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# Neutron Dosemeter Responses in Workplace Fields and the Implications of Using Realistic Neutron Calibration Fields

**D.J. Thomas, N. Horwood and G.C. Taylor**

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# NATIONAL PHYSICAL LABORATORY

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**by**

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Abstract.
The use of realistic neutron calibration fields to overcome some of the problems associated with the response functions of presently available dosemeters, both area survey instruments and personal dosemeters, has been investigated. Realistic calibration fields have spectra which, compared to conventional radionuclide source based calibration fields, more closely match those of the workplace fields in which dosemeters are used. Monte Carlo simulations were performed to identify laboratory systems which would produce appropriate workplace-like calibration fields. A detailed analysis was then undertaken of the predicted under- and over-responses of dosemeters in a wide selection of measured workplace field spectra assuming calibration in a selection of calibration fields. These included both conventional radionuclide source calibration fields, and also several proposed realistic calibration fields. The present state of the art for dosemeter performance, and the possibilities of improving accuracy by using realistic calibration fields are both presented.

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# 1 INTRODUCTION

Over recent years considerable effort has been expended in a number of laboratories worldwide to identify suitable so-called *realistic neutron calibration fields,* RNCFs, and to subsequently produce and characterise such fields[1-7]. These facilities have already found use for investigating neutron spectrometer and dosemeter responses[8,9]. The concept of using RNCFs is, in fact, sufficiently well established that an ISO Standard on "Characteristics and Methods of Production of Simulated Practical Neutron Fields" is presently being prepared[10].

The impetus for all the work on RNCFs derives from the deficiencies in the neutron dosemeters currently available to the nuclear industry. The nuclear industry is taken here to include any industry where radiation may be a hazard. It thus includes the manufacture and use of radioactive sources, nuclear fuel handling, processing, and transport, etc., in addition to the generation of nuclear power. The term dosemeter is used in this document to cover both area survey instruments and personal dosemeters.

Dosemeters should provide a measure of the *operational quantities*[11,12]: *ambient dose equivalent,* H*(10), in the case of area survey instruments, and *personal dose equivalent,* $H_p(10)$, in the case of personal dosemeters. These two quantities in turn are designed to be reasonable approximations to the legal limiting quantity which, prior to the most recent recommendations of the International Commission on Radiological Protection, ICRP, in their Publication 60[13], was *effective dose equivalent,* $H_E$, but which, on adoption of these recommendations, will be *effective dose,* E. The legal quantities are defined as weighted averages of doses in various organs of the body, and as such they are deemed to be unmeasurable, which is why the operational quantities, which were devised to be measurable, were introduced.

Although the operational quantities were devised so that they could, in principle, be realised, no practical dosemeter has yet been designed which fully achieves this aim, and a major problem with all current dosemeters is that they do not have the required dose equivalent response as a function of neutron energy over the full range of energies encountered in the workplace. Thus, although a dosemeter may be calibrated to give the correct dose equivalent response at a particular neutron energy, or for a particular neutron spectrum, it will not necessarily give the correct answer at any other energy, or for any other spectrum. For personal dosemeters there is an additional problem of poor angular dependence of response; however, this problem will not be considered here.

Some idea of the extent of the poor dose equivalent response functions of typical dosemeters is given in Figures 1(a) and 1(c), which illustrate the extent of the under- and over-responses which can occur. Details of the particular dosemeters illustrated are given in Section 6. An ideal dosemeter would have a response of unity for all energies. In Figure 1(c), the response is for $H_p(10)$ calculated for anterior-posterior, A-P, incidence.

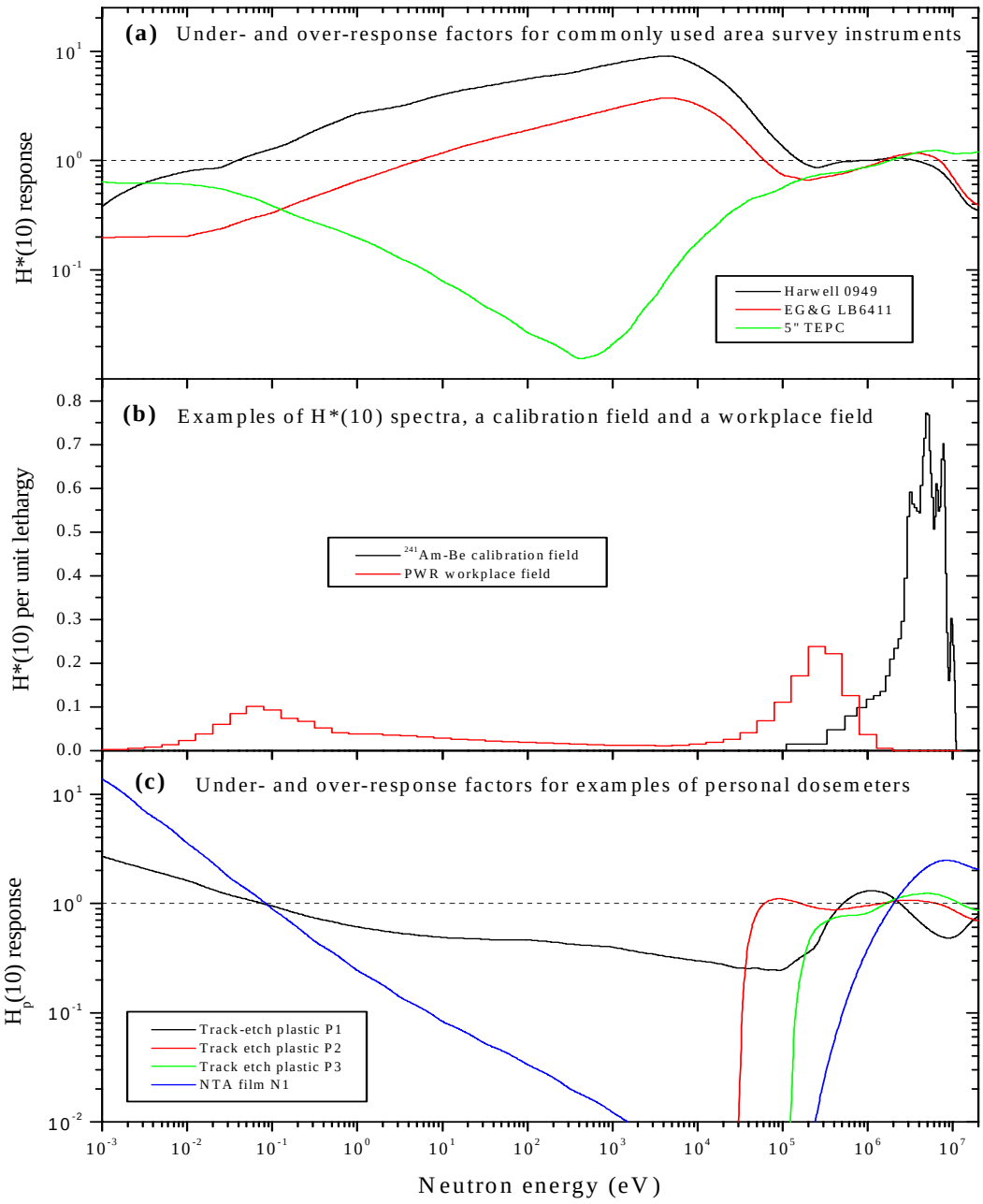



**Figure 1.** Examples of typical under- and over-response factors for area survey instruments (a) and personal dosemters (c), compared with the ambient dose equivalent spectral distributions for a typical calibration field and a soft workplace field (b).

Both area survey and personal dosemeters tend to have responses which are most nearly proportional to dose equivalent in the energy region from roughly 100 keV to 10 MeV, although some devices also respond well beyond 10 MeV. The region above 100 keV is an important one since a large fraction of the dose equivalent in the many of the spectra encountered in workplaces in the nuclear industry occurs in this region. Nevertheless, as has increasingly become apparent, particularly as a result of spectrum measurements made over the last decade or two, workplace fields often have significant numbers of intermediate and low energy neutrons, and hence significant dose equivalents in these regions; see for example, the workplace field illustrated in Figure 1(b), and in these energy regions both types of dosemeter tend to have particularly poor dose equivalent responses.

The spectra illustrated in Figure 1(b) are plotted as ambient dose equivalent per unit lethargy and are therefore only directly comparable with the responses for survey instruments. However, the corresponding plots for $H_p(10)$(A-P) would be almost identical, so Figure 1(b) can also be used for comparison with personal dosemeter responses.

The problem of poor dose equivalent response functions is exacerbated by the fact that the neutron spectra in the locations where the devices are used are mostly very different to that of the calibration field employed. Routine dosemeter calibrations are performed using radionuclide neutron sources, which tend to produce predominantly fast neutrons. A typical example is the $^{241}$Am-Be source whose dose equivalent spectrum is shown in Figure 1(b). If the spectra in the workplace fields and the calibration field were more alike, the calibration should be more appropriate, and better estimates of the dose equivalent could be expected. This is the underlying idea behind the use of RNCFs.

In the area of dosimetry for aircrew, realistic calibration fields, based on spectra at high-energy accelerators, and having neutrons with energies extending up to the region of 100 MeV, have for a number of years, been used for dosemeter calibration[14] since conventional calibration fields are considered to be quite inappropriate. In contrast to spectra at aircraft flight altitudes, most workplace fields in the nuclear industry have very few neutrons above about 5 MeV, and tend to include significant numbers of thermal and intermediate energy neutrons. It would, therefore, seem almost axiomatic that inclusion of lower energy neutrons in the calibration field should provide better calibrations. The actual situation is, however, more complicated, and this simple view is not necessarily correct. Factors which complicate this simple picture are: the range of very different spectra encountered in the workplace, the extremely wide range of neutron energies involved, the large variation of the dose equivalent per unit fluence with energy, and the very significant extent to which the dosemeter responses can deviate from the ideal. Under- or over-response can be up to a factor of ten or more at certain neutron energies.

This report addresses the extent to which RNCFs can be expected to improve matters, and investigates two main issues: a) whether suitable RNCFs can be produced in the laboratory, and b) how appropriate any single RNCF can be in terms of giving, for a range of dosemeters, generally more reliable calibrations applicable over the full range of workplace fields for which the dosemeters might be used.

An investigation of issue a) obviously requires a knowledge of the types of spectra encountered in workplace fields. Only if this information is available can attempts be made, using neutron transport codes, to model configurations of neutron sources and moderators which could be used to replicate a similar type of spectrum in the laboratory. If reasonably appropriate realistic

calibration fields can be produced in the laboratory, the next step, b) above, is to predict, using the known response functions of particular dosemeters, just how well they would perform in a range of workplace fields following calibration in the realistic laboratory spectrum. Again this process requires knowledge of the range of workplace field spectra found in the nuclear industry.

Over the last 20 or more years a large number of neutron spectra have been measured at nuclear sites. The data from most measurements made prior to about 1982 may be found in an IAEA compendium of spectra and instrument response functions[15]. A recent project, partly sponsored by the European Commission, has incorporated a considerable amount of more recent data, together with those spectra from the IAEA compendium which are most representative of workplace environments where radiation protection is an issue, into a large database[16,17]. This database is linked to a computer programme, called SPKTBIB, which allows the spectra to be displayed, compared, plotted, etc., and for the response of any dosemeters whose response function is known, to be predicted by folding the response function with the neutron spectrum. The database also includes fluence to dose equivalent conversion factor tables which are used to calculate the dose equivalent per unit fluence for spectra.

The techniques used to investigate whether suitable RNCFs can be devised are described in this report. Similar work has been undertaken previously, e.g., by Schraube et al.[5], but has never including as many workplace spectra as in the present work. It should be noted that, for an RNCF to be useful, it is not necessary that the spectrum is identical to that of the workplace field, but that it gives the correct dosemeter calibration. If, for example, a dosemeter had the correct dose equivalent response over a particular energy region, it would be unimportant to match the calibration and workplace spectra exactly in this region.

The responses investigated in this work are those of several selected dosemeters to the ICRU operational dose equivalent quantities. Values for these operational quantities at a point in a neutron field can be obtained, provided the characteristics of the neutron field, i.e., the energy spectrum, the angular dependence of the fluence, and the total fluence rate, are known, by using calculated fluence-to-dose-equivalent conversion coefficients available in the literature. The coefficients for ambient dose equivalent, usually denoted h*(10), depend only on the energy spectrum, whereas those for personal dose equivalent, denoted by $h_p(10)$, also depend on the angular distribution of the incident neutron fluence. The reading of an instrument in a field whose characteristics are known can thus be compared with the correct dose equivalent value, the ratio being the response. Conversion coefficient calculations involve firstly deriving the dose as function of linear energy transfer, L, and then weighting the dose by a quality factor Q(L) to obtain dose equivalent. One of the recommendations of ICRP Publication 60 was a change in the dependence of the quality factor on L. Use of the new Q(L) relationship increases the value of the conversion coefficients and hence changes the operational quantities. Conversion coefficients for both the old[18-20] and the new[21,22] Q(L) relationship are available.

The results presented in this report are almost entirely for the operational quantities corresponding to the new Q(L) relationship. Some comparison between the results for the old and the new quantities are presented in Section 7, but elsewhere in the document any reference to H*(10) and $H_p(10)$, or h*(10) and $h_p(10)$, refers to the new, post ICRP Publication 60, values of these quantities.

## 2 THE APPROACH TO THE INVESTIGATION

The first step in the investigation involved an examination of the workplace spectra in the SPKTBIB database to identify those features and characteristics which are important to replicate in an RNCF. Spectra were selected from the database and assigned to particular groups which were believed to be representative of the spectra in particular workplace environments. The differences between these groups, and also the differences between spectra in the same group, give an indication of the extent to which a single RNCF might be expected to apply to a wide range of environments. The most important features to be replicated in an RNCF were then identified, and neutron transport calculations were undertaken to identify laboratory configurations which could reproduce these features. The investigation of the spectra is described in Section 3, while the transport calculations are described in Section 4.

From the various calculated laboratory configurations a selection was made of the most promising RNCF spectra, and their ability to provide improved dosemeter calibrations was investigated and compared to the results for calibrations with conventional radionuclide source calibration fields. The procedure adopted is outlined below.

A number of dosemeters for which reasonable response function data are available were chosen, see Section 7. SPKTBIB was then used to fold both workplace and calibration spectra with the dosemeter response functions and with fluence to dose equivalent conversion factors to predict:

A - the dosemeter reading per unit fluence in the calibration field,
B - the dosemeter reading per unit fluence in the workplace field,
C - the dose equivalent per unit fluence in the calibration field,
D - the dose equivalent per unit fluence in the workplace field.

The dose equivalent in each case was the appropriate quantity for the type of instrument, i.e. either H*(10) for an area survey instrument, or $H_p(10)$ for personal dosemeter.

The calculated values for A, B, C, and D, were then used to derive:

A/C i.e. the dose equivalent response of the device as determined in the particular calibration field, (C/A is the calibration factor for that device in that field.)

The next step is to calculate:

$B \times C/A$ which is the response of the device in the workplace field, after being calibrated to give the correct response in the calibration field,

and finally the quantity $R_H$ given by:

$B/D \times C/A$ which is the ratio of the response in the workplace field to the true value of the relevant dose equivalent quantity.

For an ideal dosemeter $R_H$ would always be one. The extent to which the values differ from unity for various workplace spectra and the dependence on the calibration field is the subject of this report.

The conversion coefficients $h_p(10)$ used to derive $H_p(10)$ were all calculated for a slab phantom, see for example reference 21 or 22. They are usually written as $h_{p,slab}(10)$, but are indicated in this document simply by $h_p(10)$ for convenience. Also, the values used for $h_p(10)$ are those for A-P irradiation and so apply only to front-on irradiation of an individual. Thus, although this report gives a picture of those problems with personal dosemeters which result from the poor energy dependence of their responses, it does not give information on the problems resulting from poor angular response.

It should be noted that the quantity in which the "reading" and the response function of the dosemeter is expressed may be: pulses from the sensor of an area survey instrument, pits or tracks in the sensitive material of a passive personal dosemeter, or the analogue or digital display of some dosimetric quantity from any active device. In view of the way the final quantity is calculated in terms of ratios, the actual quantity used is immaterial since it cancels out.

It is important to remember that all the results presented in subsequent sections are based on computer predictions and are only as good as the input information used in the calculations, i.e., the accuracy of the response functions, the correctness of the measured workplace spectra, and of the predicted realistic calibration spectra. SPKTBIB contains spectra derived from a large number of sources worldwide, and no serious attempt was made to check the reliability of the data. In fact, little more can be done other than to ensure that the spectral shapes are at least plausible for the particular environment. The results presented here are entirely dependent on the correctness of the original spectral measurements; however, some degree of confidence can be derived from the sheer number of spectra used in the analysis which should tend to 'dilute' the effects of a few bad measurements.

## 3 CHOOSING GROUPS OF SPECTRA WITH COMMON FEATURES

Personnel in the nuclear industry are exposed to a range of rather different spectra. Since it is unlikely that a single calibration spectrum will be applicable to all environments, the spectra from the SPKTBIB database which were used in the present investigation were divided into a number of groups, within which the spectra were expected to be reasonably similar. This approach has certain advantages. Firstly convenience, since it makes the handling of the data and the interpretation and display of the results simpler. Secondly, although it is not expected that a single RNCF will be universally applicable, any RNCF should hopefully be applicable for several types of environment. The division into groups of spectra with similar characteristics should help in identifying those environments where the use of a particular RNCF might provide improved dose equivalent estimates.

The basis used for choosing members of spectral groups was simply - similarity of workplace environments. Spectra were not examined when choosing members of the various groups. The only criterion was that every spectrum in a group was produced by the same basic type of neutron source, and involved a similar degree of shielding. Thus, reactor environments and nuclear fuel fabrication areas would come in entirely different groups, despite the original neutrons being produced mainly by the fission process in both cases, due to the very different amounts of moderating and shielding material involved. The approach was to make the decision solely on the basis of the information which a health physicist would have available in normal circumstances which would not, in general, include information on the neutron spectrum. (If this was available,

correction factors for dosemeters could be calculated and the dosimetry problem for that environment would be solved.) The approach was thus to mimic the position of a health physicist placed in the position of trying to decide on the most appropriate calibration field to be used, or trying to derive dosemeter correction factors from information for similar environments where spectral information was available.

Eight spectral groups were chosen in total, and these were based partly on groups used in an earlier investigation[23] to determine the implications of the new dosimetric quantities recommended in ICRU Publication 60. The environments which characterised each of the groups are shown in Table 1, which also lists the average value of the fluence mean energy of the spectra within each group, and the average of the ambient dose equivalent per unit fluence values. The coefficients used to convert from fluence to H*(10) to derive the values shown in the table were those tabulated in ICRP Publication 74[21] and ICRU Report 57[22], which were derived using the quality factor to linear energy relationship, i.e., Q(L) values, proposed in ICRP Publication 60. (Average $H_p(10)$ values would be very similar to those tabulated for H*(10).) The two parameters tabulated are measures of the spectral hardness, and the groups have been tabulated in order of increasing hardness. They extend from the soft gas-cooled reactor spectra, which have an average mean energy of 0.012 MeV, up to the group of spectra characteristic of radionuclide source fabrication plants and areas where such sources are used which have a mean energy of 1.081 MeV.

**Table 1. The eight groups of spectra selected for the investigation**

| Group No. | Description of environments | Mean energy (MeV) | Mean H*(10) (pSv) |
|---|---|---|---|
| 1 | gas-cooled reactors in the UK | 0.012 | 18.4 |
| 2 | various PWRs in Europe and the USA | 0.024 | 26.2 |
| 3 | PWR measurements by Endres et al. in the USA | 0.075 | 54.7 |
| 4 | around transport containers for PWR fuel elements | 0.177 | 97.2 |
| 5 | around transport containers for WWR fuel elements | 0.191 | 124 |
| 6 | fuel processing, reprocessing, and storage areas | 0.634 | 164 |
| 7 | around transport containers for MOX fuel elements | 0.839 | 229 |
| 8 | source fabrication environments and source usage areas | 1.081 | 232 |

The variation of the mean energy and H*(10) values are illustrated in Figure 2. The vertical line through each point is not an error bar, but represents the range of values within the group. The length of the line is a measure of the similarity of the spectra within a group. Thus the spectra of group 3, for example, have very similar mean energies and H*(10) values, and the same is true of group 7, whereas group 6 has very large variations. The small range of values for group 3 is partly explained by the fact that all measurements were performed by the same team using the same instrumentation. The same is true of group 7; furthermore, this group only includes two measurements.

In many cases there is a large degree of overlap between the ranges of the mean energies for adjacent groups, e.g. groups 4 and 5, although spectra in groups at opposite ends of the range are clearly very different, for example there is no overlap between mean energies in groups 3 and 7. Thus, one might expect to be able to devise an RNCF which was applicable for groups 4, 5, and 6, for example, but it would be much less likely that an RNCF which was applicable for group 1 would provide suitable calibrations for group 8.

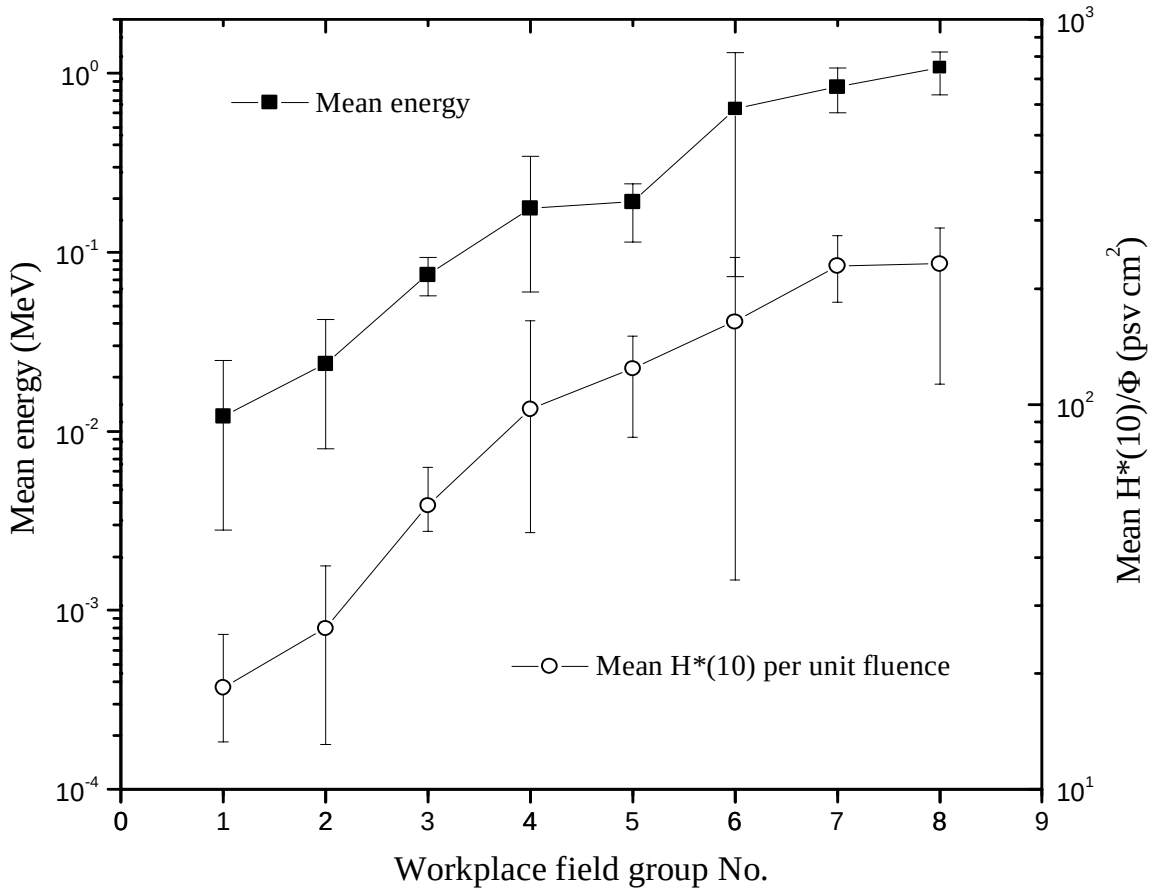



**Figure 2.** The mean energy and the mean H*(10) per unit fluence for the workplace field groups. Symbols represent mean values for the group, and the vertical lines through the symbols show the range of values, the top of the line indicating the maximum value and the bottom the minimum.

Table 2 gives the mean energies and H*(10) values for the three most commonly used radionuclide calibration sources, $^{241}$Am-Be, $^{252}$Cf, and heavy water ($D_2O$) moderated $^{252}$Cf. Also included are the parameters for an existing, well characterised, realistic field, that at the Institut de Protection et de Suûreté Nucléaire, IPSN, facility at Cadarache[1, 9], which is already available for general use. The spectra are also presented in Figure 3. Where fluence spectra are given in this report they are plotted as $E.\Phi(E)$ versus the logarithm of the energy. The $E.\Phi(E)$ representation, i.e., where each bin is a measure of the product of the energy, E, and the fluence per unit energy, $\Phi(E)$, in the bin, is identical to fluence per unit logarithmic energy interval.

Comparing the mean energies and H*(10) values of the calibration spectra with the groups listed in Table 1 shows that the existing calibration facilities tend to cover the intermediate and harder spectral groups, but no calibration fields are presently available for the very soft spectral groups. In order to perform a comprehensive investigation of the applicability of RNCFs it was therefore decided to concentrate the computational efforts on designing laboratory realistic field configurations which produced spectra with very low mean energies, comparable to those around PWRs and gas-cooled reactors. Using these spectra in conjunction with those for the calibration fields shown in Table 2 would, it might be assumed, provide calibration fields which effectively covered the range of spectra presented in Table 1. This assumption is, of course, only true in as much as the mean energy and H*(10) values are characteristics of the spectra which can be linked to the degree of dosemeter under- or over-response to be expected.

**Table 2. Radionuclide source calibration fields and the Cadarache realistic field**

| Calibration field number | Description | Mean energy (MeV) | Mean H*(10) (pSv) |
|---|---|---|---|
| 4 | Cadarache realistic field | 0.096 | 40.0 |
| 5 | $D_2O$ moderated $^{252}$Cf | 0.539 | 105 |
| 6 | $^{252}$Cf spontaneous fission | 2.13 | 384 |
| 7 | $^{241}$Am-Be ($\alpha$,n) source | 4.15 | 391 |

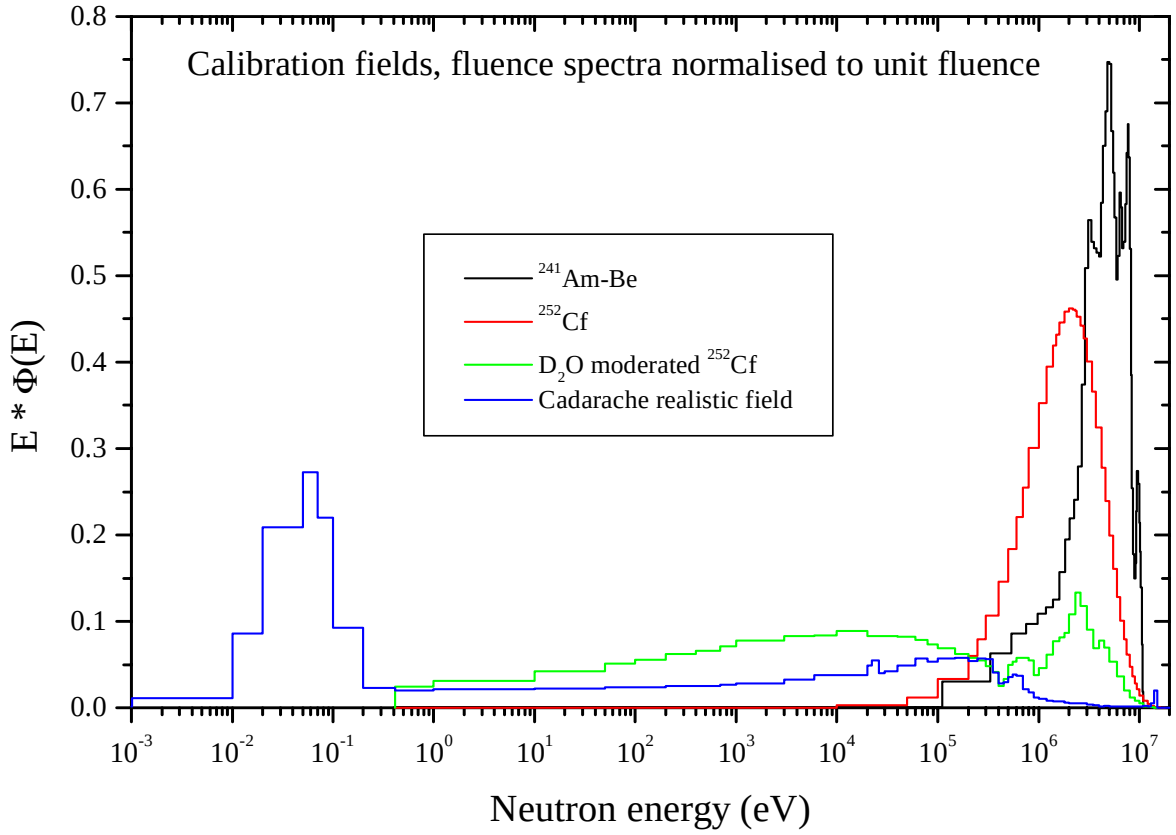



**Figure 3.** Spectra of conventional radionuclide source based calibration fields, plus that of the Cadarache realistic calibration field.

After the assignment of spectra into groups had been made, and the decision taken to try to simulate a very soft field, the spectra measured around PWRs and gas-cooled reactors were examined for common characteristics. It was immediately obvious that there was by no means a single unique spectrum characteristic of workplaces in these environments. Although this makes the problem of finding a suitable RNCF more difficult, it does not preclude the possibility on one existing since the requirement is not that the calibration spectrum is identical to the field spectrum but provides an appropriate calibration. The exact shape of the spectrum in regions where dosemeter response is proportional to dose equivalent, or where the dose equivalent contribution is very small, is not important.

Certain common features were evident in the PWR and gas cooled reactor spectra, and these were:

i) a large thermal neutron component,
ii) a significant intermediate energy component,
iii) the absence of neutrons above about 1 MeV.

The last finding is in many respects the most important characteristic to model since the highest energy neutrons in the spectrum, which are likely to contribute a large fraction of the dose equivalent, occur in an energy region where the fluence to dose equivalent conversion coefficients vary rapidly with energy. The dose equivalent per unit fluence is thus going to be particularly sensitive to the exact spectral distribution in this region. This region is also one where the response of dosemeters (personal dosemeters in particular) begin to deviate from being reasonably dose equivalent.

## 4 SIMULATION OF POSSIBLE REALISTIC CALIBRATION FIELDS

Potential realistic fields were simulated using the Monte Carlo neutron/photon/electron transport code MCNP version 4A[24], developed at the Los Alamos National Laboratory in New Mexico, USA. It is an excellent tool for investigating such realistic fields as it has very flexible geometry routines, enabling the study of a variety of different configurations and materials with relative simplicity.

MCNP does, however have its limitations. For this work, the neutron source terms have to be defined in terms of intensities, energies and angles of emission, which is ideal for radionuclide sources where this information is known, but makes the simulation of accelerator-produced neutron sources more problematic. The charged particle interactions in a neutron-producing target have to be determined separately, allowing the particle to be slowed as it crosses the target material, thereby creating a continuum of neutron energies and angular distributions, especially in 'thick' targets. Investigating the use of the Van de Graaff, for example, in the production of realistic neutron fields therefore required the development of programs that could calculate the neutron-production characteristics of the slowing charged particle in a given thickness of target material, and then convert the data into a form acceptable to MCNP.

The approach adopted at NPL in this respect was to divide a thick target into microscopic slices, each causing an energy loss for the bombarding particle of the order of a few keV (the exact amount being a parameter in the program). For each slice the mean energy of the slowing particle was calculated and then the secondary neutron energy-angle distribution determined, together with the absolute yield and the results then saved in individual files. A second program then took these files and converted them into an MCNP neutron source term of variable energy, angle and intensity.

A number of potential geometries were investigated using either accelerator-based or radionuclide source terms, using various materials as both moderators and reflectors. The radionuclide work concentrated on $^{252}$Cf, as it offers both high emission rates and a lower mean energy compared to the other two ISO-recommended sources, namely $^{241}$Am-Be and $^{241}$Am-B. Three different configurations based on $^{252}$Cf are shown in Figure 4, namely a complete enclosure, a reflector and a moderator. It can be seen that, of the three, the enclosure is by far the best, being both the softest and having the highest integral fluence, despite having a source-detector distance of 175 cm compared to 150 cm for the other two. The enclosed volume used (about 4 m$^3$) is sufficiently small to create a high fraction of lower energy scattered neutrons. In view of the success of this approach, several other configurations based on the 4 m$^3$ enclosure were investigated, the three most interesting being shown in Figure 5. Reducing the moderation from a 50 cm cone to a disk of 5 cm diameter and 2.5 cm thickness naturally increases the high energy component whilst maintaining the fluence of intermediate energy neutrons; conversely, placing the

$^{252}$Cf source inside a 30 cm diameter $D_2O$ moderator and further degrading the spectrum by a cylinder of polyethylene 30 cm in diameter and 40 cm long, creates a very soft neutron field. However, all three approaches show energy tails which extend to roughly 10 MeV. Although ideal for some workplace spectra, they were not ideal for workplaces which have few neutrons above 1 MeV.

Although less energetic sources exist ($^{241}$Am-Li, $^{241}$Am-F), their spectra are not as well known and their emission rates are very low. Nevertheless, it may be worth investigating these in the future, as a source-based realistic calibration field facility.

In order to avoid the problems of the high energy neutron tail, accelerator-based reactions such as $^{7}$Li(p,n), T(p,n) and D(d,n) were investigated, since the incident charged particle energies can be selected to limit the maximum energy of neutron produced from 5 MeV down to 1 MeV or less. These accelerator-based models, however, could not use an enclosure as described for the radionuclide source work due to the logistical difficulties of manoeuvring such a massive artefact in the environs of the accelerator beam line and target assembly. This meant that the moderation of the neutron energies had to be achieved by other means.

Whilst performing the accelerator-based calculations, it quickly became clear that the $^{7}$Li(p,n) reaction was better suited than the other two, for two reasons:

i) it has the highest yield per incident proton and
ii) produces the lowest neutron energies.

For these reasons, the bulk of the modeling concentrated on this reaction.

A large number of different moderating schemes were investigated, utilising reflectors and moderators of a variety of materials, three of which can be seen in Figure 6. The configuration most appropriate for the requirements of the project was clearly configuration (a): the 40 cm diameter spherical moderator of $D_2O$ around a “thick” $^{7}$Li(p,n) target (“thick” in this instance meaning of sufficient thickness to slow a 3.5 MeV proton to 1.9 MeV - the threshold of the reaction). This combination had the advantage of limiting the neutron fluence at the highest neutron energy (about 2 MeV) whilst creating a moderated spectrum without excessive numbers of thermal neutrons.

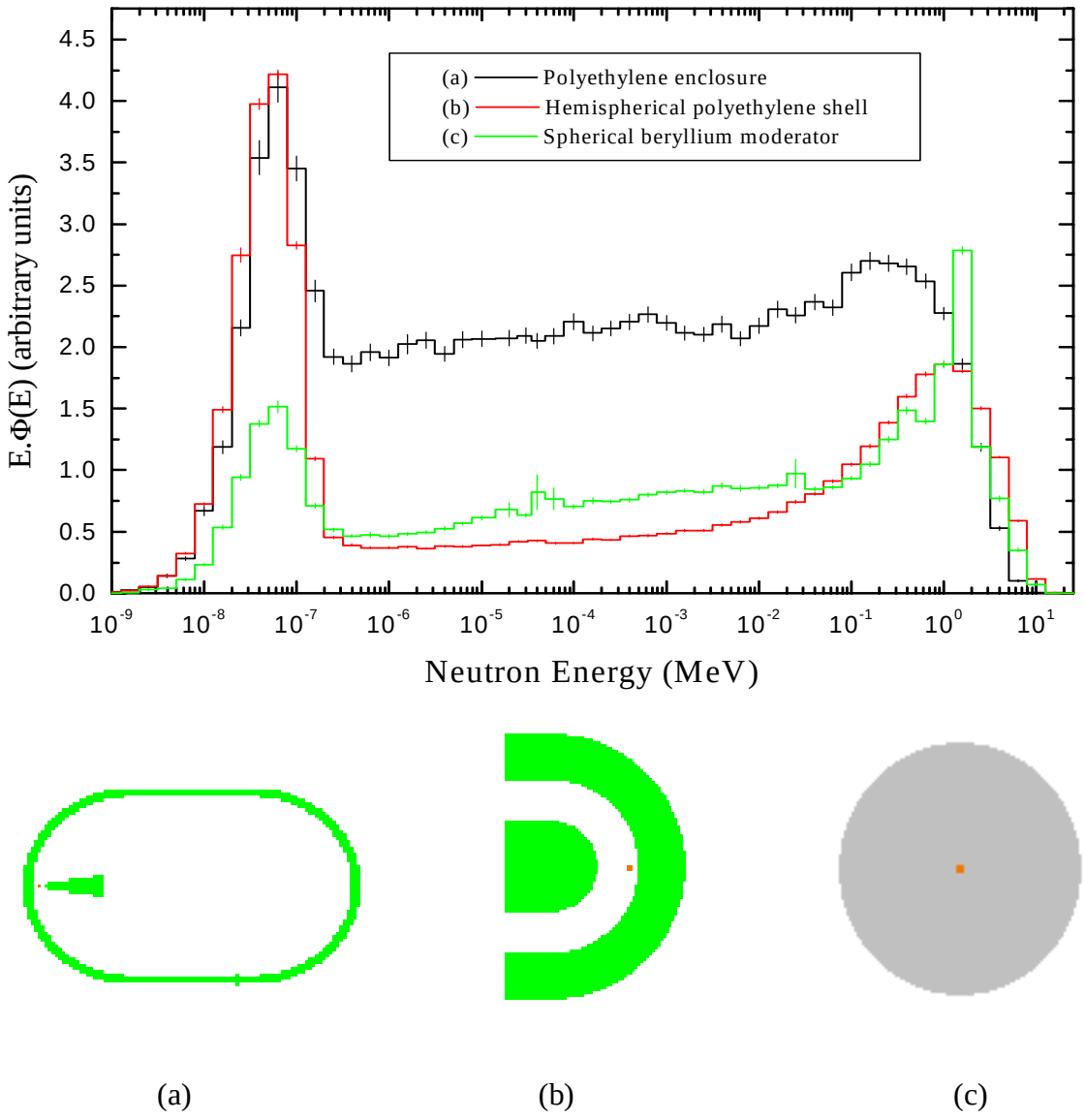



**Figure 4.** Comparison between spectra produced by degrading the neutrons produced by $^{252}$Cf. (a) Cylindrical polyethylene enclosure 100 cm long, inner diameter (id) 160 cm, outer diameter (od) 170 cm, with hemispherical ends. Source 5 cm inside first hemispherical shell, detector at centre point of opposite hemispherical shell (source-to-detector distance (SDD) 175 cm). 50 cm long blocker cone 3 cm in front of source. (b) Hemispherical polyethylene shell, id 20 cm, od 30 cm, source 2.5 cm inside shell (SDD 150 cm), 10 cm diameter hemispherical blocker, centred at center point of shell. Cylindrical extensions to both shell and blocker 5 cm long. (c) Spherical beryllium moderator, 30 cm diameter (SDD 150 cm).

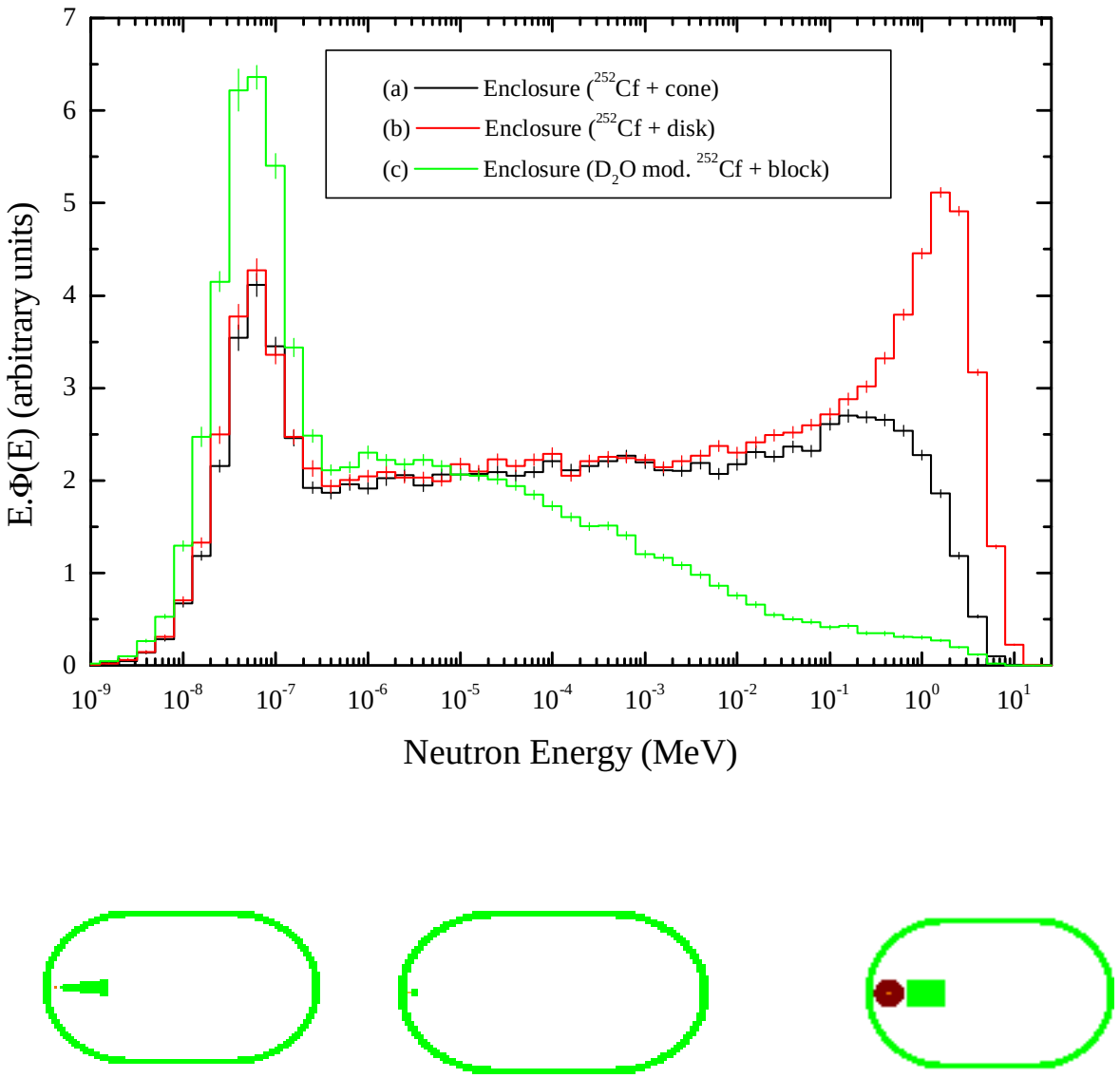
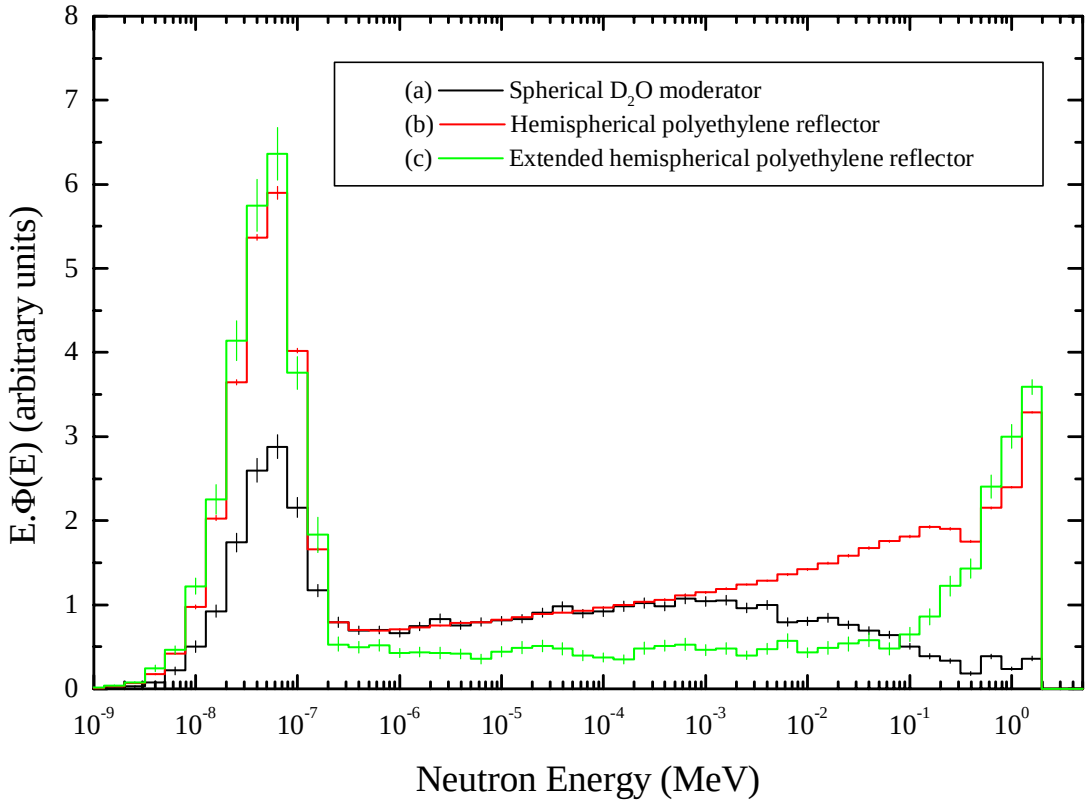
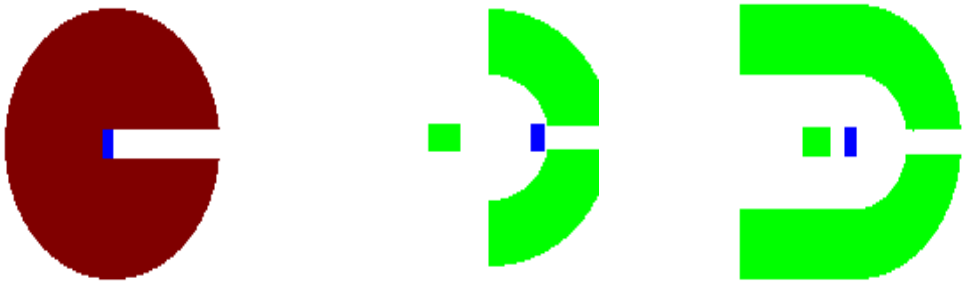



**Figure 5.** Comparison between spectra produced using the polyethylene enclosure for different configurations of $^{252}$Cf source (detector located at central point of second hemispherical shell in all cases). (a) Source 5 cm inside first hemispherical shell (SDD 175 cm), 50 cm long blocker cone 3 cm in front of source. (b) Source 5 cm inside first hemispherical shell (SDD 175 cm). Disk blocker 5 cm diameter, 2.5 cm thick, 3 cm in front of source. (c) Source within 30 cm diameter $D_2O$ moderator, centred 20 cm within first hemispherical shell (SDD 160 cm). Cylindrical blocker, 30 cm diameter, 40 cm thick, 5 cm in front of $D_2O$ moderator.



(a) (b) (c)

**Figure 6.** Comparison between spectra produced by degrading the neutrons produced by 3.5 MeV protons on $^{7}$Li (detector 150 cm from target in all cases): (a) 40 cm diameter sphere of $D_2O$ centred on the target. (b) Hemispherical shell of polyethylene, id 20 cm, od 40 cm, target 1 cm inside shell, cylindrical blocker 4 cm diameter, 5 cm long 14 cm in front of target. (c) As (b) except: target at centre point of hemispherical shell (cylindrical blocker therefore 5 cm in front of target) and inclusion of 22 cm long cylindrical extension to hemispherical shell. The dark blue rectangle represents a water cooling element on the face of the neutron producing target.

Reducing the upper limit of the neutron energy was then investigated simply by lowering the incident proton energy, as shown in Figure 7. Reducing the incident proton energy from 3.5 MeV to 2.3 MeV reduces the maximum neutron energy produced from about 1.9 MeV to 565 keV. This ability to alter the maximum neutron energy in a region where the fluence to ambient dose equivalent conversion factor is increasing provides extra flexibility when creating accelerator-based realistic fields.

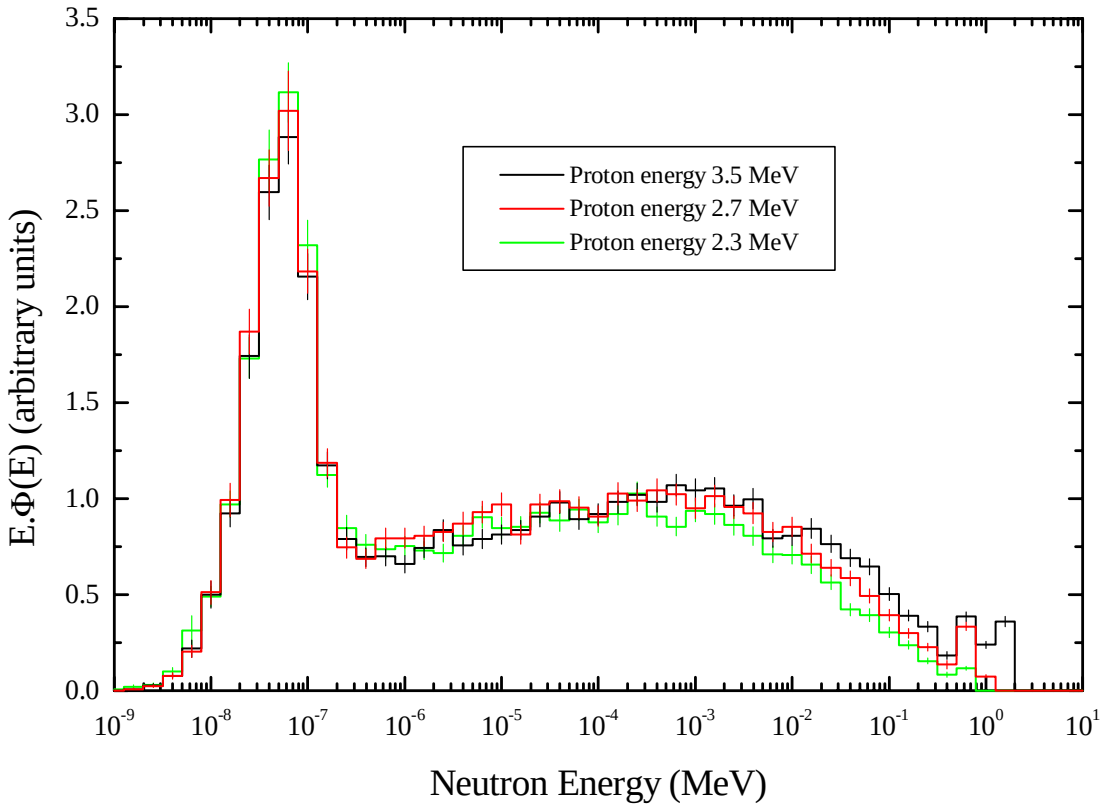



**Figure 7.** Comparison between spectra produced by varying the incident proton energy for the $^{7}$Li(p,n) reaction moderated by a 40 cm diameter sphere of $D_2O$.

## 5 THE CHOICE OF CALIBRATION FIELDS TO BE INVESTIGATED

Since one of the main aims of this work was to investigate the extent to which dosemeter under- or over-response depends on the spectrum of the calibration field, the calibration fields to be included in the investigation were chosen to have as wide a range of mean energies as possible. The conventional calibration fields, i.e. $^{241}$Am-Be, $^{252}$Cf, and $D_2O$ moderated $^{252}$Cf, were obvious choices. These have rather high mean energies as shown in Table 2, although the $D_2O$ moderated $^{252}$Cf field has a mean energy within the range of values for the workplace fields shown in Table 1. The existing RNCF at Cadarache was also chosen since it is well characterised, and has a mean energy which is significantly lower than that of $D_2O$ moderated $^{252}$Cf.

In order to extend the investigation, calibration fields with mean energies at the bottom of the range were required. Three fields, which the results of Section 4 indicate could be simulated in the laboratory, were chosen. Two of these were similar in being based on the use of the $^{7}$Li(p,n) reaction and a $D_2O$ moderator, the only difference being the energy of the proton beam used to bombard the lithium target. These fields are designated by "$^{7}$Li(p,n) $E_P$ = 2.3 + $D_2O$" for bombardment with 2.3 MeV protons, and "$^{7}$Li(p,n) $E_P$ = 3.5 + $D_2O$" for 3.5 MeV protons. The third field, which is designated as "Enclosure + $D_2O$", is based on the use of a $D_2O$ moderated $^{252}$Cf source in a small polyethylene enclosure. The enclosure produced a significant scattered neutron component in the field, and there was also an additional moderator block of 40 cm of polyethylene to further reduce the energy of the neutrons. The characteristics of the three chosen fields are listed in Table 3 which also includes details for the $D_2O$ moderated $^{252}$Cf for comparison. The spectra of these three fields are shown in Figure 8 which similarly includes the $D_2O$ moderated $^{252}$Cf spectrum for comparison. Although the $^{7}$Li(p,n) $E_P$ = 3.5 + $D_2O$ spectrum and the Enclosure + $D_2O$ spectrum have very similar mean energies and average H*(10) values, the spectral shapes are rather different and so both were included in the analysis.

**Table 3. Three proposed realistic calibration fields with the $D_2O$ $^{252}$Cf source for comparison**

| Calibration field number | Description | Mean energy (MeV) | Mean H*(10) (pSv) |
|---|---|---|---|
| 1 | $^{7}$Li(p,n) reaction, 2.3 MeV protons, with $D_2O$ moderator | 0.0083 | 15.8 |
| 2 | $D_2O$ moderated $^{252}$Cf in polyethylene enclosure with moderator block | 0.0325 | 21.2 |
| 3 | $^{7}$Li(p,n) reaction, 3.5 MeV protons, with $D_2O$ moderator | 0.0374 | 27.2 |
| 5 | $D_2O$ moderated $^{252}$Cf | 0.539 | 105 |

The calibration fields chosen provide a selection of spectra with mean energies extending from less than the average mean energy for the softest workplace spectral group, to greater than that for the hardest workplace group. The distribution of mean energies for both calibration fields and workplace field groups is illustrated in Figure 9.

## 6 THE CHOICE OF DOSEMETERS TO BE INVESTIGATED

In order to use the computer program SPKTBIB to predict dosemeter responses in various workplace fields the response function of the dosemeter over the full energy range of interest, i.e. the thermal region to about 20 MeV, needs to be available. This was therefore one of the main considerations in choosing dosemeters to investigate. The second criterion was that they were dosemeters which were either currently in use, or were under consideration for use, in the UK[1].

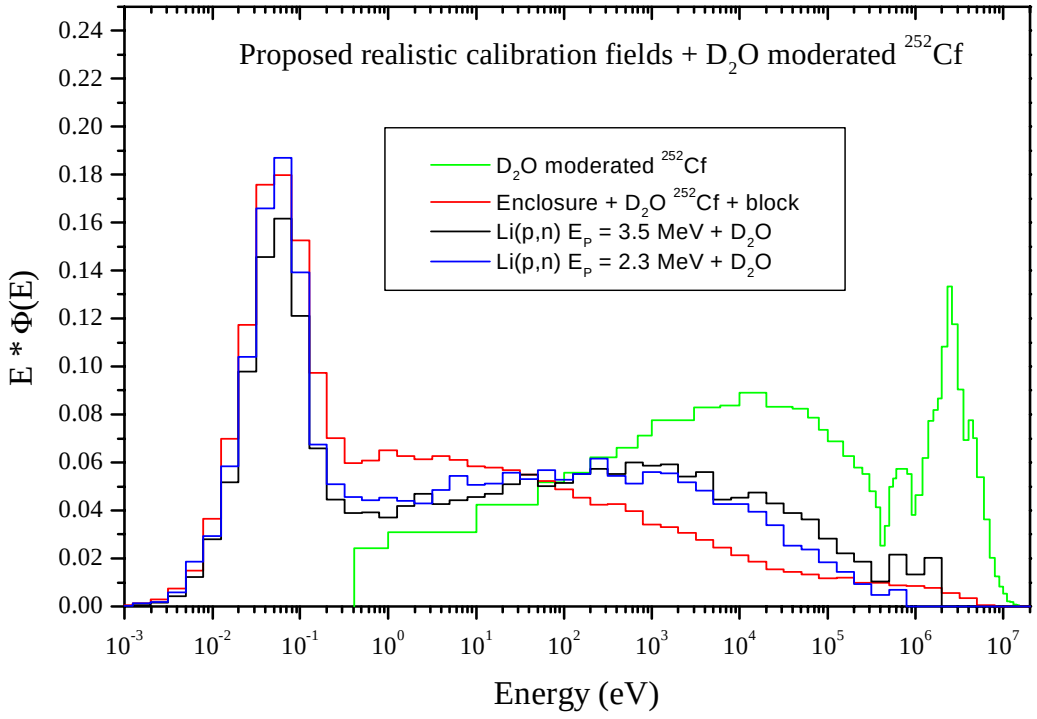



**Figure 8.** Spectra of the three proposed new realistic neutron calibration fields, plus $D_2O$ moderated $^{252}Cf$ spectrum for comparison.

[1] Note: mention of any particular commercial product in this report does not in any way imply recommendation or endorsement by the National Physical Laboratory.

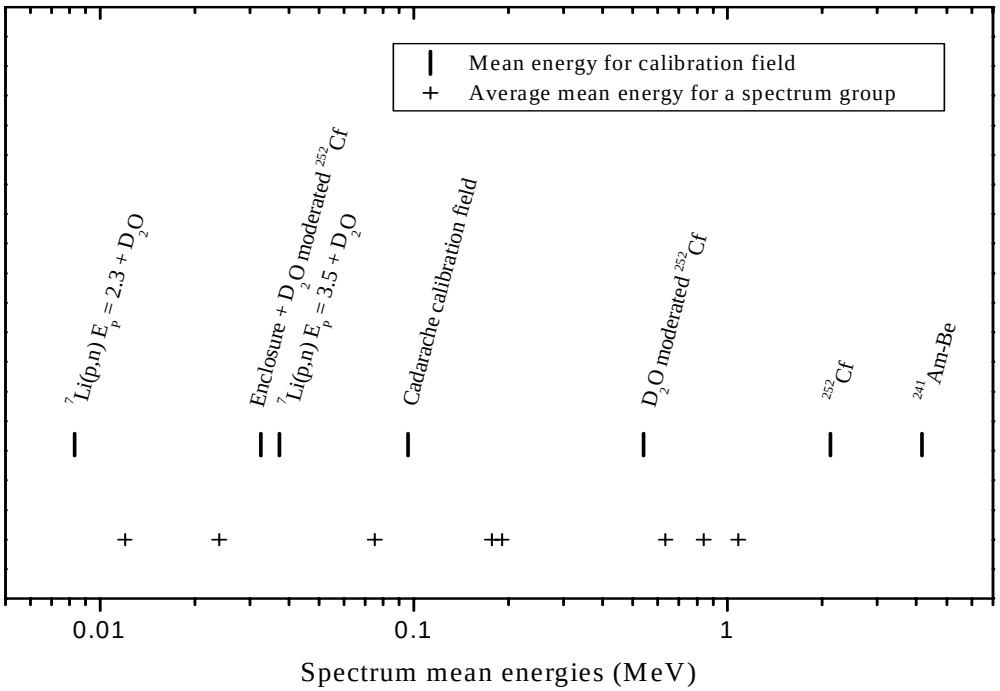



**Figure 9.** Comparison of average mean energies for the eight selected spectral groups with the mean energies of various existing and proposed calibration fields.

All the dosemeters considered, with the exception of one of the area survey instruments, were originally designed to measure the quantities in use prior to the changes recommended by ICRP Publication 60. Some were, in fact, conceived prior to the introduction of the ICRU operational quantities, and were designed to measure the earlier limiting quantity, maximum dose equivalent, MADE[25]. The implications of the various changes in the quantities for the results of the present investigation are, however, minimal. The changes in the fluence to dose equivalent conversion coefficient curves have mostly been in terms of the overall normalisation, and the shapes have changed little. Allowance for the changes in the quantities can thus, to a large extent, be made simply by changing the quantity used at the calibration stage. The effects of the changes resulting from the recommendations of ICRP Publication 60 were nevertheless investigated, and the calculations confirmed that the effect was small. Some typical results are presented in Section 7.

### 6.1 Area survey instruments

Five area survey instruments were chosen, and their characteristics are outlined in the sub-sections below. Four were 'conventional' area survey devices based on a thermal neutron sensor at the centre of a moderating sphere or cylinder of polyethylene. The size of the moderator, and certain internal embellishments, e.g. the presence of a perforated cadmium or borated plastic shell, are designed to give the device a response function shape which matches the fluence to H*(10) conversion coefficient curve as a function of neutron energy. The degree to which the response function matches this curve is a measure of the extent to which the response is proportional to dose equivalent.

The fifth instrument was a 5" diameter tissue equivalent proportional counter, TEPC, whose underlying principle of operation is rather different from the other four dosemeters. It provides a measure of the dose distribution as a function of lineal energy, which is taken as an approximation of linear energy transfer, L, and from this information an estimate can be made of both photon and neutron dose equivalent. For the TEPC to provide ambient dose equivalent readings the requirements for the response function shape are, however, the same as for the four moderator-based devices. (TEPCs are made commercially in the USA, hence the non SI unit for the diameter. This dimension, in inches, tends to be used as a label for the counter size.)

Figure 10 shows the fluence response functions and compares them to the fluence to ambient dose equivalent conversion coefficient curve. All the curves have been normalised so that, when folded with a $^{252}$Cf spectrum, they give either unit response, in the case of the dosemeters, or unit H*(10) in the case of the conversion coefficients. (The dose equivalent responses shown in Figure 1(a) represent the ratios of the dosemeter fluence responses to the fluence to dose equivalent conversion coefficients.)

### 6.1.1 Harwell Instruments Model 0949 Neutron Dose Equivalent Monitor

This instrument consists of a spherical $^{3}$He proportional counter at the centre of a 20.8 cm diameter polyethylene sphere. Originally known as the type 0075, the instrument is also often described as the Leake counter[26, 27]. The same sphere size and central thermal neutron sensor are also used in the NE Technology Mark 7 NRM, and in the Harwell Instruments N91, so their responses should be very similar if not identical.

The response function used for this instrument[28] was based on data reported by Harrison[29], but also contains some additional, more recently measured, data. Figure 10 shows that over most of the energy range of interest this device tends either to measure the dose equivalent correctly or over-respond, and the over-response can be up to a factor of nine at intermediate energies. The response in a workplace field would thus be expected to always be at, or above, the correct value.

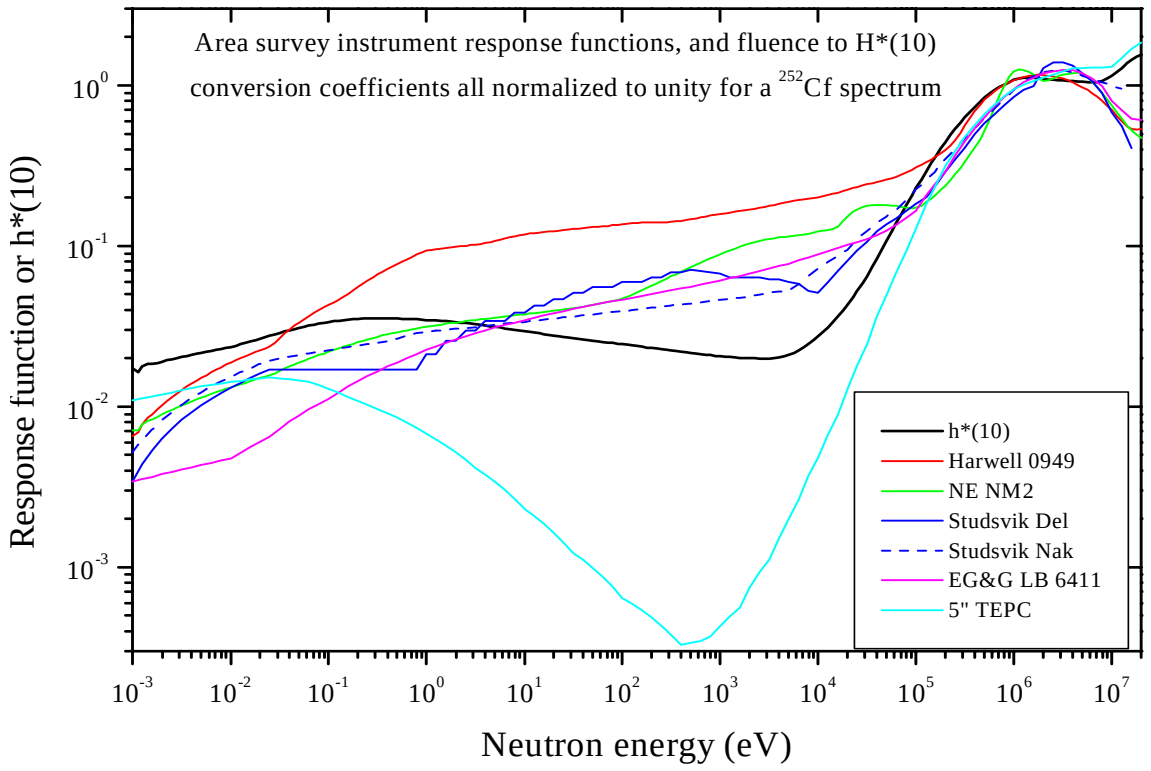



**Figure 10.** Fluence response functions for area survey instruments compared with the fluence to ambient dose equivalent coefficient curve.

### 6.1.2 NE Technology Neutron Monitor Type NM2

The central thermal neutron sensor for this instrument is a cylindrical boron trifluoride, $BF_3$, proportional counter, and the polyethylene moderator is also cylindrical with a diameter of 21.6 cm and a length of 25 cm. It is similar in design to an instrument described by Andersson and Braun[30], although the moderating cylinder of the NM2 is slightly shorter and wider. This design of instrument is sometimes referred to as an Andersson-Braun type monitor.

No detailed evaluation of the response function for this instrument has been published, and the response curve used[28] is probably not as reliable as that for the 0949 instrument. The shape of the function is somewhat different to that for the 0949 having a degree of under-response in the 100 keV to 1 MeV region, less of an over-response in the intermediate energy region, the maximum value being a factor of between five and six, and an under response at thermal energies.

### 6.1.3 Studsvik 2202 D Neutron Dose Rate Meter

The Studsvik 2202 D, originally described by Widell and Svansson[31], has certain similarities to the NM2, being based on a cylindrical $BF_3$ central sensor. Its cylindrical moderator is about 2 cm shorter, and the end of the cylinder furthest from the electronics has a rounded end giving it a more isotropic response.

Again, no detailed evaluation of the response function has been published, and for the present exercise two functions were used. One was obtained from Delafield at AEA Technology[32], and

represents a rough evaluation based on a limited data set. The other function was taken from a paper by Nakamura et al.[33] which tabulates a series of response values at 23 neutron energies. Nakamura's data set, however, contain no values below 0.414 eV and the response curve was therefore extended into the thermal region using data obtained from the graph given in the instrument manual. The response functions probably have rather large uncertainties, and one of the reasons for using the two functions was to obtain some idea of the uncertainties these introduce in the calculated workplace responses.

### 6.1.4 EG&G Berthold LB6411

This instrument has a $^{3}$He detector at the centre of a 25 cm diameter polyethylene moderator. The central sensor is more efficient than that of the other instruments considered, and sensitivity of the device is thus higher. This instrument also differs in that it was specifically designed to measure the new operational quantities resulting from the changes to the Q(L) relationship recommended in ICRP Publication 60.

The LB 6411 has probably the best known response function of any of the survey instruments considered. Its response has been calculated at a large number of energies using the MCNP neutron transport code, and has also been measured at several monoenergetic energies and with a thermal beam[34]. Its response function is rather similar to that for the NM2 and the Studsvik, all three having a degree of under-response in the 100 keV to 1 MeV region, an over-response in the intermediate energy region, and an under response at thermal energies.

### 6.1.5 A 5" TEPC

The final survey instrument, a 5" TEPC, was included because its response function is dramatically different to that of 'conventional' moderator-based devices. As can be seen from Figure 10, the TEPC under-responds significantly in the intermediate energy region. A TEPC based device can be significantly lighter than conventional survey instruments, and interest in its use for area monitoring has been expressed in a number of quarters. A 5" diameter instrument was chosen since response function data were available for this size detector. The only presently commercially available TEPC-based instruments, the HANDI and the REM 500, both unfortunately use 2" diameter counters; however, the differences in the response functions between a 2" and a 5" counter are not expected to be very significant since both are designed to mimic a 2 μm volume of tissue. The 5" device will, nevertheless, be more efficient.

A response function for use in the present work was derived using data from two sources: an evaluation by Waker[35], and recent Monte Carlo calculations at NPL[36]. Both approaches gave very similar curves except that the minimum of the dip in the intermediate energy response in the calculations by Taylor at NPL was at a slightly higher energy. The response function used for the present work was a simple average of the two.

## 6.2 Personal dosemeters

Six personal dosemeters were included in the study. Four were based on poly allyl diglycol carbonate, PADC, track-etch plastic, commonly known under the trade name CR-39, and two were NTA film. The choice reflects the types of personal dosemeters commonly used in the UK. Differences in the responses for the PADC plastic based dosemeters from the various dosimetry services arise from: the use of plastic from different manufacturers, variations in etching techniques, different reading methods, and different designs for the holder of the track-etch element.

The response functions used for all six dosemeters were based on an extensive set of measurements performed at NPL[37,38], supplemented by additional information where available, in some cases from the dosimetry services who issue the dosemeters. More detailed information about the dosemeters can be found in references 37 to 39. Both PADC and NTA film sensors exhibit an energy threshold, which usually occurs in the 100 to 200 keV region for PADC, and at about 500 keV for NTA film, below which the detection efficiency for events due to n-p scattering is negligible. Dosemeter response in the workplace will be very sensitive to the exact energy of this threshold, and this is dependent on factors such as those outlined above, material supplier, etc. Both PADC and NTA film can also detect thermal neutrons, either directly, or by using a converter material, and the response of a dosemeter in a field with low-energy neutrons depends on whether this detection mechanism is utilised. The six response functions represent different combinations of threshold energies and the presence or absence of a thermal response. All six are shown in Figure 11, where they are compared with the fluence to personal dose equivalent conversion coefficient curve. As for the area survey instruments, all the curves have been normalised to unity when folded with a $^{252}$Cf spectrum.

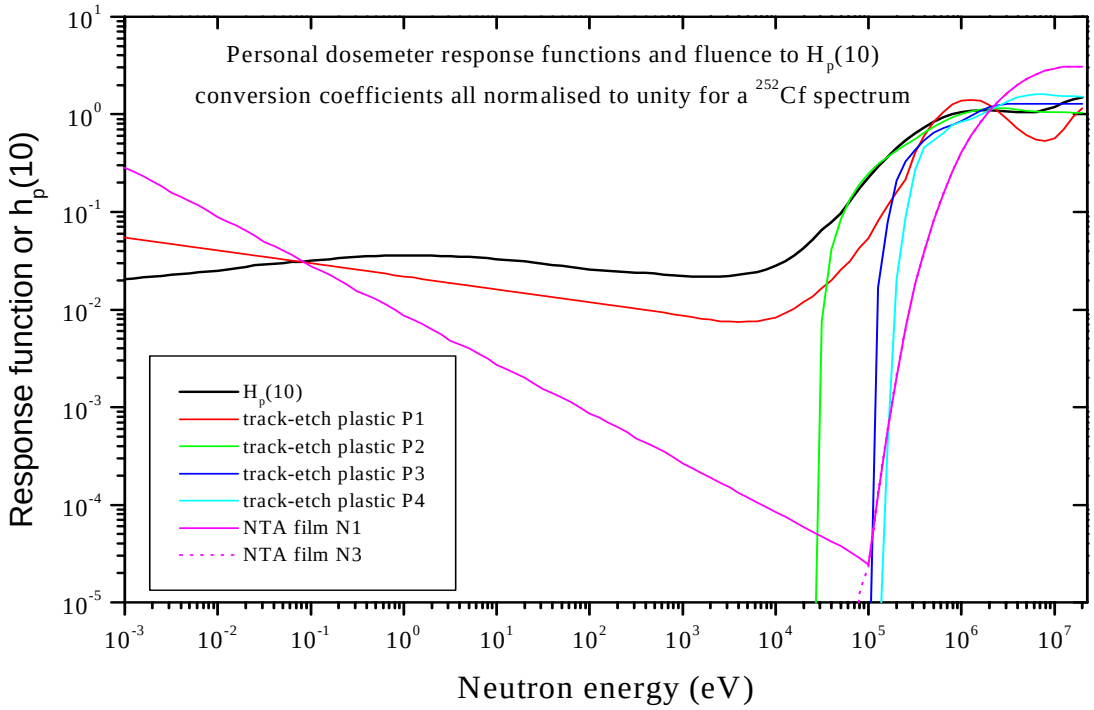



**Figure 11.** Fluence response functions for personal dosemeters compared with the fluence to personal dose equivalent (A-P) conversion coefficient curve.

It should be noted that the results presented for personal dosemeters in the next section represent a prediction for their performance in a plane parallel beam of neutrons. The angular dependence of the response of these types of dosemeters is not ideal; and they have a tendency to underestimate $H_p(10)$ for neutrons incident at angles approaching $0^o$ if calibrated to have the correct response for neutrons of normal incidence. Their responses in workplace fields, where neutrons are usually incident from many angles, will thus tend to be reduced, relative to the correct value.

One notable exclusion from the list of personal dosemeters selected for this study is the albedo dosemeter. There were two main reasons for this. Firstly, they are little used in the UK, and where they are used, mainly around commercial reactors, the dose equivalents seen are very low. Secondly, they are not calibrated in conventional calibration fields such as those from radionuclide sources. The usual approach is to calibrate them at thermal energy, and assume they give an acceptable measure of the dose equivalent up to a particular energy, usually about 25 keV. The dose equivalent from higher energy neutrons is determined, either by using other personal dosemeters, e.g. PADC, or by using site specific correction factors derived from measurements of the field[40].

### 6.2.1 PADC track-etch plastic personal dosemeter P1

The fluence response function for PADC dosemeter P1 differs from those for the other three PADC-based devices in exhibiting a response to thermal and intermediate energy neutrons. This is achieved by locating the PADC element in contact with the nylon holder. Protons from $^{14}N(n,p)^{14}C$ reactions in the nylon are detected by the plastic. The response at intermediate energies is mainly due to detection of backscattered thermal neutrons from the body of the wearer, and the device thus has some of the characteristics of an albedo detector. Data for the response below the fast neutron threshold were calculated, by the dosimetry service, using the Monte Carlo code MCNP, and were normalised to a thermal neutron calibration. Although the device still under-responds at intermediate energies, the presence of a thermal and intermediate energy response is expected to greatly improve performance in soft neutron fields.

### 6.2.2 PADC track-etch plastic personal dosemeter P2

The response function measurements described in reference 37 were performed over a range of neutron energies extending as low as 100 keV; this lower limit being chosen because PADC dosemeters were believed to have a threshold for detecting fast neutrons somewhere above this energy. For dosemeter P2 this turned out not to be the case, and the measurements indicated that the device had a reasonable dose equivalent response down to at least 100 keV. In the absence of any data below this energy, the measured fluence response was extrapolated smoothly to lower energies. This process indicated that the response ceases to be proportional to dose equivalent somewhere very roughly in the energy region between 30 and 60 keV. In view of the extrapolation process, the shape of the response function below 100 keV is, however, very uncertain. Nevertheless, this device certainly has the lowest threshold for fast neutron detection of the four PADC dosemeters investigated here.

### 6.2.3 PADC track-etch plastic personal dosemeter P3

Dosemeter P3 is in many respects a conventional PADC dosemeter with a threshold which is somewhat higher in energy than for P2. The response as a function of energy decreases as the energy decreases more rapidly than for P1.

### 6.2.4 PADC track-etch plastic personal dosemeter P4

Dosemeter P4 has a detection threshold at a higher energy than any of the other PADC-based devices, and as such would be expected to have the largest under-response in workplace fields. This is, however, probably not a true reflection of the capabilities of this particular dosemeter. P4 contains three elements of PADC arranged on a small foam pyramid. None of the elements was normal to the direction of incidence of the neutrons used when measuring the response function. The mechanism whereby events are recorded in PADC plastic results in the detection threshold energy increasing as the angle of incidence decreases from $90^{o}$ towards $0^{o}$. The main characteristic of dosemeter P4 is that it has a much more isotropic dose equivalent response, and the advantage of this design can only be assessed if the angular dependence of the neutrons in the field is taken into consideration.

### 6.2.5 NTA film personal dosemeter N1

NTA film exhibits a higher energy fast neutron detection threshold than PADC track-etch plastic and this fact is shown clearly in Figure 11. The response also appears to continue to increase with neutron energy up to about 10 MeV. NTA film has an inherent thermal neutron sensitivity, from the presence of nitrogen in the emulsion, and the response of dosemeter N1 thus shows a significant response at thermal energies. There is also a small, but nevertheless non-zero, response in the intermediate energy region. This intermediate energy response was calculated simply from the $^{14}N(n,p)^{14}C$ cross section, without including any allowance for a response to thermal neutrons backscattered from the body of the wearer. In reality, therefore, the intermediate energy response is probably better than that shown.

### 6.2.6 NTA film personal dosemeter N3

Some dosimetry services exclude thermal neutrons from NTA film elements, by covering them with a layer of cadmium, for example. The reason is presumably to make the dosemeter simply a fast neutron device without any of the complexity of a poorly known intermediate and thermal energy response. Dosemeter N3 is of this type. The response function was obtained by assuming a device with exactly the same fast neutron response as for dosemeter N1, but a zero response for intermediate and thermal energies.

The dosemeters designated P1, P2, P3, P4, and N1 are the same as those designated by these codes in references 37, 38, and 39. Dosemeter N3 does not correspond to N2 in references 37 and 39, but is in fact a hypothetical dosemeter, being simply N1 with the thermal and intermediate energy response removed.

## 7 RESULTS

The results presented, separately for each of the selected spectral groups, in this section are for the new, post ICRP Publication 60, values of the operational quantities. The differences in the results for the old and the new quantities are, however, very small. There are two reasons why this is the case. Firstly the fact that the shapes of the curves for the old and the new conversion coefficients are very similar, and secondly the fact that all the responses calculated here for workplace fields were derived assuming that the dosemeter had been calibrated to give the correct dose equivalent for a chosen calibration field (see the discussion in Section 2). In this way the effect of the different absolute magnitudes of the new and old conversion coefficients is removed, and differences between results for the two versions of the quantity arise only from differences in

the shapes of the conversion coefficient curves. The differences in the shapes are rather small, as shown in Figure 12.

All the calculations of responses, as performed with SPKTBIB, were actually made for both the old and the new quantities, but the only data for the old quantities shown are those in Figures 13 and 14. These plots compare the results for the two quantities and illustrate that the differences are not significant within the context of the present work. Each figure presents data for one general type of dosemeter, i.e., area survey or personal, in one spectral group. Thus Figure 13 displays results for area survey instruments in the gas-cooled reactor group of spectra, while Figure 14 presents those for personal dosemeters in the types of fields found around transport containers for PWR fuel. The data in both figures are for the calibration fields listed in Table 2. Results for the old quantity are given at the top, and for the new quantity at the bottom. For each dosemeter the average value of the response for all the spectra in the group is plotted, and a different symbol is used to denote the different calibration fields. The vertical line through each symbol is not an error bar, but represents the range of responses for the spectra within the group; the top of the line indicating the maximum value, and the bottom the minimum.

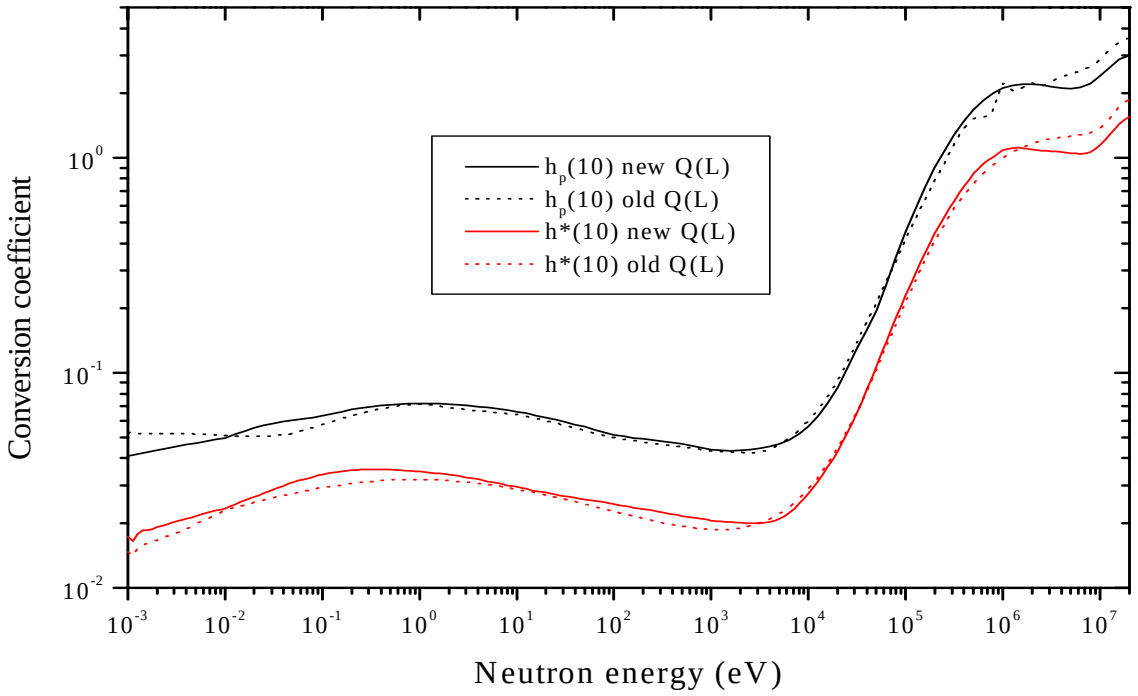



**Figure 12.** Fluence to ambient and personal dose equivalent conversion factors, h*(10) and $h_p(10)$ resectively, initially normalised to unit dose equivalent for a $^{252}$Cf spectrum. Values of $h_p(10)$ have subsequently been multiplied by 1.2 to separate the curves from those for h*(10).

The differences in the results for the old and new quantities are minimal, although there is a tendency, particularly for survey instruments, for the responses for the new quantities to be lower than for the old. This is true even for the LB6411 instrument which was actually designed to have a response matching the new operational quantity. An explanation of the differences can be found by careful examination of the fractions of the dose equivalent in a particular spectrum which occur in energy regions where the shapes of the old and new conversion coefficient curves differ.

The remainder of this section presents the results for the responses of the chosen dosemeters in the eight spectral groups, including information on the dependence on the calibration field used.

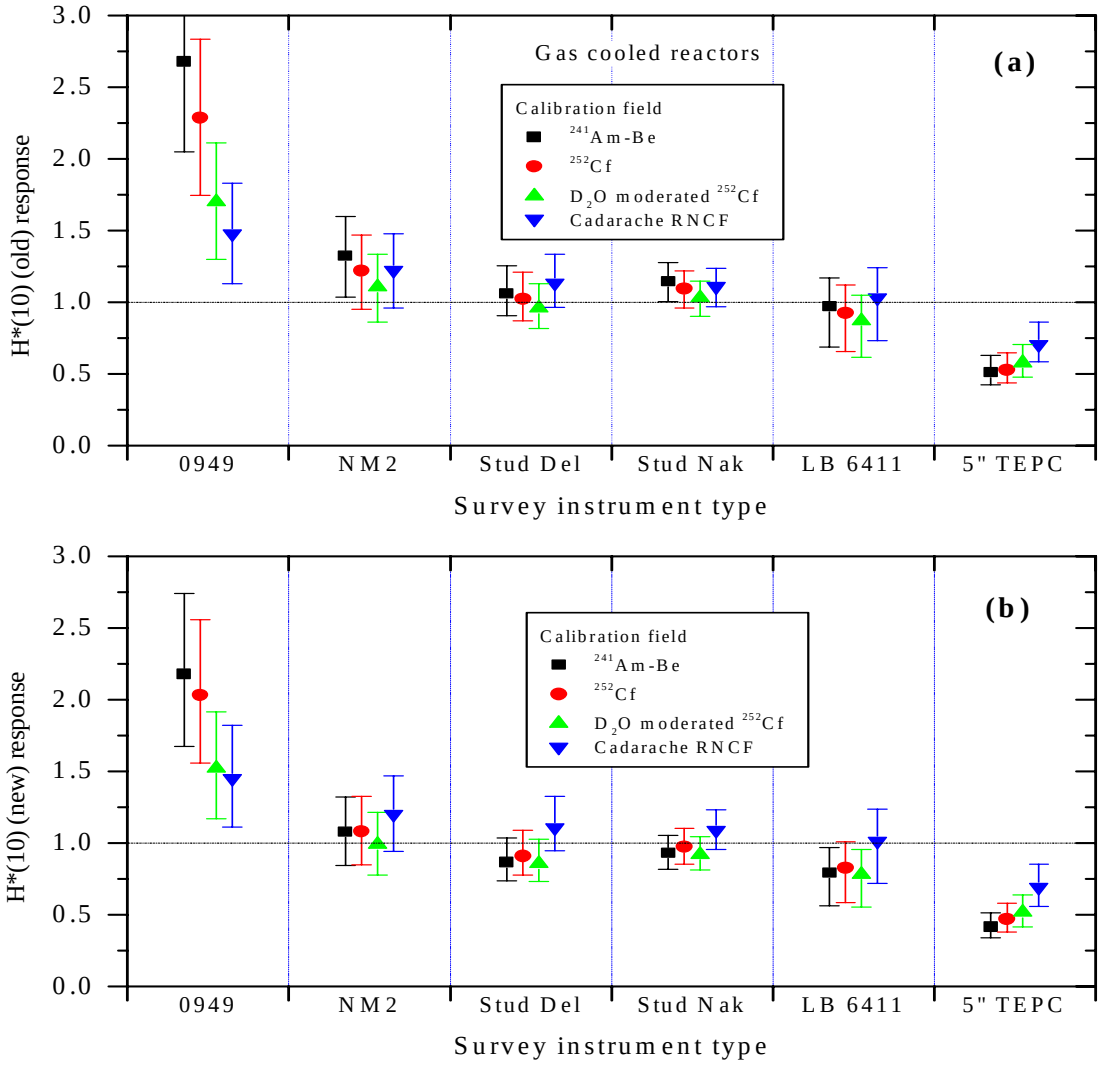



**Figure 13.** Responses for survey instruments: Harwell 0949, NE Technology NM2, Studsvik 2202D - Delafield and Nakamura evaluations, EG&G LB 6411, and 5" TEPC for a group of spectra typical of those found in workplaces around gas cooled reactors. The upper figure, (a), gives the values for the old operational quantity, and the lower (b), for the new operational quantity. Symbols represent mean values of the responses for the group, after calibration in one of the four calibration fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

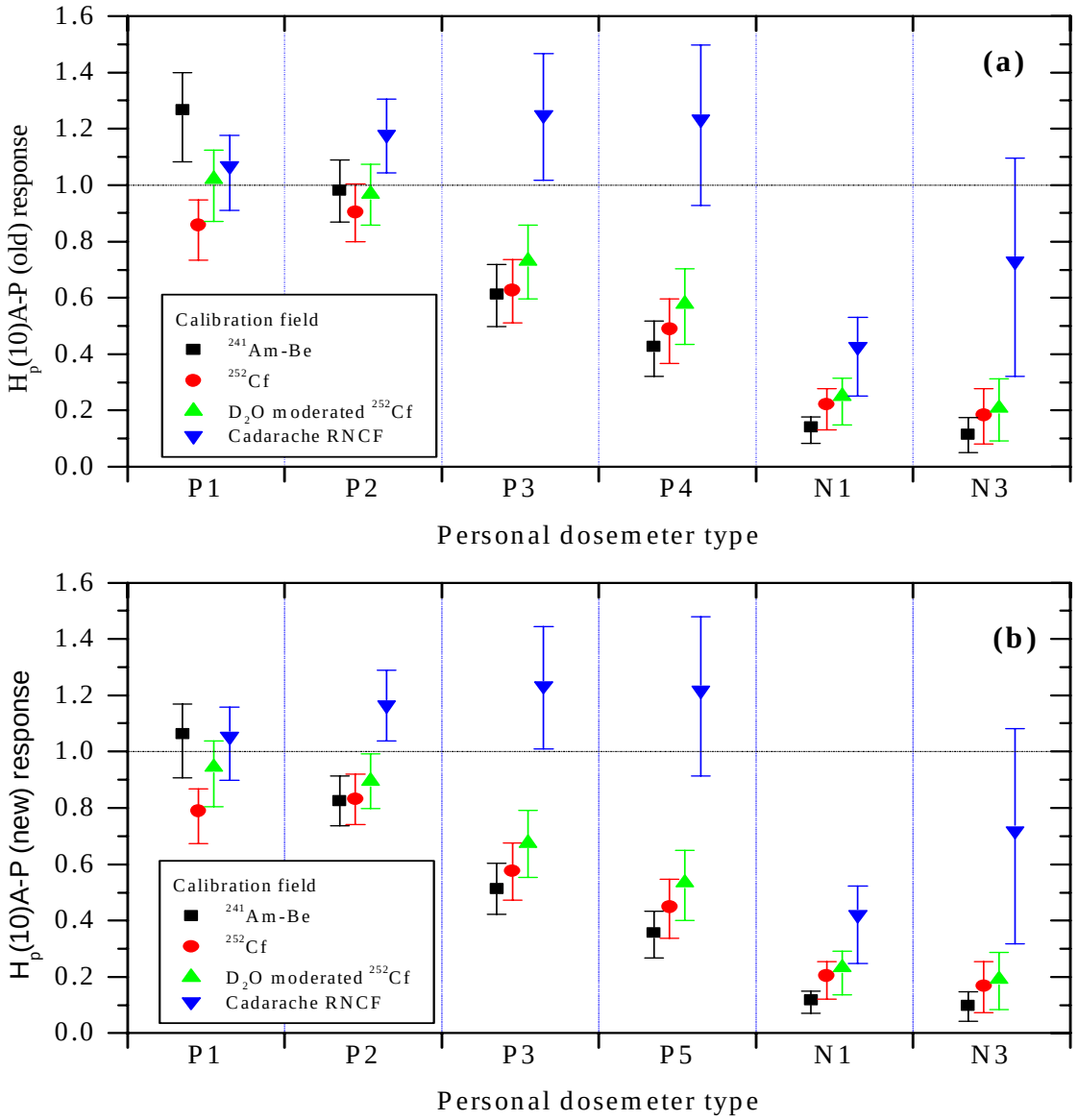



**Figure 14.** Responses for personal dosemeters: P1, P2, P3, P4, N1, and N3 for a group of spectra typical of those found around transpor flasks containing PWR fuel elements. The upper figure, (a), gives the values for the old operational quantity, and the lower (b), for the new operational quantity. Symbols represent mean values of the responses for the group, after calibration in one of the four calibration fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

For each group there is a plot of the spectra included in that group. The spectral data in SPKTBIB were obtained from a number of sources including: existing compilations, published papers, laboratory reports, and private communications. In some cases, the information about the measurement location is very meagre, and the identification of the spectra in the figures has therefore been mostly restricted to a simple indication of the source of the data. These plots are intended only to give a rough indication of the kind and range of spectra included in a particular group.

Following the plot of the spectra are two further figures, one giving the results for the area survey instruments, and one for the personal dosemeters. Each of these two figures is split into two parts, corresponding to the two sets of calibration fields chosen. That corresponding to the conventional calibration fields of Table 2 is at the top of the figure, and is labelled (a), while that corresponding to the realistic calibration fields listed in Table 3 is at the bottom of the figure, and is labelled (b). The $D_2O$ moderated $^{252}Cf$ calibration field is included in both (a) and (b) to provide a point of reference to facilitate comparisons. The format for presenting the data is rather similar to that for Figures 13 and 14 in that the average value for the responses for all spectra in the group is plotted as a symbol, with different symbols corresponding to different calibration fields. A vertical line through the symbol indicates the total range of values from the minimum response, indicated by the bottom of the line, to the maximum, indicated by the top.

It is important to remember that the results for personal dosemeters are for normal incidence on the dosemeter, i.e., they are a measure of the A-P performance of the device. In fields where neutrons arrive from other directions, and this is the majority of cases, the results would also depend on the angular dependence of the response of the dosemeter.

### 7.1 Gas-cooled reactors in the UK

The eight spectra in this group are plotted in Figure 15a. They were measured either by AEA Technology, Harwell[41], or by NPL[42,43], and represent the majority of the available measured workplace spectra around this type of reactor. One spectrum from reference 41, which was measured on a reactor pile cap, was not included in the set. In view of the reduced shielding at this point the spectrum would not be expected to fit in with the others in the group, and special dosimetry requirements apply in this environment where the neutrons are incident mainly from below the position of an individual. All the measurements were performed either with Bonner spheres, or a combination of hydrogen recoil counters and Bonner spheres. The spectra have a low mean energy, the lowest of all the groups, a large thermal neutron component, and practically no neutrons, and hence dose equivalent, in the energy region above about 1 MeV.

Figure 15b presents the data for area survey instrument response in these fields. For the Harwell 0949, which has the largest over-response at intermediate energies, the dependence of the response on the calibration field is very marked, going from an average over-response of nearly a factor of 2.2 for calibration in an $^{241}Am$-Be field, to an average under-response of 24% for the lowest mean energy RNCF. The response decreases monotonically with the mean energy of the calibration spectrum. For the other moderator-based instruments, i.e. the NM2, the Studsvik 2202D, and the LB 6411, the responses are surprisingly good, regardless of calibration spectrum. In the majority of cases, the responses for these three instruments are correct to within about 20%, which is quite reasonable for radiation protection purposes. There is, however, a tendency for the responses to be a little low, and the use of RNCFs does not improve matters, except perhaps, a little surprisingly, the Cadarache RNCF. The rather good response values of the NM2,

2202D and LB 6411 are due to the over-response and under-response in different energy regions cancelling, although the net effect on average, for the 2202D and the LB 6411 at least, is an under-response for the total spectrum. There is little difference between the results for the two evaluations of the Studsvik 2202D response function.

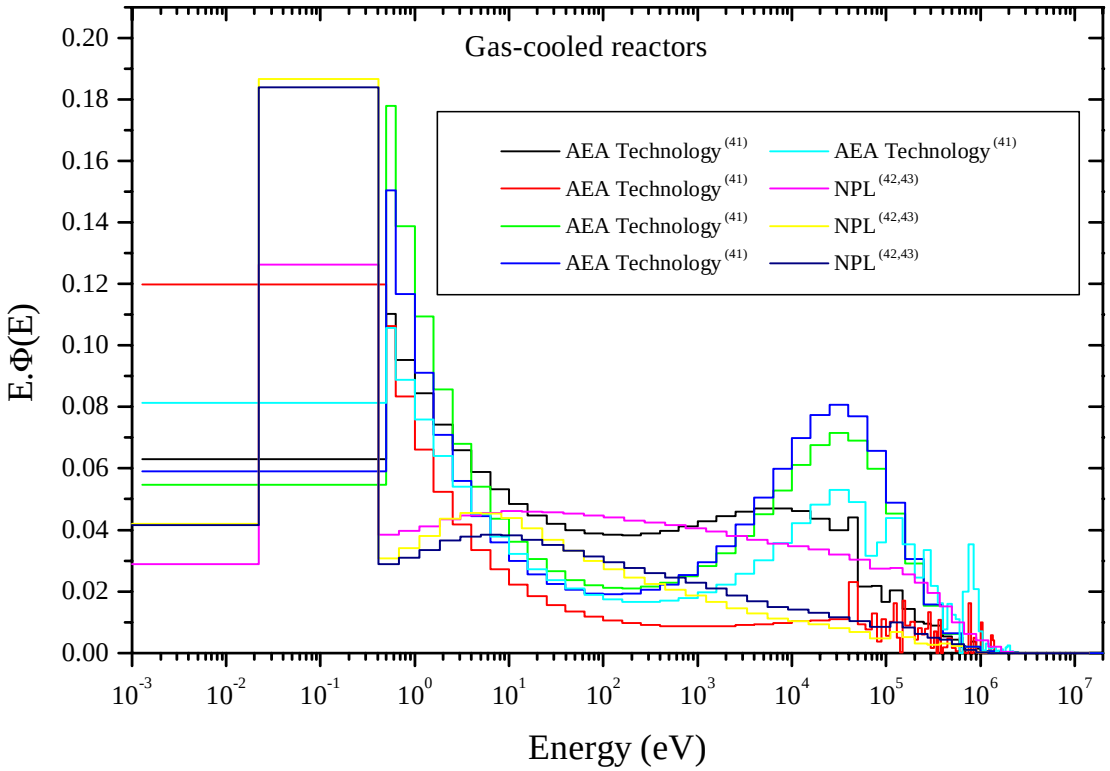



**Figure 15a.** Group of spectra typical of those found in workplaces around gas-cooled reactors in the UK.

For high energy calibration fields the TEPC under-responds, and the response gradually increases as the mean energy of the calibration spectrum decreases. The results for the 5" TEPC tend to be a mirror image of the 0949 when viewed in terms of the deviation from the ideal, i.e., from the line corresponding to a response of unity. This reflects the fact that the dose equivalent response functions of these two devices tend to be mirror images of each other, the 0949 over-responding in the intermediate energy region where the TEPC under-responds.

In Figure 15c the results for the personal dosemeters are presented. Dosemeter P1, which has a response to thermal and intermediate energy neutrons, does rather well for all calibration fields. The reason for this must again be the cancellation of under- and over-response in different areas of the spectrum. For the conventional radionuclide source calibration fields, dosemeters P2, P3, and P4 under-respond by progressively larger amounts, reflecting the increasing energy of the thresholds for these dosemeters on going from P2 to P3 to P4. Use of the RNCFs tends to reduce the under-response, but as the calibration fields get progressively softer, the range of responses for the group tends to increase, i.e., the vertical line through the symbol gets longer.

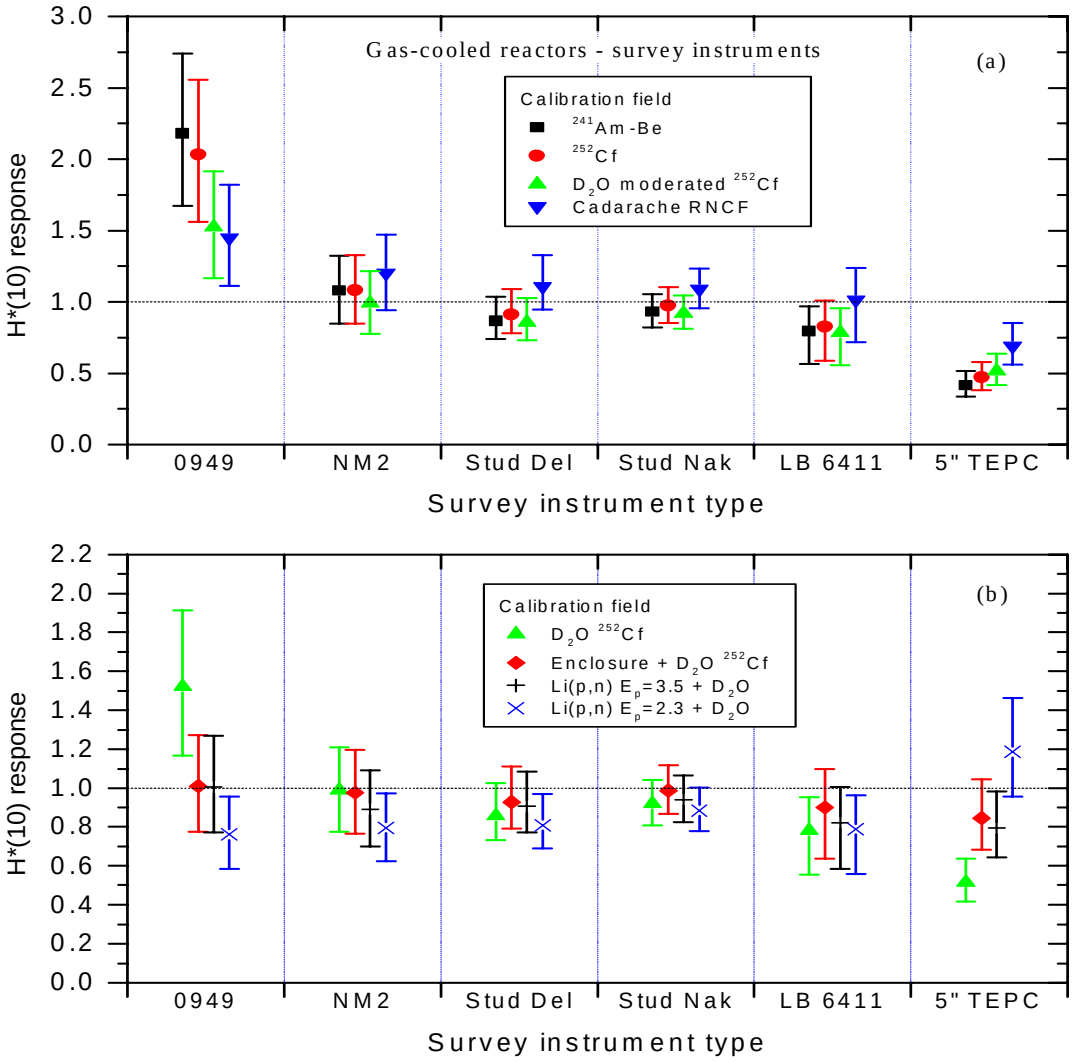



**Figure 15b.** Responses for survey instruments: Harwell 0949, NE Technology NM2, Studsvik 2202D - Delafield and Nakamura evaluations, EG&G LB 6411, and 5" TEPC for a group of spectra typical of those found in workplaces around gas-cooled reactors. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

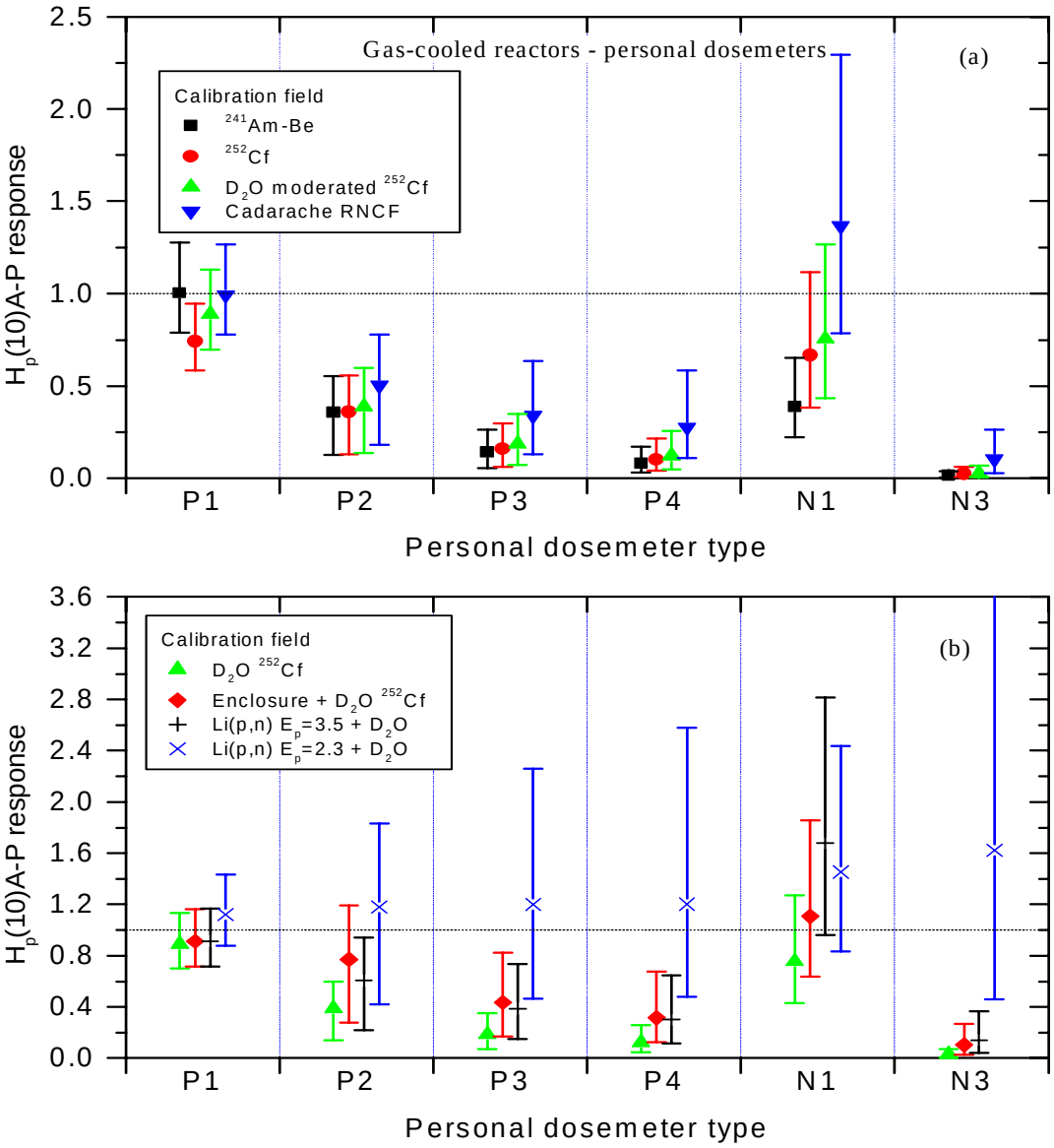



**Figure 15c.** Responses for personal dosemeters P1, P2, P3, P4, N1, and N3 for a group of spectra typical of those found in workplaces around gas-cooled reactors. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

For the two NTA film dosemeters the characteristics are similar to those for the PADC devices. Where there is a thermal and intermediate energy element to the overall response the dosemeter at least provides a reading, although a very variable one which is dependent on the calibration field. For the NTA film dosemeter where the thermal response has been suppressed, the device under-responds significantly when using all calibration fields except the very softest. For the radionuclide source calibration fields the response is practically zero. For the softest calibration field the responses for the various spectra of the group vary enormously from an under-response of just over 50%, to an over-response by a factor of 4.2.

The wide range of responses when using a soft calibration field is largely a consequence of the different spectral shapes of the calibration field and the workplace field at the high energy end of their spectra. For NTA film dosemeter N3, for example, the dosemeter only responds to a small part of the spectrum at the high energy end. In the calibration process, the response to this limited portion of the spectrum is equated with the dose equivalent of the whole spectrum. For the workplace field, dosemeter N3 once again only responds to a small part of the spectrum. If, however, this part of the spectrum contains a fraction of the dose equivalent of the total spectrum which differs from that in the calibration spectrum, the measured response will be in error. It is thus a problem of inadequate sampling of the spectra by the dosemeter.

### 7.2 Various PWR stations in Europe and the USA

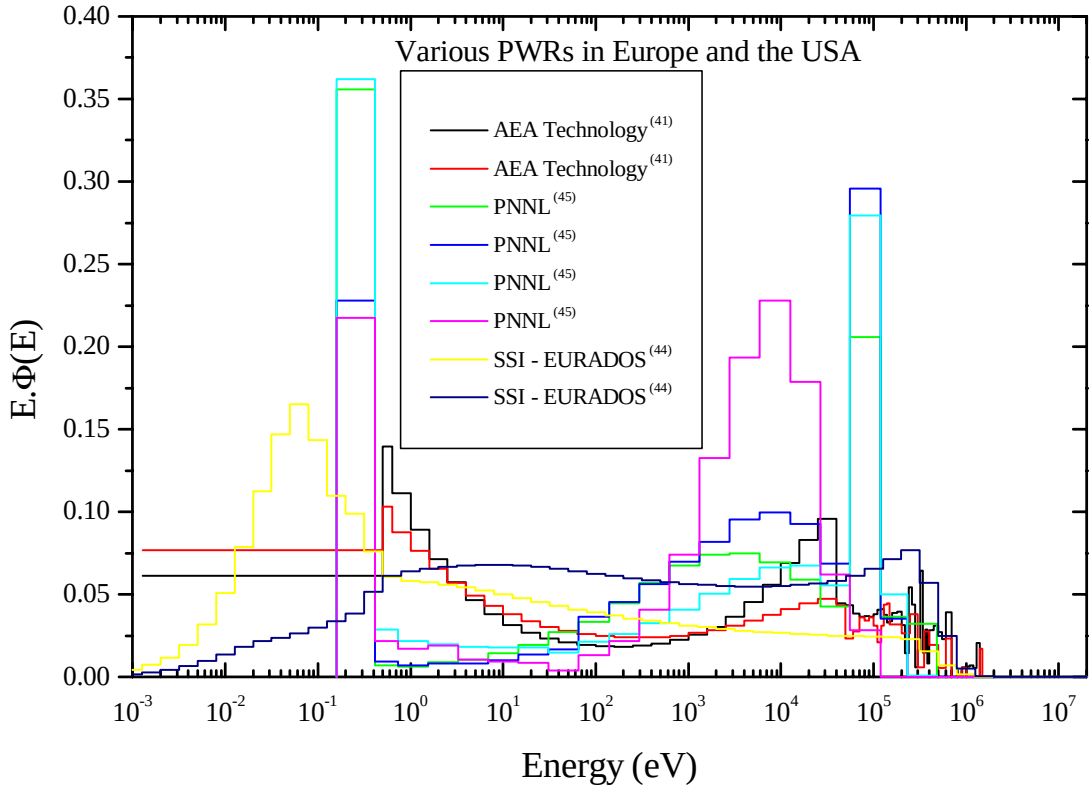



**Figure 16a.** Group of spectra typical of those found in workplaces around various PWRs in Europe and the USA.

The spectra included in this group are shown in Figure 16a. They come from three sources. Two were measured at a Swiss PWR[41], two at a Swedish PWR[44], and the remaining four at a US PWR station[45]. All measurements were made inside containment, or at an entry point to containment. The main characteristics of the spectra, i.e. large thermal and intermediate energy components and few fast neutrons, are similar to those of the gas-cooled reactors, although the mean energy is a little higher. From the figure it can be seen that there are significant differences between the measured spectral shapes, and some spectra perhaps exhibit rather unexpected features.

Results for the responses of area survey instruments are shown in Figure 16b, and there are certain similarities to the corresponding results for the gas-cooled reactor fields. On average the 0949 over-responds in the spectra of this group, although the degree of over-response decreases as the mean energy of the calibration field decreases. The TEPC shows the reverse of this trend. As was the case for the gas-cooled reactor fields, the NM2, the 2202D and the LB 6411 do reasonably well, although the range of responses for the spectra in the group is larger. There is also less of a tendency to under-respond.

As illustrated in Figure 16c, all the personal dosemeters under-respond if calibrated in radionuclide source fields. The use of lower-energy RNCFs increases the response, but at the expense of a large range of response values over the group. This variation occurs for the same reason as outlined for the gas-cooled reactors, i.e., poor sampling of the spectrum by the personal dosemeters.

### 7.3 PWR measurements by Endres et al. in the USA

All the spectra in this group come from a series of measurements performed by Endres et al.[46] within containment at various US PWR stations. The original data were given as "differential flux" values ($cm^{-2}$ $MeV^{-1}$ $s^{-1}$) at point energies. These had been re-binned and converted to fluence per unit logarithmic energy interval in reference (15), and it is in this format that the spectra are presented in Figure 17a. The average mean energy for the spectra of the group is quite significantly higher than for the previous group, 0.075 MeV compared to 0.024 MeV, and there are more neutrons in the higher energy region. The sharp cut-off in the spectra at about 0.2 eV is probably unrealistic, and may represent some problems in the re-binning of the original data. However, the total fluence values have been checked, and shown to agree with the values in the original report.

Figure 17b shows the responses of the area survey instruments, and it is apparent that for this group the softest calibration spectra are too soft for some devices. This can be seen from the results for the 0949, which under-responds if calibrated in any one of the three softest calibration fields, and the TEPC which over-responds if calibrated in the same three fields. The remaining instruments do reasonably well, although there is a tendency for them to under-respond, particularly for the softer calibration fields. The effects of differences in the two evaluations for the Studsvik 2202D response function are a little more evident for this group, with the Delafield data predicting somewhat lower responses than the Nakamura data.

For the PADC and NTA personal dosemeters, the results, shown in Figure 17c, can be understood on the basis of the explanations given for the results for first two groups. The radionuclide source based calibration fields are too hard, and result in under-response in the workplace fields. However, as softer and softer fields are tried, the problems of the small overlap between energy regions where the dosemeter response function is significant, and the regions in the workplace and calibration field spectra where the dose equivalent occurs, increasingly becomes a problem. The result is the possibility of large over-response as well as under-response.

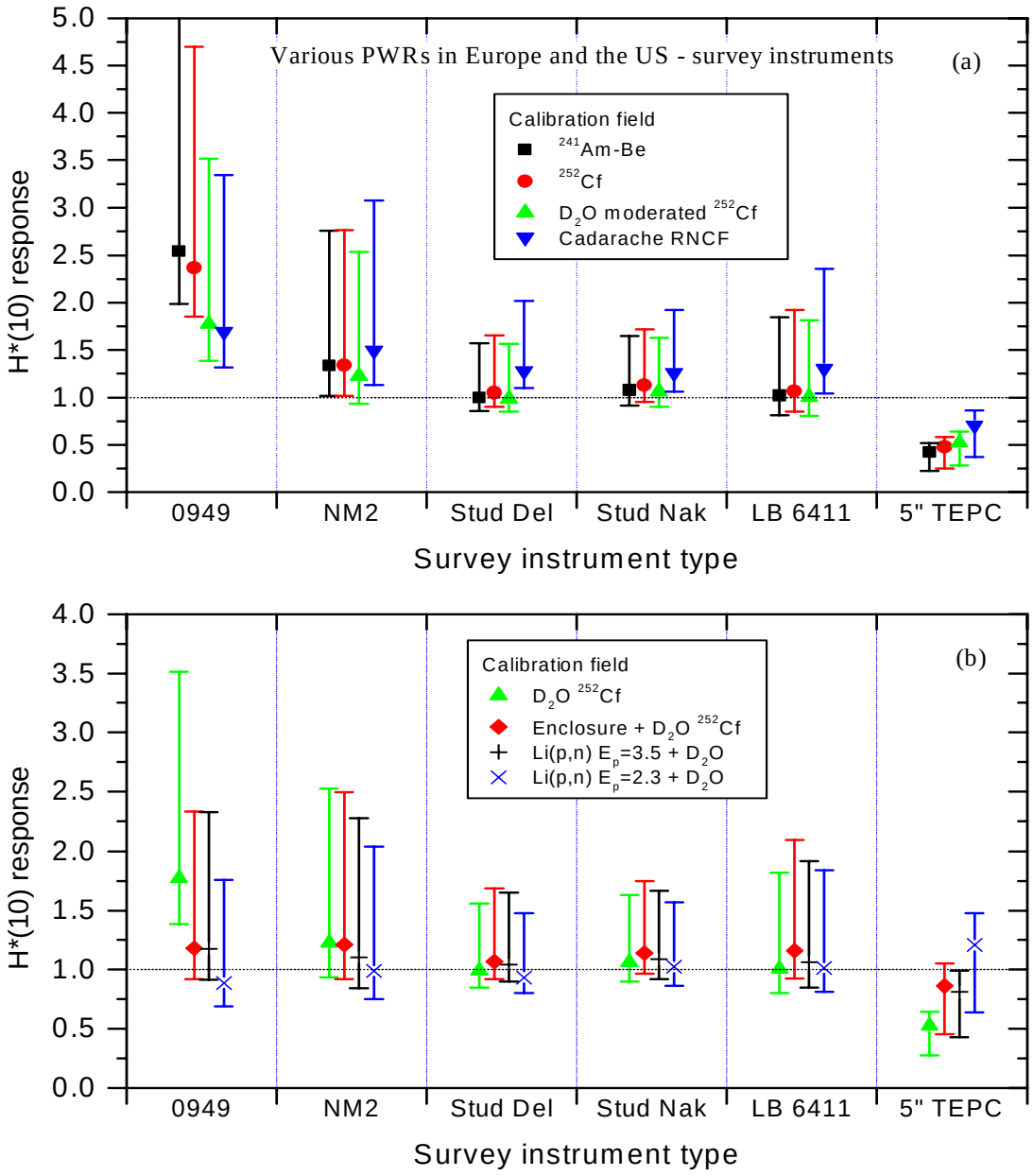



**Figure 16b.** Responses for survey instruments: Harwell 0949, NE Technology NM2, Studsvik 2202D - Delafield and Nakamura evaluations, EG&G LB 6411, and 5" TEPC for a group of spectra typical of those found in workplaces around various PWRs. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

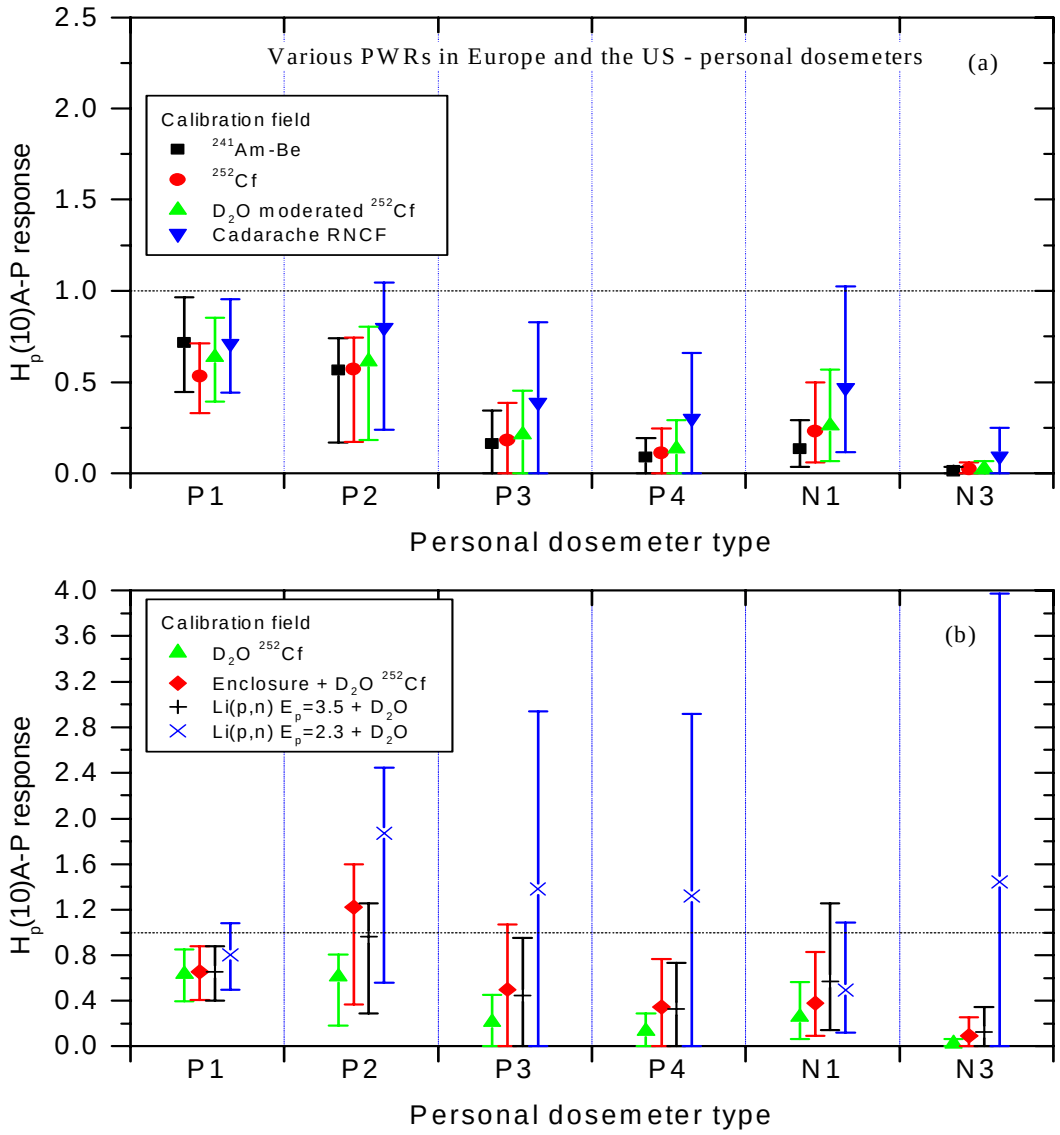



**Figure 16c.** Responses for personal dosemeters P1, P2, P3, P4, N1, and N3 for a group of spectra typical of those found in workplaces around various PWR stations. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

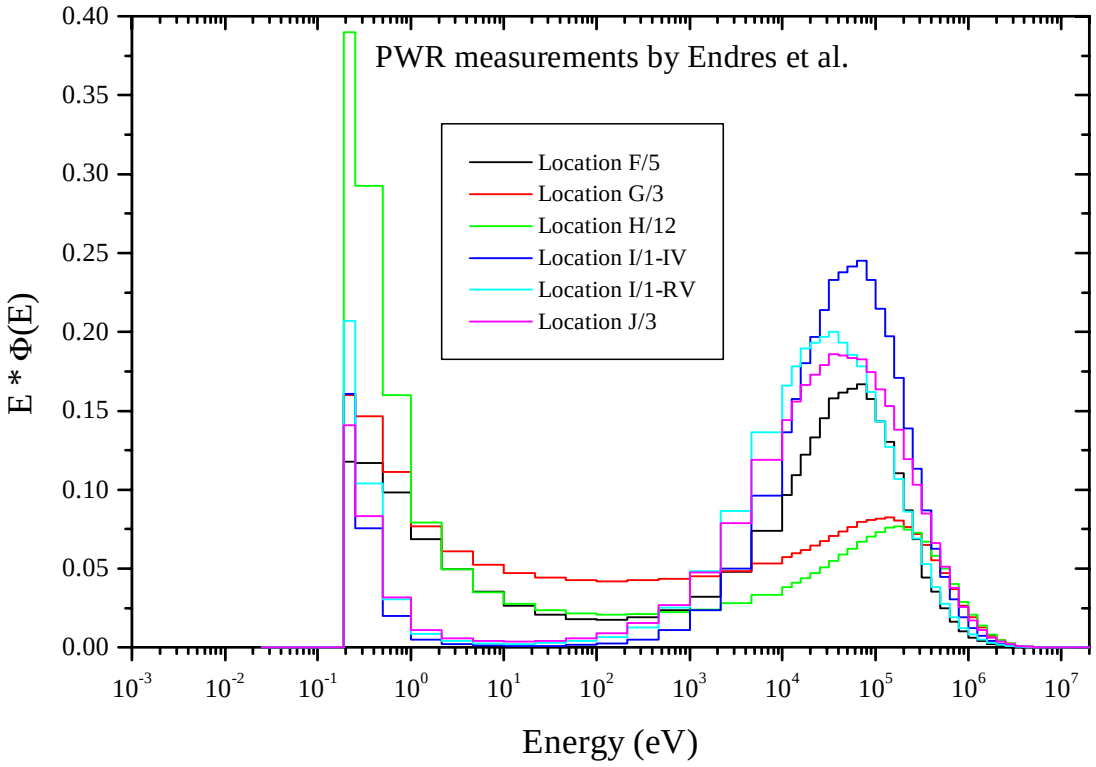



**Figure 17a.** Group of spectra measured by Endres et al.[46] at various PWR stations in the US.

For dosemeter N3 the average over-response in the workplace fields, if calibration is performed in the softest calibration field, is a factor of 5.8, i.e., off-scale in the figure. For dosemeters P1 and N1, which have a thermal response in addition to the fast response, the results are much less dependent on the calibration field used, but tend still to be low.

### 7.4 Around transport containers for PWR fuel elements

This group consists of spectra typical of those to which personnel in the vicinity of loaded PWR fuel transport containers are exposed, and contains seven spectra. One was measured near a transport container in France[47], two in Switzerland[48], and three in Sweden[44]. As can be seen in Figure 18a, the two spectra measured around containers in Switzerland appear to be harder than the others in the group. The average mean energy of all seven spectra is 0.177 MeV.

From Figure 18b, which shows the survey instrument results, it appears that the Cadarache RNCF is particularly appropriate for these spectra, even though the mean energy of this particular RNCF is much lower at 0.096 MeV. The other three RNCFs do not give improved results.

For personal dosemeters, dosemeter P1 does rather well regardless of calibration field, as illustrated by Figure 18c. For the other dosemeters, the use of RNCFs counteracts the under-response which results from calibration in radionuclide source based fields, but tends to overcompensate in a number of cases giving gross over-responses; the maximum factor being about 11 for dosemeter N3.

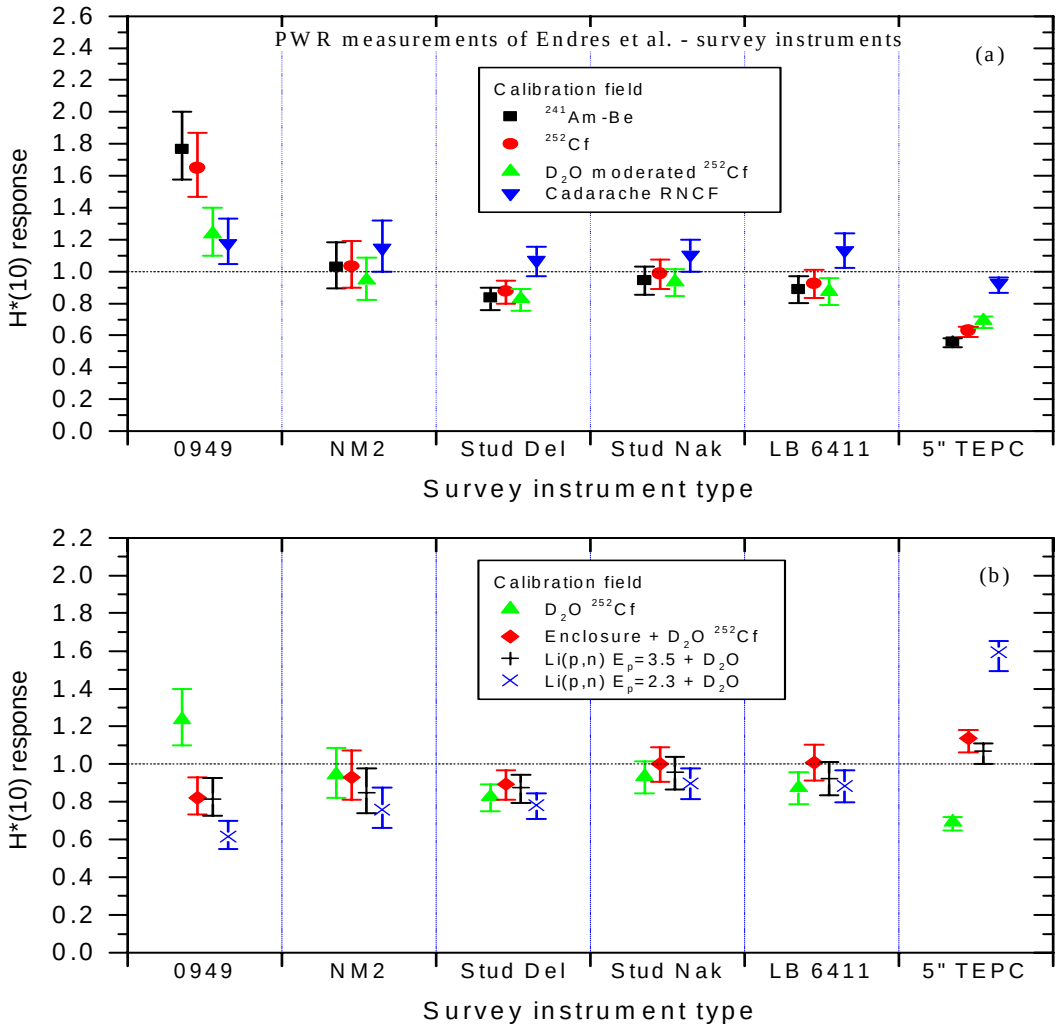



**Figure 17b.** Responses for survey instruments: Harwell 0949, NE Technology NM2, Studsvik 2202D - Delafield and Nakamura evaluations, EG&G LB 6411, and 5" TEPC for a group of spectra measured inside containment of PWRs by Endres et al. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

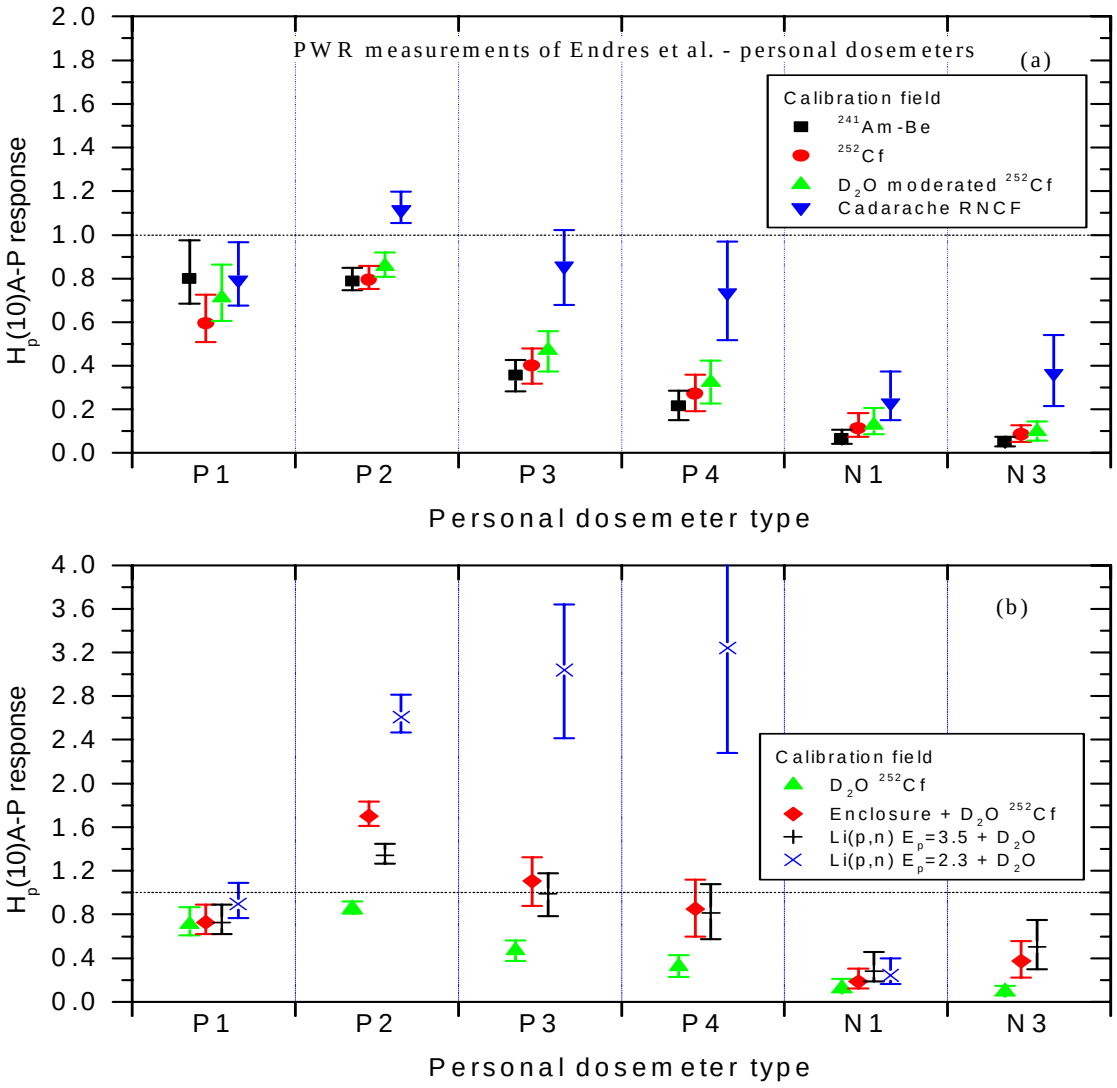



**Figure 17c.** Responses for personal dosemeters P1, P2, P3, P4, N1, and N3 for a group of spectra measured inside containment of PWRs by Endres et al. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

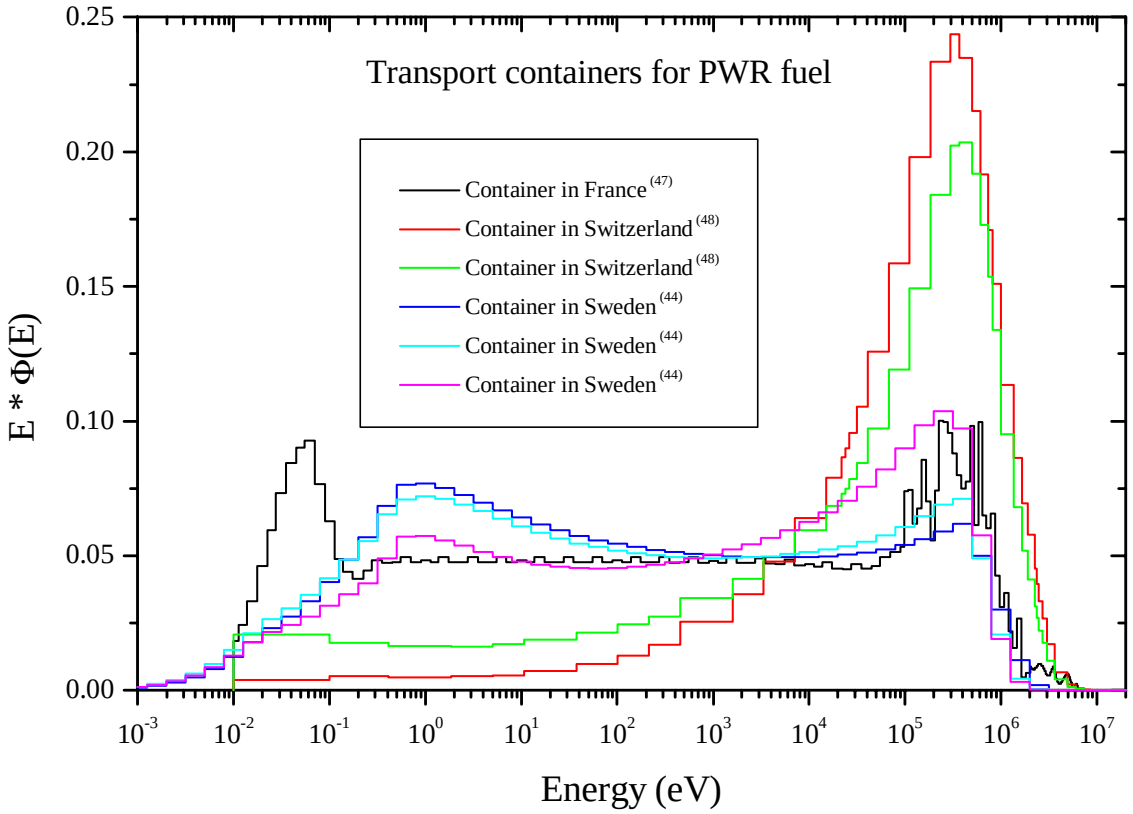



**Figure 18a.** Group of spectra typical of those found around transport containers for PWR fuel.

### 7.5 Around transport containers for WWR fuel elements

SPKTBIB contains a set of spectra measured around transport casks containing WWR spent fuel elements[49]. These were gathered together forming a group with an average mean energy of 0.191 MeV, only slightly higher than the value for the group for PWR transport containers. The data for the WWR transport containers was analysed in the same way as the other groups and gave results which, although slightly different in detail, exhibited very similar features to those for PWR fuel containers, and are therefore not shown here. The conclusions about the use of RNCFs for the PWR transport container environments apply equally to the environments around WWR casks.

### 7.6 Nuclear fuel processing, reprocessing and storage areas

The spectra in this group are shown in Figure 19a. They come from three sources representing measurements at facilities in the UK[43], in France[50], and in Germany[51]. These spectra are noticeably harder than those of the earlier groups, with fewer neutrons at thermal and intermediate energies, and a quite significant fluence above 1 MeV. The mean energies and mean H*(10)/fluence values for this group extend over a wider range than for any other group - see Figure 2. This implies that one, or more, of the spectra do not belong in this group, and the procedure of selecting spectra simply on the basis of source type and degree of shielding may not have worked well in this instance. This is discussed further in Section 8, but for the present investigation of dosemeter responses all the spectra shown in Figure 19a were included.

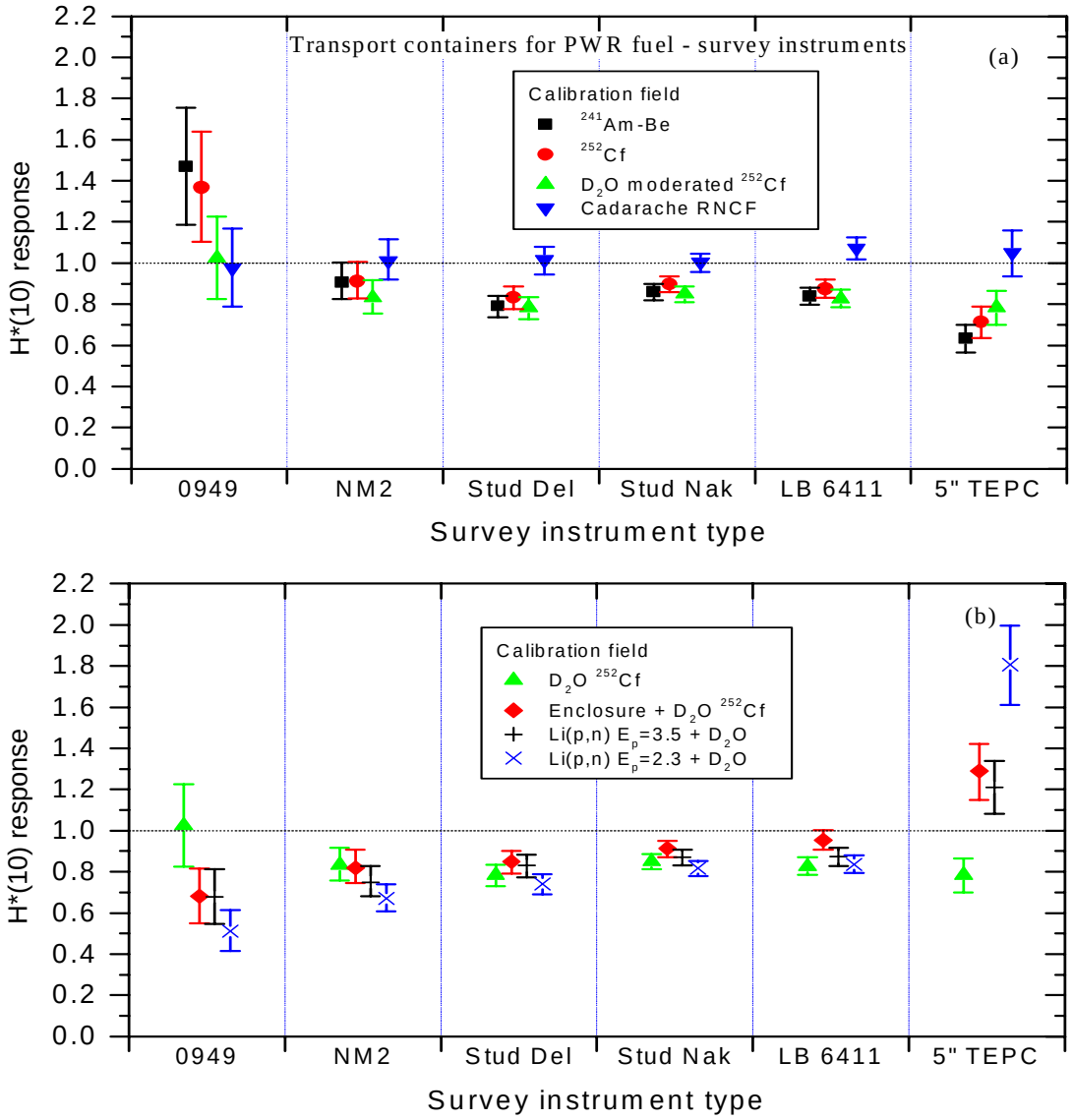



**Figure 18b.** Responses for survey instruments: Harwell 0949, NE Technology NM2, Studsvik 2202D - Delafield and Nakamura evaluations, EG&G LB 6411, and 5" TEPC for a group of spectra typical of those found around transport containers for PWR fuel. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

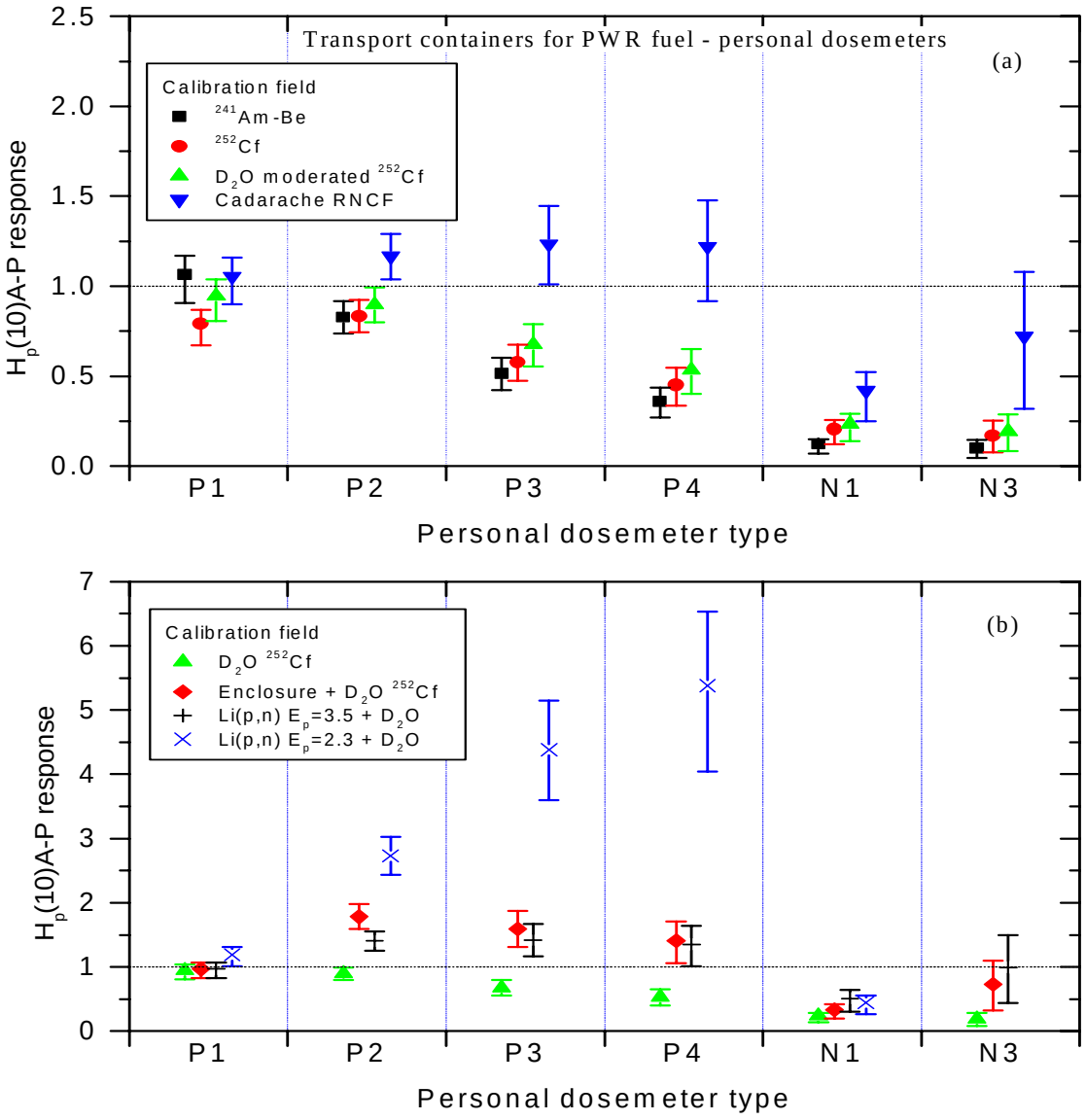



**Figure 18c.** Responses for personal dosemeters P1, P2, P3, P4, N1, and N3 for a group of spectra typical of those found around transport containers for PWR fuel. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

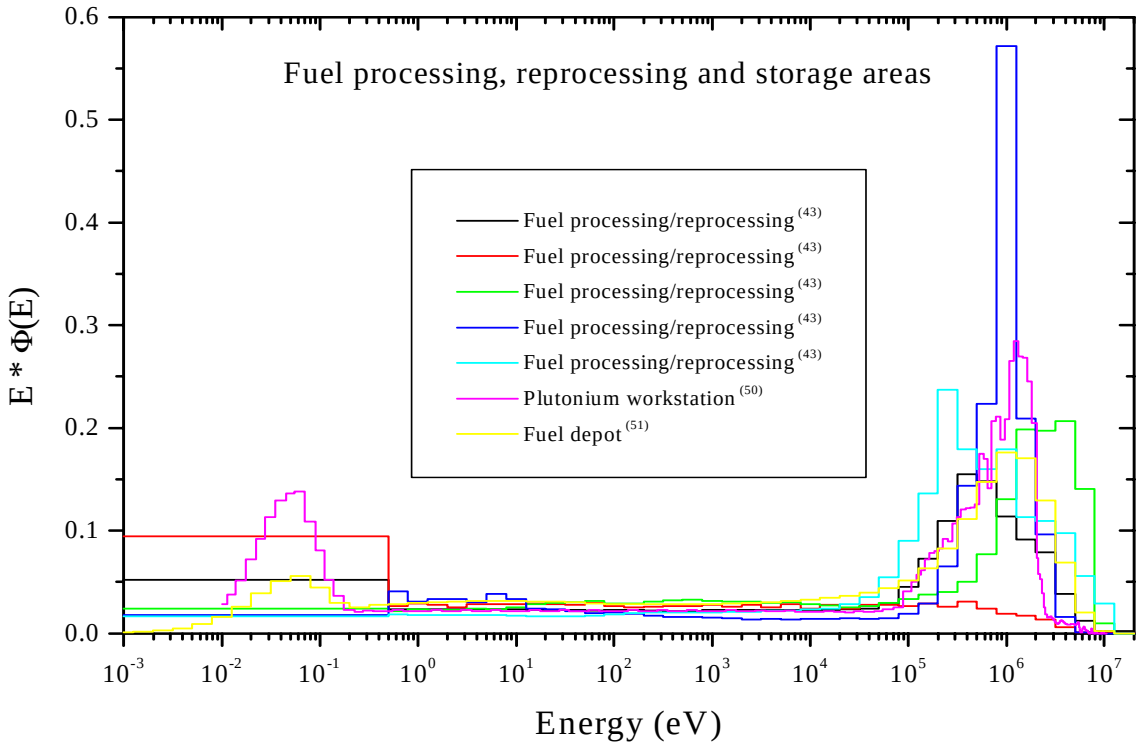



**Figure 19a.** Group of spectra typical of those found in workplaces around fuel processing, reprocessing and storage facilities.

Survey instrument responses are shown in Figure 19b. Most of the instruments respond reasonably well if the radionuclide source based fields or the Cadarache RNCF are used for calibration, although there is a tendency for under-response in general. The NM2, 2202D, and the LB 6411 still do rather well even if the softer RNCFs are used, but for the 0949 and TEPC these RNCFs are too soft, and result in under- and over-responses respectively.

For personal dosemeters calibrated in the radionuclide source based fields, the general under-response is much less than for earlier softer spectral groups, as shown in Figure 19c (a). In fact, for calibration with $D_2O$ moderated $^{252}Cf$, the average response is within about 25% of the correct answer for all the dosemeters. For the softer RNCFs all the dosemeters, with the exception of P1 over respond, in some cases by very large amounts.

### 7.7 Around transport containers for MOX fuel elements

The current version of the SPKTBIB data library contains only two spectra measured around transport containers for MOX fuel elements. This is unfortunate since MOX fuel elements are expected to produce higher neutron dose rates than conventional fuel, and neutron dosimetry may thus be a significant problem. The two spectra[18,52] were nevertheless included in the present analysis, and were included as a separate group since, as shown in Figure 20a, their spectra are very much harder than those measured around, for example, PWR fuel containers.

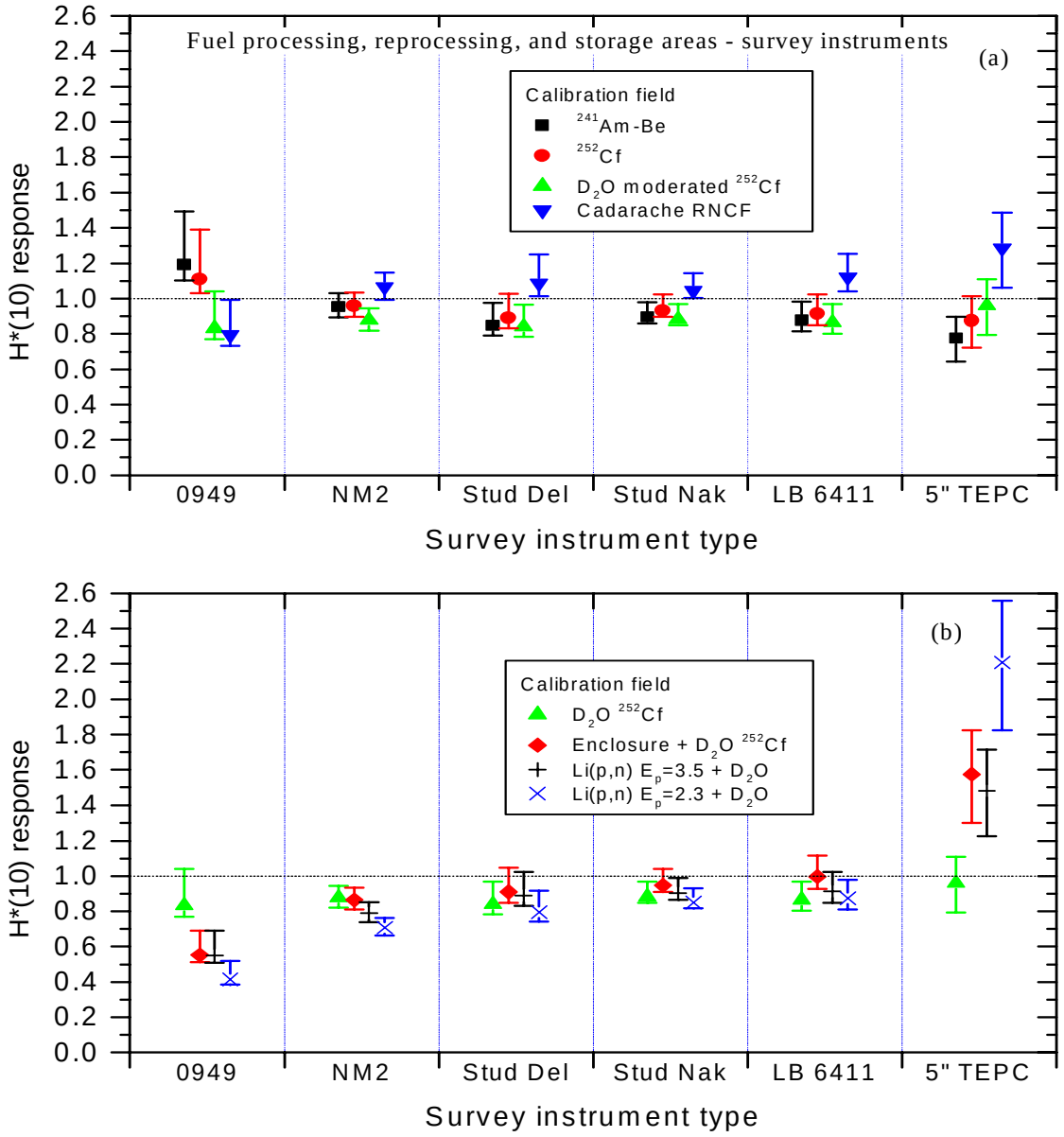



**Figure 19b.** Responses for survey instruments: Harwell 0949, NE Technology NM2, Studsvik 2202D - Delafield and Nakamura evaluations, EG&G LB 6411, and 5" TEPC for a group of spectra typical of those found in workplaces around fuel processing, reprocessing, and storage areas. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

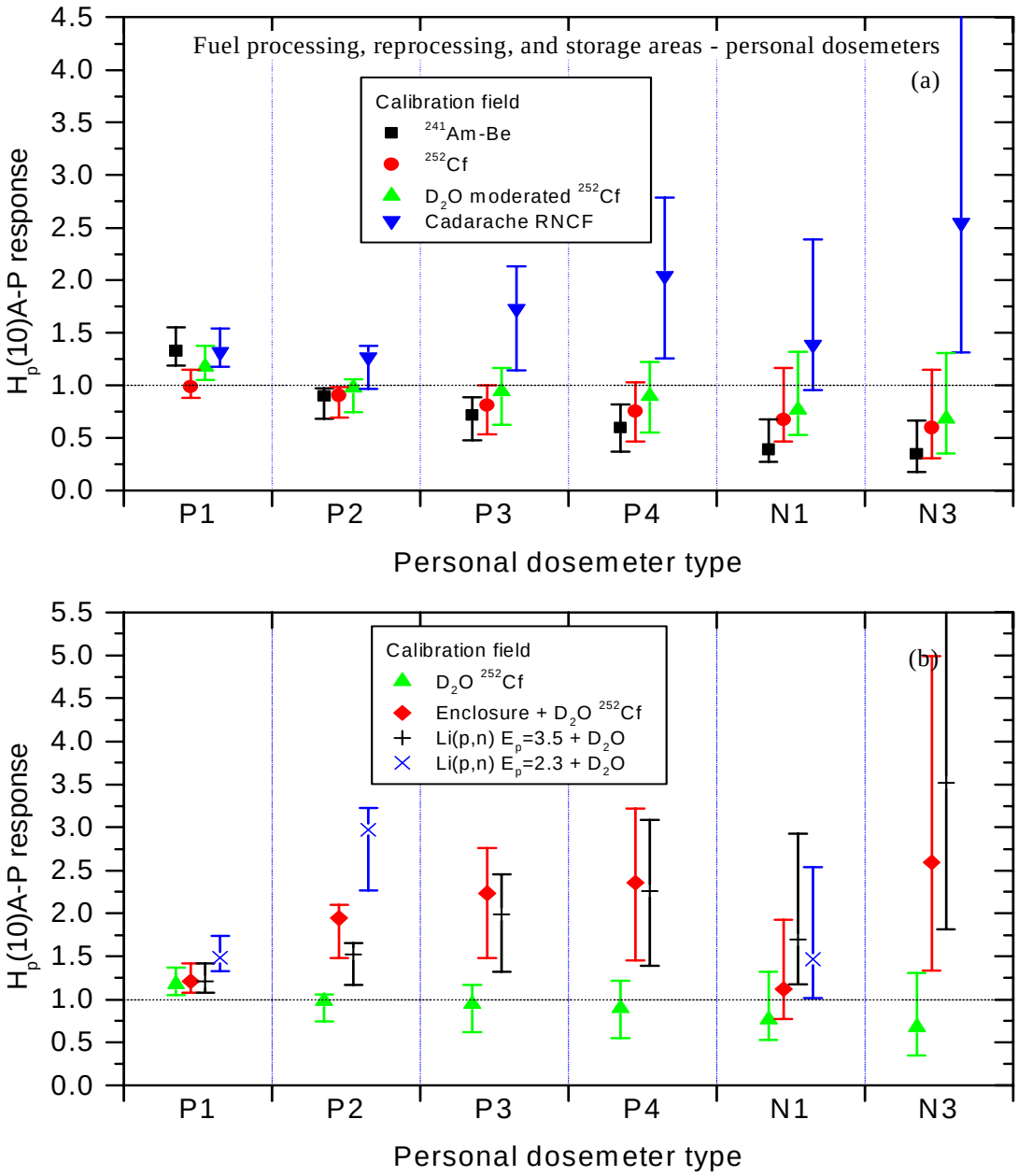



**Figure 19c.** Responses for personal dosemeters P1, P2, P3, P4, N1, and N3 for a group of spectra typical of those found in workplaces around fuel processing, reprocessing, and storage areas. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

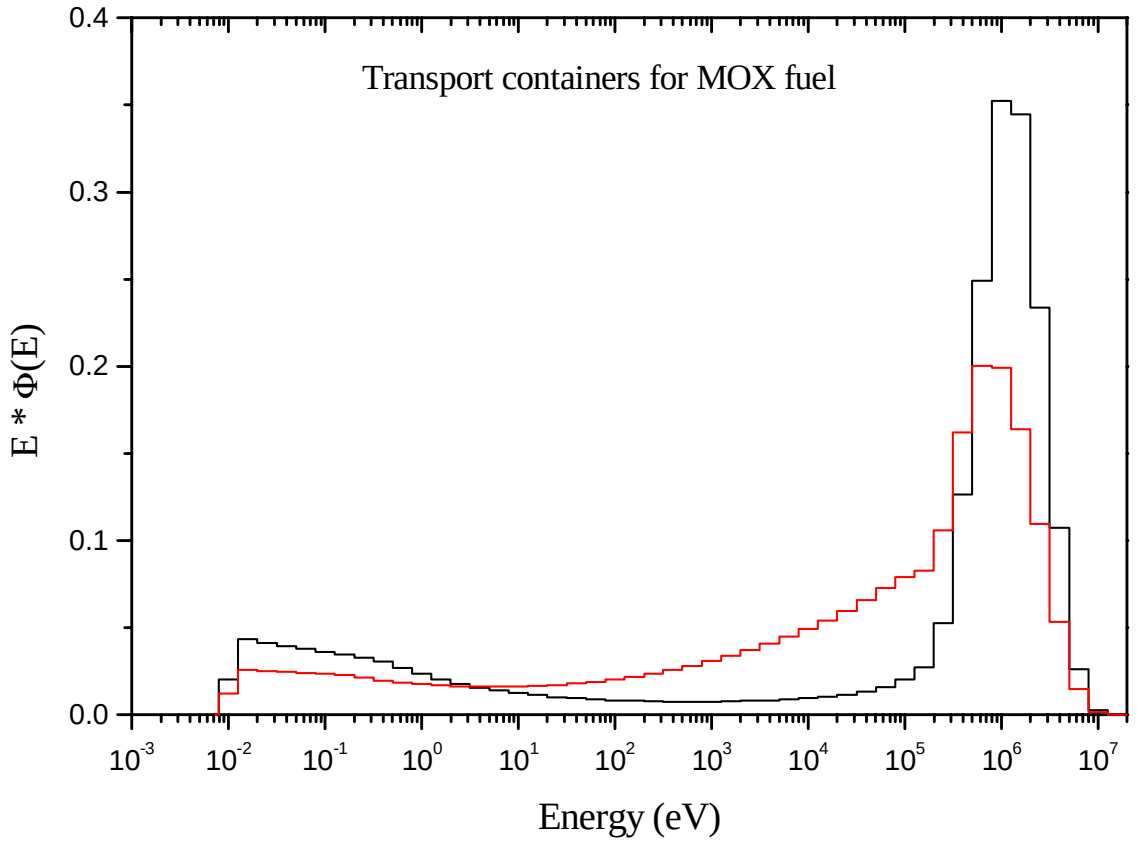



**Figure 20a.** Two spectra typical of those found around transport containers for MOX fuel[52].

Since the spectra of this group have a rather high mean energy, the conventional radionuclide source based calibration fields are expected to be reasonably appropriate, and for survey instruments this is the case, as can be seen from Figure 20b. The RNCFs, however, have spectra which are too soft, and although the trio of instruments comprising the NM2, the 2202D, and the LB 6411 perform reasonably well, the 0949 and TEPC under-respond and over-respond respectively if these soft calibration fields are used.

For personal dosemeters, none of the calibration fields are ideal, as can be seen from Figure 20c. $D_2O$ moderated $^{252}Cf$, with a mean energy of 0.54 MeV, compared with a mean energy of 0.84 MeV for the MOX fuel container fields, is the best overall. None of the soft RNCFs are at all appropriate.

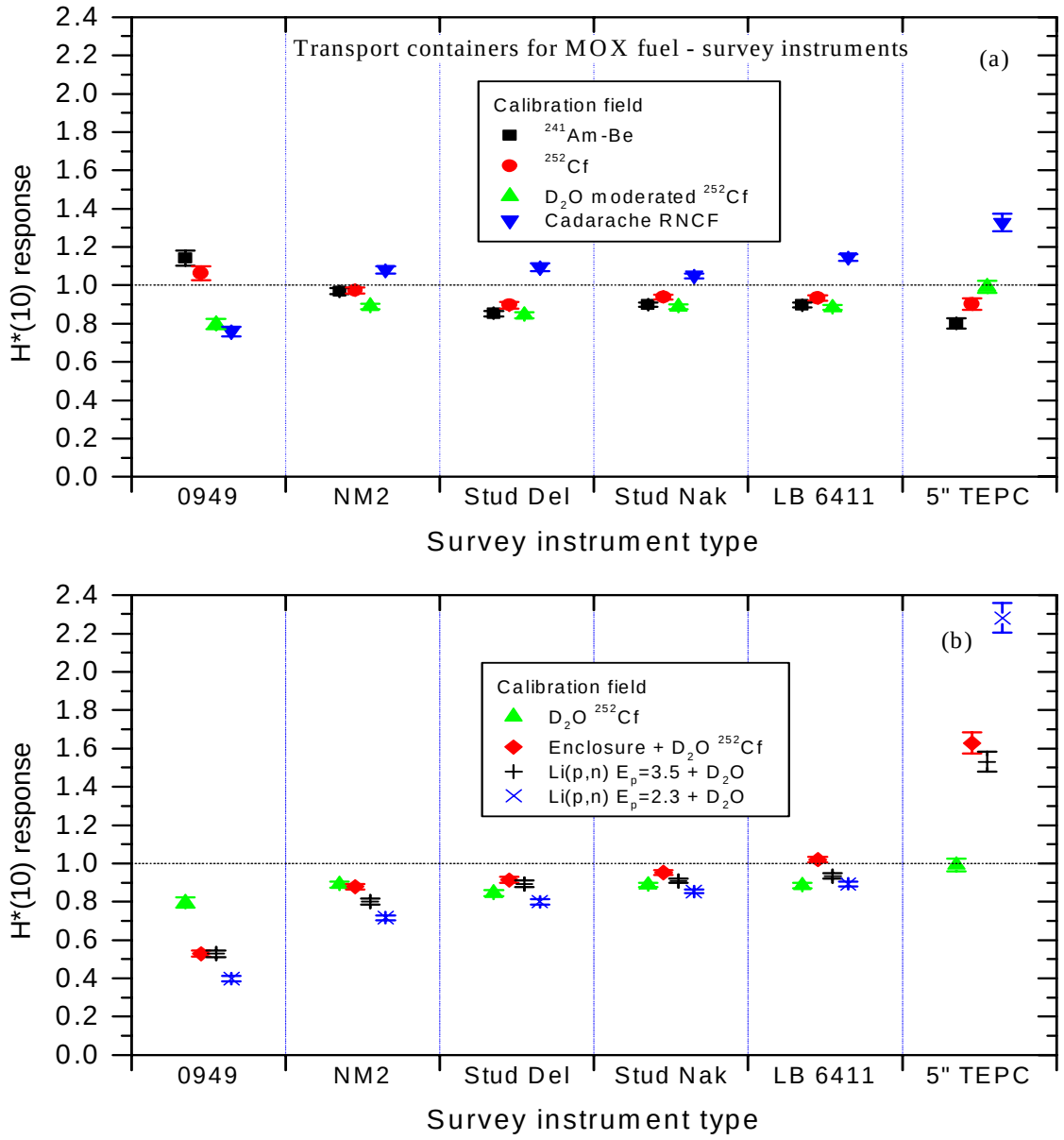



**Figure 20b.** Responses for survey instruments: Harwell 0949, NE Technology NM2, Studsvik 2202D - Delafield and Nakamura evaluations, EG&G LB 6411, and 5" TEPC for a group of spectra typical of those found around transport containers for MOX fuel elements. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

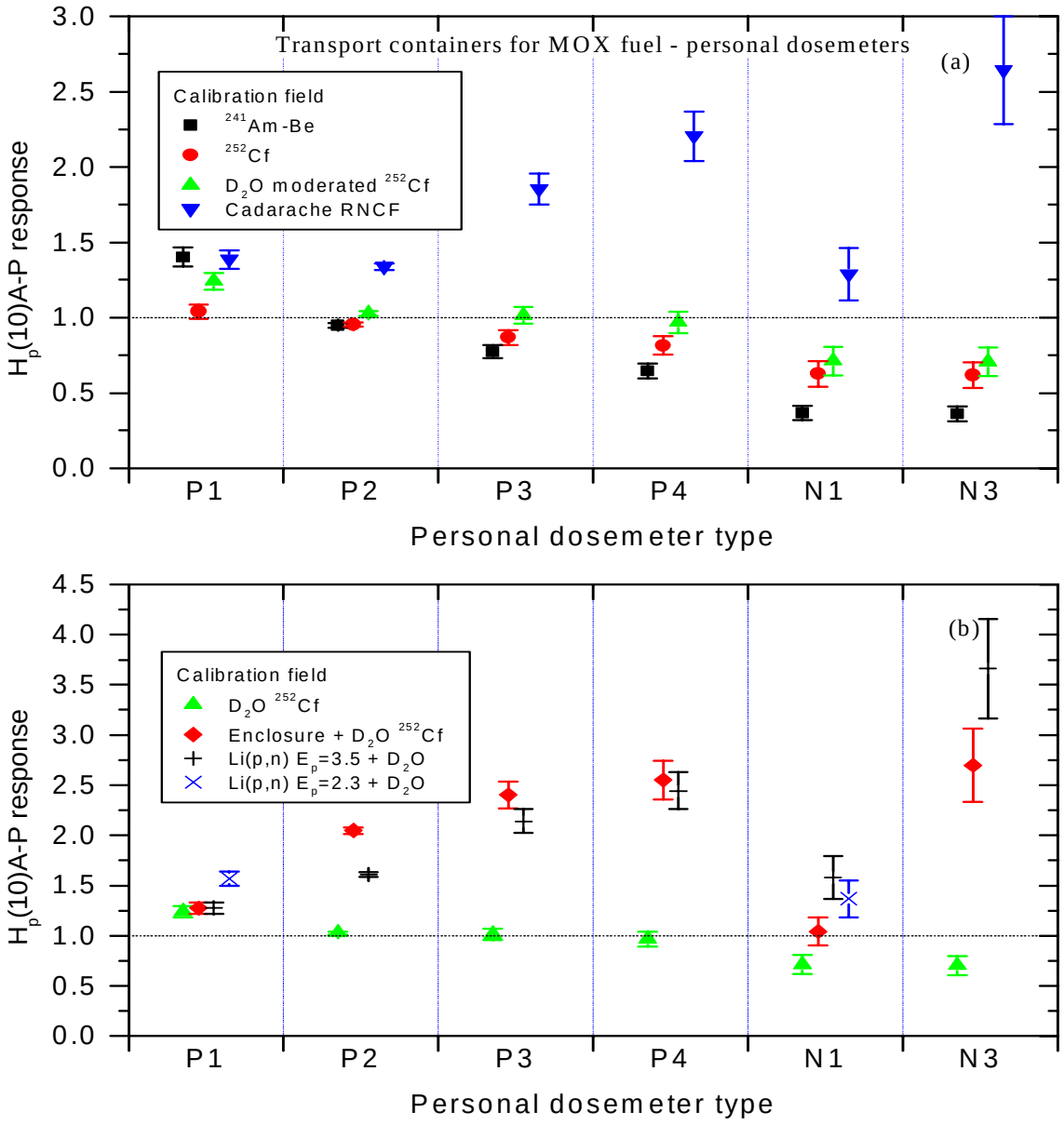



**Figure 20c.** Responses for personal dosemeters P1, P2, P3, P4, N1, and N3 for a group of spectra typical of those found around transport containers for MOX fuel elements. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum

## 7.8 Source fabrication environments and source usage areas

This group has the highest mean energy of the eight. The spectra, shown in Figure 21a, were obtained from two sets of measurements, one in the UK[53], and one in Germany[51]. They cover fields where the amount of shielding is small so that the scattered lower energy component is small in relation to the predominant high energy neutron peak.

As might be expected for such spectra, the conventional radionuclide source based fields provide a reasonable calibration for the survey instruments although, as with many of the selected spectral groups, there is a tendency to underestimate the new dose equivalent quantity. The response data are shown in Figure 21b. The results for the proposed RNCFs reveal that they are not the most appropriate for this group, although the NM2, the 2202D, and the LB 6411 results are still reasonable.

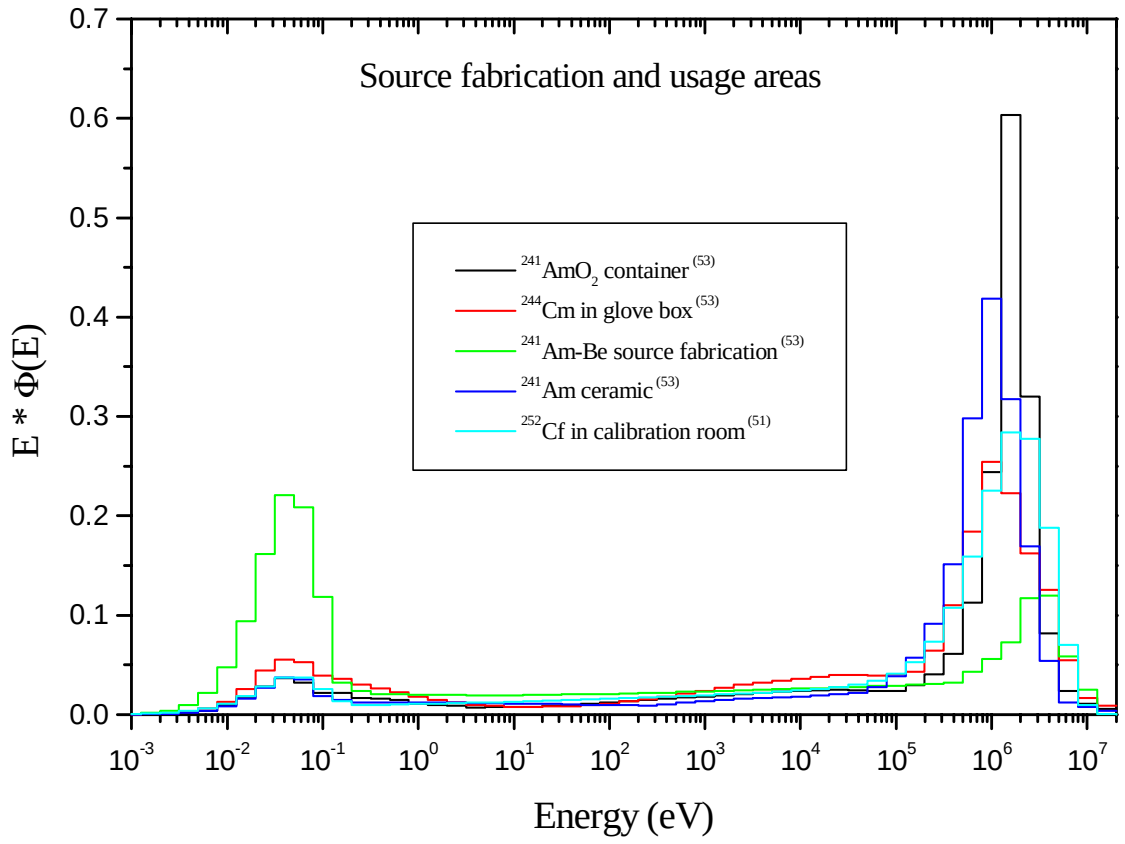



**Figure 21a.** Group of spectra typical of those found in workplaces where radionuclide sources are fabricated, or are used, e.g. for calibration.

Similar comments to those above for the survey instruments apply to the personal dosemeters. The responses are shown in Figure 21c. The radionuclide source based fields provide a reasonable calibration, $D_2O$ moderated $^{252}Cf$ in particular is a good calibration field for all six dosemeters, but the soft RNCFs are inappropriate for all except perhaps dosemeter P1.

## 8 IDENTIFYING SPECTRA WITH SIMILAR CHARACTERISTICS

In neutron protection-level dosimetry there is often a requirement to characterise spectra in particular workplace fields, without, if possible, going to the trouble and expense of performing a full spectrometry measurement. Reasons for wanting this information include: a) to identify the most appropriate calibration field, or b) to estimate potential dosemeter under- or over-response in that field from known under- and over- responses in other fields. One approach, that used in the present work, is to base this characterisation simply on the type of neutron source, the degree and type of shielding and moderation, and the amount of scattering in the environment. This does not always work, as evidenced by the data for spectral group 6 in Figure 2 where one or more spectra appear to be different from the remainder resulting in a very broad spread of mean energy and $H^*(10)/\Phi$ values. The reasons may be, for example, that the main source of neutrons has not been correctly identified, or that the presence of streaming paths through shields introduces unexpected neutrons into the field. It would be useful to have another simple method of characterising the type of spectrum.

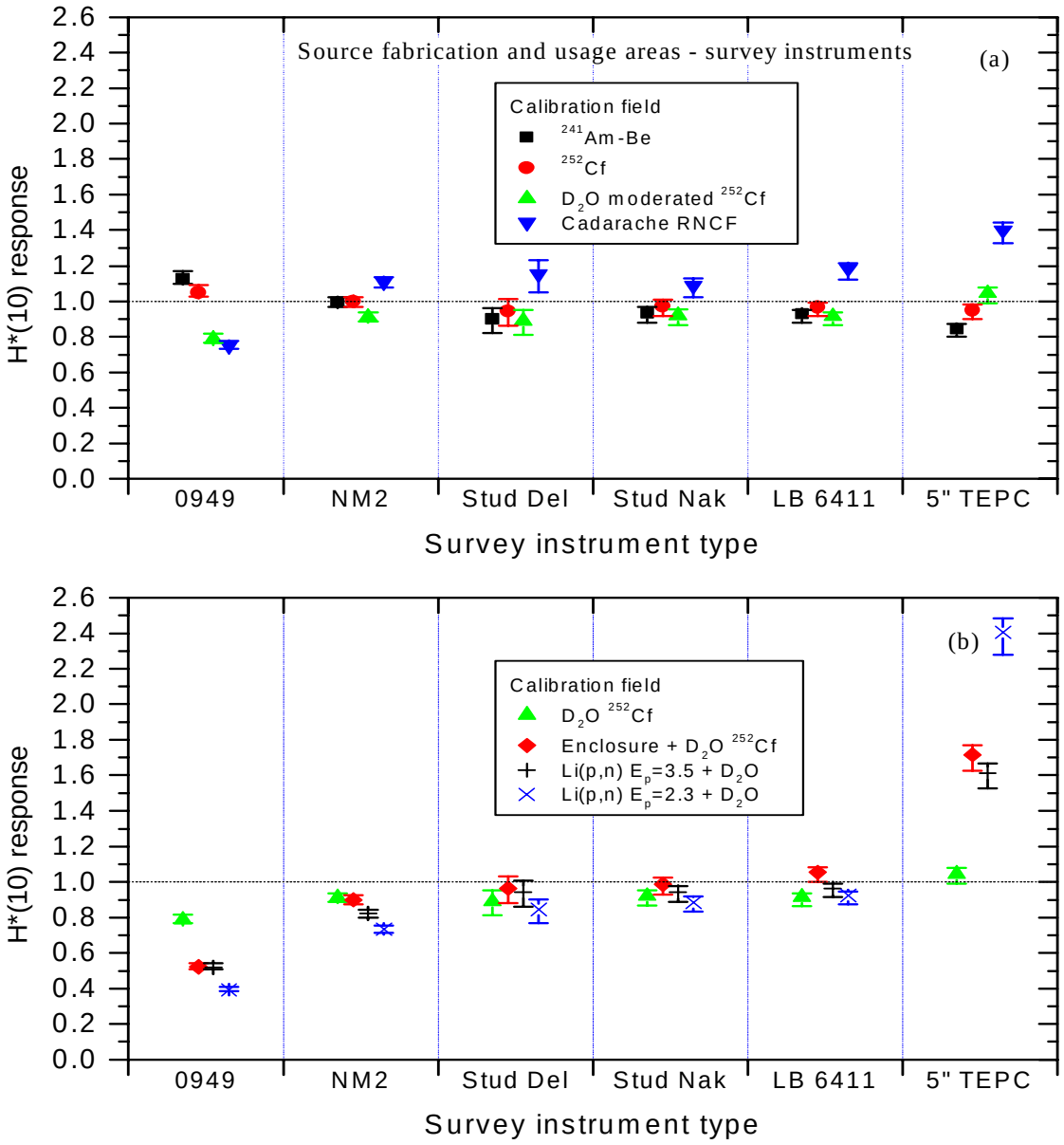



**Figure 21b.** Responses for survey instruments: Harwell 0949, NE Technology NM2, Studsvik 2202D - Delafield and Nakamura evaluations, EG&G LB 6411, and 5" TEPC for a group of spectra typical of those found in areas where radionuclide sources are fabricated and where they are used. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

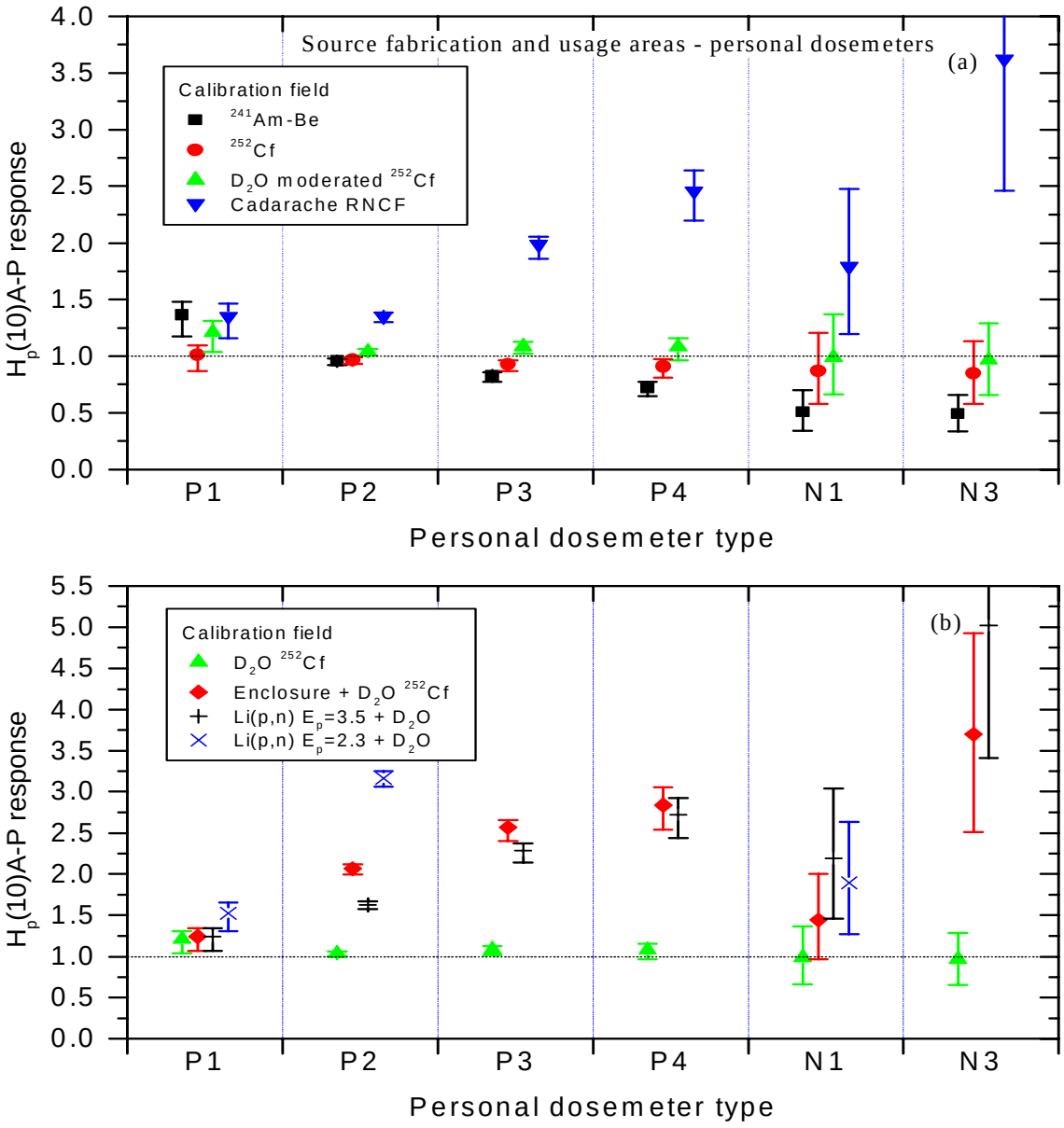



**Figure 21c.** Responses for personal dosemeters P1, P2, P3, P4, N1, and N3 for a group of spectra typical of those found in areas where radionuclide sources are fabricated or where they are used. Symbols represent mean values of the responses for the group, after calibration in one of the seven chosen fields, and the vertical lines through the symbols show the range of response values, the top of the line indicating the maximum value and the bottom the minimum.

Information can be obtained from any two devices which have different response functions. However, the 0949 and 5" TEPC have characteristics which suggest that they might provide the best combination of two instruments for providing useful information. These characteristics are: that one instrument, the 0949, over-responds significantly in the intermediate energy region whereas the other, the TEPC, under-responds significantly in this region, i.e., the differences are in opposite directions hence maximising the sensitivity. The ratio of their readings should provide information on the nature of the spectrum. There is evidence that this is likely to be the case from the results of Section 7 where the responses of the two devices, and the variation of the responses with calibration field, tend to mirror each other if viewed in terms of the deviation from a correct dose equivalent reading.

To test this approach the ratio of the 0949 response to the 5" TEPC response was calculated for each spectrum in group 6, and the data are shown in Figure 22. The fact that spectrum number 2 within the group is obviously very different to the others, and is much softer than the others, is immediately apparent. Viewing the spectral data in Figure 19a confirms this.

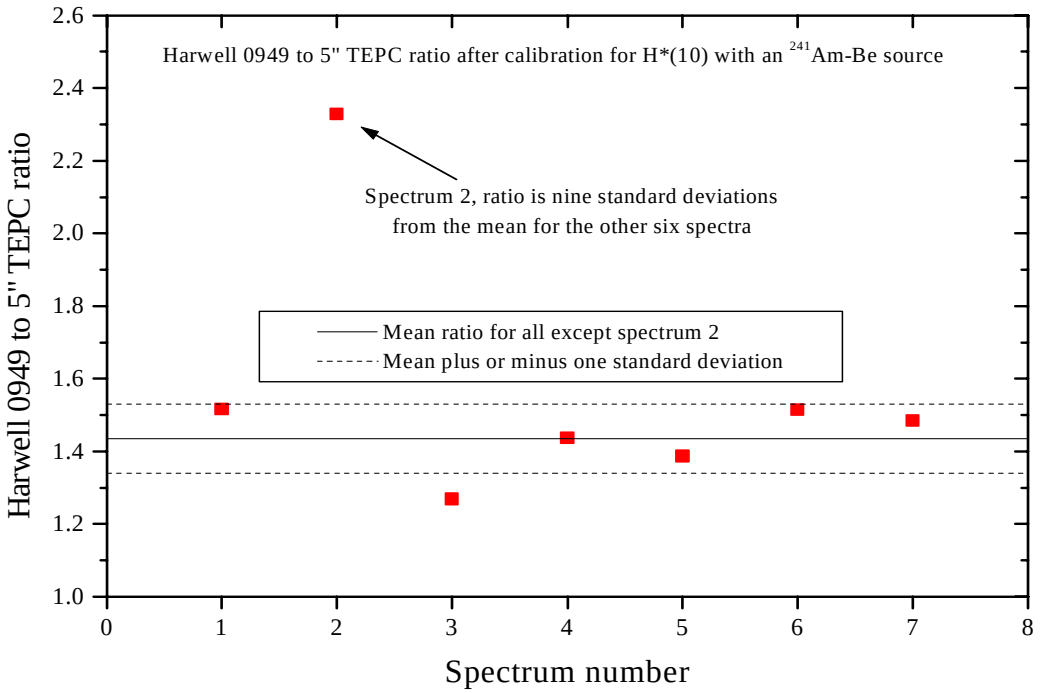



**Figure 22.** Ratio of Harwell 0949 response to a 5" TEPC response for the spectra of group 6, all measured in fuel processing, reprocessing, or storage areas.

The approach thus appears to provide useful information, and has the advantage over, for example, looking at the ratio of a 3" to a 9" Bonner sphere responses, of being based on commercially available instruments. The idea of using the 0949 and a TEPC together to obtain additional information is not new. It has been suggested by Naismith et al.[54] that using this combination, and an algorithm to combine their readings, would directly provide a reliable estimate of the dose equivalent.

## 9 OBSERVATIONS AND CONCLUSIONS

A number of observations can be drawn from this work concerning not only the use of RNCFs, but also the performance of presently available dosemeters in workplace spectra.

1. Some area survey instruments perform rather well for the whole range of spectra chosen. When calibrated with $^{241}$Am-Be, $^{252}$Cf, or $D_2O$ moderated $^{252}$Cf the NM2, the 2202D, and the LB 6411 all provide readings which are rarely more than about 20% from the true value. This is the result of over- and under-response in different energy regions cancelling. Unfortunately, their responses for the new (post ICRP 60) values of ambient dose equivalent tend to be low. The reason for this can be seen by examining the LB6411 response function in Figure 1a since those for the NM2 and 2202D are both rather similar. Much of the dose equivalent in many workplace fields arises in the energy region between roughly 100 keV and 1 MeV where these devices under-respond. There can also be a significant component of the dose equivalent in the thermal region where they again under-respond. There is only rarely a dominant component of the dose equivalent in the intermediate energy region where these devices over-respond.

Certain caveats to the above observation need to be born in mind. Firstly, the response functions used for the investigation of these instruments, with the exception of the LB 6411, are not very well known, and the results, of course, depend on the shape of the response function. These shapes are, however, believed to be generally correct, and, as illustrated by the similarity of the results for the two evaluations of the 2202D, the results do not appear to be critically dependent on the fine details of the shape. Secondly, the NM2 and 2202D, being cylindrical devices, do not have an isotropic response. The results presented are for side-on incidence, but workplace fields are rarely plane parallel beams, in fact, the angular dependence is usually not known, so it is not generally possible to ensure side-on incidence. Nevertheless, the overall results for all three devices are surprisingly good, and it should be possible to allow for the slight under-response by applying suitable correction factors.

2. For the 0949 instrument, the energy region where the device over-responds, and the extent of this over-response, is larger than for the other three moderator based devices. This means that it has a much greater tendency to over-respond in workplace spectra, and this can be by up to a factor of two, or even more, in the very softest fields if the device is calibrated with $^{241}$Am-Be or $^{252}$Cf sources. In some situations, e.g., where the dose rates are generally low and accurate estimates are not required, this may be seen as an advantage since the results at least always err on the side of safety. If the instrument is calibrated with a $D_2O$ moderated $^{252}$Cf source, then results are generally improved, although under-response is then possible in the harder spectra. The 0949 is spherical, hence has a near isotropic response, and is lighter than the other three moderator-based devices, thus making it more convenient to use. Its combination with a 5" TEPC, which tends in general to under-respond for spectra where the 0949 over-responds, can provide

information on the type of spectrum, as was shown in Section 8, and as demonstrated in reference 54, can provide a means of deriving an improved estimate of the dose equivalent.

3. For PADC track-etch and NTA film personal dosemeters the picture is more variable. For dosemeters, such as P2, P3, P4, and N3, which are basically 'threshold' detectors with no response below a particular energy, the tendency, if calibrated in any of the conventional radionuclide source calibration fields, is to underestimate the personal dose equivalent. The reason for this is quite simply that there are regions of the workplace spectrum which do not contribute to the reading. Figure 1 illustrates this point. The lower the threshold energy for the dosemeter the better the performance, hence P2 appears better than P3, which in turn appears better than P4. There is, however, the important proviso that the results quoted in this report are all for normal incidence, whereas dosemeter P4 was designed to have an improved angular response, which is an important aspect not covered here. In cases where most of the dose equivalent is at the higher neutron energies these devices do reasonably well, with P2 doing particularly well in the three spectral groups with the hardest spectra.

Dosemeters such as P1 and N1, which have a thermal response, and hence also a response to intermediate energy neutrons via the albedo from the body of the wearer, tend to do significantly better than corresponding dosemeters with similar threshold energies but no thermal response. Hence N1 performs better than N3, and P1 somewhat better than P2, P3, and P4, although there are cases for hard spectra where the shape of the response function for P1, which oscillates above and below the ideal dose equivalent response in the region around 1 MeV, make it possible for this device to over-respond in the hard workplace fields.

4. Considering next the use of RNCFs, the overall picture is complex. Concentrating first on area survey instruments. For the NM2, 2202D, and LB 6411, the responses are relatively insensitive to the calibration field. The differences in the results for the various calibration fields reflect the fact that these fields have different fractions of their dose equivalent in regions where the dosemeters have their maximum under-or over-response. Nevertheless, the overall general picture remains one where the under-and over-response in different energy regions tend to cancel, and the dosemeter readings are relatively good.

The 0949 and 5" TEPC results are very much more sensitive to the calibration field used. For both devices, the use of a soft calibration field when the instrument is used in a soft workplace field, improves the accuracy of the response, see Figures 15b and 16b. However, the use of a soft calibration field when the devices are used in hard spectra is inappropriate to the extent that the 0949 under-responds, and the TEPC over-responds, see Figures 18b to 21b.

5. The adverse effects of using inappropriate RNCFs are even more evident for the personal dosemeters. Amongst these dosemeters, P1 and N1 are the least dependent on the calibration field used, and this is because they sample the greatest fraction of the spectrum. But even for these two dosemeters, the workplace field responses are quite sensitive to the calibration field. For N1, use of a soft RNCF does generally increase the response. However, the response is still low in many of the soft spectra investigated, and as the spectra get harder the tendency becomes one of over-responding, without there being, at any point, a range of workplace fields for which the response is correct.

For dosemeters P2, P3, P4, and N3 this behaviour is even more pronounced. The use of soft RNCFs has the expected result of increasing the response in soft workplace fields, but the

problem is that the workplace responses vary wildly from under-response to rather large over-response for rather small changes in the calibration spectrum shape. Many of the responses for dosemeters P2, P3, P4, and N3 in all but the softest workplace fields are off-scale in Figures 17c to 21c for the cases where soft RNCFs are used.

The sole requirement for an RNCF, when used with threshold detector type of dosemeters whose response above the threshold is reasonably dose equivalent, is that it has the same fraction of the personal dose equivalent in the energy region where the dosemeter responds as exists in the workplace field. From the results shown in Figures 15c to 21c this is apparently difficult to achieve. This is perhaps not totally surprising. If the total dose equivalent of a spectrum is being estimated by sampling only a small fraction of the spectrum, and the correction factor for the undetected part of the field, which is derived from the measurement in the calibration field, is large, then any small variation in the fraction of the workplace field sampled, gets amplified enormously.

For dosemeters P2, P3, P4 and N3, selection of the right RNCF is critical, and there is the real danger that the use of an inappropriate realistic field can be worse than using a conventional field. At least with conventional radionuclide calibration fields it is known that the responses for these dosemeters in workplace environments will be either correct, or low; but they will not be wildly too high.

The advantages of sampling a reasonable fraction of the spectrum, even if the response is not completely dose equivalent in all regions, is highlighted by the present results; dosemeters P1 and N1 being good examples.

In conclusion, the use of RNCFs, at first sight a very promising approach to correcting dosemeter responses in workplace fields, has its limitations. RNCFs are most useful for devices such as the 0949 and the TEPC which sample the total energy range of interest, but exhibit significant under- or over response in some regions. However, there are alternative area survey instruments available which provide very reasonable results, provided some form of correction is made for their general tendency to slightly underestimate the new ambient dose equivalent quantity.

For personal dosemeters, which tend to only sample a fraction of the spectrum, the sensitivity of the RNCF technique to the need to have these fractions the same in the calibration field and the workplace fields, makes the approach questionable.

There are some cases where RNCFs work well. Use of the Cadarache RNCF with area survey instruments when used around PWR transport flasks is an example, see Figure 18b, but the general message of the present work is to highlight the importance of matching the RNCF to the workplace field rather closely.

The development of broad-range neutron fields in the laboratory should be looked upon more as a test bed for investigating dosemeters and spectrometers rather than a routine calibration field. (The cost of anything more complex than a simple radionuclide source based calibration facility is likely to be prohibitive for routine use.) There is a genuine need for fields in which spectrometers can be validated over the full range of their operation. New dosemeters continue to be developed, and old ones improved, with the consequent need to test these devices. Work to develop active personal dosemeters is underway in a number of centres worldwide, and these will need to be tested over the full range of operation. It is not possible to produce monoenergetic intermediate

energy neutrons using accelerators, and very few reactor-based filtered beams are now available. The importance of testing the response of dosemeters in the intermediate region was highlighted by the case of a novel active personal dosemeter which responded well at thermal energies, and above about 100 MeV, but which over-responded by large amounts at intermediate energies[55]. This fact was not evident until type test measurements were performed with intermediate energy neutrons. A low-energy broad-range field would be particularly useful for bench-marking albedo dosemeters, for which there are at present no suitable calibration fields.

An important feature of a testbed facility would be flexibility to change the spectrum relatively easily. Use of an accelerator-based system, producing broad-range spectra with suitable intermediate energy components, has advantages in that the spectrum can be changed easily and predictably by altering the accelerator beam energy. The system described in Section 4, based on the use of the $^{7}$Li(p,n) reaction and a $D_2O$ moderator appears to fit these criteria.

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