

REPORT

Measurement of the fast neutron component in the beam of the NPL Thermal Neutron Column using a Bonner sphere spectrometer

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ABSTRACT

Following a recent refurbishment of the NPL Thermal Neutron Facility, the spectrum of the epithermal and fast neutron component of the beam produced by the thermal column of this facility was measured over the energy range from thermal to 20 MeV using a Bonner sphere spectrometry system. The effect of the presence of epithermal and fast neutrons on the measured response of commonly-used thermal neutron dosimeters was calculated.

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Approved on behalf of Managing Director, NPL, by
Dr Julian Hunt, Head, Centre for Ionising Radiation Metrology

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1 INTRODUCTION

The NPL Thermal Neutron Facility, commonly known as the "thermal pile", is used mainly for assessing the thermal response of neutron sensitive devices such as area survey instruments and personal dosimeters. Thermal neutron fields are produced by the moderation of fast neutrons that are produced by the action of deuteron beams on beryllium targets. For any device larger than a few centimetres the field used is that of the thermal column. This is an arrangement for extracting a beam of thermal neutrons from within the pile.

The thermal beam always contains an epithermal and fast neutron component due to fast neutrons that are not completely thermalised. Unfortunately, the nature of this component may vary with use of the facility. This is due the deuteron beam reacting with deuterium that has been deposited in the beryllium targets and a tantalum "beam-dump" plate and also with possible contaminants of the targets and tantalum plate such as carbon from the vacuum system. These can affect the relative proportions of the thermal neutron, epithermal and fast components of the thermal neutron beam.

Most commonly used dosimeters are sensitive to the epithermal and fast neutron component present in the field. Their thermal neutron response is usually measured by irradiating the dosimeters free-in-air, and then enclosed in cadmium; the response measured in cadmium is then subtracted from the response free-in-air to give the thermal response.

There are situations, however, where the measurement with the device enclosed in cadmium presents problems, for example, where signal cables are involved, or where dosimeters need to be irradiated on a phantom. To understand the results of irradiations without a cadmium cover, a knowledge of epithermal and fast component is required.

A recent refurbishment of the NPL Thermal Neutron Facility involved the replacement of the original beam line, and the fitting of a fresh tantalum "beam-dump" plate. This was expected to reduce the production of epithermal neutrons from the beam striking the tantalum plate. It was therefore particularly appropriate to measure the spectrum of the epithermal and fast component of the thermal column beam following these changes.

The NPL Bonner sphere (BS) set was used to determine the neutron energy spectrum over the energy range from thermal to 20 MeV at a reference position in the centre of the thermal column beam where calibrations of thermal neutron dosimeters are normally carried out.

A spectral determination with a BS system involves making measurements with a thermal neutron detector positioned at the centre of a number of different diameter spheres of polyethylene. Each sphere plus thermal neutron detector combination has a different sensitivity to different parts of the neutron spectrum, and a measure of the overall spectrum can be unfolded from the measured count rates for the different spheres.

From the present measurements the proportion of the epithermal and fast neutron components in the beam of the NPL Thermal Neutron Column were derived relative to the thermal neutron component. This information was then used to calculate, for commonly used dosimeters irradiated in the thermal column beam, the response due to epi-cadmium neutrons as a ratio of the thermal response.

2 NPL THERMAL NEUTRON FACILITY

The NPL Thermal Neutron Facility was designed primarily for producing a precisely-controlled, well-characterised thermal neutron field in a cavity near the centre of a large graphite moderator block, or 'pile'. It has been described in detail by Ryves and Paul, 1968 [1].

Fast neutrons are produced by bombarding two beryllium targets with a 2.8 MeV deuteron beam from the NPL 3.5 MV Van de Graaff accelerator. The semi-circular beryllium targets are fixed 160 cm apart in a horizontal beamline which passes through the entire length of the moderator block. The targets are mounted equi-distant from the centre of the graphite block and a servo control system equalises the fraction of the deuteron beam incident on each target. At the entrance to the moderator block, a tantalum semi-circular plate is fixed vertically in the beamline, see Figure 1 and 1a. This acts as a "beam-dump" and forms part of the pile control mechanism. The primary neutrons are moderated by the graphite producing a thermal neutron field at a sufficient distance from the targets.

The neutron production in the pile and the fraction of the deuteron beam striking the beryllium targets and tantalum plate is controlled by signals from three ionisation chambers. Two ionisation chambers are positioned below the beryllium targets underneath the beamline and the other ionisation chamber is positioned below the central cavity. The ionisation chambers monitor the neutron output from the targets and their response is used to control a servo-system which acts upon vertical and horizontal steering plates in the beamline. The central ionisation chamber controls the horizontal deflection of the beam and thus the distribution of beam between the targets and tantalum plate. The ionisation chambers below the targets control the vertical deflection of the beam to give approximately equal thermal neutron outputs from the two targets. The servo-system can be preset to give the desired thermal neutron flux output which is controlled by means of the horizontal beam deflection.

In addition to the thermal neutron field produced there is an epithermal component consisting of primary neutrons which have not been moderated to thermal energies. The primary neutrons are produced within the pile from the d-Be reaction, and to a lesser extent, from the d-D reaction and from the action of the deuteron beam on contaminants deposited on the beryllium targets and the tantalum plate. All three reactions contribute to the neutron field, but the ratio of the thermal component to the fast and epithermal component will vary depending on the deuteron beam conditions and the cleanliness of the vacuum system, targets and tantalum plate.

For the irradiation of large objects a 'thermal column' was incorporated above one of the beryllium targets in the graphite moderator block. The column consists of a stainless steel cylinder with cadmium lined sides and a cross sectional area of 1000 cm². The length of the column can be adjusted in half metre steps, from 1 m to 3 m. The thermal neutron fluence is monitored by a ²³⁵U fission chamber positioned in the graphite between the bottom of the thermal column and the beryllium target. This monitor can be calibrated in terms of the fluence at any position in the thermal column, using the gold activation technique [2].

3 NPL BONNER SPHERE SET

NPL has two well-characterised BS sets, of which the set with a ³He proportional counter as the central detector was used for the present work. The other set, based on gold activation foils, is used in applications where the fluence rates are very high. The ³He detector used is an SP9 type (Counter serial No 8829-448,D was used for the present measurements) manufactured by Centronic Ltd., and consists of a spherical stainless steel shell containing ³He at a pressure of approximately 200 kPa.

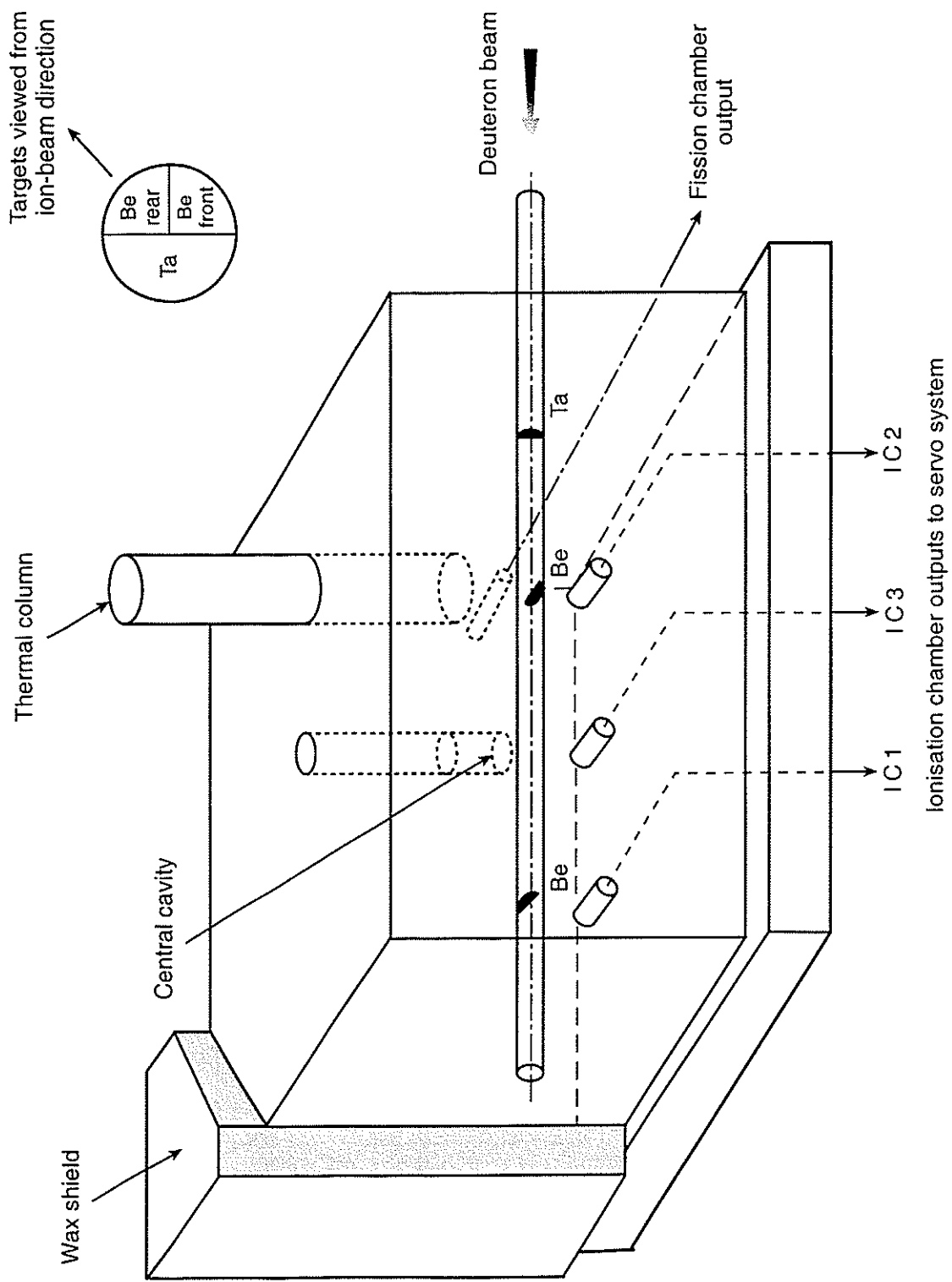


Figure 1. Schematic diagram of the NPL Thermal Neutron Facility

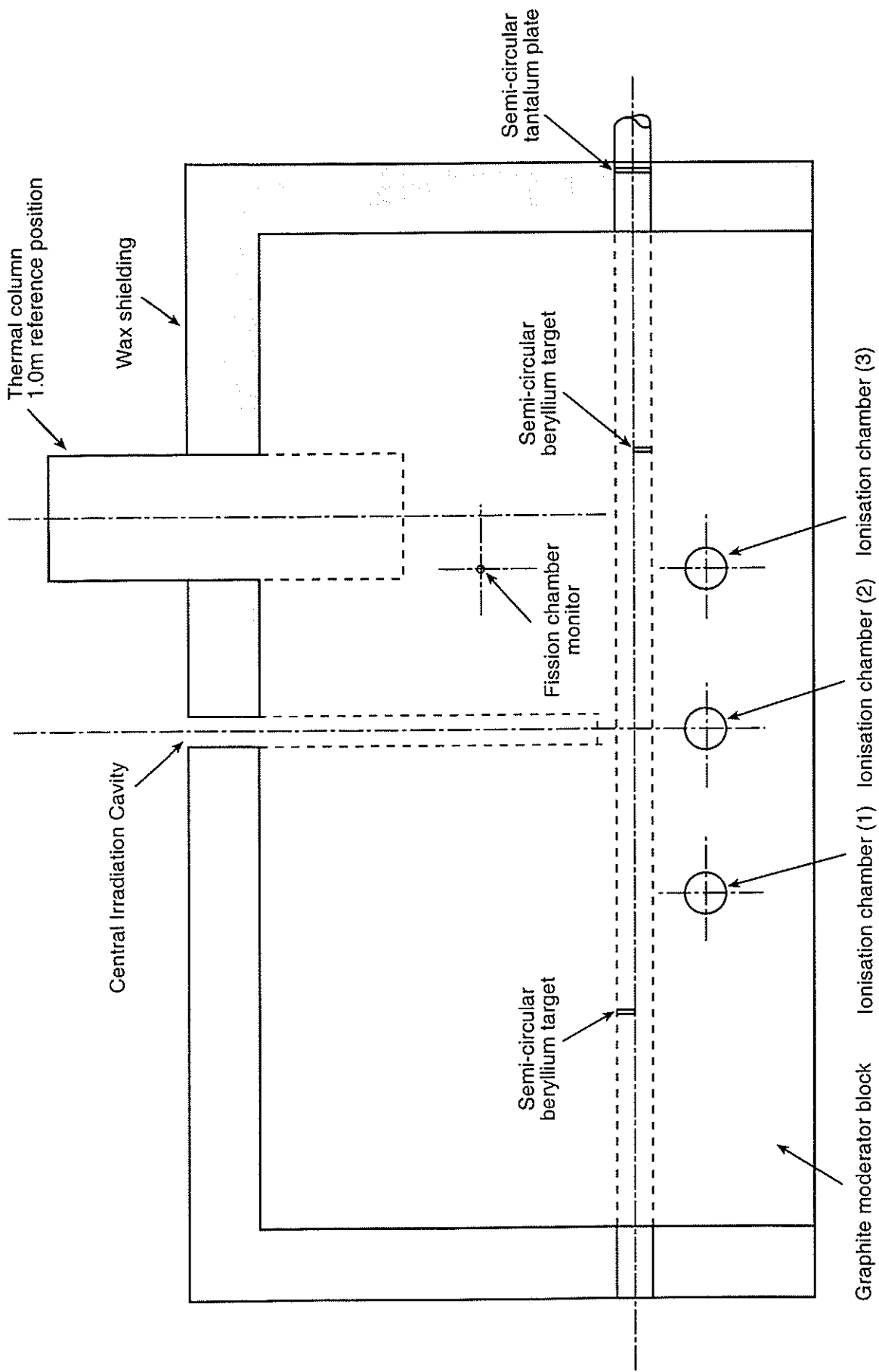


Figure 1a. Side view of graphite moderator block showing relative positions of the targets, irradiation positions and the neutron monitors

Neutrons are detected by the ${}^3\text{He}(n,p)\text{T}$ reaction which has a large, and well known, cross section in the thermal neutron region. A detailed description of the ${}^3\text{He}$ counter based BS set, and the derivation of the required response function, is given by Alevra et al., 1988 and 1992, [3], [4] and by Thomas et al., [5]. A typical charged particle spectrum seen in the ${}^3\text{He}$ detector is shown in Figure 2.

The ${}^3\text{He}$ counter based BS spectrometer has available nine spheres of diameters 3", 3.5", 4", 5", 6", 8", 10", 12" and 15", all of which are used with the same central SP9 counter. (Traditionally BS sets are made with integral inch diameters, and these values are used as convenient labels for the individual spheres.) For the present work all sphere diameters were used except the 12" and 15" which were too large to fit in the thermal column beam without scanning.

4 THERMAL NEUTRON IRRADIATIONS

The ${}^3\text{He}$ detector was supported by threads free-in-air and irradiated with its major axis perpendicular to the thermal neutron beam. A repeat measurement was made with the ${}^3\text{He}$ detector on each day that the measurements were carried out to check the stability and reproducibility of the detector, and also the deuteron beam conditions in the NPL Thermal Neutron Facility. Figure 3 shows details of the positioning of the bare ${}^3\text{He}$ detector and of the Bonner spheres in the thermal neutron beam.

The Bonner spheres were irradiated bare and enclosed in 1.5 mm thick cadmium to absorb all the thermal neutrons below about 0.5 eV. The Bonner spheres were placed on low-mass supports which positioned the centres of the spheres at approximately 1.60 m above the graphite layer at the base of the thermal column. The major axis of the central detector was arranged to be vertical so that the electrical connection was on the opposite side of the sphere to the incident thermal neutron beam.

A thin aluminium plate across the top of the 1.5 m thermal column enabled the spheres to be placed centrally in the thermal neutron beam. Prior to the irradiations the column was evacuated to a pressure of 3×10^{-2} mbar. The effective centres of all the spheres were positioned within 1 mm of the 1.60 m position except for the 10" diameter sphere whose effective centre was 27 mm above this position. Within the cadmium enclosure the centres of the spheres were arranged to be at the same height above the base of the thermal column as in the free-in-air measurements.

The ${}^3\text{He}$ detector was irradiated, both bare and cadmium-covered, on a number of separate days to check consistency of positioning and the reproducibility of the Van de Graaff deuteron beam conditions. These repeat measurements showed very good repeatability to within 0.5%.

The response of a cylindrical BF_3 proportional counter tube, normalised to the fission chamber monitor, was used to measure the change in thermal neutron fluence with distance "d", above the base of the thermal column at several positions along the axis of the neutron beam, above and below the 1.60 m position so that a small correction to the BS responses could be made for their slightly different heights above the 1.60 m position.

The fluence received by each BS was determined by a fixed ${}^{235}\text{U}$ fission counter monitor whose response was calibrated in terms of fluence rate measured free-in-air at the 1.6 m position using the gold foil activation technique. For the fluence rate measurement, a pair of gold foils were irradiated after the Bonner sphere irradiations, with one foil enclosed in a 1 mm thick cadmium metal box to enable a correction for the epi-cadmium neutron component to be made.

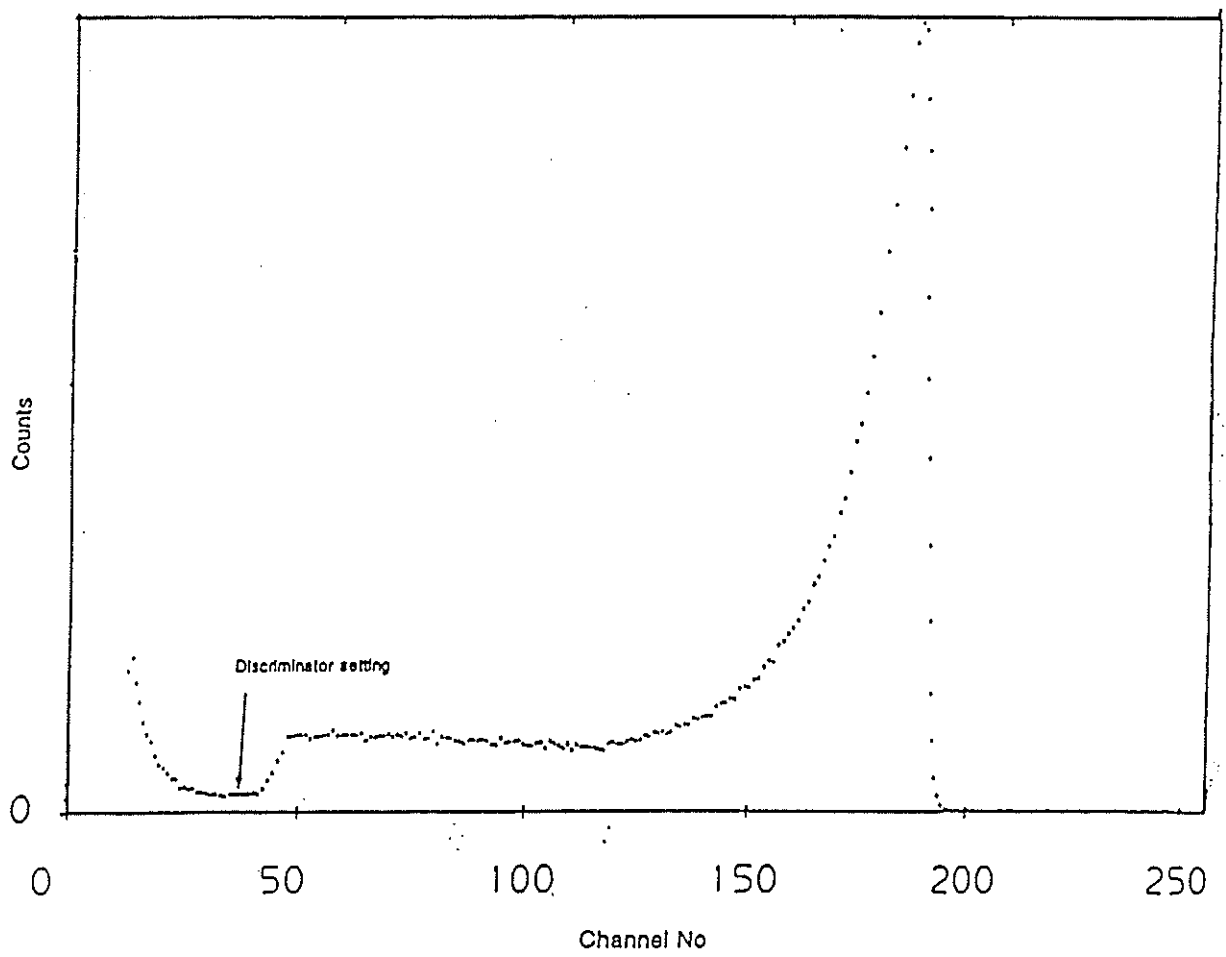


Figure 2. Typical charged particle spectrum in the SP9 ^3He proportional counter.

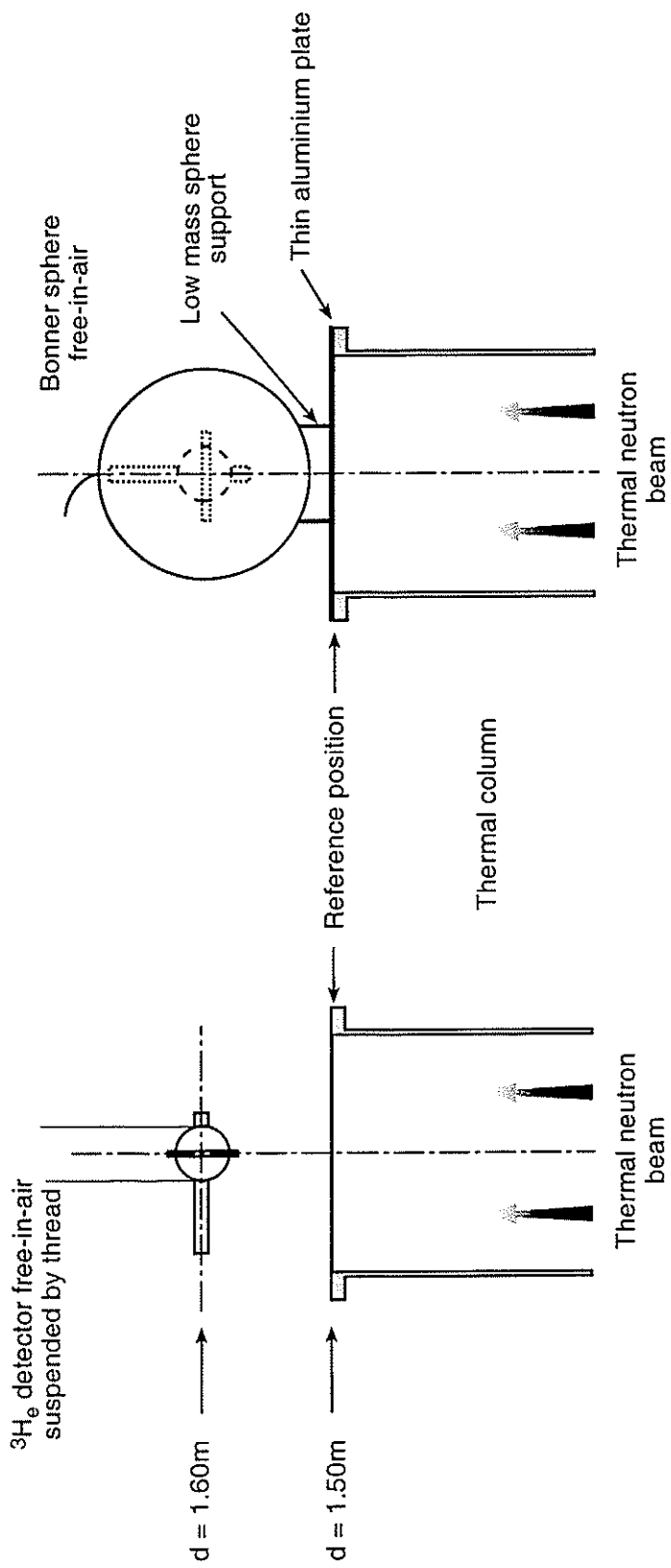


Figure 3. Positioning of the detector and Bonner spheres above the thermal column

5 ANALYSIS OF BONNER SPHERE RESPONSES

For each Bonner sphere, and for the bare SP9 counter, the count rate per unit fission counter pulse was calculated for irradiations with and without cadmium covers and for the difference between these two. The results are shown in Table 1. In Table 2 the results are presented normalised to the thermal neutron fluence as measured by gold foil activation. A typical uncertainty budget is shown in Table 3.

A similar set of measurements was undertaken with the same BS set in 1989, as part of a programme to characterise the thermal response of the set [5], and the results from the 1989 measurements are also presented in Table 2 where they are compared to the present results. For the bare SP counter the agreement is excellent, and for the 6", 8", and 10" spheres the differences are less than 8%. For the 3", 3.5", 4", and 5" spheres, however, the differences are all greater than 12%. This is well outside what would be expected taking into account the measurement uncertainties. The reasons for these differences are not yet fully understood, although subsidiary data from the present measurement programme have indicated some possible causes.

All the present measurements were performed at almost the same height (1.6 m) in the thermal column beam, and this was also the height at which the fluence measurements with the gold foils were performed. In the work undertaken in 1989 the gold foil measurements, and those for the SP9 counter were made at a height of 1.75 m within the column beam, i.e. 25 cm above the aluminium plate located at the 1.5 m position - see Figure 3. Irradiations of the spheres were performed by mounting them directly on the aluminium plate, supporting them on small polystyrene rings, and this resulted in their centres being at a range of different heights extending from 4.5 cm (3" sphere) to 13.4 cm (10" sphere) above the aluminium plate.

To provide corrections for the variation of fluence with height, a set of measurements was undertaken with a BF_3 proportional counter to measure this variation, c.f. the BF_3 counter measurements made for the present work. The assumption is made that the thermal spectrum does not change over the range of heights involved. Although this assumption is probably valid for the present measurements, where the largest correction was for a height difference of 2.7 cm, it may not be true for the differences of up to 20.5 cm involved in the 1989 measurements.

Recent data from gold foil measurements at different heights have shown that the cadmium ratio, and hence the neutron spectrum, and most importantly the temperature of the thermal peak, varies with height. The temperature used in the analysis of the 1989 data was derived from the gold foil cadmium ratio measured at the 1.75 m position [5]. The assumption of an unvarying thermal spectrum, i.e. unvarying thermal peak temperature, may not be justified, and the net effect is the possibility of some error in the thermal responses measured for the spheres, although not for the SP9 counter, in 1989. The smaller the sphere diameter, the larger the difference in height between the centre of the sphere and the position of the gold foil fluence measurement, and the larger the possible error. This would explain qualitatively the figures for the ratio of the 1989 to 1999 measurements shown in the final column of Table 2 where the difference tends to increase as sphere size decreases.

The present set of measurements provides data to investigate any errors in the BS thermal response functions, and a review of these is planned. It should be noted, however, that the original measurements agreed reasonably well with Monte Carlo neutron transport calculations of the thermal responses, so a full elucidation of the matter may involve further measurements and calculations.

| Bonner sphere size | Bonner sphere responses corrected to the 1.6 m position and normalised to the fission counter pulse rate | | | d (m) |
|--------------------|--|-------------|------------|-------|
| | Bare | in Cd | Difference | |
| SP9 counter | * 9.667 (14) | 0.1318 (10) | 9.535 (60) | 1.600 |
| 3" | * 5.404 (16) | 1.429 (4) | 3.975 (29) | 1.600 |
| 3.5" | 4.889 (16) | 1.634 (6) | 3.255 (26) | 1.600 |
| 4" | * 4.694 (10) | 1.729 (3) | 2.965 (20) | 1.599 |
| 5" | * 3.695 (10) | 1.713 (4) | 1.982 (14) | 1.600 |
| 6" | 2.985 (12) | 1.546 (6) | 1.439 (16) | 1.601 |
| 8" | 1.477 (6) | 0.941 (3) | 0.536 (7) | 1.600 |
| 10" | * 0.740 (3) | 0.539 (2) | 0.201 (4) | 1.627 |

"d" is the actual distance of the sphere centre above the graphite.

The uncertainties are Type A only and include uncertainty components for medium term stability of the thermal pile and positioning. The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a level of confidence of approximately 95%.

* Weighted mean values of several measurements.

Table 1. Measured responses to neutrons from the NPL Thermal Neutron facility normalised to the fission counter monitor.

| Bonner sphere diameter | Bonner sphere response normalised to the thermal neutron fluence | | | | |
|------------------------|--|--------|--------------------|------------------|-----------|
| | Bare | in Cd | Difference (#) (‡) | 1989 measurement | 1989/1999 |
| SP9 counter | 2.626 | 0.0358 | 2.590 (17) (41) | 2.595 | 1.002 |
| 3 | 1.468 | 0.388 | 1.080 (8) (18) | 1.237 | 1.145 |
| 3.5 | 1.328 | 0.444 | 0.884 (7) (15) | 1.016 | 1.149 |
| 4 | 1.275 | 0.470 | 0.805 (6) (13) | 0.912 | 1.133 |
| 5 | 1.004 | 0.465 | 0.538 (4) (9) | 0.611 | 1.136 |
| 6 | 0.811 | 0.420 | 0.391 (4) (7) | 0.407 | 1.041 |
| 8 | 0.401 | 0.256 | 0.145 (2) (3) | 0.156 | 1.076 |
| 10 | 0.201 | 0.147 | 0.055 (1) (1) | 0.058 | 1.055 |

Type A uncertainties

‡ Total uncertainty including that for the calibration of the fission counter

The expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a level of confidence of approximately 95%.

Table 2 Measured responses to neutrons from the NPL Thermal Neutron facility normalised to the thermal neutron fluence.

| Symbol | Source of uncertainty | Value | Probability distribution | Divisor | c_i | u_i (%) | v_{eff} |
|--------------------|---|-------|--------------------------|------------|-------|-----------|-----------|
| N | Standard deviation, \sqrt{N} | 1000 | normal | 1 | - | 0.10 | ∞ |
| N_{Cd} | Standard deviation, $\sqrt{N_{Cd}}$ | 775 | normal | 1 | - | 0.13 | ∞ |
| | Reproducibility of field | 1200 | normal | 1 | 1.0 | 0.30 | ∞ |
| $N - N_{Cd}$ | $\sqrt{[(N+N_{Cd})] / (N-N_{Cd})}$ | 0.32% | normal | 1 | 1.0 | 0.32 | ∞ |
| ϵ_{FC} | Calibration of fission counter | 0.72% | normal | 1 | 1.0 | 0.72 | ∞ |
| | Response of fission counter (> 10^6 events) | 0.1% | normal | 1 | 1.0 | 0.10 | ∞ |
| d_1 | Height of sphere above ref. position | 2 mm | rectangular | $\sqrt{3}$ | 0.2 | 0.15 | ∞ |
| d_2 | Vertical position of centre of sphere | 1 mm | rectangular | $\sqrt{3}$ | 0.2 | 0.07 | ∞ |
| r | Horizontal position | 2 mm | rectangular | $\sqrt{3}$ | 0.02 | 0.02 | ∞ |
| $u(\epsilon_{th})$ | Combined standard uncertainty | - | normal | - | - | 0.78 | ∞ |
| U | Expanded uncertainty | - | normal (k=2) | - | - | 1.56 | ∞ |

Table 3 Typical uncertainty budget for a single measurement of the thermal neutron fluence response of a Bonner sphere positioned at 1.6 m.

In the example above, N is the number of events recorded by the Bonner sphere free-in-air and N_{Cd} the number of events recorded when enclosed in cadmium. About 10^6 events were accumulated when irradiating the sphere free-in-air and about 6×10^5 events when irradiated in cadmium, normalised to the same number of fission counter events.

The uncertainty due to the medium-term reproducibility of the thermal neutron field (0.2%) was added to the epithermal response (N_{Cd}).

Repeat measurements with the central ^3He detector, free-in-air and cadmium covered yielded an expanded uncertainty of about 1.1%.

The implications of possible errors in the BS response functions in the thermal region for the present measurements of the total spectrum are that the fluence in the thermal region may be slightly in error. The effects of small errors in the BS thermal response functions are, however, countered by the data for the bare SP9 counter which, because of its higher thermal sensitivity, has a large influence on the results for the thermal region. There is no reason to question the fast neutron response functions of the BSs, so the analysis in the higher energy region should be reliable.

Deriving a spectrum from a set of BS readings is possible because the large spheres are most sensitive to neutrons in the high energy region, and hence give information about the fluence in this region, whereas the smaller spheres are more sensitive to lower energy neutrons. These characteristics are illustrated in Figure 4 where the response functions of the seven spheres and the SP9 counter used in the present work are shown.

When BSs are used at NPL to determine a spectrum over the full energy range from thermal to 20 MeV, the derived spectrum is usually presented in an energy group structure of 52 bins of equal width on a lethargy scale, with five bins per decade. Since there are only eight measured responses, and 52 bins, the unfolding problem is mathematically underdetermined. This is the usual case for BSs, but evidence from various international spectrometry and unfolding intercomparisons, [6,7] have shown that very reasonable results can still be obtained, although some additional information, e.g. smoothness, non-negativity, is often used.

The approach to BS unfolding at NPL is to use the code STAY'SL. This requires an *a priori* estimate of the spectrum to be given. However, because this estimate is given with uncertainties, and these can be large, only very rough *a priori* information is needed. The process is essentially one of adjusting the *a priori* spectrum in the light of the measured BS data. Although it is certainly true that the more accurately the *a priori* spectrum is known, the more accurate will be the final spectrum, provided it is consistent with the measured sphere responses, experience has shown that STAY'SL can provide reliable results even when the *a priori* information is very limited.

For the present unfolding of the free-in-air measurements the *a priori* spectrum assumed was a thermal Maxwellian peak at the temperature indicated by the gold foil cadmium ratio[5], and a 1/E component extending up to 8 MeV. The upper energy was chosen on the basis of measurements of the spectrum from 2.8 MeV deuteron bombardment of beryllium targets [8]. A spectrum with a 1/E dependence, although appearing flat when plotted using a lethargy representation, corresponds to a rapid increase in the number of neutrons per cm² per MeV as the energy decreases. This is what would be expected for a fast neutron spectrum moderated in a graphite pile.

The magnitude of the Maxwellian thermal peak in the *a priori* spectrum was determined from the measured count rate of the SP9 counter and its known thermal response. An option in STAY'SL allows the program to re-normalise the *a priori* spectrum to give the best fit to the measured responses before beginning any spectrum adjustment. This feature was used to optimise the magnitude of the 1/E component of the *a priori* spectrum by varying this magnitude manually until the normalisation factor was close to one. STAY'SL was then run to adjust the spectrum, and the results are presented in Figure 5 where both the *a priori* and the adjusted spectra are shown.

The lethargy representation of Figure 5 is the usual format for presenting spectra which extend over the large energy range from thermal to the MeV region since it shows clearly the fraction of the fluence in the thermal, epithermal, and fast regions. It does, however, tend to hide the very rapid rise in the number of neutrons per unit energy as the energy decreases.

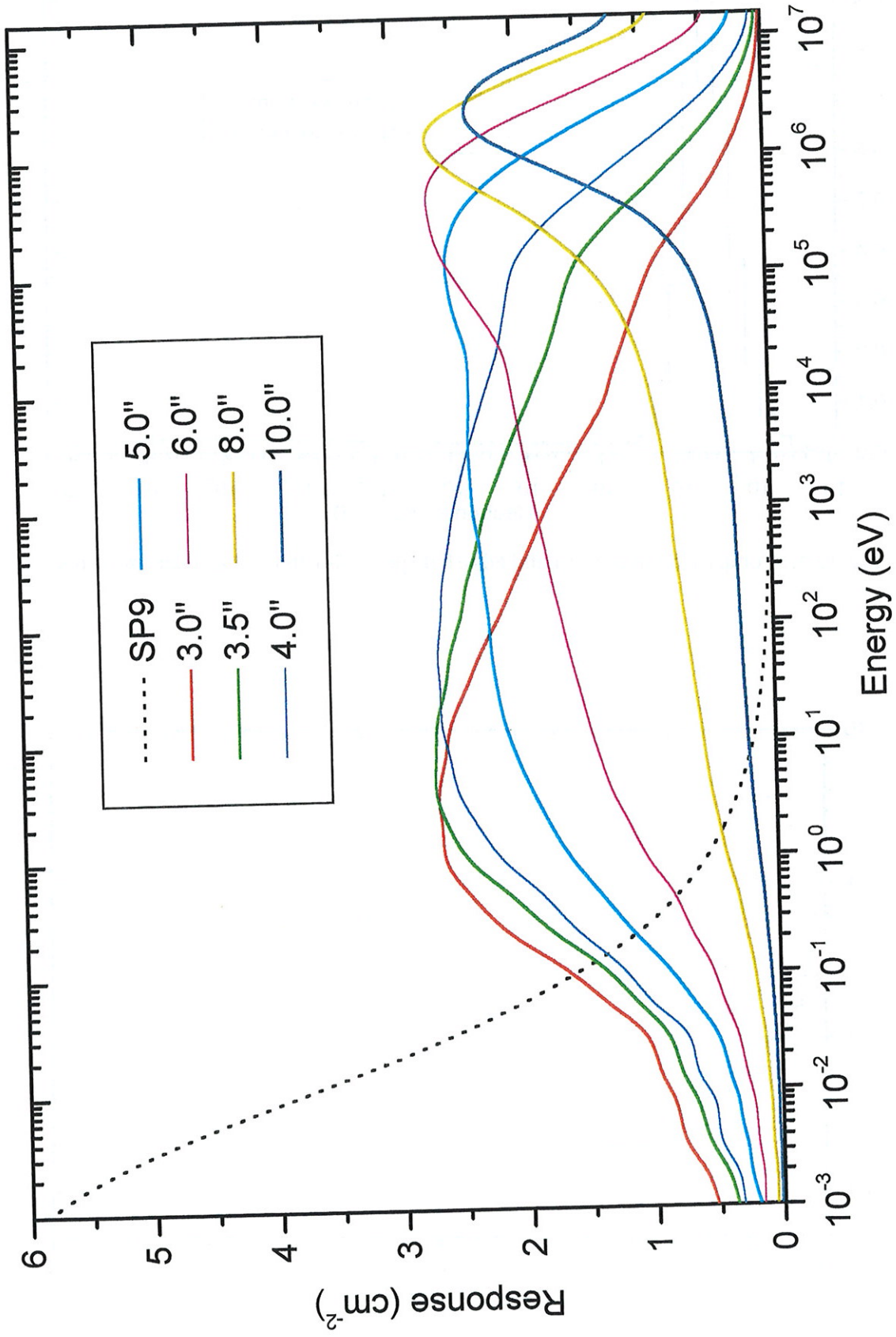


Figure 4. Response functions of the NPL Bonner spheres

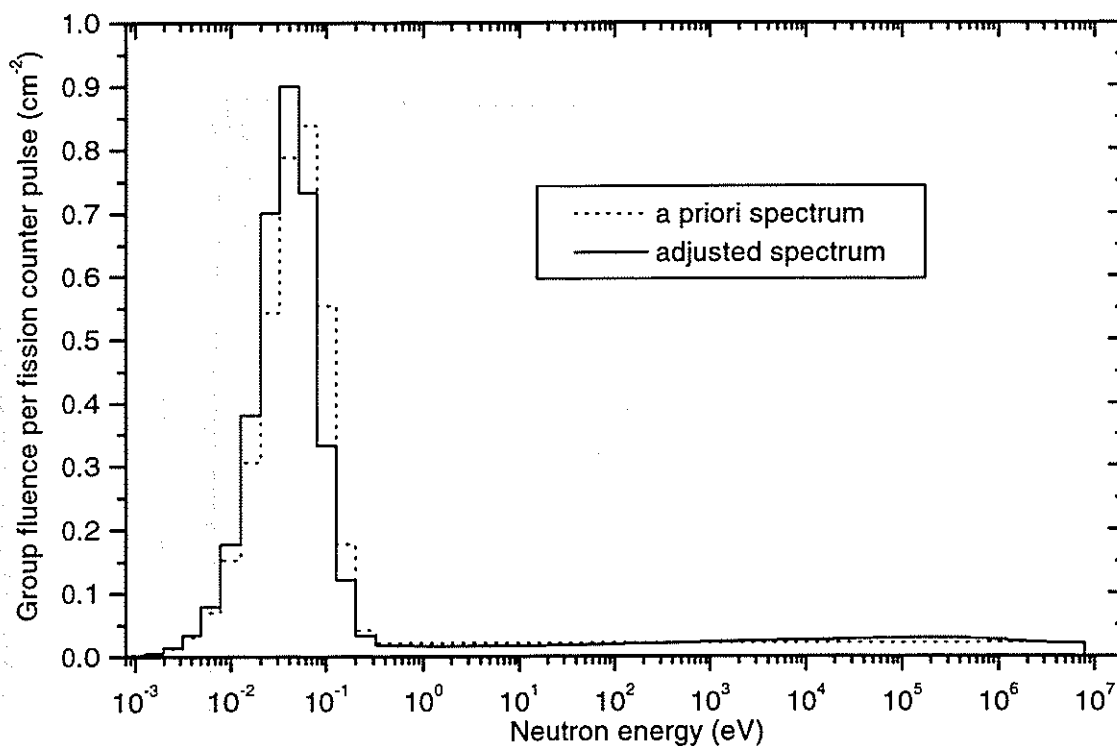


Figure 5. Comparison of a priori and adjusted spectra for free-in-air measurements

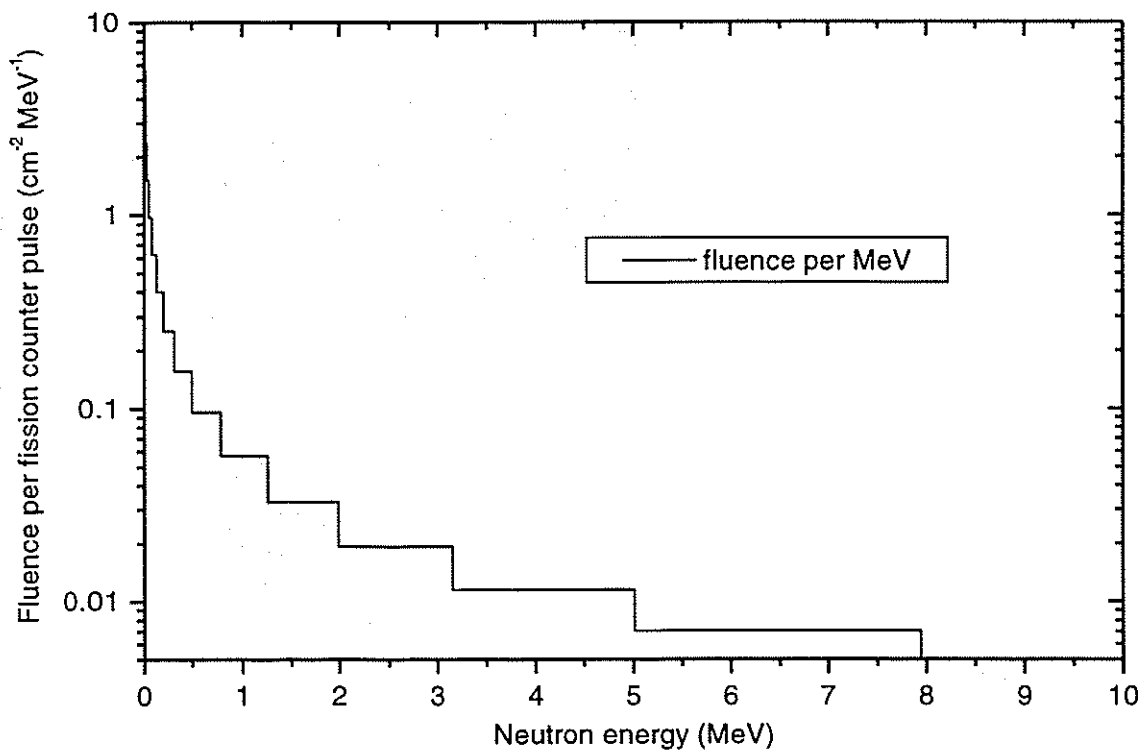


Figure 6. Free-in-air spectrum plotted as fluence per unit energy on a linear energy scale

For this reason the adjusted spectrum is shown again in Figure 6, but here in a fluence per unit energy representation on a linear energy scale. Note that the ordinate scale is now logarithmic to encompass the large range of values.

From Figure 5 it can be seen that the adjustment introduced by STAY'SL to the $1/E$ part of the spectrum between 0.5 eV and 8 MeV is quite small. There is an increase in the fluence in the 10 keV to 1 MeV region, and a decrease in the epithermal region just above the thermal peak. The biggest change introduced by STAY'SL is to move the thermal peak down in energy. One possible explanation for this is that the sphere response functions in the thermal region are slightly too high, as discussed earlier in this section. The sphere thermal responses calculated by STAY'SL from the product of the spectrum and the response functions in the thermal region would then be larger than the measured responses. As can be seen from the shapes of the response functions in Figure 4, one way for the program to decrease the predicted sphere responses, while in fact increasing the SP9 counter thermal response, is to move the peak down in energy.

For the final adjusted spectrum, the fluence above the so-called cadmium cut-off energy of 0.5 eV is about 19% of the total fluence. In terms of dose equivalent, the epi-cadmium component is much larger. The exact value depends on the particular dose equivalent quantity considered, but in all cases it is more than 200% of the thermal value.

Analysis of the under-cadmium data should provide additional information on the epi-cadmium part of the spectrum, and this should agree with the free-in-air results. To derive an *a priori* spectrum for unfolding the under-cadmium data the effect of the cadmium cover on the free-in-air spectrum was estimated by using Cd(n, γ) cross section data to calculate the attenuation in the 1.5 mm thick cadmium cover. Cadmium cross sections were obtained from the 1990 International Reactor Dosimetry File [9] (IRDF90), and the attenuation was calculated for each bin of the spectrum. The spectrum derived in this way was used as the *a priori* data for unfolding using the under-cadmium data, and the resulting spectrum is shown in Figure 7 together with the free-in-air spectrum and the under cadmium spectrum predicted from this. A lethargy representation is used for this figure, but in contrast to Figure 5, the ordinate is logarithmic to highlight the epithermal and fast components.

The main effect of the STAY'SL adjustment has been to increase the fluence in the epithermal region around 0.5 to 10 eV, and to decrease it in the 1 to 100 keV region. The overall epi-cadmium fluence has, however, not changed much. An explanation of the increase in the 0.5 to 10 eV region may again come from the fact that the sphere thermal response functions are thought to be slightly high. During the free-in-air analysis the thermal peak was reduced in energy. If it was higher in energy there would be a somewhat higher fluence in the region just above 0.5 eV. A qualitative investigation of this can only be undertaken when the sphere thermal response functions have been reviewed.

It is clear that the epi-cadmium spectra unfolded from the free-in-air data and the under cadmium data are not completely compatible. The differences can be used as an estimate of the uncertainties in the derived epi-cadmium spectrum. The implications of the different spectral shapes for the ratios of the epi-cadmium fluence and dose equivalent values to the thermal values are, nevertheless, small as illustrated in Table 4. All effective dose and dose equivalent values have been calculated using the conversion coefficients recently published by the ICRP and ICRU [10,11]

From experience in comparisons of BS spectral measurements [6], the uncertainties in the integral quantities are expected to be of the order of 10% at the 68% confidence level. A reliable uncertainty analysis for the fluences in the various bins of the spectrum is not at present possible. The mathematical tools to provide this information are in place, but it requires reliable estimates of variances and covariances for both the *a priori* spectrum and

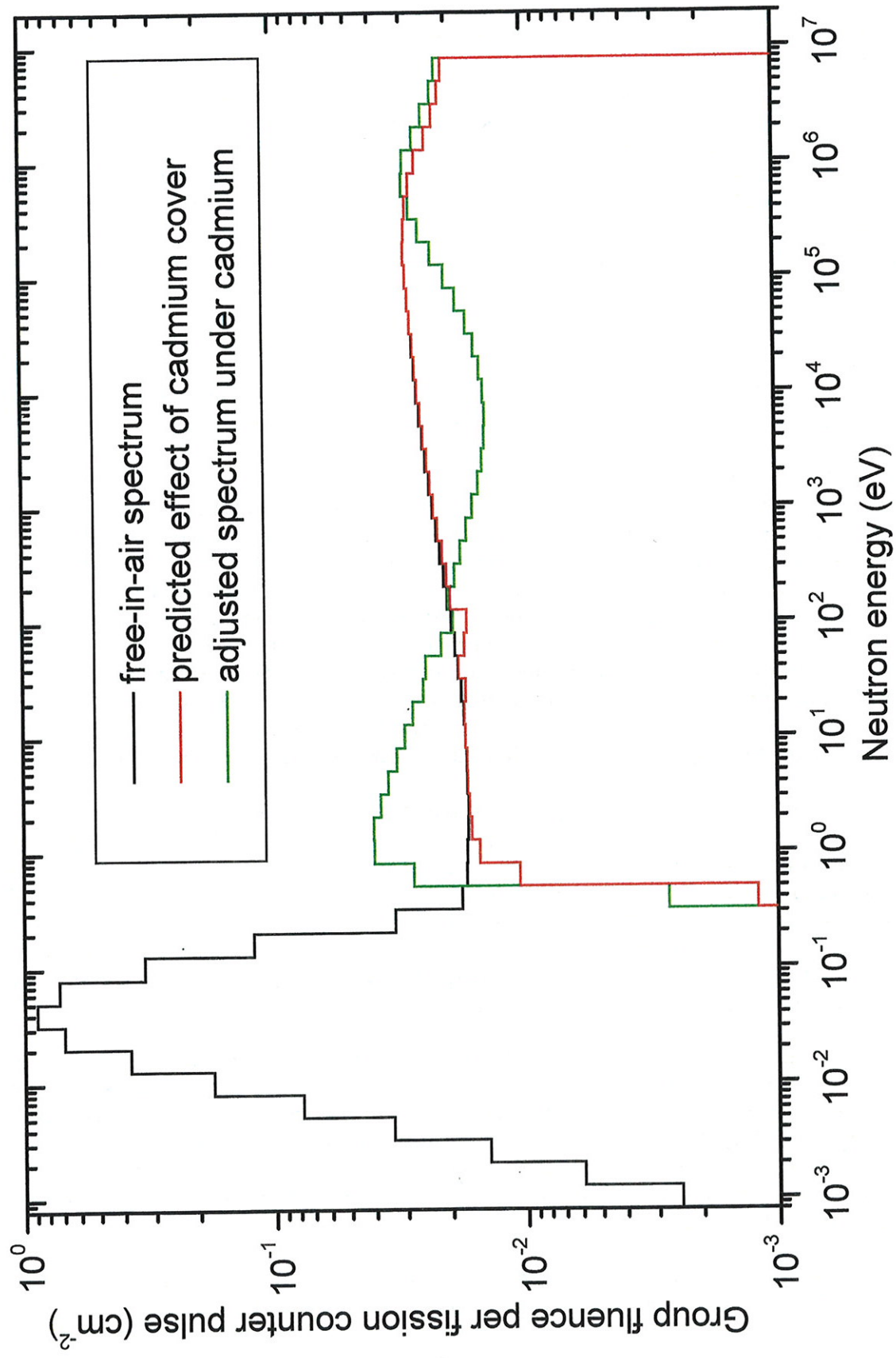


Figure 7. Spectrum under cadmium cover

the response functions, as well as for the measured responses. These data are not presently available, and uncertainty estimation for spectra unfolded from BS measurements remains an unsolved problem.

| Quantity (per unit fission counter pulse) | Value in thermal region | Value in region above 0.5 eV | | Average ratio of region above 0.5 eV to thermal |
|---|----------------------------|------------------------------|--------------------------|--|
| | | Free-in-air results | Under-cadmium results | |
| Fluence [cm ⁻²] | 3.53 | 0.82 | 0.85 | 0.24 |
| E (A-P) [pSv] | 29.5 | 74.2 | 76.6 | 2.56 |
| H*(10) [pSv] | 39.8 | 86.8 | 89.1 | 2.21 |
| H _p (10)(A-P) [pSv] | 41.3 | 90.6 | 93.1 | 2.22 |

Table 4. Fluence and dose equivalent values, normalised to the fission counter

6 RESPONSE OF DOSEMETERS

Although the component of the neutron fluence with energy >0.5 eV in the thermal column field is only about 19% of the total fluence, the effective dose or dose equivalent values corresponding this fluence are more than twice the values for the thermal component. Similarly, for dosimeters, which are designed to measure the quantity dose equivalent, the responses to the >0.5 eV component would be expected to be much greater than the response to the thermal component. However, because neutron dosimeters do not have response functions which are truly dose equivalent, the contribution from the >0.5 eV component will not necessarily match the value for the appropriate dose equivalent quantity as given in Table 4. Area survey instruments should measure the quantity ambient dose equivalent, for which the contribution from neutrons above 0.5 eV is about 2.2 times the thermal contribution. The corresponding ratios for the responses of several commonly used area survey instruments are given in Table 5. These values, are not derived from experiment, but were predicted by folding the response functions of the dosimeters with the spectrum from the free-in-air measurement.

| Instrument | Harwell 0949 | NE NM2 | Studsvik 2202 D | EG&G LB6411 | 5" TEPC |
|------------|-----------------|-----------|--------------------|----------------|------------|
| Ratio | 2.69 | 3.71 | 3.48 | 7.80 | 3.91 |

Table 5. Ratios of response to neutrons with energy >0.5 eV to that for thermal neutrons, for the field of the NPL thermal column, for several survey instruments.

Response functions for the survey instruments were obtained from several sources. Those for the Harwell 0949 and Nuclear Enterprises NM2 instrument from reference 12, for the Studsvik 2202 D from references 13 and 14, for the EG&G LB6411 from reference 15, and for the TEPC from references 16 and 17.

In general the ratio of response to >0.5 eV neutrons to that for the thermal neutrons is greater for the area survey instruments than the corresponding ratio for the relevant dose equivalent quantity, $H^*(10)$. For the EG&G LB6411 the value is considerably greater than for the other instruments reflecting the low thermal response of this device compared to the other instruments.

For personal dosimeters, the response in the NPL thermal column is very dependent on the type of dosimeter. The two types most commonly used in the UK are based on either poly allyl diglycol carbonate, PADC, track-etch plastic (commonly known under the trade name CR 39), or NTA film. Both of these may or may not have a thermal response, depending on the design of the dosimeter [18]. For an example of a PADC dosimeter with a thermal response, (PADC 1 from reference 15), the ratio of the >0.5 eV response to the thermal response is about 1.56. For a particular example of NTA film dosimeter (N1 in reference 18), the ratio is about 0.94. These ratios are smaller than those for survey instruments reflecting the general lack of response to intermediate energy neutrons for these personal dosimeters.

7 CONCLUSIONS

The present measurements have shown that the recent refurbishment of the NPL Standard Thermal Neutron facility has not caused significant change to the epithermal and fast neutron components but that the thermal spectrum does change with height in the thermal neutron beam and consequently the gold foil cadmium ratio used to calculate the thermal neutron fluence also changes.

Gold foil measurements are now performed on a regular basis at, or close to, the position at which dosimeters or survey instruments are to be calibrated in order to reduce the uncertainty in the cadmium ratio when measured at a significantly different height in the thermal neutron beam.

Regular gold foil measurements, performed as part of the routine thermal pile quality checks, monitor any change in the cadmium ratio caused by changes in the epithermal and fast neutron components and also monitors the stability of the thermal pile electronics and target conditions.

The present measurements, when compared to earlier measurements undertaken in 1989 to determine the response functions of the BSs in the thermal region, indicate some deficiencies in the earlier measurements which may have resulted in errors of up to about 10%. Although these errors would not be of great importance in the typical measurements for which BSs are used, i.e. measurements to determine dose equivalent values where the dose equivalent from higher energy neutrons dominates, the errors need to be investigated, probably in conjunction with repeat calculations of the thermal response functions. This is planned as a future project.

The figures, given in Section 6, for the fractions of the readings of dosimeters irradiated in the thermal column beam which are due to the epi-cadmium neutrons were derived from the unfolded spectrum and the dosimeter response functions. Measurements with these dosimeters would provide useful integral data which would provide a check on the validity of both the derived spectrum and the response functions used for the dosimeters.

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