well-collimated, low-background beam of thermal neutrons.

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1. INTRODUCTION

In 1960 it was proposed at Risö to attempt a precision measurement of the radioactive half-life of the neutron. This immediately drew attention to the need for a clean, high-intensity beam of low-energy neutrons. A beam facility for the purpose was developed at the Risö DR 3 reactor (enriched, heavy-water moderated), providing a well-collimated, low-background beam essentially free of fast neutrons and gamma rays. The facility was used for the neutron half-life measurements; it may also be used in a variety of future experiments, e. g. capture gamma-ray studies, structure determinations, and inelastic neutron scattering investigations.

The neutron half-life measurement¹⁾ is conceptually simple: A collimated neutron beam is passed through a 4π -beta spectrometer of known sensitive volume, in which the beta particles from neutron decay are detected. The beam continues through a thin-walled ^3He proportional counter in which the neutron density is measured. The half-life is obtained directly from the beta detection rate and the number of neutrons in the sensitive volume of the beta counter.

The experiment entails measurement of a beta decay rate of about five per second. The beta detectors are, of necessity, sensitive and relatively large. They must in any case be well shielded from the room background associated with the reactor; but from the very fact that they must be near the beam arises much of the reasoning behind the facility design. Beam-associated background is particularly undesirable because of the difficulty in subtracting it from the effect being measured.

Figure 1 will help to visualize the arrangement of the beam facility components and the experimental equipment associated with the neutron-half-life measurement. The beam is formed when neutrons from the D_2O reflector strike a thin H_2O scatterer placed in one of the tangential through-tubes of the reactor. Some of the neutrons are scattered down the length of the helium-filled pipe toward the experimental apparatus. The radiation from the scatterer is first collimated prior to emerging from the reactor face (the "inner collimator"). The beam then passes through a liquid-nitrogen-cooled bismuth filter, which greatly attenuates both fast-neutron and gamma-ray components in the beam. A second collimator (the "outer collimator") defines the beam for passage through the 4π -beta counter and the ^3He counter. The beam is stopped by a beam catcher consisting of a ^6Li plate recessed into a large, heavy concrete block. All equipment external

to the reactor is well shielded in order to reduce the background to an acceptable level.

Careful consideration must be given to the handling of the beam at each stage. The DR 3 reactor is eminently suitable for the extraction of clean beams as the beam tubes are tangential to the core and pass through the heavy-water reflector at a distance from the core sufficient to reduce the fast-neutron contribution to a low level. The great diffusion length in heavy water (approximately 100 cm) provides a high thermal flux at the tube position.

There are many ways to obtain a clean, low-background beam. For example, if, instead of tangential beam holes, a thermal column were available, one method would be to sink an evacuated tube into the material of the thermal column. However, tangential holes have a clear advantage over such an arrangement from the standpoint of beam intensity.

The following section describes in detail the individual components of the Risø beam facility. The in-pile equipment serves primarily to determine beam characteristics, while the out-of-pile components are concerned mainly with beam handling. Figure 2 shows a cross-section view of the apparatus.

2. FACILITY COMPONENTS

2.1. In-Pile Equipment

Figure 2 shows the positions of the beam plug (of which the neutron scatterer and the inner collimator are parts), the bismuth filter and the shutters. Figure 3 traces the path of the beam through the apparatus. These figures will help to understand the following descriptions of individual components.

The reactor facility used in beam extraction is a helium-filled tube, 17.5 cm in diameter, running through the heavy-water reflector tangentially to the core, 70 cm from the core centre. The ratio of thermal neutrons to fast neutrons and gammas is considerably larger in the tube than at the core surface.

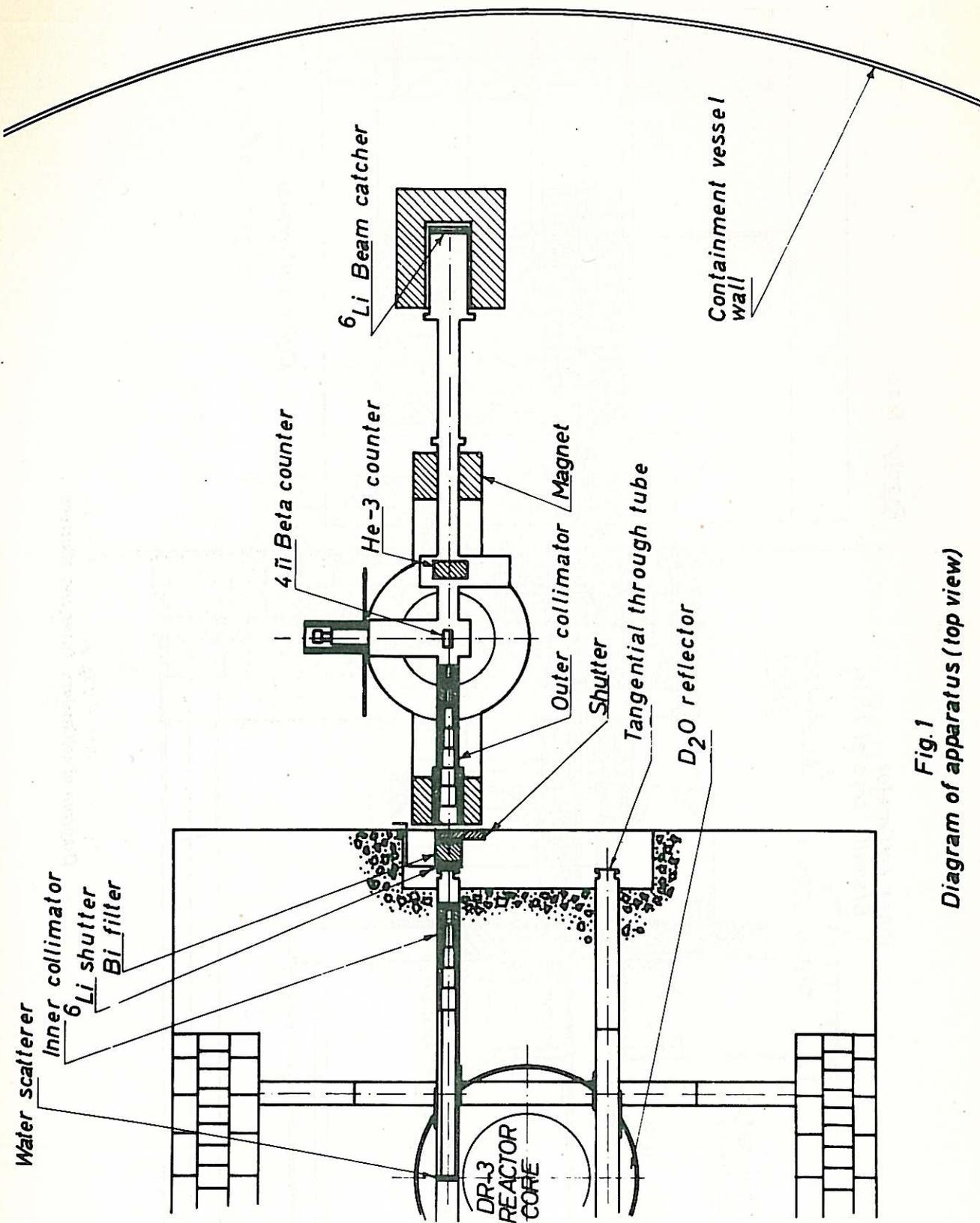


Fig. 1
Diagram of apparatus (top view)

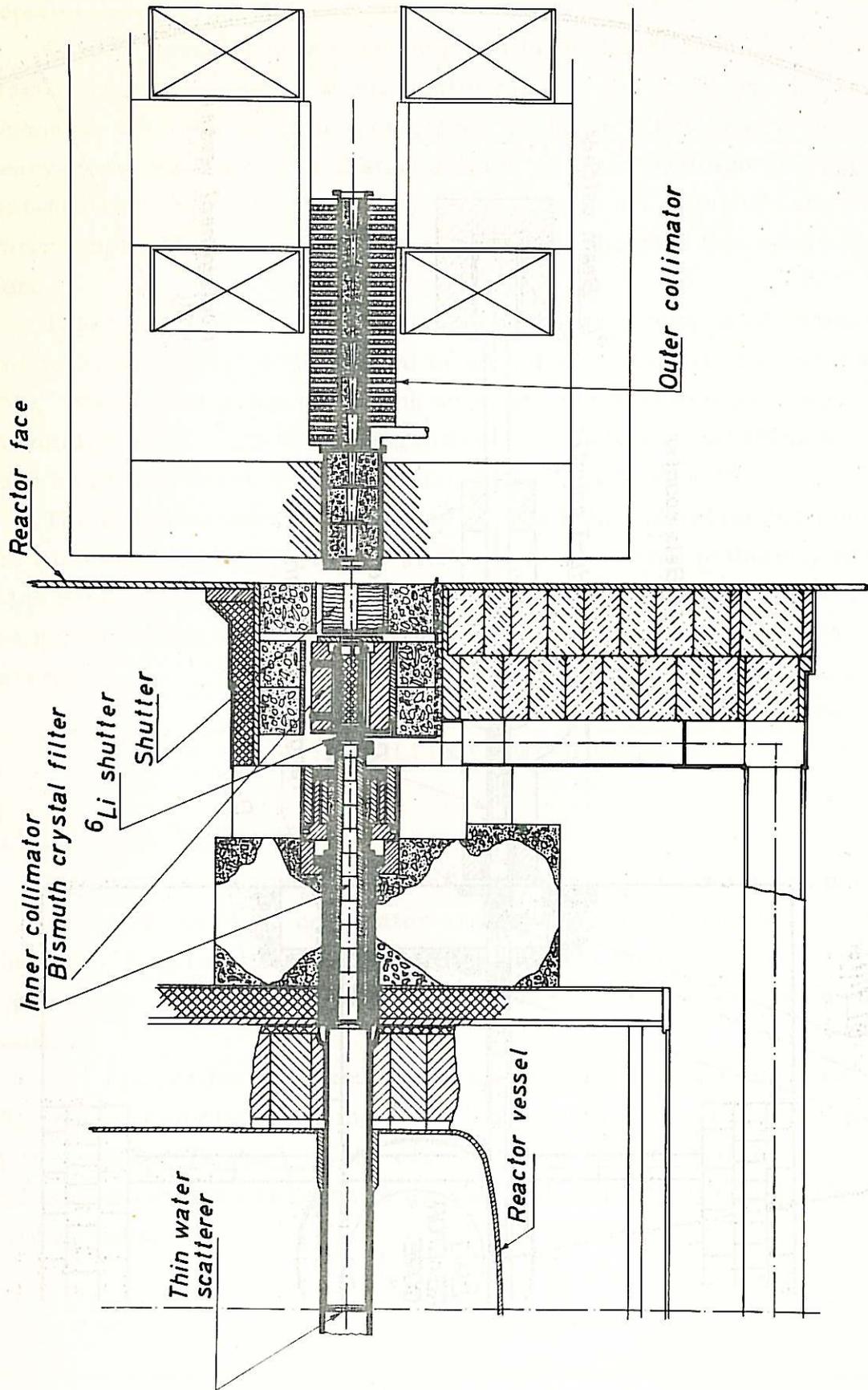


Fig. 2
Diagram of collimators, filter, and shutters

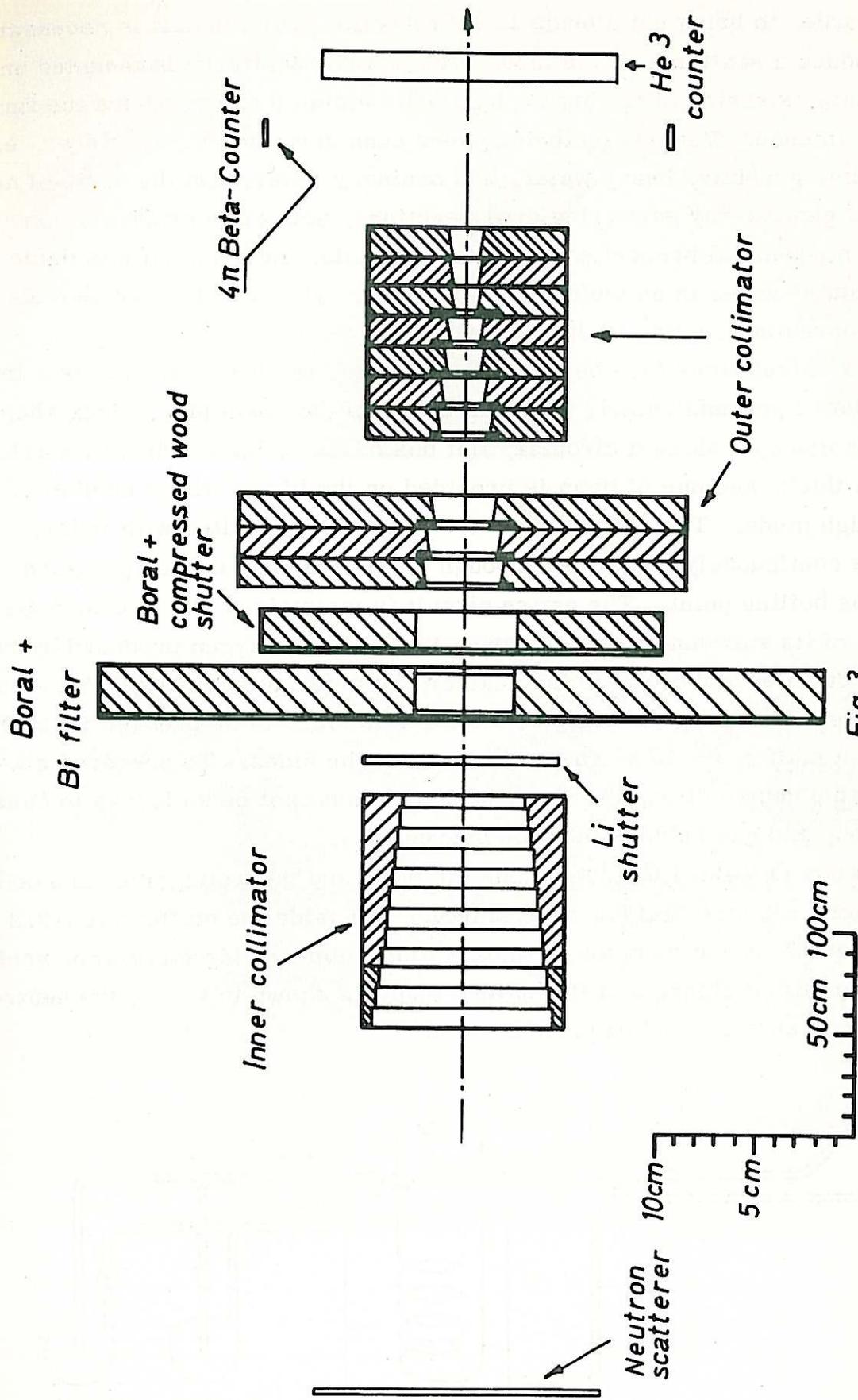


Fig. 3

Passage of beam through apparatus

2.1.1. Neutron Scatterer

In order to bring out a beam in the direction of the tube it is necessary to introduce a scatterer in the tube. The neutron scatterer is mounted on an aluminium extension of the beam plug, just outside the core where the flux is most intense. Various materials were considered for the scatterer, e.g. beryllium, graphite, heavy water, and ordinary water. On the basis of neutron and gamma-ray scattering cross sections, activation cross sections and the mechanical properties of these materials, the decision was made to use ordinary water in an aluminium container. The use of water also allowed convenient cooling of the scatterer.

Flux calculations (see below) indicated that the ideal scatterer is a thin disc, placed perpendicularly to the direction of the beam pipe. This shape was obtained by making a circular, flat box of aluminium. The sides are 0.5 mm thick, and one of them is provided on the inside with a number of 2-mm high studs. The space between the two sides is filled with water, which is continuously circulated through the box to keep the temperature below the boiling point. The entire circuit is maintained at a pressure below that of its surroundings to prevent hydrogen and oxygen produced by radiolysis from escaping inside the reactor and creating a hazard. The studs serve to overcome the tendency of the two thin sides to be pressed together, and to maintain a stable 2-mm space between the sides. To preserve stability of the neutron flux, the water pressure must not be so low as to cause cavitation, and gas bubbles must be prevented.

The box is welded together along the rim, and the water tubes are connected here. As the rim (15 cm diameter) is outside the collimator (12.2 cm diameter), it can be made of thicker aluminium, which facilitates welding.

A simplified diagram of the water circuit is shown in fig. 4; the neutron scatterer is shown in detail in figs. 5 and 6.

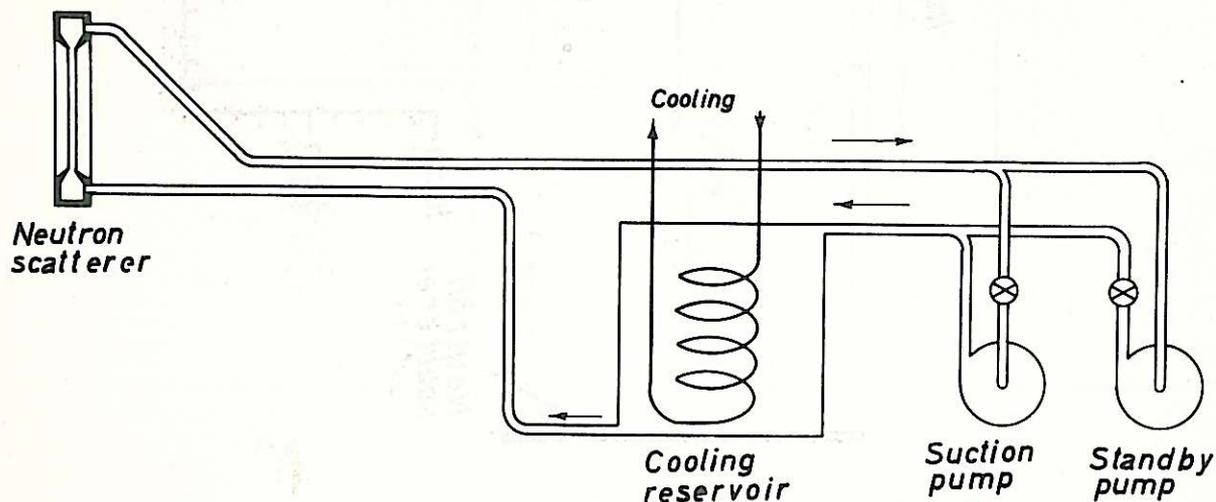


Fig. 4
Water circuit for neutron scatterer

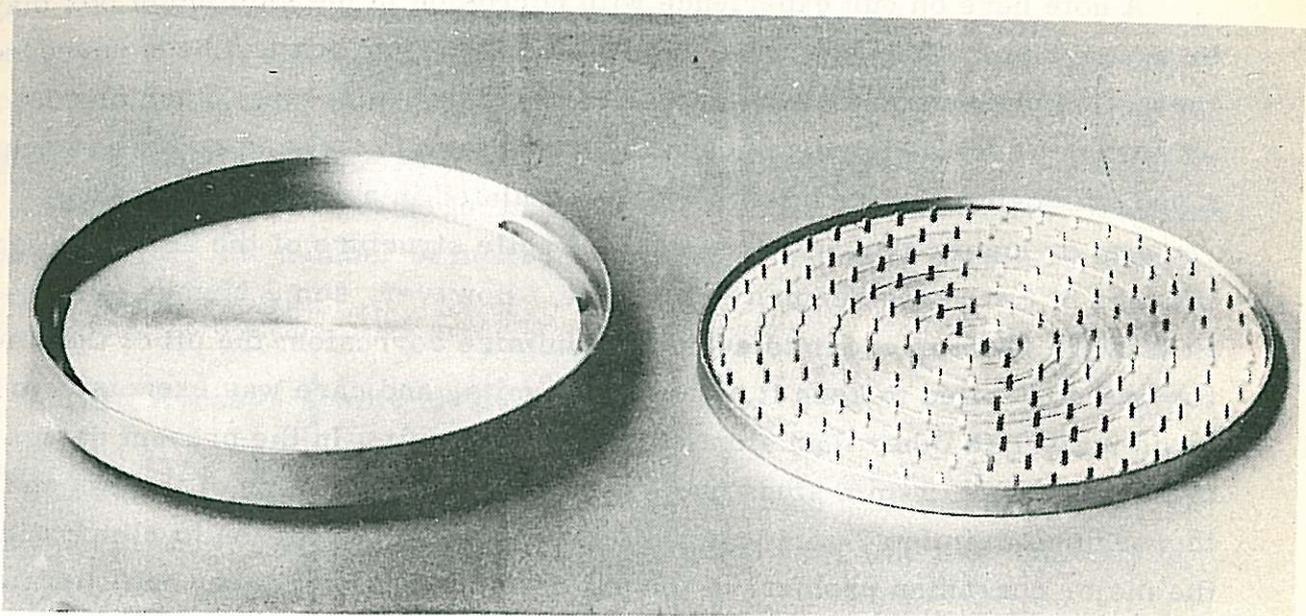


Fig. 5

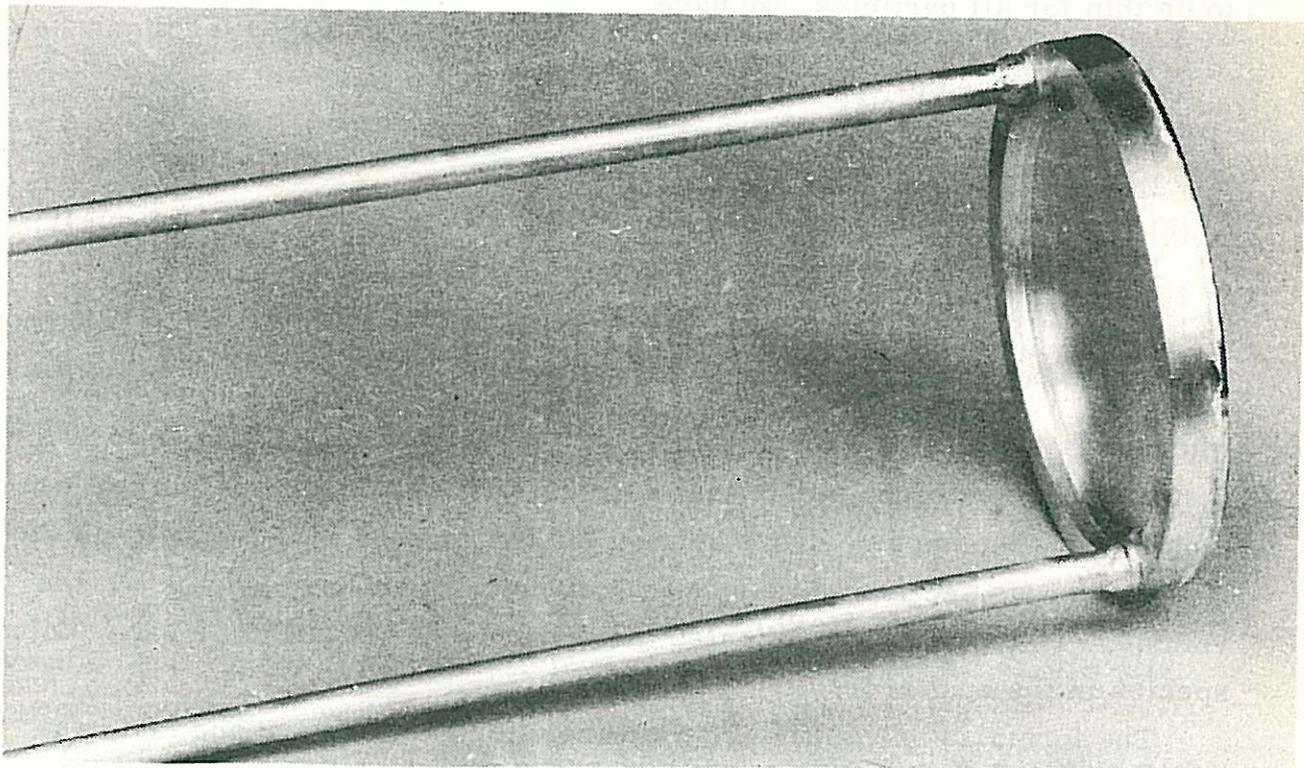


Fig. 6

A note here on our experience with corrosion in the aluminium box may be appropriate: After about two years' operation, the box had been corroded through in one spot and showed signs of corrosion in several other places, primarily where the studs touched the opposite wall. The system had been filled with demineralized water which circulated in a closed loop without renewal or monitoring. In view of the fragile structure of the scatterer, a lifetime of two years seemed reasonable. However, some further precautions were taken in order to avoid or minimize corrosion: the pH of the water was controlled to keep it within safe limits, and care was exercised to avoid materials other than aluminium in the circuit. In the present design of the scatterer, 1-mm studs project from the opposite side of the box and thereby maintain the 2-mm separation of the sides in addition to eliminating the major corrosion problem of the old design. This scatterer has operated for three years without any incident.

In calculating intensities of neutrons reaching a collimator subtending the fractional solid angle $\Delta\Omega$ we assume that fluxes are known at the position of the neutron scatterer and are isotropic. If the scatterer can be considered to be thin for all particles, we have

$$\begin{aligned} I_f &= \Sigma(\sigma_f \rho V) \Phi_f \Delta\Omega \\ I_{th} &= \Sigma(\sigma_{th} \rho V) \Phi_{th} \Delta\Omega \\ I_\gamma &= \Sigma(\sigma_\gamma \rho V) \Phi_\gamma \Delta\Omega \\ I_\gamma' &= \Sigma(\sigma_c \rho V) \Phi_{th} \Delta\Omega \end{aligned} \quad (1)$$

where I is the intensity of the beam, σ_f is the scattering cross section for fast (fission) neutrons, σ_{th} is the scattering cross section for thermal neutrons, σ_c is the capture cross section for thermal neutrons, and σ_γ is the Compton cross section. The symbol ρ denotes the atomic density, V the volume. The summation indicates the presence of one term for each nuclear species in the scatterer.

The formulas are sufficiently accurate for gamma rays and fast neutrons; however, for thermal neutrons the assumption of thinness does not hold, and the intensity must be found by integrating the scattering probability over all angles of incidence of the reactor neutrons. The scattering probability for a neutron entering a flat sheet of the thickness d at an angle θ to the normal is

$$P(\theta, d) = 1 - \exp(-d/s |\cos \theta|) , \quad (2)$$

where s is the mean free path for the scattering material.

On the assumption of an isotropic, homogeneous flux distribution around the scatterer, the number of neutrons entering the disc of area A , in $d\theta$ at θ , and in dv at v , is

$$n(v) v A |\cos \theta| \frac{1}{2} \sin \theta d\theta dv. \quad (3)$$

The beam intensity at the collimator is obtained by integrating the product of (2) and (3) over all solid angles and velocities, and then multiplying by $\Delta\Omega$.

$$I_{th} = \frac{1}{2} \Delta\Omega \cdot A \int_v n(v) v \int_{-\pi/2}^{\pi/2} |\cos \theta| \sin \theta \left[1 - \exp\left(-\frac{d}{s |\cos \theta|}\right) \right] d\theta dv. \quad (4)$$

In conventional approximation, s is set equal to a spectrum-averaged mean free path ($s_{av} = 0.29$ cm for H_2O). If this is done, the integrations in (4) yield

$$I_{th} = \frac{1}{2} A P(d) \phi_{th} \Delta\Omega , \quad (5)$$

where $P(d)$ can be interpreted as the average scattering probability. On the basis of the definition of the exponential integral, $P(d)$ can be shown from (4) and (5) to be

$$P(d) = 1 - 2E_3\left(\frac{d}{s}\right).$$

Note that expansion of $P(d)$ to first order in (d/s) reduces (5) to expression (1). Also, for an infinitely thick scatterer, $P(d) = 1$, i. e., all neutrons are scattered.

$P(d)$ is shown in fig. 7 as a function of the dimensionless variable d/s and of d for H_2O .

In calculating the intensity from (5), we have assumed isotropic emission of the neutrons. This is valid for $d \ll s$. For $d \gg s$, the emission will follow a cosine law because of multiple scattering of the neutrons before they are emitted. It can be shown that this gives an intensity along the