normal which is twice the average. In the present case, with $d \approx s$, the cosine law will not hold exactly, but it is still preferable to orient the disc perpendicularly to the collimator axis. Any other orientation would require more material for the same intensity to be obtained, and hence would increase the background. The intensity will be between once and twice that calculated in (5).

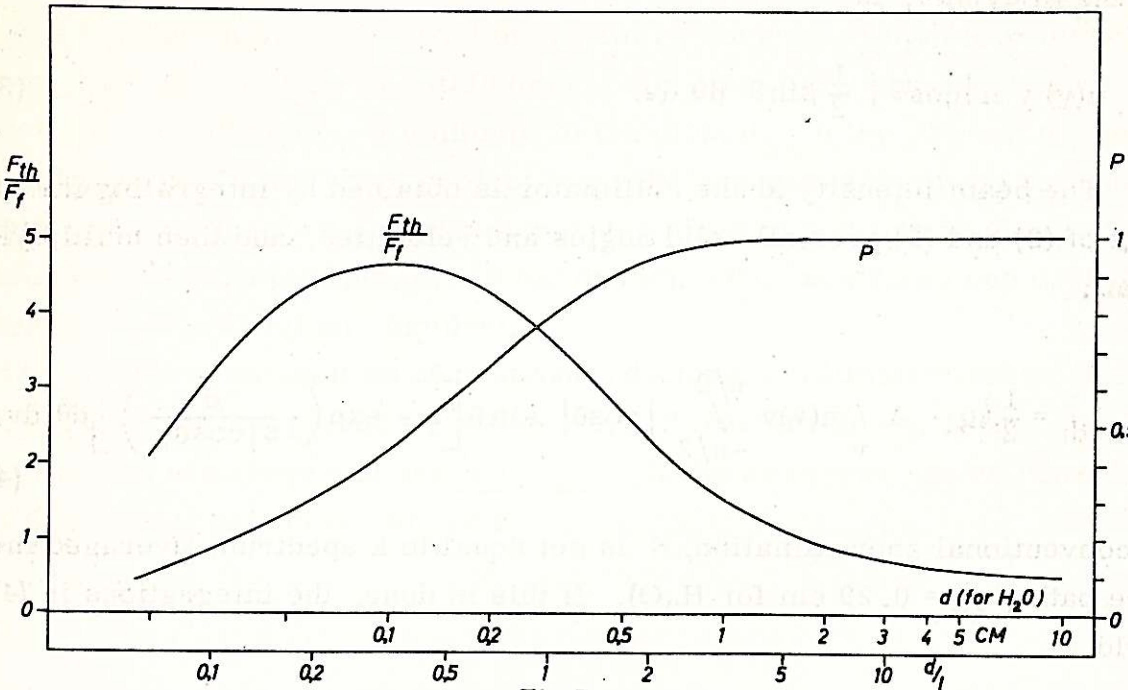

Fig. 7

Functions used in water scatterer design

In the calculation of the gamma intensities the Compton-scattered gamma intensity has been reduced by a factor of approximately four; this is an estimated mean value that corrects for the original assumption of isotropic flux distribution to account for the Compton scattering angular distribution. Note that these scattered gamma rays are of lower energies than the reactor core gammas. Similar arguments can be applied to the fast-neutron flux; however, the scattering cross section does not change as rapidly with angle, and therefore no correction factor has been applied. All intensities can be expressed by $I = \frac{1}{2}F(d)\Phi A \Delta\Omega$, where F(d) is the generalized average scattering probability (P(d) for thermal neutrons). Figure 7 shows the variation of P(d) and the ratio F_{th}/F_f with d. As a compromise between the two conflicting requirements, i.e., a large P(d) and a large F_{th}/F_f ratio, a thickness of 2 mm was chosen for this application. Table I, below, lists the factors influencing the intensities for d = 2 mm (and for $d \to \infty$ by way of illustration). The numbers given for thermal neutrons are the average intensities; no thickness correction has been applied. Also listed are the calculated intensities with and without the bismuth filter (described in a later section of this report) and, for comparison, measurements of the actual beam.

Table I

Radiation intensities in the beam

F(d) is listed for the actual scatterer and for an infinitely thick scatterer. Intensities refer to the position of the last defining aperture (4.2 m from the scatterer), where $A\Delta\Omega = 4.15 \times 10^{-5}$ cm^2.

	Thermal neutrons	Fast neutrons	Compton γ	Capture γ
Core flux (n/cm^2 sec)	1.6×10^{14}			
Flux at scatterer (cm^2 sec)$^{-1}$	5.2×10^{13}	2×10^{11}	4×10^{13}	(5.2×10^{13})
F(d) (for d = 2 mm)	0.662	0.15	0.02	0.009
F(d) (for $d \to \infty$)	1.0	1.0	0.25	1.0
I (particles/sec)	7.1×10^8	6.3×10^5	1.66×10^7	0.97×10^7
I (incl. Bi filter)	4.7×10^7	2.5×10^3	5	3+545[a]
I (measured)	5.4×10^7	2.3×10^3	Total gamma $< 10^3$ (2 mR/h)	

[a] Capture gammas coming from neutron capture in Bi, attenuated by the Bi, contribute approximately 545 γ/sec.

2.1.2. Beam Plug

The beam plug (fig. 8) consists essentially of two concentric stainless-steel tubes. Water supply lines for the neutron scatterer and for cooling the front end of the plug run between the tubes, and the rest of the region is filled with lead and with epoxy resin loaded with lead. The inner tube, which contains the inner collimator, is closed at both ends by 2-mm thick aluminium windows. The beam plug, which is normally in vacuum, can be filled with water to form an effective beam shutter. If so, the water is circulated to provide proper cooling and to avoid concentration of radiolysis gases. The beam tube extends through the reactor shielding and ends in a "vestibule box" recessed 78 cm from the outer face into the reactor shield. The beam plug extends 10 cm into the vestibule box and is here provided with connections for remote thermometer elements, cooling water, scatterer water, and evacuation lines.

The rest of the vestibule box is occupied by (1) a shutter of lithium carbonate, enriched in ^{6}Li; (2) the liquid-nitrogen-cooled bismuth filter; (3) a shutter of boron and high-density wood. (The shutters are further described below.) The remainder of the space is packed with blocks of heavy concrete.

2.1.3. Inner Collimator

The inner collimator is designed to shield against radiation from the walls of the tube while being open to radiation coming from the thin neutron scatterer. The front section of the collimator is made of lead, the remainder of stainless steel. This design was chosen as a compromise between simple design considerations and optimum shielding properties.

2.1.4. Bismuth Filter

The bismuth filter, cooled by liquid nitrogen, has been described in detail in ref. 2. Only a summary of its properties is included here: The bismuth "single crystal" was grown from high-purity materials to produce a block consisting of a few crystals[3]. When etched, the surface of the block showed approximately 15 separate crystals of various sizes. The block was machined to a cylinder 7 cm in diameter and 32 cm long (see fig. 9). The cylinder is jacketed in steel, and this assembly is suspended in an evacuated steel housing, as shown in fig. 10. Liquefied high-purity nitrogen (oxygen free) is circulated in a closed loop through the jacket by a small centrifugal pump[4] to transfer the heat to a reservoir of ordinary nitrogen outside the reaetor. Aluminium foils at the end of the jacket serve as heat radiation shields to maintain the bismuth at a uniform temperature. The time constant for cooling was found to be 6 h. The transmitted neutron density, averaged over all energies in the thermal region, is 16% when the bismuth is at liquid nitrogen temperature, as compared with only 6% at room temperature. The normal Maxwellian spectrum of the slow neutrons is altered by the bismuth; the actual distribution[5] is shown in fig. 11. The spectrum shape has to be taken into account when corrections to the ^{3}He detector are evaluated. The transmission of other radiation through bismuth is very low. Fast-fission neutrons are attenuated by a factor of approximately 5000, and gamma rays by a factor of 10^{6}. In fact, the gamma radiation present in the beam after it has passed through the filter consists mostly of neutron-capture gammas from the last centimetres of bismuth (see table I).

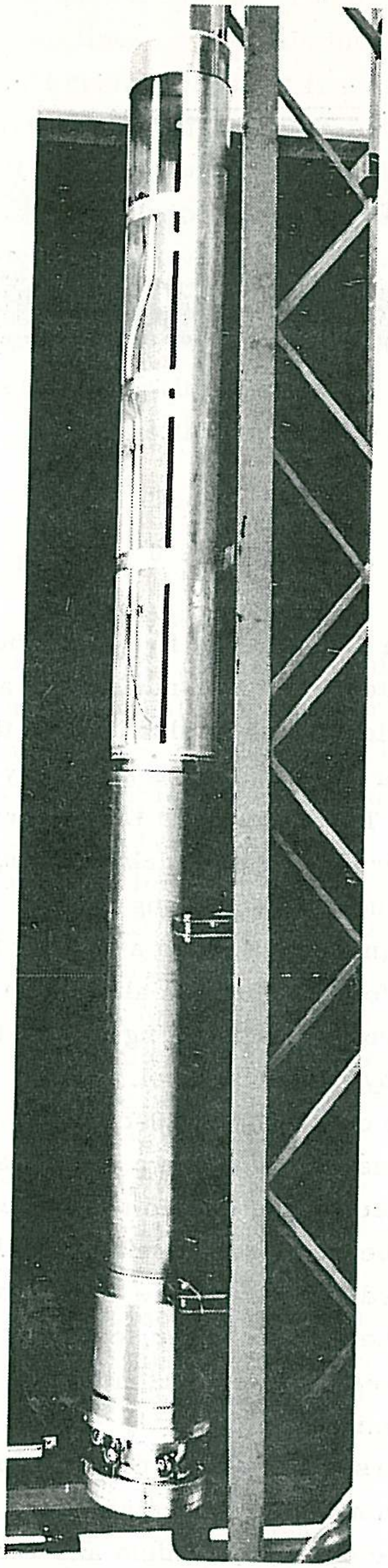

Fig. 8

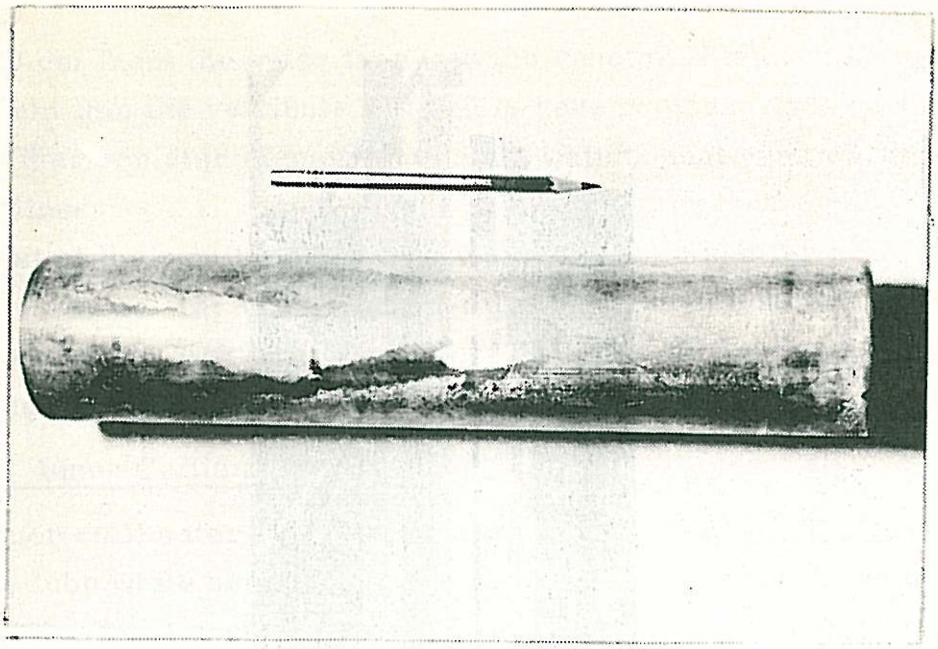

Fig. 9

2.1.5. Shutters

The first shutter in the series of five in the beam facility is located between the inner collimator and the bismuth filter and is made of lithium carbonate. This material, which is also used in the outer collimator, has been described elsewhere[6)], but again a summary of important characteristics is relevant here: The material is Li_2Co_3, with the lithium enriched to 95% ^{6}Li. The shutter is 0.33 cm thick, yielding a transmission of only 3.4×10^{-5} for thermal neutrons. During neutron irradiation, some tritium is produced by the ^{6}Li (nα) reaction; to avoid any health hazard the lithium carbonate disc is therefore enclosed in aluminium. The shutter is supported on an arm extending through the shielding so that the shutter can be moved in and out of the beam by remote control.

The second shutter consists of a 20-cm thick block of high-density wood, the inner side of which is covered by two boral plates to stop thermal neutrons. A 5-cm-diameter hole is drilled through both materials, and the block moves on roller bearings so that either the hole or the solid part of the shutter can be moved in line with the beam. Inasmuch as the beam, after passing through the bismuth filter, consists primarily of thermal and fast neutrons, the shutter is quite efficient and is used to obtain information on the background radiation.

Three more shutters have been installed in the facility in this position for the study of the various beam-associated background components. These three shutters are made of boron, lithium and aluminium.

The numbers in the last three lines in table I refer to the beam at the location of the last defining aperture in the outer collimator, with the inner collimator evacuated and all shutters open. The beam intensities (particles/ cm^2 sec) given in the last two lines of the table include the 16% transmission of the cold bismuth filter and remain constant from the final aperture to the beam catcher (since no part of the beam is intercepted or attenuated between these points). The intensity transmission is lower than the density transmission because the average velocity of the emitted spectrum is considerably lower. The ratio of the average velocities with the bismuth filter to those without it is approximately 0.42. The final aperture is 10 mm in diameter and therefore has an area of $\pi/4$ cm^2. The beam fluxes (particles/ cm^2 sec) may be calculated at this point by dividing by the area of the aperture, but these values will change as the beam diverges in its passage to the beam catcher.

2.2. Out-of-Pile Equipment

The set-up outside the reactor face is designed to (1) collimate the clean beam from the bismuth filter to obtain the desired size at the counting chamber without introducing additional background radiation; (2) transport the beam to the nonradiating beam catcher; (3) shield the counters in the counting chamber as much as possible from radiation from the surroundings, the bismuth filter and the collimator.

The 4π-beta counter and the ^{3}He neutron density monitor[7)] are considered parts of the neutron half-life measuring equipment rather than of the beam facility, and they are described here only insofar as they affect the beam facility design requirements. Fig. 3 shows the location of the two NE-102 scintillator plates within the 4π-beta counter in relation to the neutron beam. The ^{3}He neutron density monitor is retracted from the beam during measurements with the 4π-beta counter.

The entire outer collimator section of the beam tube is suspended from two adjustable brackets attached to the magnet yoke and used for alignment. Accurate alignment is important for several reasons: Unless the outer and inner collimators are carefully aligned, some radiation will strike the lead cones, resulting in scattered neutrons or gamma rays that may reach the scintillator plates. Also, it is important that the beam travels down the rest of the beam pipe without hitting the walls, and that it is absorbed completely by the beam catcher.

Alignment was achieved by the aid of a pinhole camera which photographed the images of the key internal elements. The camera was provided with a small hole allowing the passage of a neutron beam, which impinged upon a silver plate backed with X-ray film.

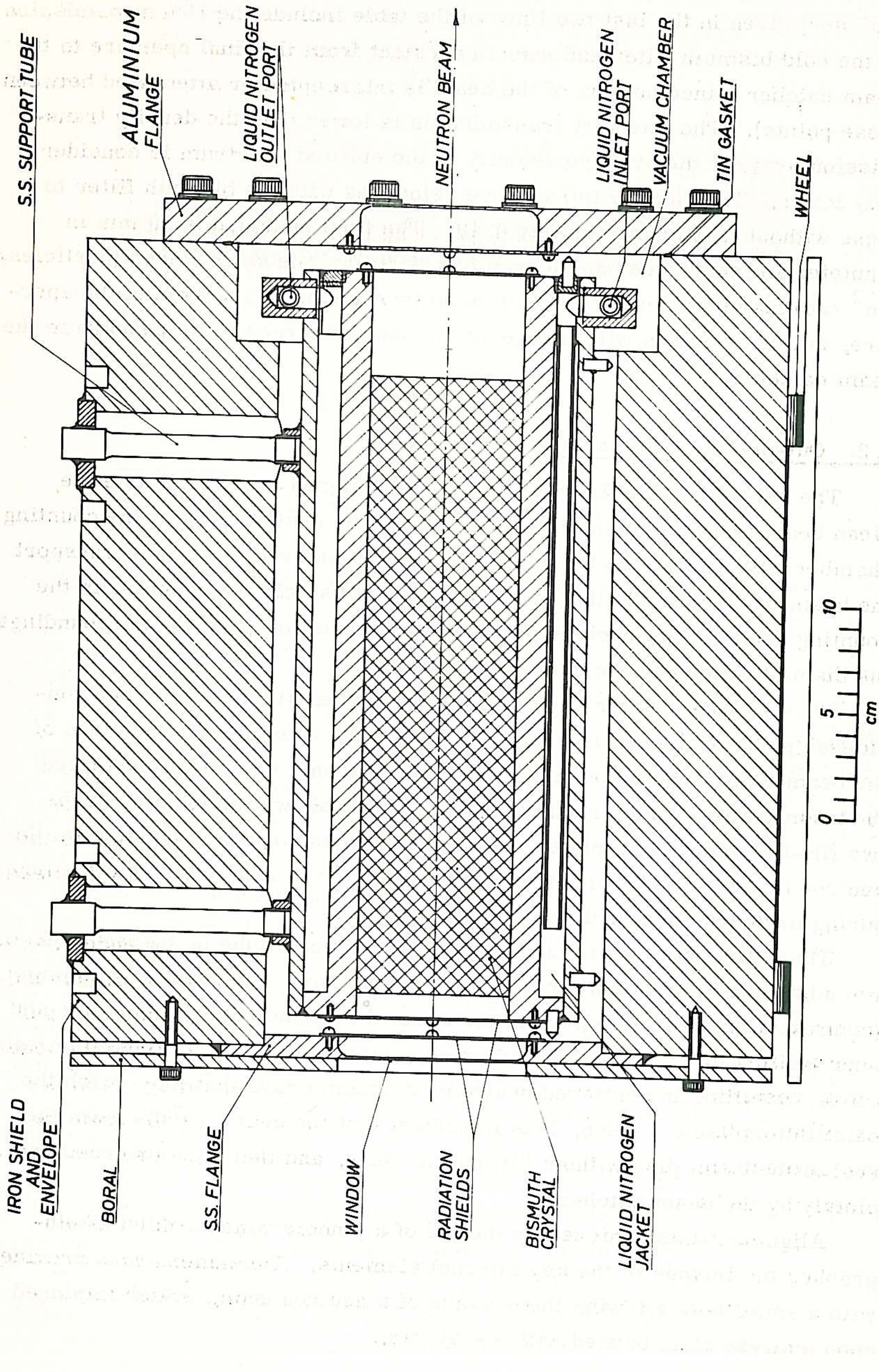

Fig.10 Bismuth filter

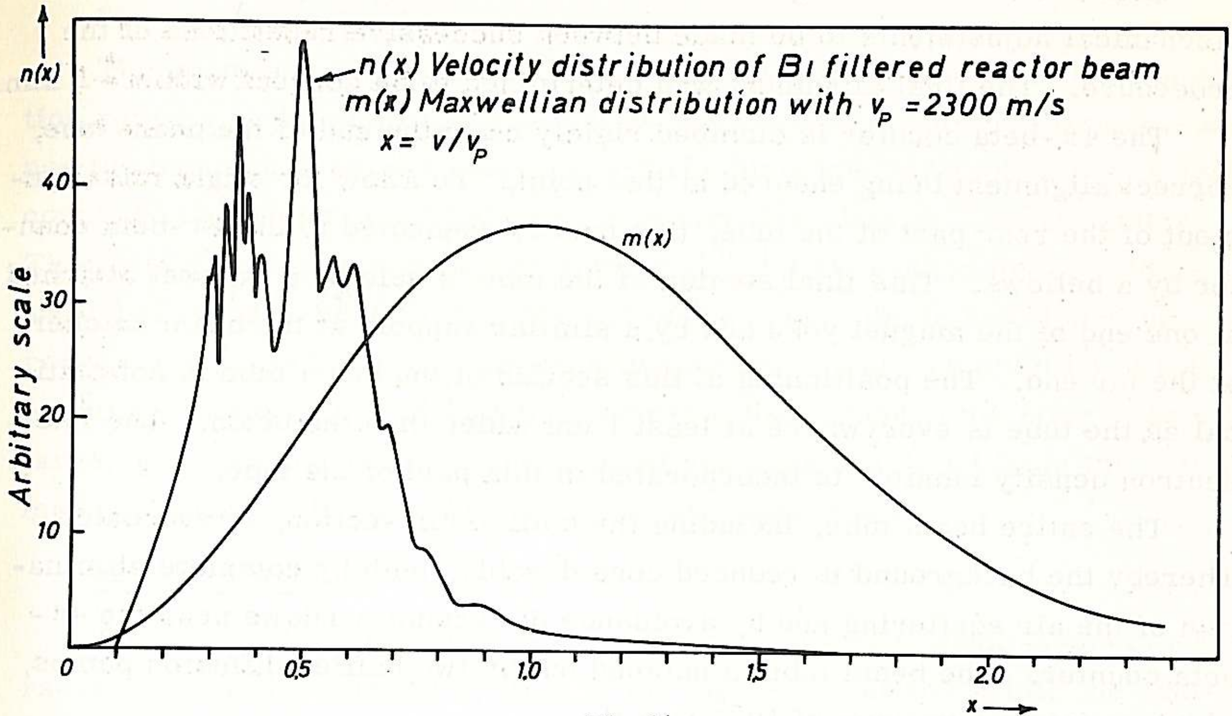

Fig. 11
Neutron spectra

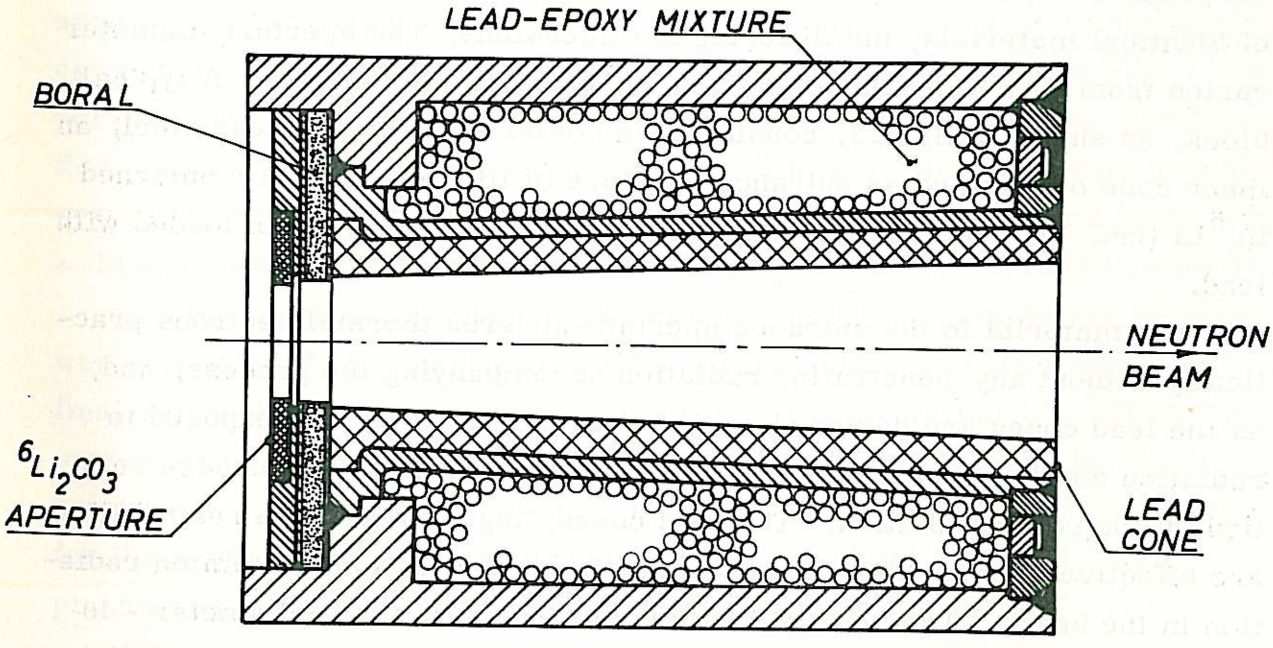

Fig. 12
Collimator block (typical)

Examination of each exposure indicated the magnitude and direction of mechanical adjustments to be made between successive repetitions of the procedure. The final alignment was determined to be correct within $\pm$ 1 mm.

The 4π-beta counter is clamped rigidly on to the end of the beam tube, correct alignment being ensured at that point. To allow for slight misalignment of the rear part of the tube, this part is connected to the 4π-beta counter by a bellows. This final section of the tube is held by a bracket attached at one end of the magnet yoke and by a similar support at the beam catcher, at the far end. The positioning of this section of the beam tube is not critical as the tube is everywhere at least 1 cm wider than the beam. The ^{3}He neutron density monitor is incorporated in this part of the tube.

The entire beam tube, including the collimator section, is evacuated. Thereby the background is reduced considerably, both by complete elimination of the air scattering and by avoidance of vacuum windows near the 4π-beta counter. The beam tube is pumped out by two baffled diffusion pumps, which maintain a vacuum of 10^{-5} mm Hg.

2.2.1. Outer Collimator

The first part of the beam tube contains the outer collimator and the scintillator shield block. The collimator consists of seven blocks (fig. 3) of identical materials, but differing in dimensions; The aperture diameter varies from 37 mm in the front block to 10 mm in the last one. A typical block, as shown in fig. 12, consists of an outer shell of stainless steel, an inner cone of lead and an entrance aperture of lithium carbonate enriched in ^{6}Li (ref. 6). The remaining space is filled with epoxy resin loaded with lead.

The material in the entrance aperture absorbs thermal neutrons practically without any penetrating radiation accompanying the process; and, as the lead cones are designed so that their surfaces are not exposed to radiation coming through the inner collimator, collimation produces very little background radiation. The lead cones, together with the resin filling, are effective in absorbing the accompanying fast-neutron and gamma radiation in the beam. The last collimator aperture - 10 mm in diameter - is followed by the shield cone, consisting of three blocks that have no defining apertures, but form a single cone. Again, the cone angle has been chosen so that no radiation from the beam hits the lead, but maximum shielding of the scintillator plates against radiation from the preceding collimator is obtained. Fig. 3 shows the configuration.

2.2.2. Beam Catcher

The beam must be stopped in such a way that only a minimum of radiation returns to the scintillator plates in the 4π-beta counter. For this reason the beam catcher was placed at a large distance (3.5 metres) from this counter, and the beam was stopped by a circular plate of ^{6}Li carbonate. This "plate" actually consists of powdered $^6Li_2CO_3$ packed inside a thin-walled aluminium container. The end of the beam tube is positioned in a recess in a large block of high-density concrete. Upon completion of the facility, studies of the background indicated that although the effect was not large, gammas from capture of thermal neutrons scattered from the catcher made an observable contribution to the total background.

2.2.3. Shielding

A considerable effort has been made to prevent any beam-associated radiation from leaving the vicinity of the beam tube at any point; the scattering of such radiation into the 4π-beta counter is clearly undesirable. The entire beam tube from reactor face to beam catcher is surrounded with a massive shield of lead and high-density wood, 10 to 15 cm thick.

The room background was minimized by building a wall of concrete blocks around the entire experimental apparatus. The large block containing the beam catcher is part of the rear wall away from the reactor. The concrete floor supporting all of the apparatus is thick enough to act as an effective shield in that direction. The top has been left open to provide access for an overhead crane. A corrosion study set-up on top of the reactor caused some difficulty for a time, but was shielded with lead when it was identified as a radiation source.

During the first year of the experiment the various shield components were redesigned and rearranged several times until the background was finally brought down to an acceptable level. The background has not been measured in terms of flux. Instead, the actual count rates in the plastic scintillators are given in table II. These rates are the relevant criteria for the neutron half-life measurement, but may also be applied in the planning of other low-background experiments using the beam facility.

The two detectors within the 4π-beta counter are NE-102 plastic scintillators as mentioned above (see figs. 1 and 3). Each has the dimensions 0.32 x 5 x 10 cm, and the total detector volume is therefore 32 cm^3. The scintillators are positioned 9 cm from the centre of the beam, which has a radius of 1.3 cm at that point. The neutron beam in the spectrometer has a total linear density of 500 neutrons/cm (~5 x 10^7 neutrons/sec at $\bar{v}$ = 1000 metres/sec).

With a discriminator setting of 150 keV, the background count rates are as seen in table II.

Table II

Contributions to the background count rate

Room background		
	All sources (reactor at 10 MW, shutters closed)	5.0 c/s
Beam-associated background		
	Fast-neutron and gamma	0.5 c/s
	Capture gamma (collimating system and catcher)	0.2 c/s

3. CONCLUSION

A beam facility has been designed and constructed for use in neutron half-life and other measurements. The facility is installed in one of the tangential through-tubes in the DR 3 reactor at Risö and provides an extremely well-collimated, low-background beam of good intensity. Design considerations and calculations are reviewed in this report, and descriptions of the several pieces of equipment in the facility are given. Measurements of the various radiation components of the beam and of the backgrounds finally obtained are presented.

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