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Investigation of a possible replacement for cadmium as a thermal neutron absorbing material in neutron instruments

by

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Abstract
Thin layers of cadmium metal are commonly used around neutron detecting devices to absorb thermal neutrons. The application may be to separate out completely the device's response to thermal neutrons from its response to higher energy neutrons, or simply to modify the response to thermal neutrons. Cadmium is used because it has an absorption cross section which is very high in the thermal region, but which drops off rapidly above about 0.5 eV. However, because of potential health hazards, which have significant implications when disposing of devices containing cadmium, there is a strong incentive to find a suitable alternative material for this application. This report covers an investigation of possible alternative materials.

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Contents

1. Introduction

Cadmium is commonly used in nuclear measurements and in various applications in the nuclear industry, because of its property as an absorber of thermal neutrons. This property is a result of the element's very high cross section for absorbing low-energy neutrons via the (n,γ) capture reaction – see Figure 1. The cross section is sufficiently large that, even in the energy region near the dip in the cross section at about 0.04 eV, a 1 mm thick layer of cadmium stops about 99.998% of all neutrons in a beam of that energy. For anything other than a beam, e.g. an isotropic distribution, the attenuation produced by a 1 mm cover around a device is even greater because of the longer average path lengths through the cadmium.

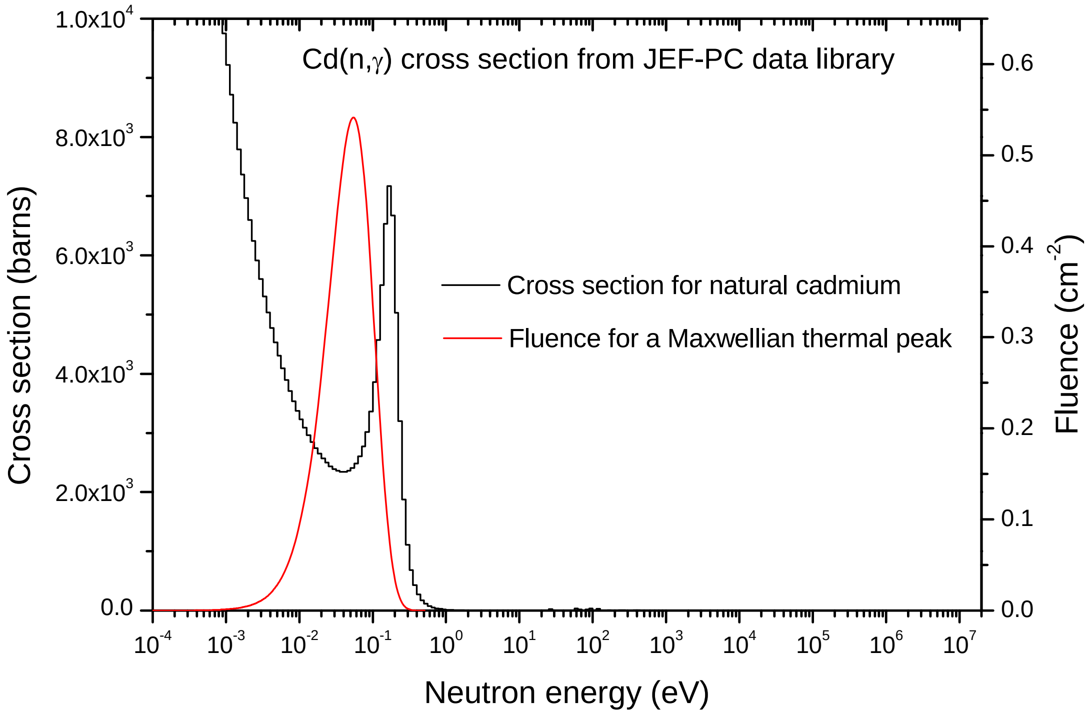

Figure 1. Neutron capture cross section for natural cadmium[(1)] compared with the spectrum of a typical thermal distribution in a good moderator

The definition of what constitutes a thermal neutron distribution is not completely clear-cut. In a good moderator material, neutrons slow down until they cannot lose any further energy in collisions with the atoms of the material and they form a Maxwellian spectral distribution where the energy of the peak is related to the temperature of the moderator. For a good moderator at 20.4 ^{o}C this energy is 0.0253 eV, and the thermal spectrum shown in Figure 1 corresponds to a Maxwellian distribution with this peak energy. A 1 mm thick cadmium shield would absorb essentially all of the neutrons in such a distribution. However, most workplace neutron fields do not consist solely of thermal neutrons, but contain intermediate-energy and high-energy neutrons extending, in most cases, up to several MeV. If a measuring device responds to neutrons over the whole of this energy range, a measurement with and without a cadmium cover allows that part of the response which is due to thermal neutrons to be identified. A 1 mm cadmium cover essentially lets through all neutrons above an energy of about 0.5 eV, and absorbs all neutrons below that energy. For this reason 0.5 eV is often considered as the upper energy limit of the thermal neutron region and it is called the cadmium cut-off energy.

Natural cadmium has eight stable isotopes. However, only one, ^{113}Cd, exhibits a very large capture cross section. The natural abundance of ^{113}Cd is only 12.22%, but the capture cross section is sufficiently large that isotopically enriched material is not necessary.

There are basically three different ways in which cadmium is used in nuclear applications.

a) It is used for measurements of the intensity of the thermal fluence component in neutron fields. Many neutron detectors have high efficiencies for thermal neutrons, and low efficiencies for intermediate and high-energy neutrons. These detectors can be used to measure the thermal component in a neutron field. However, because their response to neutrons above the thermal energy region is not zero, a measurement with and without a cadmium cover is needed to correct for the response to neutrons above the cadmium cut-off. In this way an accurate determination of the thermal neutron fluence can be made.

b) Many instruments and devices incorporate detectors which are primarily sensitive to thermal neutrons, but are actually used to measure neutron fields over a much wider energy range. This is achieved by introducing some moderating material to slow down the fast neutrons. For example, neutron area survey instruments often consist of a thermal neutron detector at the centre of a moderator such as polyethylene. Another example is the albedo dosemeter, which is essentially a thermal neutron detector mounted in a holder positioned on the body of an individual. The dosemeter responds both to directly incident thermal neutrons and thermal neutrons backscattered from the body. In this case, the human body is the moderator. Survey instruments and personal dosemeters should have the appropriate dose equivalent response over all energies. Cadmium is frequently used to improve a device’s response by modifying the shape of its response function,

c) Cadmium is used as a general absorber of thermal neutrons to reduce their effects in terms of dose, or their effects within nuclear systems. The classic example is the use of cadmium as control elements in nuclear reactors.

Unfortunately, cadmium is highly toxic. Its presence in the body is linked to kidney dysfunction, respiratory problems, bone disease, and human carcinogenesis. Cadmium and its compounds are controlled by law via the 'Red List'[§] such that their disposal is strictly controlled. Hence, many companies are reluctant to include cadmium in their products since a disposal route must be in place to ensure that its discharge to water is controlled. Those who are involved with neutron shielding and with instrument design are urgently looking for a suitable replacement. The UK MoD, in particular, is very keen to avoid items on the ‘Red List’. The aim of this work is to investigate suitable replacement materials and to provide quantitative data about their low energy shielding characteristics. The investigation has concentrated on applications such as those outlined in a) and b) above. There are unlikely to be changes in reactor construction materials. Other safety considerations will be overriding, and cadmium will continue to be used under rigorous control.

§ The Environmental Protection (Prescribed Processes and Substances) Regulations 1991 set out a list of prescribed substances that require close monitoring and control before they can be discharged to water – see http://www.epaw.co.uk/EPT/law.html. This is popularly called the "Red List".

2. Identification of possible replacement materials

The degree of thermal shielding provided by a material is proportional to the product of the thermal neutron absorption cross section and the number density of the atoms. A good shielding material must therefore have a very high thermal neutron cross section and, if the material is to be in a thin layer, a relatively high density. Figure 1 shows that cadmium has an extremely large cross section, of roughly 2400 barns, for the (n,γ) reaction at 0.0253 eV. In addition, cadmium has the further advantage of a large resonance peak in its (n,γ) cross section at about 0.16 eV. The sharp drop in the cross section at the upper edge of this peak results in a well-defined cut-off energy, at 0.5 eV for 1 mm of cadmium, where neutron absorption below this energy is very high, and above this energy rapidly becomes negligible. Any replacement should ideally have similar characteristics. It must also be available in a form suitable for manufacture.

A search was made through the cross section data libraries for a suitable material. Several materials are known to have high thermal neutron cross-sections. These include ^{10}B and ^{6}Li. Lithium is difficult to use as a shielding material. As a metal it is unstable, as a compound it would need containing, and there are no easily available materials with a high enough lithium content. Materials containing boron are readily available, and a boron loaded polymer, Flex Boron, is sold as a thermal neutron shielding material. Gadolinium and indium are also employed as thermal neutron absorbers in reactor control applications and were therefore included in the list of test materials. The cross sections for the relevant neutron absorbing reactions are shown in Figure 2.

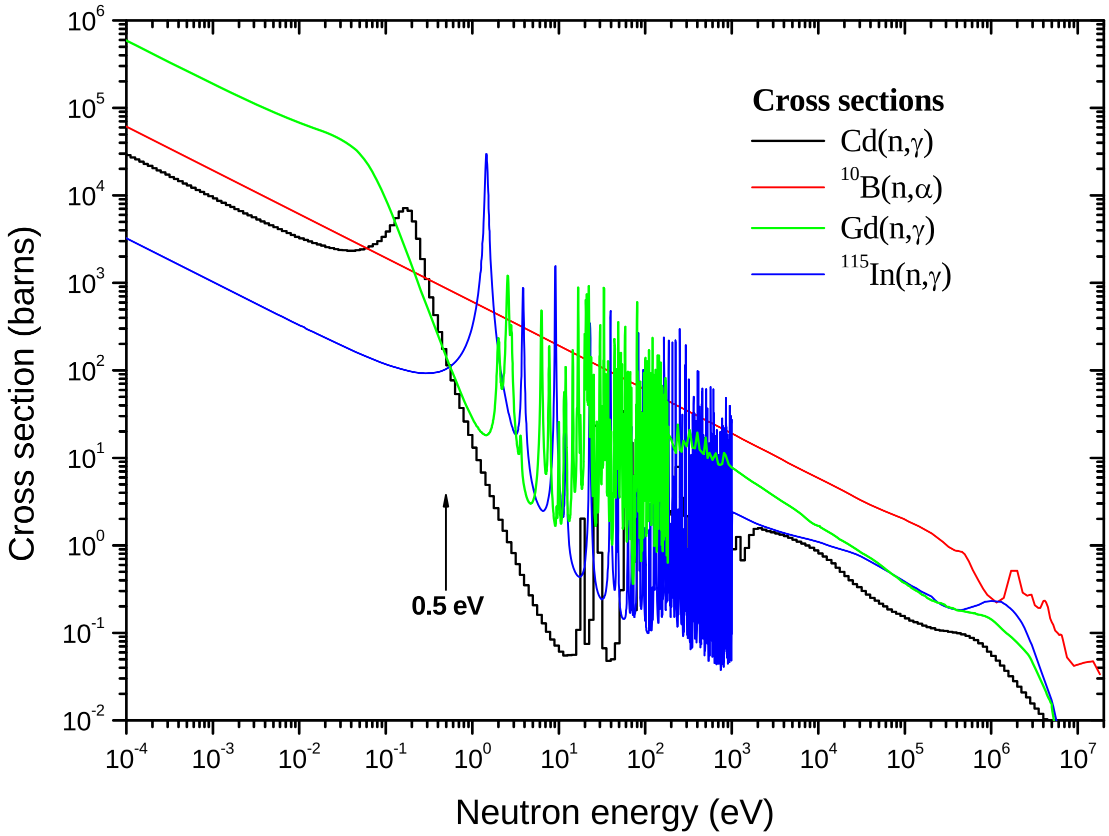

Figure 2. Cross sections for cadmium and possible replacement absorber materials. The plots for cadmium and gadolinium are for the natural material whereas for boron and indium they are for specific isotopes.

The cross section plotted for boron(2) in Figure 2 is for ^{10}B. The natural element is 19.9% ^{10}B and 80.1% ^{11}B, but the ^{11}B thermal (n,α) cross section is roughly two orders of magnitude smaller than that for ^{10}B, although the shape is very similar. One problem with using boron may be that of obtaining a high enough density of ^{10}B atoms without using enriched material.

Gadolinium has seven stable isotopes. Two isotopes, ^{155}Gd (14.80%) and ^{157}Gd (15.65%), have the appropriate absorption cross sections as regards a replacement for cadmium. Unfortunately, they have many resonances in the 2 eV to 10 keV region which are likely to produce unwanted absorption of higher energy neutrons. The other isotopes of gadolinium all have very much lower thermal absorption cross sections, see Figure 3, but also have resonances in the region above 2 eV which will result in absorption of intermediate energy neutrons. Indium has two isotopes, ^{113}In and ^{115}In. However, ^{115}In has an abundance of 95.71% and, since it has an absorption cross section an order of magnitude larger than that for ^{113}In in the thermal region, its properties will dominate. The gadolinium and indium data were extracted from a web site(3) maintained by the Korea Atomic Energy Research Institute, KAERI, and are derived from ENDFB evaluations(4).

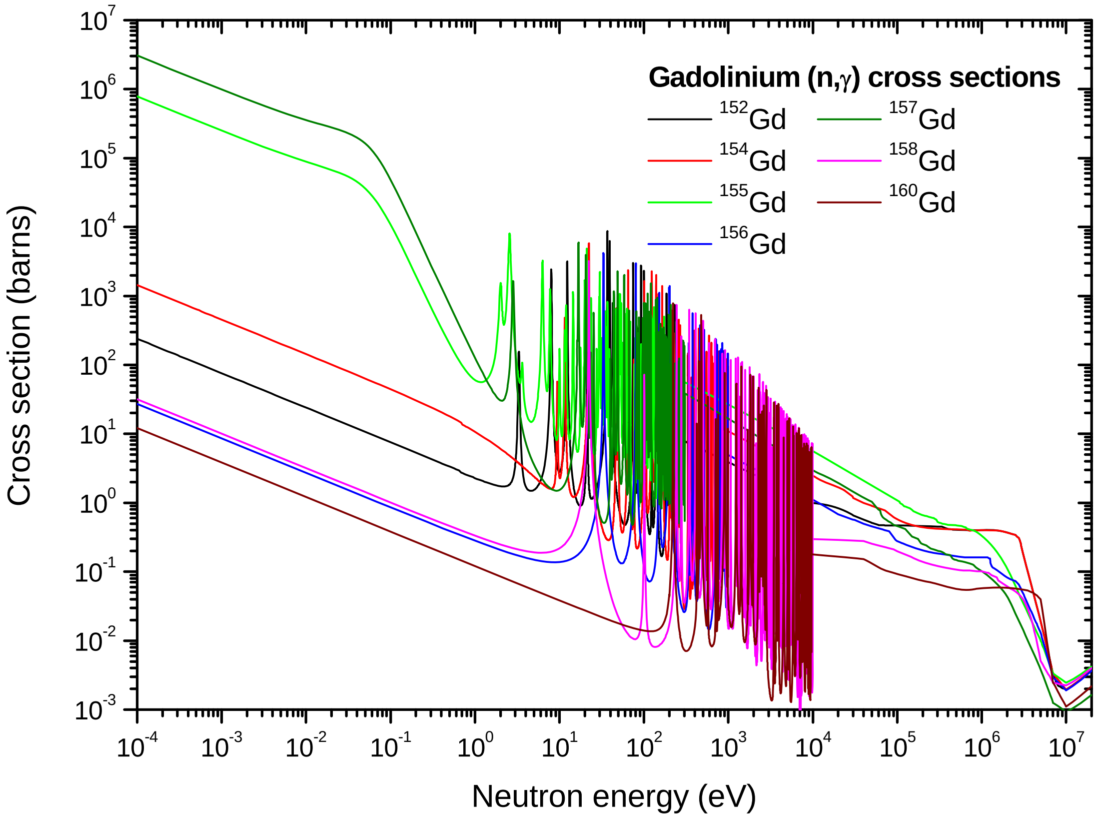

Figure 3. (n,γ) cross sections for the gadolinium isotopes

Samples of the three chosen materials, Flex Boron, indium and gadolinium were obtained, in various thicknesses where possible. The Flex Boron was obtained from John Caunt Scientific, JCS, in sheets of thickness 3.2 mm. Both metals were obtained from Goodfellow, the gadolinium in 0.5 mm sheets, and the indium in 0.5 mm and 1 mm sheets. Cadmium was already available at NPL. Approximate costs for the selected materials are given in Table 1.

Table 1. Typical material costs per sheet

Material	Thickness	Dimension	Approximate cost
Cadmium	1.0 mm	100 mm × 100 mm	£110
Flex Boron	3.2 mm	305 mm × 610 mm	£270
Gadolinium	0.5 mm	100 mm × 100 mm	£1130
Indium	1.0 mm	100 mm × 100 mm	£280

3. Investigation

Two approaches were used to investigating the characteristics of the chosen materials – measurement and calculation. The measurements involved choosing a commonly used thermal neutron detector and investigating its response with and without shields of the chosen test materials in the beam of the NPL thermal column. The detector was a proportional counter containing BF_3 gas in which neutrons are counted by detecting ionisation induced by the alpha particles and ^{7}Li recoils produced in the $^{10}B(n,\alpha)^{7}Li$ reaction. A cadmium sleeve which is routinely used with this device was already available. Results for the proposed replacement materials were compared with those obtained using cadmium as the thermal neutron absorber.

In the calculational approach several calculations were performed using the Monte Carlo neutron transport code MCNP(5). A first set determined the response of the thermal detector used in the measurements as a function of energy over the range from thermal to 20 MeV. These calculations were performed for the detector bare and under various thicknesses of the chosen absorbing materials for a series of point energies. The second set attempted to simulate the measurements in the NPL thermal column. The calculations at point energies provided information which helped explain the varying experimental results for the different materials, and also the results of the calculations performed to simulate the measurements.

3.1. Calculation of attenuation as a function of neutron energy

The MCNP models were drawn up using information from engineering drawings of the BF_3 tube supplied in confidence by the manufacturer, Centronic Ltd. The ^{10}B enrichment of the gas was taken as 96%. The shield material was modelled as a cylindrical tube. The detector was situated in a vacuum, and the neutron source was a plane parallel beam of monoenergetic neutrons incident normally to the cylindrical axis of the detector.

The track length estimate tally (F4:n) with a tally multiplier (FM) card was used to give the α-particle production, through the $^{10}B(n,\alpha)$ reaction, per cm^3 in the BF_3 active volume per starting particle history. The tally multiplier consisted of the product of the active volume of the BF_3 gas, the area of the surface from which the neutron source spectrum is sampled, and the number density of the gas in units of atoms (barn cm)$^{-1}$.

The atom densities of boron and hydrogen in Flex Boron in the model were taken from a data sheet supplied by Thermo Electron Corporation(6). Flex Boron consists of boron in a silicone elastomer, and the other components were assumed to be carbon, silicon, and oxygen. The atom density of carbon was estimated by assuming that there were 4 carbon atoms for every boron atom, and 3 carbon atoms for every hydrogen atom. The oxygen and silicon number densities were chosen such that the overall density agreed with the data sheet figure of 1.64 g cm^{-3}, taking one oxygen atom to one silicon atom.

Figure 4 is shows the ratio of the count rate from the BF_3 detector shielded to that for the bare detector as a function of neutron energy. It provides clear insights into the expected performance of the chosen materials as absorbers of thermal neutrons.

For 1 mm of cadmium, the shielded to bare ratio increases from a value of essentially 0 to a value of 1 over a very small range of energies centred at 0.5 eV. Above this energy, it is almost constant at a value of 1 except for some minor dips due to resonances at energies just above 100 eV. At the highest energies, the ratio increases again because of (n,2n) reactions. Nevertheless, its capacity to act as a shield cutting out thermal neutrons and allowing through intermediate and high energy neutrons is obvious.

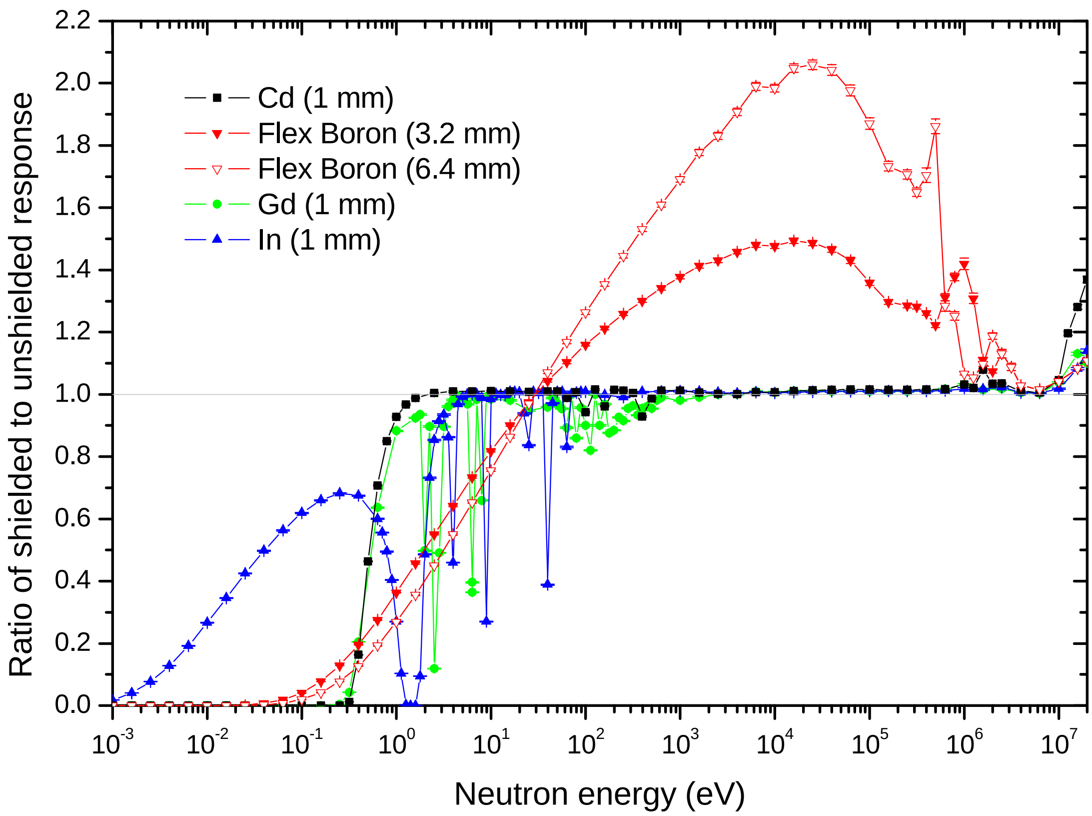

Figure 4. Shielded thermal detector response divided by bare detector response as a function of neutron energy.

Gadolinium produces an almost equally sharp cut-off in the 0.5 eV region, but unfortunately also absorbs neutrons in the energy region from 1 to 10 eV because of the resonances in the cross sections of the various isotopes. Again there is some neutron production via (n,2n) reactions at high energies.

The curve for Flex Boron demonstrates that it is a good thermal absorber for energies up to 0.1 eV, but the shielded to bare ratio does not rise as sharply as for cadmium or gadolinium. The explanation for this can be found in Figure 2 where it can be seen that the cadmium and gadolinium cross sections decrease rapidly in the region of 0.5 eV, whereas the ^{10}B cross section decreases steadily with the classic 1/*v* shape exhibited by many materials. (*v* is the neutron velocity and is a measure of the length of time for which a neutron is in the vicinity of a nucleus and subject to attraction by the strong nuclear force.) The shape of the curve for ^{10}B exhibits a characteristic not shown by any of the other materials. The shielded to bare ratio becomes greater than 1 in the intermediate energy region. The reason for this is that the Flex Boron includes materials other than boron, in particular hydrogen, and so acts as a moderator to the fast neutrons, slowing them down to energies where the BF_3 detector has a high response. A comparison of the responses for 3.2 mm and 6.4 mm of Flex Boron in Figure 4 brings this out clearly.

Indium would appear from Figure 4 not to be a very good candidate. For a 1 mm thick layer, there is not enough absorption in the thermal region, but the absorption in the intermediate energy region, particularly between 1 and 100 eV, is already rather high.

3.2. Measurements

The thermal neutron absorption characteristics of the three trial materials, gadolinium, indium and Flex Boron, and of cadmium were compared using a BF_3 proportional counter, type 5EB/40/13, serial no.PL879/T, from Centronic Limited. The counter has an active length of 50 mm, an outside diameter of 13 mm, and contains enriched boron trifluoride at a pressure of 400 mm of Hg. It was operated at +1095 V and the lower level discriminator was set at the mid-point in the valley between the low amplitude events (noise and gamma ray interactions) and the start of the 'wall effect' continuum.

A number of cylindrical sleeves of each material were constructed so that a range of thicknesses could be used to shield the BF_3 counter. Each sleeve was constructed by wrapping it around a former and butting one edge of the material against the other to form a cylinder. The gadolinium sleeves required a slight overlap to aid the cylinder formation and were held in shape with Sellotape. All the sleeves were 100 mm in length and fully covered the sensitive length (50 mm) of the BF_3 when in position. It was found that this length of shield was adequate in the beam of the BPL thermal column. For an isotropic neutron field the shield would need to cover the full length of the BF_3 tube and also the ends. Various thicknesses were used in the experiments – see Table 2.

Table 2. Sleeve thicknesses used to shield the BF_3 detector

Material	**Sleeve thicknesses (mm)**
Cadmium	0.5, 1.0, 1.0 + 0.5
Gadolinium	0.5, 2 × 0.5, 3 × 0.5
Indium	0.5, 1.0, 1.0 + 2 × 0.5
Flex Boron	3.2, 2 × 3.2

The irradiations were carried out at the NPL thermal pile facility(7) at the 1.5 m reference height in the thermal column with the column evacuated. The BF_3 detector was fixed in a horizontal position with its major axis perpendicular to the thermal neutron beam and with the centre of the neutron-sensitive volume aligned with the centre of the incident neutron beam. The positioning of the BF_3 enabled the sleeves of different absorber materials and thicknesses to be fitted without disturbing the position of the BF_3 detector.

The sleeves were fitted over the BF_3 detector with the 'join' facing away from the source of thermal neutrons and care was also taken to ensure that the joins in consecutive sleeves did not coincide.

During the irradiations events from the BF_3 detector and a fission chamber (FC) used to monitor the thermal fluence were recorded simultaneously, and the BF_3 detector counts were normalised to the FC counts. Dead time corrections were applied to the rates in both instruments.

Results of the measurements are listed in Table 3 for the range of materials and thicknesses used. They are presented as the quotient of the BF_3 counts under the shielding material to the counts of the bare detector, both readings being normalised to unit count in the FC monitor.

Table 3. The relative response of the BF_3 detector shielded with different thicknesses of various materials.

Shield thickness (mm)	**BF_3 detector response in shield divided by 'bare' response**			
	Cadmium	**Flex Boron**	**Gadolinium**	**Indium**
0.5	0.01428 (9)	—	0.01535 (17)	0.6507 (15)
1.0	0.01210 (8)	—	0.01225 (15)	0.4448 (10)
1.5	0.01147 (10)	—	0.01067 (14)	—
2.0	—	—	—	0.2324 (6)
3.2	—	0.02801 (16)	—	—
6.4	—	0.00477 (13)	—	—

Uncertainties, shown in brackets refer to the digit in the last place or places. They are from counting statistics only (1σ), and range between 0.2% and 2.7%.

3.3. Calculations to simulate the measurements

The spectrum in the thermal column needs to be known in order to simulate the experimental measurements with MCNP. A measure of the spectrum, covering the whole energy region from thermal to 20 MeV, can be determined using a Bonner sphere (BS) spectrometry set. Measurements have been performed with the NPL BS set, which is based on a ^3He central detector; Results were obtained free-in-air, and also under cadmium cover[(8)]. These should agree for the spectrum in the region above the cadmium cut off, but the agreement is rather poor, as illustrated in Figure 5.

In Figure 5 the spectrum measured free-in-air is shown together with the spectrum measured with the BS set irradiated within cadmium covers. Also shown is the predicted spectrum under cadmium cover derived by multiplying the free-in-air spectrum with a function giving the transmission of neutrons through 1 mm of cadmium, c.f. Figure 4. It is clear that this predicted spectrum does not agree well with the spectrum actually measured under cadmium, particularly in the region around and just above 1 eV. This is unfortunate since the measured BF_3 detector data is particularly sensitive to the spectrum in this region. The report of these measurements, reference (8), suggests some reasons for this discrepancy. It is a limitation of BS measurements that they are very good at measuring the total fluence, but, because of their poor energy resolution, they do not always get the fluence in exactly the right energy region.

The MCNP models referred to in section 3.1 were modified to include an energy distribution for the NPL thermal column rather than single energies. The free-in-air BS measurement of the total spectrum was initially used as the energy spectrum. Although the calculated bare detector response was in reasonable agreement with the measured value, considering that some parameters, e.g. the exact pressure of the BF_3 gas, the boron enrichment, and the exact active length, are not known precisely, values for the ratio of the predicted response of the BF_3 tube under cadmium and gadolinium divided by the 'bare' response were very small, at least a factor of 2 lower than the measurements. This discrepancy was assumed to be due to the poor knowledge of the thermal field in the region just above the cadmium cut-off. Since the BS measurement of the spectrum under cadmium indicates that there is significantly more fluence in this region than was found in the free-in-air measurements an attempt was made to use these results.

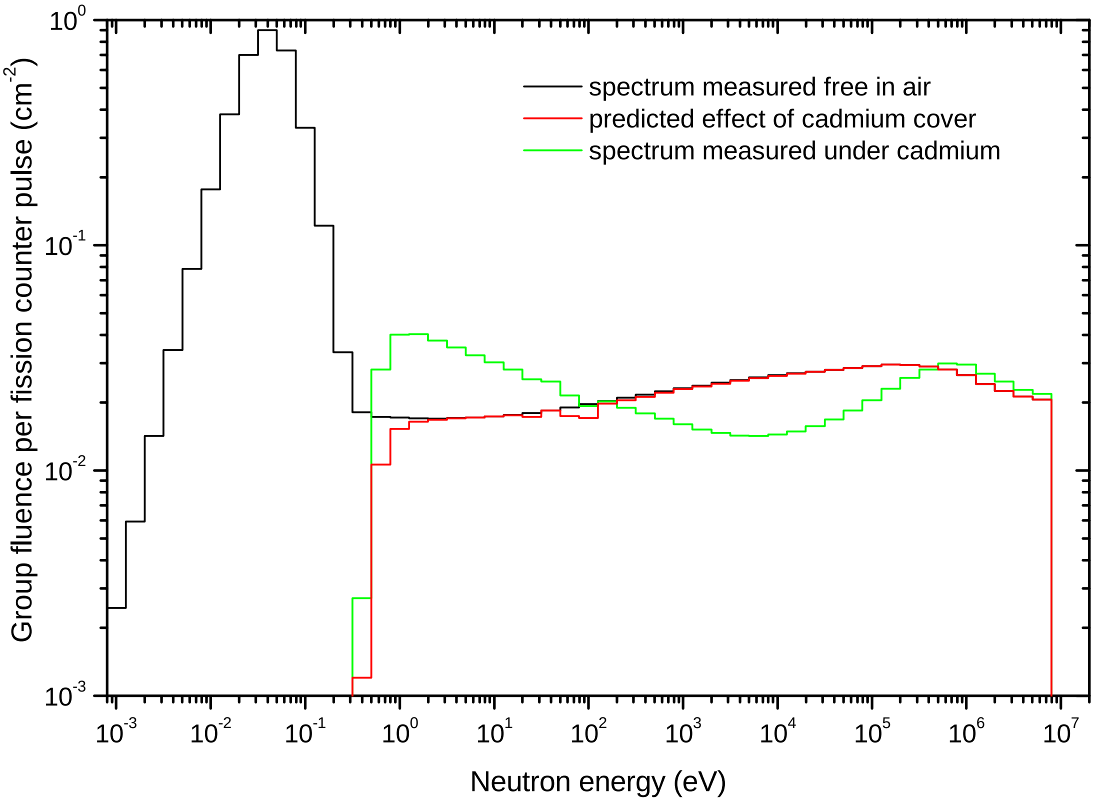

Figure 5. Bonner sphere measurements of the fast neutron component in the thermal column field.

The MCNP model was run, for each shield and thickness combination, with a thermal spectrum and the BS under-cadmium spectrum separately. The response was taken to be the sum of these two values weighted according to the relative fluence for these two components given in reference (8). The thermal spectrum used was the MCNP built-in source probability function (number 5) corresponding to an evaporation spectrum of the form $f(E)=CE\,\exp(-E/kT)$ with $kT = 27.8$ meV. This value for kT was derived from recent measurements with gold foils bare and under cadmium cover. This approach gave values for the ratio of the response of the BF_3 tube under all shield materials divided by the 'bare' response which agreed better with measurements than those calculated with the measured free-in-air spectrum.

3.4. Comparison of measurements and calculations

The measured value for the bare BF_3 detector counts per FC count, for measurements with the BF_3 at the 1.5 m reference height was 0.8046 ± 0.0007, the uncertainty quoted being due purely to statistics. This is the value after subtraction of the counts under 1 mm of cadmium from the bare detector counts and thus represents the response to sub-cadmium-cut-off neutrons. Values for the sub-cadmium-cut-off neutron fluence per FC count are routinely determined from fluence measurements with gold activation foils. The results vary a little with time; however, an average value from recent calibration measurements for the true sub-cadmium-cut-off fluence per FC count at the height where the measurements were made is (4.37 ± 0.10) cm^{-2}, the uncertainty deriving from the spread of these calibration measurements. The measured fluence response of the BF_3 detector is thus (0.1840 ± 2.3%) cm^2. For a pure Maxwellian spectrum at a *kT* value of 27.8 meV the response calculated by MCNP was 0.2234, which is 21% higher. There are, however, significant uncertainties which contribute to the calculation, for example, those in cross sections, boron enrichment, gas pressure, and the active length of the detector. Given these, the level of agreement is probably as good as can be expected.

In Figure 6 the measured data for the ratios of shielded to bare counts from Table 3 are plotted and compared with the calculations performed to simulate these measurements. In the calculation of these ratios, the effects of the uncertainties listed above which influence the calculation of the absolute value of the response of the bare detector largely cancel out and are unimportant. Figure 7 and Figure 8 provide information which helps in understanding the measured data and their relation to the calculations. Figure 7 is a plot of the response function as calculated with MCNP for the bare BF_3 detector and for this detector covered in the various shielding materials considered. Figure 8 is similar, as it includes response function data for the BF_3 detector shielded by cadmium, Flex Boron, and gadolinium, but it also shows the estimate of the spectrum in the NPL thermal column as used in the calculations.

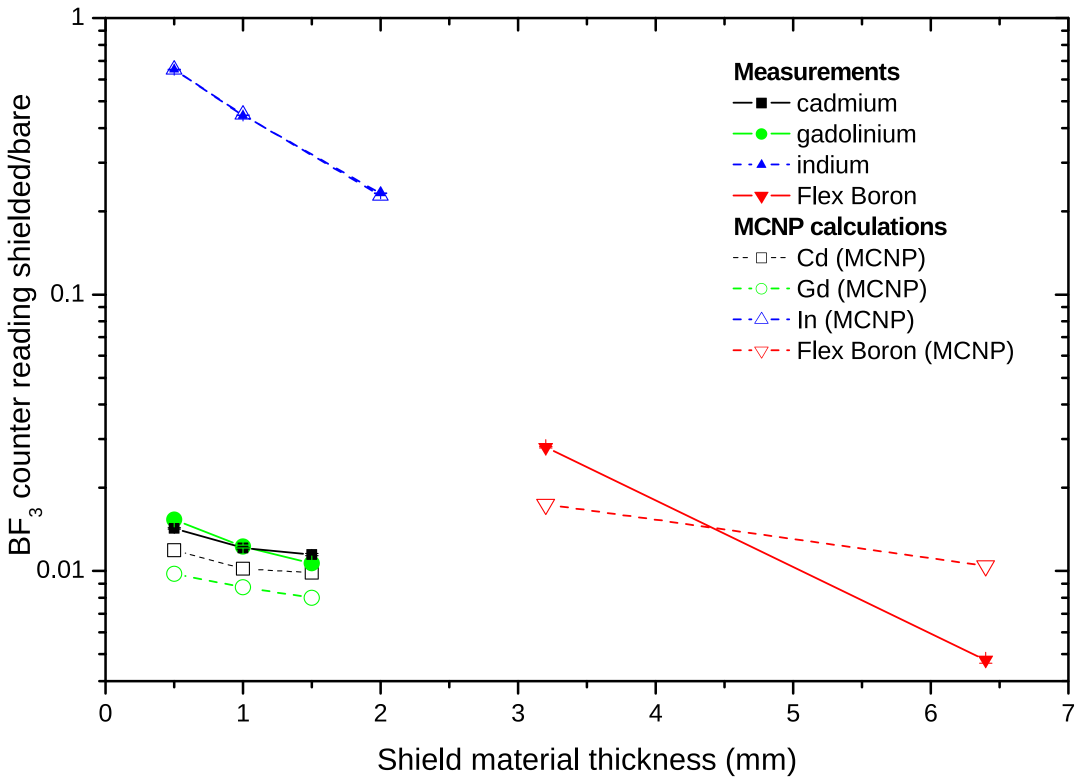

Figure 6. Comparison of measured and calculated values for the ratio of shielded/bare response for the BF_3 detector. Statistical uncertainties are smaller than the symbols.

The ratio of BF_3 detector shielded response to bare response for 1 mm of cadmium is 0.01210, i.e. the response under cadmium is only about 1.2% of that bare. Figure 7 shows how the bare BF_3 detector response increases exponentially with decreasing energy, and

Figure 8 shows how the thermal component dominates in the NPL thermal column spectrum. These features explain the large response of the bare detector. The epi-cadmium fluence, i.e. that above 0.5 eV, is 24% of the thermal fluence. From the under-cadmium response function shown in Figure 8 it is clear that the BF_3 detector with cadmium cover will only see a small fraction of these epi-cadmium neutrons in the region around 1 eV. The rather small value of 1.2% for the shielded to bare ratio is thus qualitatively entirely to be expected. The calculated value shown in Figure 6 is, however, about 20% lower than the measurement.

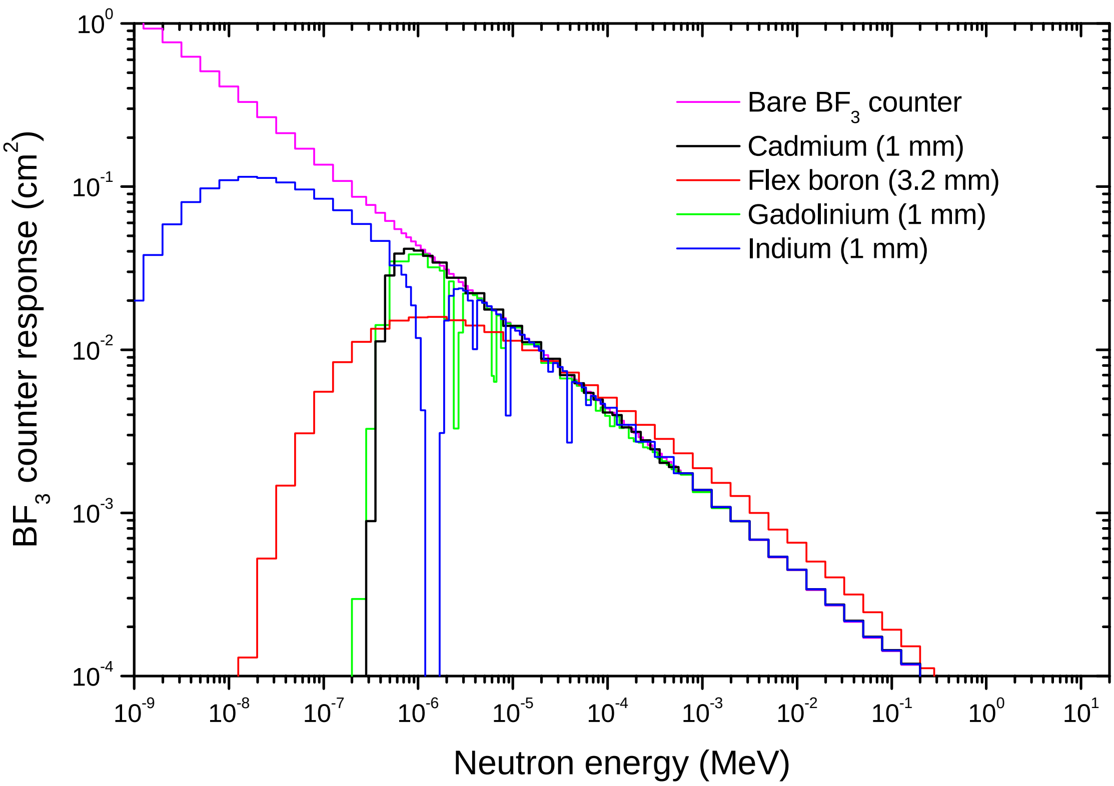

Figure 7. Response functions of the bare BF_3 detector and this counter covered with cadmium, Flex Boron, gadolinium, or indium. Note the logarithmic scale for the response.

The probable reason for this discrepancy is the poor knowledge of the spectrum used in the calculations in the energy region around 1 eV. Figure 8 shows the spectrum used in the calculations. In the region immediately below 1 eV the spectrum has a dip. This feature resulted from the way the spectrum was derived from a combination of a Maxwellian thermal peak and the BS measurements under a cadmium cover. The ratio of shielded to bare responses for the BF_3 detector is very sensitive to the precise number of neutrons in the region around 1 eV. If the three bins constituting the dip in the spectrum, which is difficult to explain on physical grounds, were replaced by a flat spectrum with the fluence value equal to that just above 1 eV, much better agreement between calculation and measurement would be achieved. The discrepancy between calculation and measurement is thus probably a result of poor knowledge of the spectrum in the region around 1 eV.

A comparison of the measured and calculated ratios for indium shown in Figure 6 reveals excellent agreement. The ratio for 1 mm of indium is, however, 0.4265, i.e. nearly 43%, c.f. 1.2% for 1 mm of cadmium. It is clear from the response function for the BF_3 detector under a 1 mm thick indium sleeve, shown in Figure 7, and the NPL thermal column spectrum, shown in Figure 8, that the main contribution to the counts under indium comes from thermal neutrons which penetrate the indium cover. The calculation is thus insensitive to the precise details of the epi-cadmium spectrum and the agreement illustrates MCNP's capabilities when the important elements of the problem can be accurately defined.

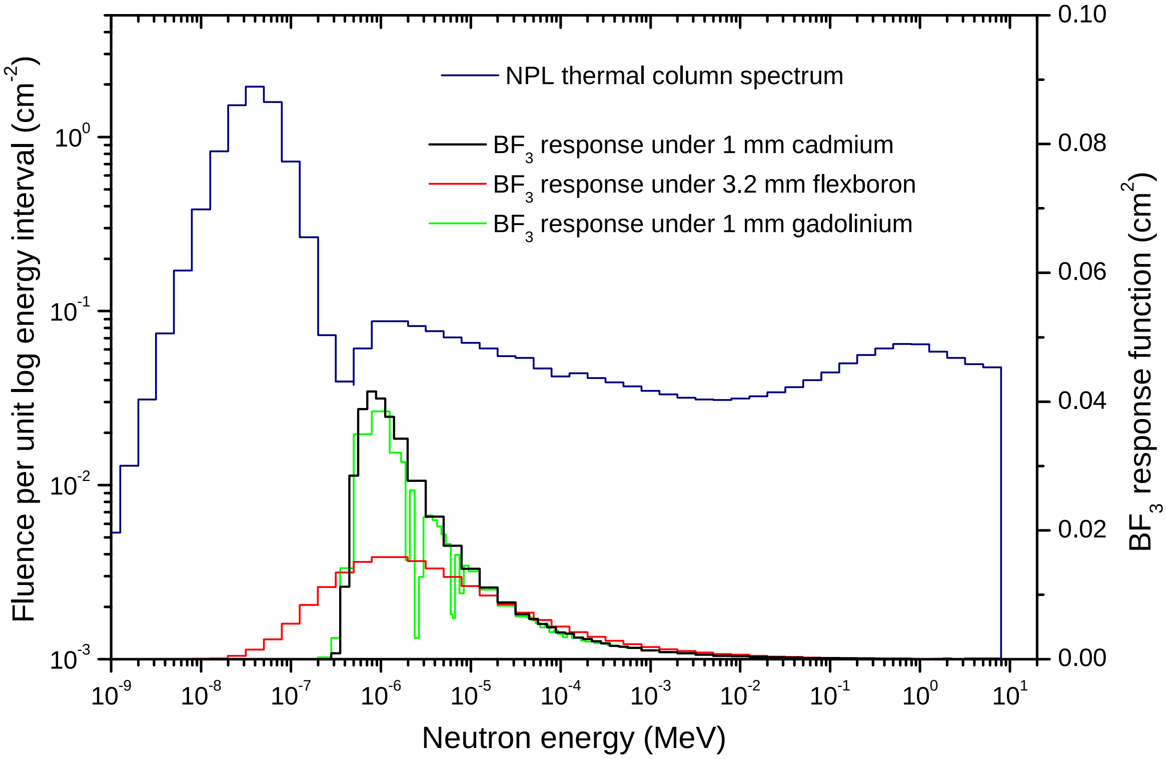

Figure 8. Response functions for BF_3 counter with cadmium, Flex Boron, or gadolinium shields compared to the spectrum of the NPL thermal column facility used in the calculations. The spectrum is plotted with a logarithmic ordinate axis (left), whereas the response functions have a linear ordinate axis (right).

A comparison of the ratio of shielded to bare counts for the BF_3 for Flex Boron thicknesses between 3.2 and 6.4 mm with that for cadmium would appear to indicate that it might be a good alternative to cadmium. However, the curve for the response function with Flex Boron shown in Figure 4, and also the data in Figure 7 and Figure 8 provide a warning that this is not really the case. It is clear from Figure 4 that Flex Boron does not provide a sharp cut-off in the 0.5 eV region, but exhibits a much more gradual rise in the response with increasing energy compared to cadmium. More than that, the ratio of the shielded response to the bare response becomes greater than unity for the energy region between about 30 eV and the MeV region. The reason for this is presumed to be the moderation of these neutrons which occurs in the constituents of the Flex Boron other than the boron, the hydrogen in particular, reducing the energy of the neutrons rather than absorbing them. Boron can thus be used to absorb thermal neutrons, but not to provide a clean filter which absorbs only thermal neutrons without affecting higher energy neutrons. The disagreement between calculation and measurement can again probably be attributed to poor knowledge of the exact shape of the epi-cadmium spectrum, although the cross-over between the calculation being lower than experiment to it being higher is difficult to explain.

From the data shown in Figure 6, gadolinium appears to have the most suitable characteristics as a replacement for cadmium. Figure 2 shows that the thermal cross section of natural gadolinium is actually higher than that for natural cadmium. However, the gadolinium cross section does not exhibit the large resonance peak at about 0.16 eV evident in the cadmium cross section, and so the cut-off may not be as sharp. In addition, it can be seen, again from Figure 2, that gadolinium has resonances in the intermediate energy region which are likely to result in unwanted absorption of neutrons in this energy range. This effect is also illustrated in Figure 7 and Figure 8 where the response can be seen to have sharp dips in the 1 to 10 eV region. The ratio of shielded to bare counts for gadolinium might thus be expected to be less than for cadmium, and the calculations do predict this; however, the measurements reveal near identical ratios for 1 mm of cadmium or gadolinium – see Figure 6. The explanation of the difference between calculation and measurement for gadolinium must be similar to that for the case of cadmium, i.e. that the shape of the NPL thermal column spectrum is not well known in the energy region around 1 eV where the shielded detector response is a maximum.

4. Conclusions

The agreement between calculation and measurement shown in Figure 6 is at first sight a little disappointing for cadmium, gadolinium and Flex Boron. However, a probable reason for this has been identified, i.e. the limited knowledge of the NPL thermal column spectrum in the region just above the cadmium cut-off energy of 0.5 eV. This provides an incentive to improve this knowledge, possibly using the types of measurements described in this report. Nevertheless, the use of the NPL thermal column is very appropriate for these measurements since it highlights the sort of environments in which measurements with and without cadmium cover are important. If the field had been a pure thermal Maxwellian distribution for example, the reading under cadmium would be zero.

Gadolinium appears to be the best candidate as a replacement for cadmium. It is, however, considerably more expensive, see Table 1. The measured values indicated that it was an ideal replacement in terms of its neutron absorbing properties, but the predicted transmission factor for monoenergetic neutrons shown in Figure 4, and the resonance dips in the response function for the BF_3 under gadolinium shown in Figure 7 and Figure 8 raise some questions. These resonance dips are, however, very narrow and their effects may not be too significant. Boron can be used in some applications, but indium does not appear to have the required characteristics.

Either gadolinium or boron can be used in applications described under b) in the introduction, i.e. modifying the response function shape for survey instruments and dosemeters, provided the user does not simply assume that all thermal neutrons will be absorbed, and that a transport code is used to predict precisely the effects of the absorbing material. The fact that Flex Boron can actually increase the response in the intermediate energy region needs to be considered since this may be the opposite of what is required. Modern calculation codes will allow for these effects, but it is as well that an instrument designer is aware of them in advance.

One rather specialist application of thermal neutron absorbers is in spectrometry systems where two thermal neutron detectors, one with and one without shielding material are used to provide information on the spectrum in the intermediate and thermal energy regions. These are usually associated with high resolution instruments, e.g. hydrogen recoil counters and/or scintillators which cover the higher energy region. This approach to deriving thermal and intermediate energy data is rather imprecise and in view of the large uncertainties inherent in the approach either gadolinium or boron could probably be used. Ideally any unfolding procedure for deriving the spectrum should take into account the response function shapes for the bare and shielded thermal detectors.

Cadmium still appears to be the best material for application a) as described in the introduction. This application is rather specialist, usually undertaken only be experimental physicists, who will probably continue to use cadmium but with precautions, e.g. cadmium covers can be laminated to avoid direct contact with the skin. The problem of manufacturing the cadmium covers remains. This should be done with all necessary care, wearing gloves and a face mask, the work ideally being undertaken in a fume cupboard.

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