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Report

NPL REPORT
DQL RN008

Thermal fluence and dose equivalent standards at NPL

David J. Thomas and
Peter Kolkowski

NOT RESTRICTED

March 2005

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Thermal fluence and dose equivalent standards at NPL

by

David J. Thomas, and Peter Kolkowski

Radioactivity and Neutron Team, DQL
National Physical Laboratory, Teddington, Middlesex

Abstract
A detailed description is given of the conventions used at NPL when deriving and quoting thermal neutron fluence standards. The way in which dose equivalent quantities are derived from these fluences is explained.

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National Physical Laboratory
Teddington, Middlesex, United Kingdom, TW11 0LW

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1 Introduction

Thermal neutron fluence standards have been available at NPL since the facility, commonly known as the thermal pile, was set up in the late 1960s by Ryves and Paul[1]. The thermal fluences are produced by moderating fast neutrons, produced by bombarding beryllium targets with beams of deuterons from the 3.5 MV Van de Graaff accelerator, in a large graphite block. Fluences are measured using the activation of thin gold foils, and are monitored by fission chambers within the graphite pile.

Two locations are available for performing irradiations. One is at the bottom of a vertical, 9 cm diameter, hole giving access to a small area near the centre of the pile. At this location the fluence has a reasonably uniform spatial distribution, and fluence rates in the range from about 10^4 to 3×10^7 cm^{-2} s^{-1} are achievable. The hole diameter is, however, small and most objects, with the important exception of activation foils, have to be irradiated in the field of the 'thermal column'. This is a larger diameter hole, also in the top of the pile, but in this case situated so that it is almost over one of the beryllium targets. A stainless steel tube, cadmium-lined on its curved surface but not on its base, is placed in the hole. The tube comes in sections and may be either 1 m or 1.5 m long. When the tube is 1.5 m long it can be evacuated to reduce attenuation of the thermal beam. The neutron beam emerging from this tube is reasonably uniform over a horizontal circular area of about 30 cm diameter, although the intensity falls off as the height increases. However, the maximum fluence rate achievable is only about 4×10^4 cm^{-2} s^{-1}. In addition to thermal neutrons the column fluence also contains a component of higher energy neutrons. The spectrum of the higher energy neutrons has been measured[2], and the fast fluence has been determined relative to the thermal component. Although the higher energy fluence is only about 24% of the thermal fluence, the dose equivalent due to the fast component is more than a factor of two greater than that due to the thermal neutrons.

Historically standard fluences produced at NPL have always been quoted using the Westcott convention[3,4]. This allows a measure of the fluence to be given with small uncertainties. Although this approach is ideal for comparing thermal cross sections in activation measurements, it is not the quantity required when using the thermal facility to calibrate devices used to measure neutron dose equivalent, for example area survey instruments or personal dosemeters.

This report gives an overview of the Westcott convention, explains the various Westcott fluences which are commonly defined, describes how they are derived from gold foil activation measurements, and how the 'true' fluence values are determined. Finally, it describes how dose equivalent values are derived from these fluences. The uncertainties in these quantities, all estimated as standard uncertainties at the 66% confidence level, are also discussed.

2 The Maxwellian thermal neutron distribution

For neutrons at thermal equilibrium in an ideal moderating material the energy spectrum approximates to a Maxwellian distribution. This spectrum is presented in the literature in several different forms which should be clearly distinguished. In particular, the spectrum is

sometimes presented in terms of the neutron density and sometimes in terms of the fluence rate. The neutron density distribution can be expressed as a function of the neutron velocity, v, or the energy, E, see equations (1) and (2) below[5,6]:

$$\frac{n(v)\mathrm{d}v}{n} = \frac{4}{\sqrt{\pi}}\left(\frac{m}{2kT}\right)^{3/2} v^2 \mathrm{e}^{(-mv^2/2kT)}\mathrm{d}v = \frac{4}{\sqrt{\pi}}\left(\frac{v}{v_T}\right)^2 \mathrm{e}^{(-v/v_T)^2}\frac{\mathrm{d}v}{v_T} \qquad (1)$$

$$\frac{n(E)\mathrm{d}E}{n} = \frac{2}{\sqrt{\pi}}\left(\frac{E}{kT}\right)^{1/2} \mathrm{e}^{(-E/kT)}\left(\frac{\mathrm{d}E}{kT}\right) \qquad (2)$$

where:

- $n(v)$ is the neutron density as a function of the velocity v,
- n is the total neutron density,
- m is the neutron mass,
- k is Boltzmann's constant, (8.617×10^{-5}) eV K^{-1}
- T is the moderator temperature in Kelvin,
- $v_T = (2kT/m)^{1/2}$ is the neutron velocity for energy kT, and
- $n(E)$ is the neutron density as a function of the energy E.

The neutron density distribution, $n(E)$, is shown as a function of E/kT in Figure 1.

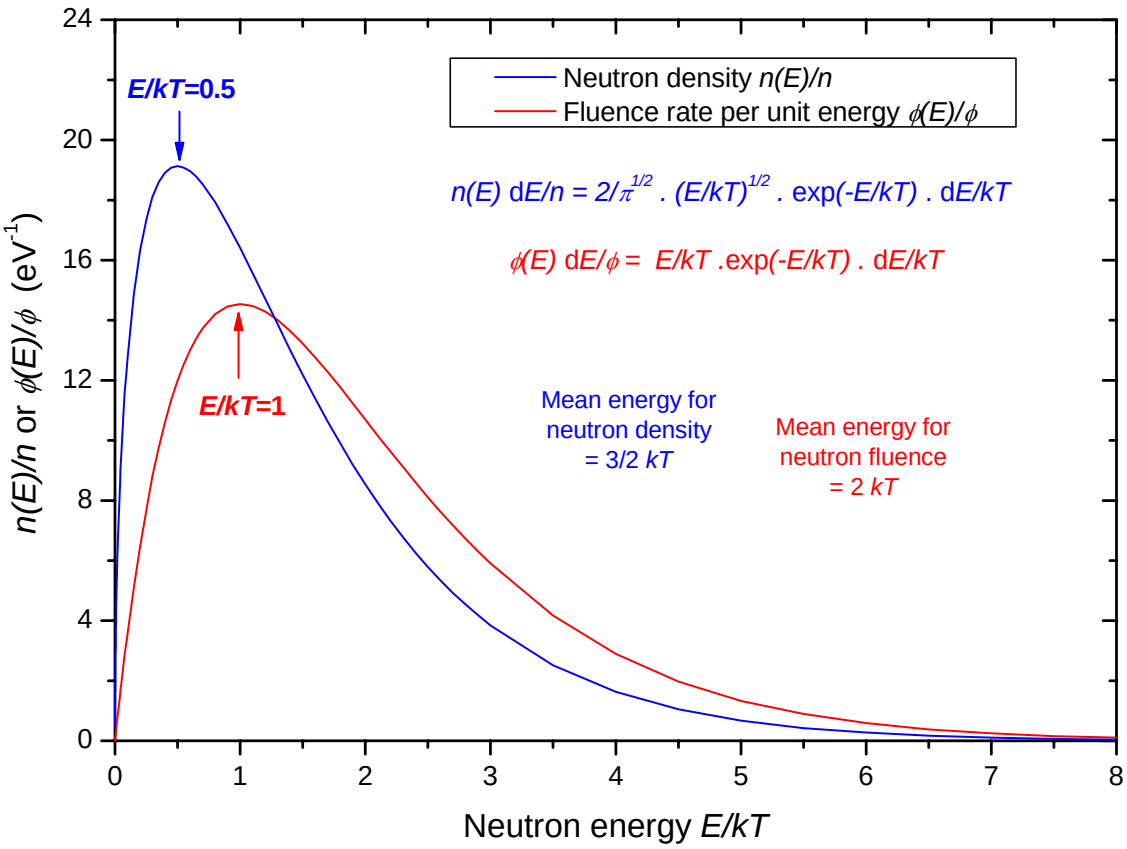

Figure 1. Maxwellian thermal neutron distributions for the neutron density and the fluence rate both as a function of energy.

If one considers the thermal neutron distribution of eq. (1) with *dn* neutrons cm^{-3} having a velocity between *v* and *v+dv*, i.e. *dn = n(v)dv*, then the fluence rate, $d\phi$, of neutrons with velocity between *v* and *v+dv* is given by eq. (3):

$$d\phi = \phi(v)dv = n(v)vdv \tag{3}$$

where $\phi(v)$ is the fluence rate as a function of velocity *v*.

This could be the fluence rate passing through a thin activation foil for instance. For a beam of thermal neutrons all travelling in one direction the relationship shown in eq. (3) is fairly obvious. If there are *n(v)* neutrons per cm^3, all of velocity *v*, all travelling in the same direction, then *n(v)v* neutrons per second will go through an area of one square cm perpendicular to the direction of motion, i.e. the number in a rectangular box of 1 cm × 1 cm × *v* cm. Although the derivation for an isotropic neutron field is not so obvious, the relationship given by equation (3) is still true[6].

The total neutron density, *n*, is given by:

$$n = \int_0^\infty n(v)dv \tag{4}$$

the total fluence rate by:

$$\phi = \int_0^\infty \phi(v)dv = \int_0^\infty n(v)\cdot v\, dv = n\cdot\bar{v} \tag{5}$$

where $\bar{v}$ is the average velocity which is given by:

$$\bar{v} = \frac{\int_0^\infty n(v)\cdot v\,\mathrm{d}v}{\int_0^\infty n(v)\mathrm{d}v} = \frac{4}{\sqrt{\pi}}\int_0^\infty \mathrm{e}^{(-v/v_T)^2}\left(\frac{v}{v_T}\right)^3 \mathrm{d}v = \frac{2}{\sqrt{\pi}}v_T \tag{6}$$

With the use of eqs (3), (5), and (6) expressions for the fluence rate distributions $\phi(v)$ and $\phi(E)$can be derived from eqs (1) and (2) and these are:

$$\frac{\phi(v)\mathrm{d}v}{\phi} = \frac{n(v)v\mathrm{d}v}{\phi} = \frac{n}{\phi}\frac{4}{\sqrt{\pi}}\left(\frac{v}{v_T}\right)^2 \mathrm{e}^{(-v/v_T)^2} v\frac{\mathrm{d}v}{v_T} = 2\left(\frac{v}{v_T}\right)^3 \mathrm{e}^{(-v/v_T)^2}\frac{\mathrm{d}v}{v_T} \tag{7}$$

$$\frac{\phi(E)\mathrm{d}E}{\phi} = \left(\frac{E}{kT}\right)\mathrm{e}^{(-E/kT)}\left(\frac{\mathrm{d}E}{kT}\right) \tag{8}$$

The fluence rate distribution as a function of *E/kT* is shown in Figure 1. It can be seen that the peak of the fluence rate distribution is at an energy *kT*, c.f. 0.5 *kT* for the density. When plotted on a linear energy scale the distributions are not symmetric, and the mean energies are 1.5 *kT* for the neutron density, and 2 *kT* for the fluence. If plotted on a logarithmic scale the distribution appears more symmetrical.

The formalism outlined above describes the thermal neutron spectrum in an ideal moderating material, however, in any real medium there are complications. Firstly, there will be slowing-down neutrons in the energy region above the Maxwellian distribution. These are normally assumed to have a 1/*E* energy dependence[(5)]. Secondly, the temperature parameterising the Maxwellian peak may not be that of the moderator material, but may be an effective temperature somewhat above the moderator temperature. Allowance must be made for these two facts. Finally, although the theory of neutron moderation predicts a Maxwellian peak and a 1/*E* component, it is to some extent a matter of faith that the actual spectrum in any particular, non-ideal, moderator assembly can be adequately described in this way unless spectrum measurements can be performed.

3 Fluence measurements and the Westcott convention

Thermal fluences are usually measured using thin activation foils. In the thermal energy region these tend to have capture cross sections which to a good approximation have a 1/*v* energy dependence. (A very simple minded explanation for this cross section dependence is that the capture probability depends on the length of time for which the neutron is in the vicinity of the capturing nucleus.)

To make allowance for slowing-down neutrons the activation measurements are performed with two foils, one bare, and one under a cadmium cover, usually 1 mm thick. The cadmium cover essentially cuts out all neutrons below the cadmium cut-off energy which is about 0.5 eV. From the bare and under cadmium activation measurement the activity induced by both the total neutron fluence rate, and by the fluence rate above the cadmium cut-off energy can be obtained, and from these various fluence rates can be derived[(7,8,9)]. The quantity often quoted is the total Westcott 'fluence' rate nv_0, where n is the total neutron density in the field, expressed as neutrons per cm^3, and v_0 is a velocity in $cm\ s^{-1}$. The quantity nv_0 thus has the correct dimensions for a fluence, i.e. $cm^{-2}\ s^{-1}$. By multiplying the fluence rate by the irradiation time a total fluence value is derived.

The reason for quoting the Westcott fluence is that the exact spectrum in most thermal neutron fields is not known. Using the Westcott convention means that this does not matter in many applications particularly those involving activation of foils.

The activation rate, per mg, of a thin foil is proportional to the product of the number of atoms per mg, *N*, the fluence rate, and the cross section. For an activation reaction where the cross section, σ, is proportional to 1/*v*, $\sigma(v) = \sigma_0 v_0 / v$ say, where v_0 is an arbitrary velocity, and σ_0 is the cross section at the velocity v_0, then the activation rate per mg, *D*, ignoring burn-up of the irradiated material, is given by:

$$D = \int_0^\infty N\phi_v(v)\sigma(v)dv = N\int_0^\infty n(v)\cdot v\cdot \sigma_0 v_0 / v\, dv = N\sigma_0 v_0 \int_0^\infty n(v)dv = N\sigma_0\, nv_0 \qquad (9)$$

i.e. the activation rate is independent of the true neutron velocity distribution, and hence the neutron energy spectrum.

Eq. (9) illustrates why the Westcott convention is useful when comparing activation measurements. The quantity obtained from a measurement with a thin activation foil is an estimate of the neutron density *n*. This could be the quantity quoted, but by convention it is not what is used. The quantity normally quoted is the Westcott fluence rate, nv_0, where v_0 is 2200 m s^{-1}, which is the velocity at the peak of a Maxwellian thermal distribution for a moderator at a temperature of 293.6 K (20.4 ^oC). For such a distribution the peak energy, given by, *kT*, is 0.0253 eV. This approach is simply a convention, and nv_0 is not equal to the true total fluence rate, this is given by $n\bar{v}$, i.e. for the true fluence rate one needs to know $\bar{v}$, see eq. (5), and hence the neutron spectrum.

The above derivation assumed a pure 1/*v* dependence for the activation cross section. This is never quite the case and the Westcott approach to deriving the fluence includes numerous correction factors, based on various assumptions, including the one that the sub-cadmium fluence can be described by a Maxwellian distribution and a 1/*E* fluence component.

Various different Westcott fluence rates can be defined[7,8,9]. The total Westcott fluence rate, nv_0, is made up of both the Maxwellian part, $n_M v_0$, and the total 1/*E* part, $n_{1/E} v_0$, i.e. the 1/*E* part extending from a defined lower energy μkT up to the highest energy considered.

$$nv_0 = n_M v_0 + n_{1/E} v_0 \qquad (10)$$

Because this is given in the Westcott convention, where v_0 is substituted for the true velocity distribution, the high energy fluence is underestimated. The analysis of the activation data also gives the sub-cadmium-cut-off fluence in the Westcott convention, $n_{th} v_0$, i.e. the total fluence below the cadmium cut-off energy, and, because of the use of v_0 rather than $\bar{v}$, this may be only slightly less than the total Westcott fluence.

The quantity $n_{th} v_0$ - $n_M v_0$ is the 1/*E* component in the energy region between μkT and the cadmium cut-off energy. The parameter μ is taken to be 3.681[9].

4 Analysis of gold foil activation measurements of the fluence

For a material which had a 1/*v* activation cross section at all energies, the total Westcott fluence could be derived from activation of a very thin foil of this material using the relationship of eq. (9), i.e. $nv_0 = D / N\sigma_0$. The activation rate, *D*, is equal to the saturation disintegration rate, and this can be determined from the induced activity at some known time after the irradiation[7,8,9] (allowing for decay both after and during the irradiation). However, there are various reasons why this simple relationship does not apply. These include: the fact that no activation reaction has a pure 1/*v* energy dependence at all energies, and for all but the very thinnest foils, self-shielding and flux depression occur. These latter two effects differ for the activation due to the Maxwellian and epithermal fluence rates, and the two

components must therefore be treated separately. This can be done if measurements are performed both for a bare activation foil and for a similar foil under cadmium cover.

The expressions relating the saturated activity of the bare foil, D_0, and of the cadmium covered foil, $D_0(Cd)$, to the various Westcott fluence rates can be found in references 7,8, and 9, and are given below for the four most important fluence rates.

$$\phi_W = nv_0 = \frac{1}{G_t} \cdot \frac{(D_0 - D_0(Cd).F)}{N\sigma_0 g} \cdot \frac{R}{(R-1)} \tag{11}$$

$$\phi_W(th) = n_{th}v_0 = \frac{1}{G_t} \cdot \frac{(D_0 - D_0(Cd).F)}{N\sigma_0 g} \tag{12}$$

$$\phi_W(M) = n_M v_0 = nv_0 \left[1 - \frac{4r}{(\pi\mu)^{1/2}} \right] \tag{13}$$

$$\phi_W(1/E) = n_{1/E}v_0 = nv_0 - n_M v_0 \tag{14}$$

Where:

ϕ_W	is the total fluence rate in the Westcott convention,
G_t	is the thermal neutron self-shielding factor,
F	is a correction factor for attenuation of epi-cadmium neutrons in cadmium,
g	is a measure of the departure of the cross section from a 1/v dependence in the sub-cadmium region,
R	is the cadmium ratio for an ideal 1/v detector, which can be derived from the cadmium ratio, $R_{Cd} = D_0 / D_0(Cd)$, for the activation foil,
$\phi_W(th)$	is the sub-cadmium cut-off fluence rate, sometimes called simply the thermal fluence, in the Westcott convention,
n_{th}	is the neutron density in the sub-cadmium-cut-off region,
$\phi_W(M)$	is the Maxwellian fluence rate in the Westcott convention,
n_M	is the neutron density in the Maxwellian distribution,
r	is a measure of the relative intensity of the epithermal component,
μ	defines the lower limit, E_Δ, of the 1/E component, $E_\Delta = \mu kT$,
$\phi_W(1/E)$	is the 1/E neutron fluence rate in the Westcott convention, and
$n_{1/E}$	is the neutron density in the 1/E distribution.

Further information about these parameters can be found in references 7,8, and 9.

When gold foils are used by NPL to determine thermal fluences the induced activity is usually determined by beta counting in a low-background 4π proportional counter[7]. This requires the β-counting efficiency, ε_β, to be known. The efficiencies for the set of foils commonly used have been determined both for bare irradiations and for irradiations under cadmium because the ε_β values differ slightly. (If the activity is sufficiently high the 4πβ-γ counting technique can be used obviating the need to know ε_β in advance.)

A FORTRAN program, WESTCT, has been written to simplify the processing of gold foil activation data to give the fluence rates. A typical output file is shown in the box below to indicate typical values for the various input parameters, and for the Westcott fluence rates. These are shown in the first part of the output file. The fluence rates $n_{th}v_0$ and nv_0 are designated by n(th)v(0) and nv(0) respectively. The terms n(M)v(0) and n(1/E)v(0) denote the Maxwellian and 1/*E* components of the fluence, $n_M v_0$ and $n_{1/E}v_0$, respectively and add up to the total Westcott fluence.

```
PROGRAM WESTCT  -  Version 1.1 compiled January 2004
THERMAL AND EPITHERMAL FLUENCES CALCULATED FROM FOIL ACTIVATION

Run date: 19-01-2004                Run time: 19:15:28

Au 4048 bare + Au4132 in Cd, NPL th col 1.5 m pos. evacuated 23/11/2001

  D0(bare)     D0(Cd)     Eff Temp
 8.1566E+00  1.0298E+00  3.1560E+02


     FCd      At Wt        G(th)      W-cott g    Sigma(0)
 1.0100E+00  1.9697E+02  9.8430E-01  1.0046E+00  9.8690E+01


   G(res)       S(0)     Res Attn f       W       W-cott K       mu
 3.6700E-01  1.7300E+01  9.9000E-01  2.7000E-02  1.9939E+00  3.6810E+00



CALCULATED RATIOS AND FLUENCES


    R(Cd)      r(T/T0)        r        R(1/v)
 7.9206E+00  2.0884E-02  2.0143E-02  9.5476E+01


  n(th)v(0)     nv(0)     n(M)v(0)   n(1/E)v(0)    n(1/E)/n(M)
 2.3852E+04  2.4104E+04  2.3533E+04  5.7110E+02    2.4268E-02


  n(M)v(BAR) =   2.7531E+04
  n(1/E)v(BAR) PER UNIT LETHARGY =   5.6801E+02
  FOR THE K AND mu VALUES USED:
  E(Cd) =  5.1227E-01   EL =   1.0011E-01
  EPITHERMAL  FRACTION f =   2.3693E-02
  n(1/E)v(BAR) BETWEEN EL AND E(Cd) =   9.2734E+02
  ( 3.3683 % OF n(M)v(BAR))

  n(th)v(BAR) =   2.8459E+04
  v(BAR)/v(0) =   1.1931E+00

  FOR THE MAXWELLIAN DISTN. v(BAR)/v(0) =   1.1699E+00
  FOR THE EPI. FLUENCE EL TO E(Cd) v(BAR)/v(0) =   2.9103E+00
  AND THUS v(BAR) FOR THIS REGION =   6.4027E+05 cm/sec
  n(M) =   1.0697E-01
  n(1/E) BETWEEN EL AND E(Cd) =   1.4484E-03 ( 1.3540 % OF n(M))
  EPITHERMAL FRACTION BETWEEN EL AND E(Cd) =   1.3359E-02
```

The sub-cadmium-cut-off fluence, $\phi_W(th) = n_{th} v_0$, does not involve the cadmium ratio, *R*, and is thus the most accurately known of the Westcott fluences. Depending somewhat on statistics, the uncertainty in this quantity, is usually of the order of 0.5% the largest contributions coming from uncertainties in deriving the gold activity from the β counting.

5 The true neutron fluence values

To derive the true fluence rate the ratio $\bar{v}/v_0$ needs to be known. Even for a perfect moderator, which would give a pure Maxwellian with a temperature of 293.6 K, $\bar{v}/v_0 = 1.128$; and since few moderator assemblies are ideal, the true value of this ratio is likely to be higher than this.

From the cadmium ratio obtained from gold foil activation measurements, i.e. (activation bare)/(activation under cadmium), an estimate for the intensity of the 1/*E* component relative to the Maxwellian component in the Westcott convention can be determined, and from these values an estimate of the effective temperature of the Maxwellian can be derived using an empirical relationship given by Geiger and van der Zwan[10]. This is shown in eq. (15).

$$\frac{T - T_M}{T_M} = C \frac{n_{1/E} v_0}{n_M v_0} \tag{15}$$

where:

T is the effective temperature,
T_M is the physical temperature of the moderator,
and *C* is a constant.

A value of 2.27 x 10^{-2} was obtained for $n_{1/E} v_0 / n_M v_0$ for the NPL thermal column from the average of several gold foil measurements[9]. Geiger and van der Zwan derived a value of 3.2 ± 0.4 for *C*, however, they quote in their paper two further values, measured by others, of 4.8 ± 1.7 and 1.65. The latter value is for a water moderator rather than a graphite one, and so is not equally appropriate. Since 3.2 is near the mean, this value is assumed for the NPL thermal pile and this gives a value of 22°C for $T - T_M$. In view of the spread of values for *C* an uncertainty of ±11°C was assumed which mainly reflects the spread of values reported for the parameter *C*.

Knowing a value for the effective temperature an estimate of $\bar{v}/v_0$ can be made for both the thermal Maxwellian and 1/*E* components, and finally an estimate for the true fluence can be derived. The relevant equations[9] are:

$$\frac{\bar{v}_M}{v_0} = \left[\frac{4T}{\pi T_0} \right]^{1/2} \tag{16}$$

$$\frac{\bar{v}_{1/E}}{v_0} = \frac{\ln(E_{\max} / E_\Delta)}{2E_0^{1/2} \left[E_\Delta^{-1/2} - E_{max}^{-1/2} \right]} \tag{17}$$

where:

$\bar{v}_M$ is the mean velocity for the Maxwellian distribution,
T_0 is 293.6 K, and $E_0 = kT_0$,
$\bar{v}_{1/E}$ is the mean velocity of the 1/*E* component,
E_{max} is the maximum energy of the 1/*E* component,
and E_Δ is the minimum energy of the 1/*E* component.

If E_{max} is set to the cadmium cut-off energy the value derived for $\bar{v}_{1/E}/v_0$ is for the 1/*E* fluence below this energy. Thus $\bar{v}$ is available for both components of the fluence below this energy, and the true sub-cadmium-cut-off fluence $n_{th}\bar{v}_0$ can be derived.

In the output data file from WESTCT shown in the box above, n(th)v(0) is the sub-cadmium-cut-off fluence rate in the Westcott convention, n(th)v(BAR) is the 'true' sub-cadmium fluence rate, and for this particular gold foil analysis it can be seen that, for the sub-cadmium region: $\bar{v}/v_0 = 2.8459/2.3852 = 1.193$. The value of 1.193 relating the Westcott sub-cadmium fluence rate to the 'true' sub-cadmium-cut-off fluence rate in the column is typical of those measured when deriving fluences, and can be compared to the value for a pure Maxwellian at room temperature (293.6 K) for which $\bar{v}/v_0 = 2/\sqrt{\pi} = 1.128$. Thus, the value for the NPL thermal column is 5.7% higher. Of this 3.7% is due to the effective temperature being higher than 293.6 K, and 2% is due to the 1/*E* component below the cadmium cut-off energy. (The ratio of the 'true' sub-cadmium fluence rate to the total Westcott fluence rate in the NPL column is: 2.8459/2.4104 = 1.181.)

There are a number of assumptions which go into the calculations so it is difficult to give an estimate of the uncertainty in the 'true' fluence. This is why the quantity quoted on certificates in the past has been the Westcott fluence. However, as the value of $\bar{v}/v_0$ for the NPL thermal column is only about 5.7% higher than that for a pure Maxwellian, the uncertainty in converting to the 'true' fluence rate should be less than this. The complexity of the dependence of $\bar{v}/v_0$ on the various parameters precludes a conventional uncertainty sensitivity analysis, however, Table 1 gives some idea of the uncertainty.

Table 1. Uncertainties in deriving the true sub-cadmium cut-off fluence rate from the Westcott sub-cadmium cut-off fluence rate. The parameters shown are those where the uncertainties have the largest effect on $\bar{v}/v_0$

Parameter	**Uncertainty in the parameter**	**Uncertainty in $\bar{v}/v_0$**
T - effective temperature	± 11 ^{0}C estimate from reference 9	± 1.7%
μ - lower limit E_Δ of 1/*E* component given by μkT	± 30% from comparison of value used at NPL (3.68) and the quoted value in reference 8	± 0.2%
R_{Cd} - cadmium ratio for gold foils	± 2% uncertainty in $D_0(Cd)$ (from statistics)	± 0.2%
F_{Cd} - attenuation factor in the cadmium	± 1% uncertainty in the factor presently used which is 1.01	± 0.1%
Total from addition of components in quadrature =		**± 1.7%**

The uncertainty in $\bar{v}/v_0$ was determined by running the program WESTCT with the parameters changed by the uncertainty. The total uncertainty in $\bar{v}/v_0$ obtained in this way was ±1.7%. In view of the uncertainties in the assumptions underlying the whole approach, i.e. that the spectrum can be adequately described as a Maxwellian and a 1/*E* component, an uncertainty of ±2% is considered a reasonable estimate to apply when converting the Westcott sub-cadmium-cut-off fluence rate to the true value.

6 Dose equivalent standards

If the thermal column is used to calibrate devices in terms of dose equivalent, not only is the 'true' fluence rate required, but also the fluence to dose equivalent conversion factor for the actual spectral distribution. Figure 2 shows a pure room-temperature Maxwellian spectrum, our best estimate of the NPL thermal column sub-cadmium-cut-off spectrum, in both cases normalised to unit fluence, and the fluence to ambient and personal dose equivalent conversion coefficients, $h^*(10)$ and $h_p(10,0^o)$, from reference (11). Note that when plotted as a fluence rate per unit logarithm of the energy, as in Figure 2, the peak of the spectrum is at $2kT$ rather than kT, the peak energy in a linear plot – see Figure 1.

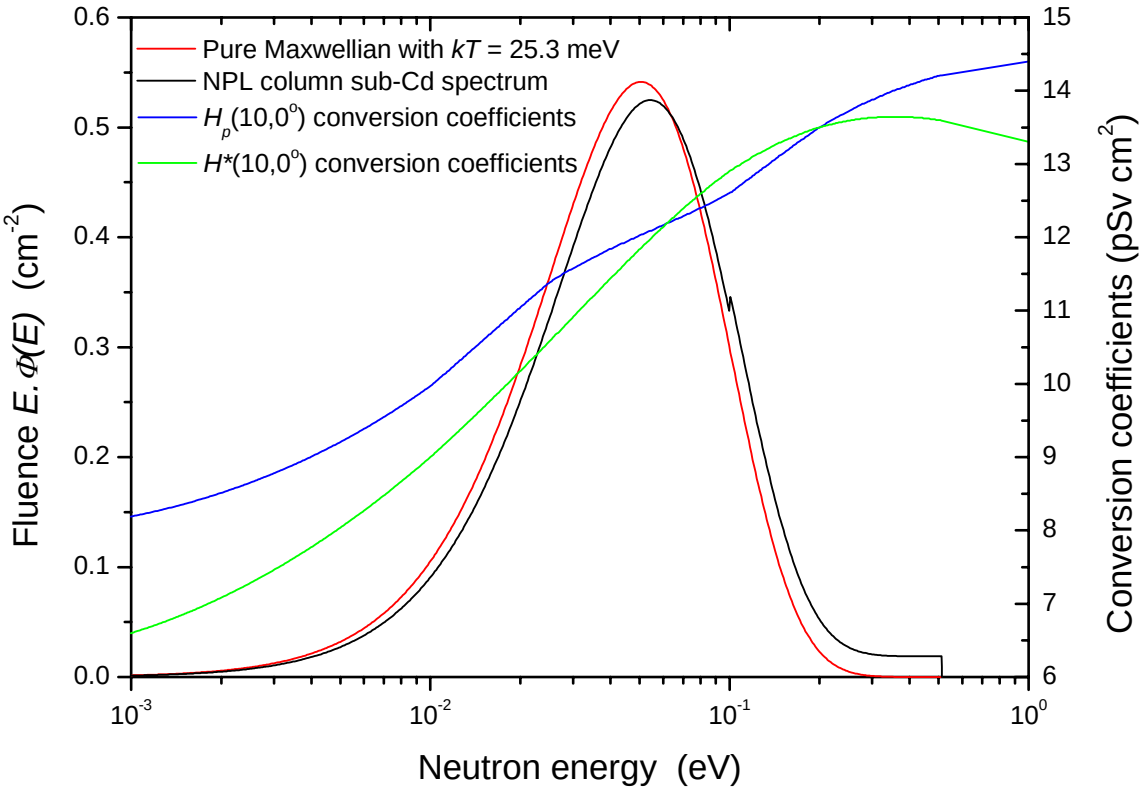

Figure 2. A pure Maxwellian distribution with kT = 25.3 meV, the NPL thermal column sub-cadmium-cut-off spectrum, and the fluence to ambient and personal dose equivalent conversion coefficients in this energy region.

The fluence to dose equivalent conversion coefficients can be computationally averaged over these spectra, and the results for $h_p(10,0^o)$ are:

$\overline{h_p(10,0^\circ)}$ = 11.8 pSv cm^2 for the NPL thermal column, c.f.

$\overline{h_p(10,0^\circ)}$ = 11.7 pSv cm^2 for a pure room temperature Maxwellian.

(c.f. $h_p(10,0^\circ)$ = 11.4 pSv cm^2 at a point energy of 0.0253 eV.)

For h*(10) the values averaged over the spectra gave:

$\overline{h^*(10)}$ = 11.5 pSv cm^2 for the NPL thermal column, c.f.

$\overline{h^*(10)}$ = 11.3 pSv cm^2 for a pure room temperature Maxwellian.

(c.f. $h^*(10)$ = 10.6 pSv cm^2 at a point energy of 0.0253 eV.)

From the above data, the uncertainty in the conversion coefficients introduced by the fact that the thermal spectrum is not simply a Maxwellian at 293.6 K is obviously small. Changing the temperature by 11^{o}C, the estimated uncertainty on its value, changes the conversion coefficients by at most 0.5%. Changing the measured epithermal fraction in the sub-cadmium region from its typical value of 3% to a value of 2% changes the coefficients by less than 0.2%. These are the parameters which have the biggest effect on the spectrum. From these arguments the uncertainty in the conversion coefficients would probably be of the order of 0.5%. However, this assumes that the spectrum can be described adequately as a Maxwellian peak and 1/*E* component. Making allowance for the fact that this assumption may not be completely correct, an uncertainty estimate of ±1% is assigned to the spectrum averaged conversion coefficients.

7 Conclusions

Thermal fluences can be measured, using the activation of gold foils both bare and under a cadmium cover, and quoted in the Westcott convention with very low uncertainties, of the order of 0.5% for the sub-cadmium-cut-off fluence. These are not, however, the fluences required when calibrating neutron sensitive devices used in radiation protection. The ‘true’ sub-cadmium-cut-off fluence, which is now quoted on NPL certificates along with the Westcott value for this fluence, is derived by multiplying the Westcott value by a correction factor. For the NPL thermal column the value of this correction factor is 1.193 with an uncertainty estimated as ±2%.

In order to convert the true fluence to dose equivalent values spectrum averaged fluence to dose equivalent conversion coefficients need to be applied.

To convert ‘true’ sub-cadmium-cut-off fluence to personal dose equivalent the coefficient to use is: $\overline{h_p(10,0^\circ)}$ = 11.8 pSv cm^2.

To convert ‘true’ sub-cadmium-cut-off fluence to ambient dose equivalent the coefficient to use is: $\overline{h^*(10)}$ = 11.5 pSv cm^2.

The uncertainty on both these conversion coefficients is estimated to be ±1%, and is small because the conversion coefficients do not change rapidly with neutron energy over the thermal region.

It should be noted that the gold foil measurements, on which the derivation of the effective temperature described in this report are based, were performed some years ago during experiments to determine the thermal response of a ^{3}He proportional counter[9]. Since that time a number of additional gold foil measurements have been performed, and analysis of these data have indicated the possibility of variation of the cadmium ratio with height in the thermal column, and also a possible dependence of this parameter on whether the column is evacuated or not. These effects are presently being investigated, and some changes may need to be made in the future to the effective temperature value used. However, in view of the large uncertainty assigned to the effective temperature, the correction factor used to convert Westcott fluence to the true fluence, and the conversion coefficients used to derive dose equivalent quantities are not expected to change by more than their estimated uncertainties.

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