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CHARACTERISATION OF A LONG COUNTER FOR JRC GEEL

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Characterisation of a long counter for JRC Geel

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ABSTRACT:

A precision long counter, based on the design of De Pangher and Nichols, and usually referred to as a De Pangher long counter, has been assembled and characterised for neutron fluence measurements at the Joint Research Centre Geel laboratory. The instrument is based on a De Pangher long counter body that was available at NPL and a new BF_3 counting tube. Efficiency and effective centre values for the instrument are presented, as a function of neutron energy, with details of the measurements and calculations that underpin these parameters that are required when deriving the neutron fluence from the counts produced by the instrument.

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Approved on behalf of NPLML by
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1 Introduction

Following discussions with Stephan Oberstedt, from Directorate G Nuclear Safety and security, Unit G.2 Standards for Nuclear Safety, Security and Safety of the European Commission Joint Research Centre (JRC-Geel), about the provision of an instrument to measure neutron fluence at Geel a request was received for: “a De Pangher assembly for neutron fluence characterisation including its characterization with radionuclide sources (Am-Li, Am-F, Am-B, Cf-252 and Am-Be)”. The requested items were:

- De Pangher assembly including a polyethylene rod:
- Appropriate BF₃ counter:
- Characterization:
- Transport:

Responding to this request NPL provided a quotation for the work, NPL Reference 2016100347, and in due course received a purchase order, no. G.B825485, for the goods. The quotation was based on the use of a De Pangher long counter body already available at NPL,

The long counter body in question was one of a number purchased by NPL from Centronic Ltd. some time in the 1960s or early 1970s. It was kept as a backup for the De Pangher long counter routinely used to measure neutron fluences produced by the NPL Van de Graaff accelerator. However, as NPL has three backups available, it was decided that one of these was surplus to requirements and could be offered as part of the package to produce a well-characterised neutron detector using NPL’s experience in measuring the properties of this type of instrument.

Long counters derive their name from their shape. They are cylindrical and are used in arrangements where the neutrons are incident on one end of the cylinder, the detection electronics, or at least the preamplifier, being positioned at the opposite end. They consist of a cylindrical moderator surrounding a thermal neutron sensitive counting tube on the central axis. The moderator slows down and moderates fast neutrons producing thermal neutrons which are detected in the central counting tube. This was historically a proportional counter containing BF₃ gas although other detectors, e.g. a ³He tube can be used. Wax was originally used for the moderator, but polyethylene, being more stable, tends to be used nowadays.

The history of the long counter can be traced by to an early paper by Hanson and McKibben⁽¹⁾. The basic rationale for the development of this type of instrument was to devise one with a flat fluence response, i.e. a response that is constant with energy, over as large a fraction of the fast neutron energy region as possible. If this can be achieved a single calibration, for example with a radionuclide source of accurately-measured emission rate, gives an instrument with a known constant fluence response over a wide energy range. Although the response of a well designed long counter can be flat to first order over a reasonable energy range, there are some oscillations and dips due to resonances in the carbon in the moderator, and for accurate fluence measurements a full response function has to be determined by measurements or calculations or ideally a combination of the two.

Later developments of the original long counter concept included changes to the moderator configuration to improve the flat response and to provide shielding for neutrons incident from the side. This is achieved by having an outer moderating layer with a thermal neutron absorbing layer between the outer shield layer and the inner moderator. A directional counter, with reduced sensitivity to neutrons from the side, is a distinct advantage when measuring neutrons from a point source as the response to scattered neutrons, which are always present in any laboratory environment, is greatly reduced thus simplifying the correction for this component.

In 1966 De Pangher and Nichols⁽²⁾ proposed a ruggedized design, which they referred to as a precision long counter (PLC), that could be built from a standard set of drawings with well defined tolerances. Polyethylene was used for the moderator as it is much more stable than wax. The advantage of this approach is that all long counters of this type should have near identical properties so that the characteristics determined for one long counter are applicable to other counters of this type after taking account of any normalisation differences due to variations in the sensitivities of the BF₃ tubes used in the individual instruments. A test of the extent to which this uniformity of properties could be relied on was undertaken in the late 1960s when a set of six De Pangher long counters were commissioned from Centronic Ltd. by various establishments in the UK⁽³⁾. The measurements confirmed that these long counters could be used as standard instruments and an approach was devised for checking individual long counters using a broad range high energy radionuclide source (²⁴¹Am-Be) to determine the overall normalisation, and one that produced low energy neutrons to check the energy dependence of the response. Unfortunately the low energy source chosen, ¹²⁴Sb-Be(γ ,n) has a very high photon dose, and needs to be regularly reactivated in a reactor, making it very difficult to use routinely.

The De Pangher PLC has a fairly flat response from about 1 keV (and possibly lower since measurements are not possible in this energy region) to roughly 6 MeV. However, for accurate fluence measurements over this region the variations in the response does need to be determined.

Because the long counter is a physically large instrument, with no obvious reference point, there is another parameter which needs to be known, and this is the effective centre for the device. It is defined as the point on the axis of the instrument for which the measured count rate, in a completely scatter free environment, falls off with a $1/r^2$ dependence on the distance, r , from the effective centre to a point neutron source. The effective centre distance, r_0 , is measured from the front face of the moderator and is added to the distance, r_1 from the point source to the moderator front face to give the distance, r . It is energy dependent increasing as the neutron energy increases. This can be thought of as the depth of the maximum of the thermal neutron distribution getting deeper into the moderator as the incident neutron energy increases. The response of the instrument, usually termed the efficiency, is defined as the count rate per unit fluence rate at the effective centre position. It has units of cm² so dividing the count rate by the efficiency gives the fluence rate in neutrons per cm² per second at the distance r from the source of neutrons. Alternatively dividing the total number of counts over a measurement period by the efficiency gives a value for the total fluence. The concept of an effective centre is only relevant for a point source of neutrons. In a plane parallel beam, for example, it would not be necessary.

2 Assembly of the long counter

2.1 The long counter body

The De Pangher long counter for the JRC (hereafter called the JRC PLC) is shown in Figure 1 positioned on a trolley on one of the four detector mounting arms in the low-scatter experimental area in the Chadwick Building at NPL. The picture shows the side and the rear face of the instrument with the end of the BF₃ tube protruding. This is connected to a preamplifier, mounted on this rear face, and cables from this go to the remainder of the electronic chain. For measurements at NPL the electronics was located in the experimental control room outside the low-scatter area.

Unfortunately none of the original documentation for this long counter has survived, but to the best of our knowledge it is a standard De Pangher PLC as constructed in the 1960s by Centronic Ltd to the design⁽⁴⁾ shown schematically in Figure 2. Note that a polyethylene source rod, as shown

in Figure 2, was present for the NPL characterisation measurements, but did not incorporate a neutron test source.



Figure 1. The JRC PLC in the low-scatter area in the Chadwick Building at NPL

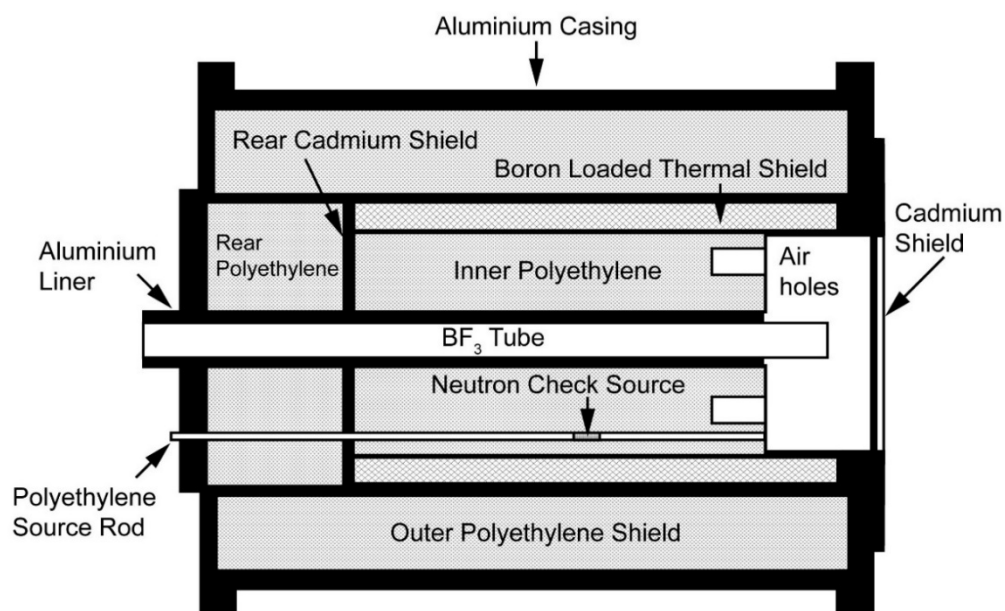


Figure 2. Schematic diagram of a De Pangher long counter (not to scale).

For measurements at NPL the long counter was mounted, as can be seen in Figure 1, on a flat mounting plate, where it was held in position by four screws through holes in the plate into the octagonal end pieces of the counter body. Plastic inserts in the holes ensured that the long counter was not earthed in the experimental area. Connection to earth was provided via the signal cables which connect the preamplifier to the remainder of the electronic chain in the experimental control room outside the low-scatter area.

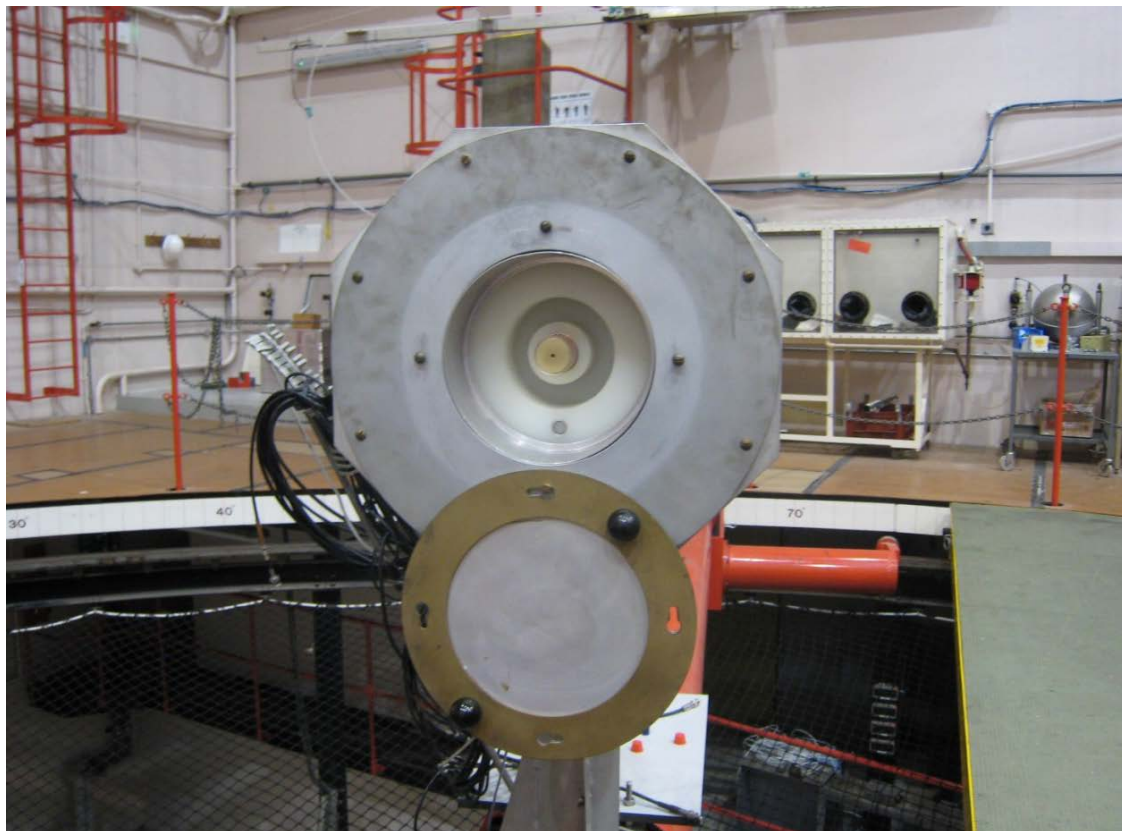


Figure 3. Front face of the JRC PLC with the cadmium shield lowered.

Figure 3 shows the end of the long counter that should face the source of neutrons. The front cadmium shield has been lowered to show the end of the moderator cylinder with the BF_3 tube protruding. The front face of the moderator has a circular trough designed to improve the flatness of the response to low energy neutrons. Effective centre distances are measured not from the outer casing, or the end of the BF_3 tube, but from the polyethylene of the moderator in the region between the BF_3 and the trough. The cadmium shield over the front minimises the response to thermal neutrons.

2.2 BF_3 counters

The Centronic version of the De Pangher PLC is designed to take a particular model of BF_3 proportional counter tube; Centronic part no. is 26EB25/38M. It is made of copper tube with reasonably thin walls to minimise neutron capture. This forms the cathode and the anode wire is mounted centrally. Each of the numbers and the combination of letters in the part no. provide information on the tube. The first number, 26, is the active length of the BF_3 region in cm. The letters EB indicate that the tube contains BF_3 enriched in ^{10}B , although the degree of enrichment is not given in the documentation provided with the counters or in the Centronic literature on its products. The second number, 25, is the BF_3 gas pressure in cm Hg (equal to 333 kPa or about 1/3 atmosphere), 38 is the tube diameter in mm, and the M signifies a metal ceramic seal at the end of the tube.

Two of these BF₃ tubes were purchased with serial nos 1717-037 and 1724-048. They were delivered with a Certificate of Conformity and a Test Results sheet. Copies of these can be found in the Appendix and have been supplied with the instrument.

The positioning of the BF₃ counter within the De Pangher body is defined by having the end of the copper tube flush with the end of the short aluminium tube attached to the back of the long counter – see Figure 4.



Figure 4. Positioning of the BF₃ counter in the long counter body.

2.3 Electronics

The electronics used to test the JRC PLC at NPL and to measure its characteristics was a conventional system of NIM modules. They are listed below with the most relevant settings:

Preamplifier	Ortec model 142 PC
High voltage	iseg NHQ 203M
	Voltage $\Rightarrow$ 900 V
Main amplifier	Ortec model 571
	Coarse gain $\Rightarrow$ 20
	Fine gain $\Rightarrow$ minimum
	Time constants $\Rightarrow$ 2.0 μ s
	Output to SCA $\Rightarrow$ bipolar
	Output to MCA $\Rightarrow$ unipolar via Ortec 427A delay amplifier
Single channel analyser (SCA)	Ortec model 551
	Window setting $\Rightarrow$ integral

The positive signal from the SCA was fed into an NPL designed Width/Delay unit that provided logic pulses both for counting in a scaler system and for gating an MCA in order to set the discriminator level in the SCA to discriminate against gamma ray events and noise. All events above this discriminator level were counted in the scaler system.

2.4 Initial testing

The pulse height spectrum, obtained using a small ^{241}Am -Be check source and BF_3 tube serial no. 1724-048 in the JRC PLC, is shown in Figure 5. A very similar spectrum was obtained with the other BF_3 .

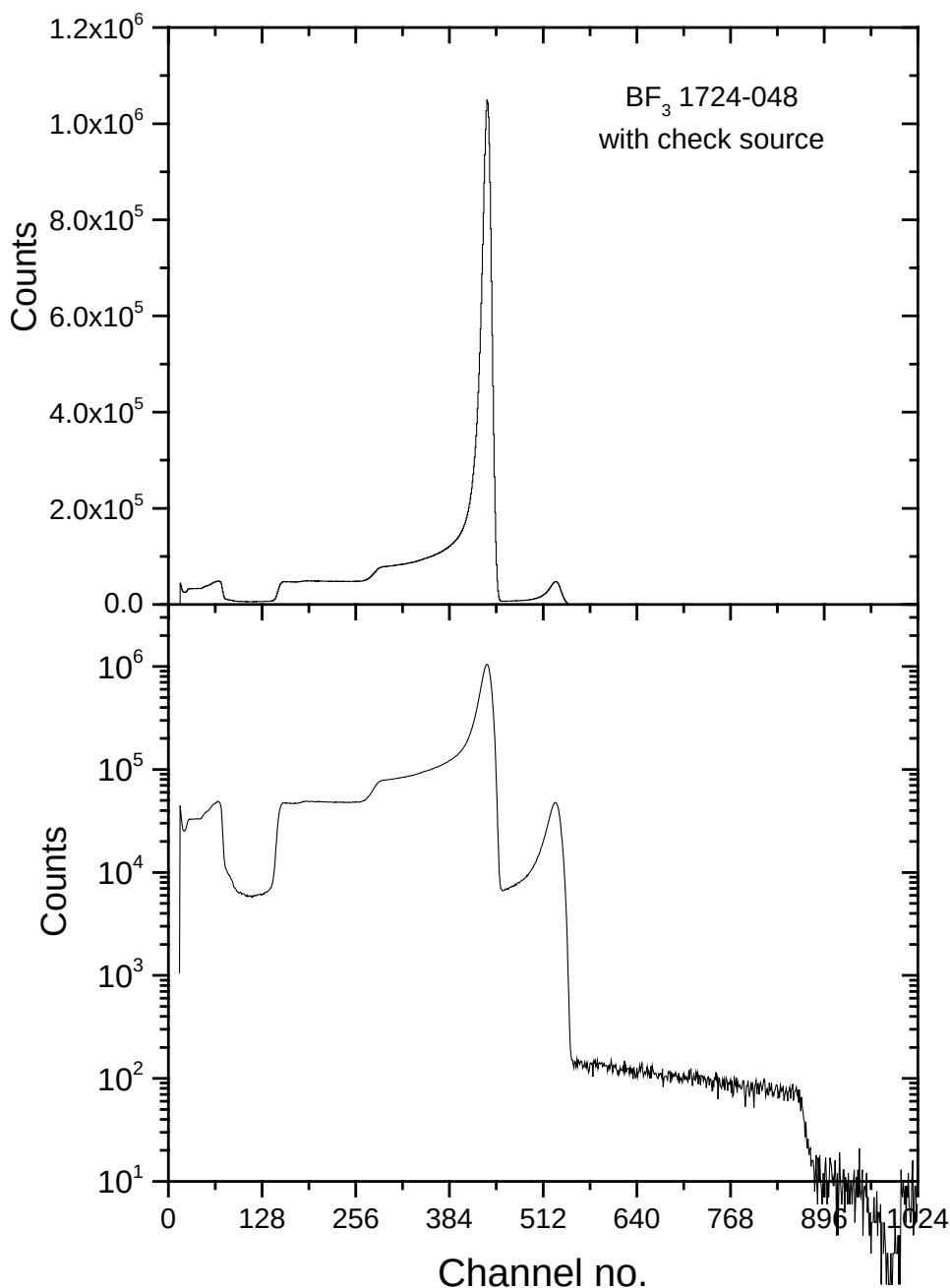


Figure 5. BF_3 pulse height spectrum on a linear y scale above and a log y scale below

The data shown in Figure 5 were accumulated without gating by the SCA output; the cut off seen at low energy is due to the MCA discriminator which was set to exclude noise but not the

low energy signals due to photons. The SCA discriminator level was set at about channel 115 in the valley between the gamma ray events and the neutron events. It was checked at regular intervals during the subsequent characterisation measurements. Although the valley is fairly wide the counts in this region are quite low, and the count rate of all the events above the discriminator is not very sensitive to the exact position of the discriminator level. Changing it from the middle of the valley to either end changes the rate by about 0.5%.

The applied voltage of 900 V is somewhat lower than that suggested by the manufacturer (1267 V see the Appendix), or that used for the NPL De Pangher long counter. However, the signal height produced by this voltage was the same as that produced by the NPL De Pangher with the same electronics. Furthermore the spectrum exhibits good resolution of the peaks, probably better than that shown in the manufacturers test results, and all the features expected of a BF_3 pulse height spectrum are present. These are: the two peaks corresponding to the two possible final states in ^7Li produced in the $^{10}\text{B}(\text{n},\alpha)^7\text{Li}$ reaction, and the two ledges, the upper energy one corresponding to the energy of the ^7Li ion being entirely lost to the wall of the proportional counter and the lower when the energy of the alpha particle is lost to the wall. No explanation for the lower voltage requirement is immediately obvious although a smaller diameter anode wire would be a possibility.

3 Characterisation of the JRC PLC

3.1 BF_3 tube relative efficiencies

BF_3 tubes tend not to have identical sensitivities, presumably because of small differences in filling gas pressure or degree of ^{10}B enrichment. To compare the relative sensitivities of the two JRC BF_3 tubes measurements were made with the small, ~ 1.1 GBq (30 mCi) ^{241}Am -Be check source usually used with the NPL De Pangher long counter to check its long term stability. The results are shown in Table 1.

Table 1. Count rates obtained for various combinations when using an ^{241}Am -Be check source

Count rate (s^{-1})		Ratios			
JRC BF_3 1724-048	JRC BF_3 1724-037	NPL BF_3 ZB-1537	JRC 037 / JRC 048	JRC 048 / NPL	JRC 037 / NPL
152.925	153.649	143.668	1.00474	1.06443	1.06947
± 0.074	± 0.034	± 0.061	± 0.00054	± 0.00069	± 0.00051
(0.05%)	(0.02%)	(0.04%)	(0.05%)	(0.09%)	(0.05%)

The two columns labelled JRC BF_3 are for the JRC long counter with one or other of the two BF_3 counters installed. The NPL BF_3 column refers to the NPL De Pangher long counter with its usual BF_3 tube. The last three columns give the ratios of count rates. The uncertainties are purely statistical and are quoted as standard uncertainties (1 sigma). Other uncertainty components are evident when making repeat measurements over a period of time due, for example, to very slight differences in the position of the source, minor variations in the discriminator level, and possible background variations. These are evident if the history of check source measurements for the NPL De Pangher are examined. The data shown in the table were, however, taken over a short period of time so the contributions of these uncertainty components is not known but would be expected to be below 0.5%. Nevertheless, Table 1 clearly shows that, although JRC 1724-037 is marginally more sensitive than JRC 1724-048, the JRC PLC with either BF_3 tube has an efficiency for the check source that is more than 6% higher than the NPL De Pangher.

When, many years ago, the check source was installed in the polyethylene source rod used with the NPL de Pangher it was not positioned as indicated in Figure 2 near the centre of the moderator

region but at the end of the rod in the vicinity of the air holes in the polyethylene moderator. Although this does not affect its use as a check source for the NPL De Pangher it may be significant when comparing the relative efficiencies of the JRC and NPL De Pangher long counters. Even a very slight difference in the length of the access hole for the rod would change the source position relative to the end of the moderator, and this would change the efficiency for detecting the neutrons from the source. The figures in Table 1 for the ratio of the JRC PLC efficiency, with either BF₃ tube, to the efficiency of the NPL De Pangher thus have an unknown uncertainty component, although this is not expected to be large, and it can be concluded that the JRC PLC has a higher efficiency than the NPL De Pangher. For the ratio of the efficiencies of the two JRC BF₃ tubes the data in Table 1 should provide an accurate value.

3.2 The long counter efficiency

As mentioned earlier the tight constructional tolerances for the dimensions of the De Pangher long counter components mean that any two counters should have the same energy response function to within a normalisation constant to allow for BF₃ tube differences. The response function of the NPL De Pangher has been studied extensively over the years and numerical values for the response as a function of energy have been derived from a combination of calculations and measurements^(5,4,6,7). Confirmation has also been obtained from international fluence comparison exercises^(8,9,10). This response function can be used for the JRC PLC after normalisation which, in principle, can be done on the basis of a measurement for the two counters with a single radionuclide neutron source. However, to increase the amount of information on which to base the normalisation, and to investigate any variation in the shapes of the two response functions, measurements were performed with a number of different radionuclide sources and also with monoenergetic neutrons. Note that all these measurements were performed with BF₃ counter serial no. 1724-048. Values for efficiencies with the other BF₃ tube 1717-037 can be obtained using the ratio given in Table 1. The effective centre does not depend on the precise efficiency or thus on small variations in the BF₃ sensitivities.

The measurements with monoenergetic neutrons simply involved comparing the count rates for the two counters positioned sequentially at the same position relative to the neutron-producing target. Similar measurements were made using radionuclide neutron sources. Because the neutron emission rate of the sources was known, having been measured in the NPL manganese bath, absolute measurements, rather than comparative ones, could be made with sources. The procedures for these three approaches are described below.

3.2.1 Absolute efficiency measurements with radionuclide sources

In this approach measurements were made with the JRC PLC at a large number of distances between the radionuclide source and the long counter. At each distance count rates were recorded both with a shadow cone in place and without one. The shadow cone blocks the direct neutrons from the source so the long counter only sees the room and air in-scattered neutrons. Without the cone the long counter sees both direct and scattered neutrons so a subtraction of the with-cone count rate from the without-cone count rate gives the count rate due to direct neutrons. A small correction is also required for air out-scattered neutrons in order to obtain the count rates that would be obtained in a completely scatter-free environment. This direct count rate, M , is then plotted as a function of the distance l to the front face and a fit made to:

$$M = \frac{k}{(l + r_0)^2} \quad (1)$$

with k and r_0 the parameters to be fitted.

The parameter, k , known as the characteristic constant⁽¹¹⁾, is related to the efficiency, ε , by:

$$\varepsilon = k / \Phi_C \quad (2)$$

where Φ_C is the ‘calibration’ fluence at 1 cm from the source, a value that was calculated from the known source emission rate and the anisotropy of the emission.

One additional feature of this approach is that values are derived for the effective centre, r_0 ; these will be discussed later.

Figure 6 shows a plot of the data from a measurement with an $^{241}\text{Am-B}$ source. The distance variations were performed automatically using a computer program to control both the source to long counter distance and the recording of the counts from the long counter.

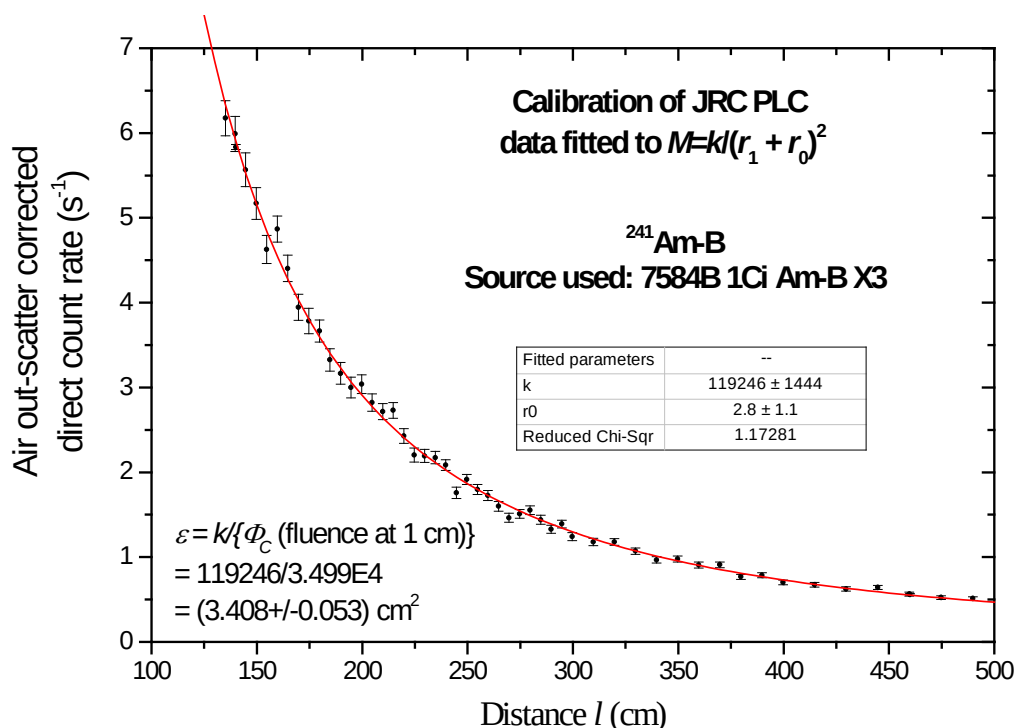


Figure 6. Data analysis of an efficiency measurement with an $^{241}\text{Am-B}$ neutron source

Table 2 lists the results for four different radionuclide sources. Data for the NPL De Pangher have been obtained over a number of years and the values shown in the table are an average of several measurements.

Table 2. Efficiencies and efficiency ratios measured with radionuclide neutron sources.

Neutron source	Measured efficiency (cm ²)		Ratio JRC/NPL
	JRC PLC	NPL PLC	
$^{241}\text{Am-Li}$	3.479 ± 0.043	3.402 ± 0.042	1.023 ± 0.018
^{252}Cf	3.543 ± 0.022	3.352 ± 0.023	1.057 ± 0.010
$^{241}\text{Am-B}$	3.408 ± 0.041	3.295 ± 0.025	1.034 ± 0.015
$^{241}\text{Am-Be}$	3.378 ± 0.022	3.207 ± 0.015	1.053 ± 0.009

3.2.2 Comparative efficiency measurements with radionuclide sources

Performing measurements at a large number of distances is time consuming, particularly for sources with low emission rates, and since the aim is to obtain information on the ratio of the JRC PLC efficiency to that for the NPL PLC a simpler approach is to just make comparison measurements at a fixed distance from the source. Because the emission from a cylindrically encapsulated neutron source is the same in all directions in a horizontal plane through the middle of a source capsule mounted with its axis vertical, measurements can be made with both long counters at the same time. An advantage of this approach is that uncertainties are small, the only important components being statistics and the uncertainty in the source to long counter distance. Table 3 lists the count rates for the two long counters and their ratio. The very different count rates for the different sources is due to the varied emission rates of these sources.

Table 3. Efficiency values from comparative measurements with radionuclide sources

Neutron source	Long counter count rate (s^{-1})		Ratio JRC/NPL
	JRC	NPL	
$^{241}\text{Am-Li}$	2.805 ± 0.006	2.705 ± 0.006	1.0367 ± 0.0037
$^{241}\text{Am-F}$	0.913 ± 0.010	0.872 ± 0.007	1.046 ± 0.014
^{252}Cf	525.5 ± 1.1	500.10 ± 0.88	1.0507 ± 0.0028
^{252}Cf	524.23 ± 0.75	499.09 ± 0.67	1.0504 ± 0.0021
^{252}Cf	Weighted mean of two ^{252}Cf measurements =		1.0505 ± 0.0017
$^{241}\text{Am-B}$	4.141 ± 0.021	3.988 ± 0.014	1.0384 ± 0.0063
$^{241}\text{Am-Be}$	15.357 ± 0.035	14.481 ± 0.073	1.0604 ± 0.0059

3.2.3 Comparative efficiency measurements with monoenergetic neutrons

Similar measurements to those described in section 3.2.2 can be performed with monoenergetic neutrons produced using nuclear reactions generated by charged particle beams from the NPL Van de Graaff accelerator. Because neutron emission intensities from the neutron-producing targets have a strong dependence on the angle relative to the charged particle beam initiating the reaction, measurements with the two long counters cannot be made at the same time, but have to be performed sequentially using monitors to relate the neutron fluence rates seen in the two measurements. The monitors used were the beam current on the neutron-producing target and a 'slab' monitor consisting of BF_3 tubes embedded in a block of polyethylene attached to the lab wall. The results are shown in Table 4.

Table 4. Efficiency values from comparative measurements with monoenergetic neutrons

Neutron energy (MeV)	Neutron producing reaction	Long counter count rate (s^{-1})		Ratio JRC/NPL
		JRC	NPL	
0.070	$^7\text{Li(p,n)}^7\text{Be}$	40.894 ± 0.055	39.700 ± 0.054	1.0301 ± 0.0055
0.144	$^7\text{Li(p,n)}^7\text{Be}$	35.56 ± 0.13	34.477 ± 0.091	1.0313 ± 0.0070
0.565	$^7\text{Li(p,n)}^7\text{Be}$	138.91 ± 0.20	134.06 ± 0.35	1.0362 ± 0.0060
2.5	$\text{T(p,n)}^3\text{He}$	4.9900 ± 0.0069	4.7675 ± 0.0070	1.0467 ± 0.0056
16.5	$\text{T(d,n)}^4\text{He}$	0.9351 ± 0.0028	0.8750 ± 0.0023	1.0687 ± 0.0068

One important aspect of the monoenergetic neutron measurements is that they cover the range from 70 keV to 16.5 MeV thus providing efficiency data over a wider range of energies than radionuclide sources.

The uncertainties for the count rates shown in Table 4 include components for statistics, distance uncertainty, and a component for uncertainty in the scatter correction performed using a shadow cone. The in-scatter correction was made because the scatter for the two measurements might have been very slightly different due to variations in the positions of other instruments in the lab resulting from having to put the two long counters at the relevant angle sequentially. (For the duration of the measurements described in this report the JRC PLC was mounted on one of the detector transport arms in the low-scatter experimental area, and the NPL PLC on another. When one long counter was positioned at the relevant angle and distance for a monoenergetic measurement, or an absolute source measurement, the other was moved as far away as possible, but not removed from the detector transport arm. The scattering field was thus slightly different for the two measurements although in practice these differences were probably negligibly small.)

The ratio JRC/NPL shown in Table 4 contains an additional component for possible variations in the fluence rate per unit monitor rate between measurements as deduced from measuring the ratio of the two monitors.

3.2.4 *Derived efficiencies for the JRC PLC*

Table 5 summarises the results from all the efficiency measurements. The term ‘Absolute’ is used to describe measurements performed with sources when using a range of source to long counter distances, and ‘Comparative’ when only a comparison of the JRC and NPL long counter count rates was made.

Table 5. Summary of efficiency ratio measurements.

Source of neutrons	Energy (MeV)	Ratio JRC/NPL
Monoenergetic	0.070	1.0301 ± 0.0055 (0.54%)
Monoenergetic	0.144	1.0313 ± 0.0070 (0.68%)
²⁴¹ Am-Li Absolute	0.53	1.023 ± 0.018 (1.7%)
²⁴¹ Am-Li Comparative	0.53	1.0367 ± 0.0031 (0.30%)
Monoenergetic	0.565	1.0362 ± 0.0060 (0.58%)
²⁴¹ Am-F Comparative	1.3	1.046 ± 0.014 (1.3%)
²⁵² Cf Absolute	2.2	1.0571 ± 0.0097 (0.92%)
²⁵² Cf Comparative	2.2	1.0505 ± 0.0017 (0.16%)
Monoenergetic	2.5	1.0467 ± 0.0056 (0.54%)
²⁴¹ Am-B Absolute	2.7	1.034 ± 0.015 (1.4%)
²⁴¹ Am-B Comparative	2.7	1.0384 ± 0.0063 (0.60%)
²⁴¹ Am-Be Absolute	4.3	1.0532 ± 0.0085 (0.81%)
²⁴¹ Am-Be Comparative	4.3	1.0605 ± 0.0054 (0.54%)
Monoenergetic	16.5	1.0687 ± 0.0068 (0.64%)

The data are presented graphically in Figure 7 where the energy on the x-axis is on a logarithmic scale in order to spread out the data. Although the error bars appear large, the majority of the uncertainties, quoted as standard uncertainties, are less than 1%.

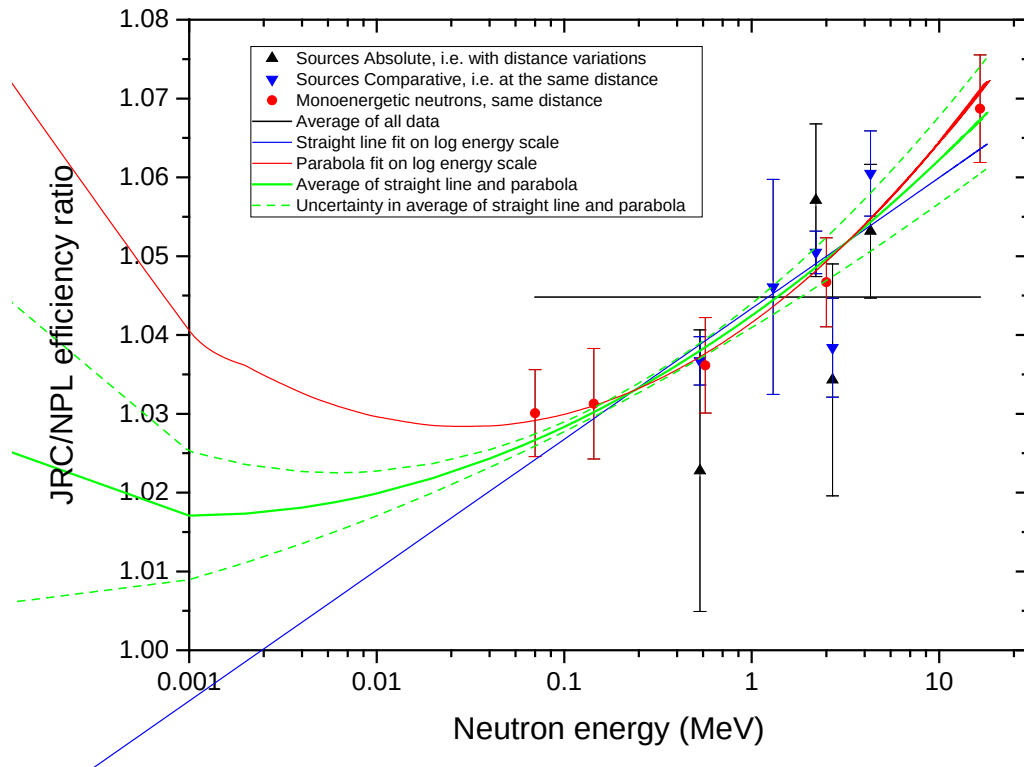


Figure 7. Measurements of the relative efficiency of the JRC and NPL De Pangher long counters

The evidence from Figure 7 suggests that the ratio of efficiencies, JRC/NPL, increases slightly as the neutron energy increases. This could be due to a number of reasons; slight differences in the long counter construction or the density of the polyethylene for example. In view of this it was decided to derive a function relating the JRC PLC response function to that for the NPL PLC rather than a single normalisation factor. Two functions were tried, a straight line and a quadratic and the lines obtained are plotted in the figure.

Over the range where measured efficiency ratios are available either fit would appear to be acceptable. However, it would be useful to be able to use the long counter down to lower energies, e.g. 1 keV, where accurate fluence measurements are particularly difficult. The x-axis in Figure 7 has been deliberately extended down to this energy, despite the fact that there is no experimental data below 70 keV, in order to see how the fitted curves behave in this region. It appears that the straight line fit decreases too quickly, and the quadratic actually ‘turns over’ and begins to increase again. For this reason the pragmatic approach of taking the average of these two was adopted, and this gives a plausible prediction for the low energy region.

The efficiency values obtained in this way are tabulated in Appendix 2. They are also plotted in Figure 8 and Figure 9. Figure 8 covers the full energy range and the data are displayed with a logarithmic energy scale. Figure 9 provides a view of the important energy region between 1 and 7 MeV. The peaks and dips in this energy range correspond to resonances and other features in the cross section of the carbon which is one of the main elements in the polyethylene moderator. If the long counter is used with monoenergetic neutrons it is recommended that the energies where the response function varies rapidly are avoided.

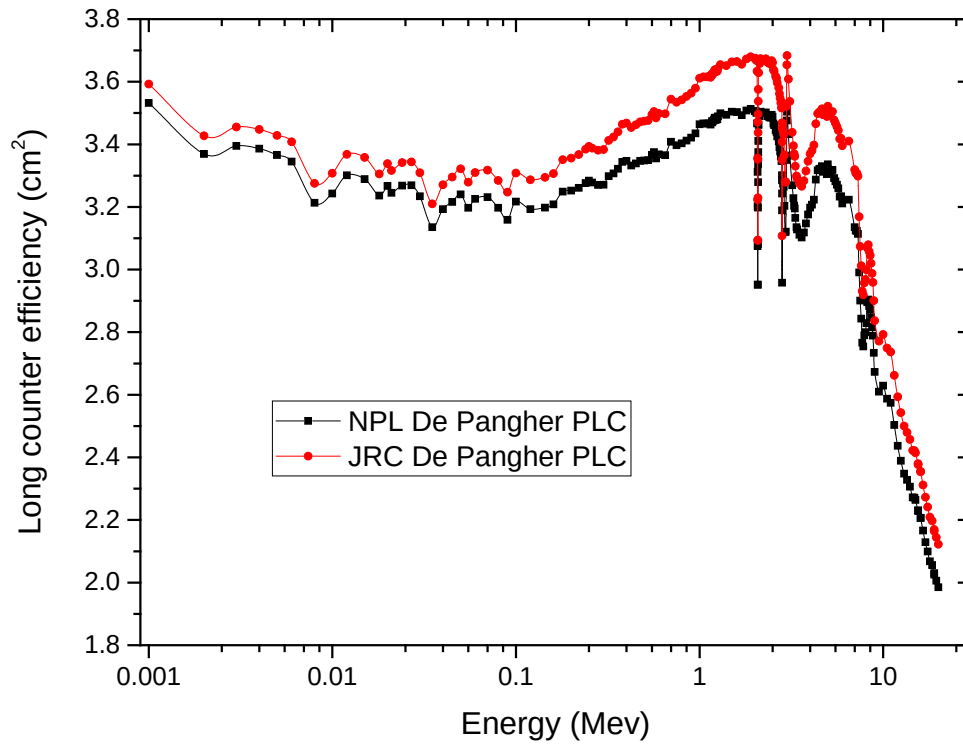


Figure 8. Efficiency curve derived for JRC PLC by comparison with that of the NPL PLC

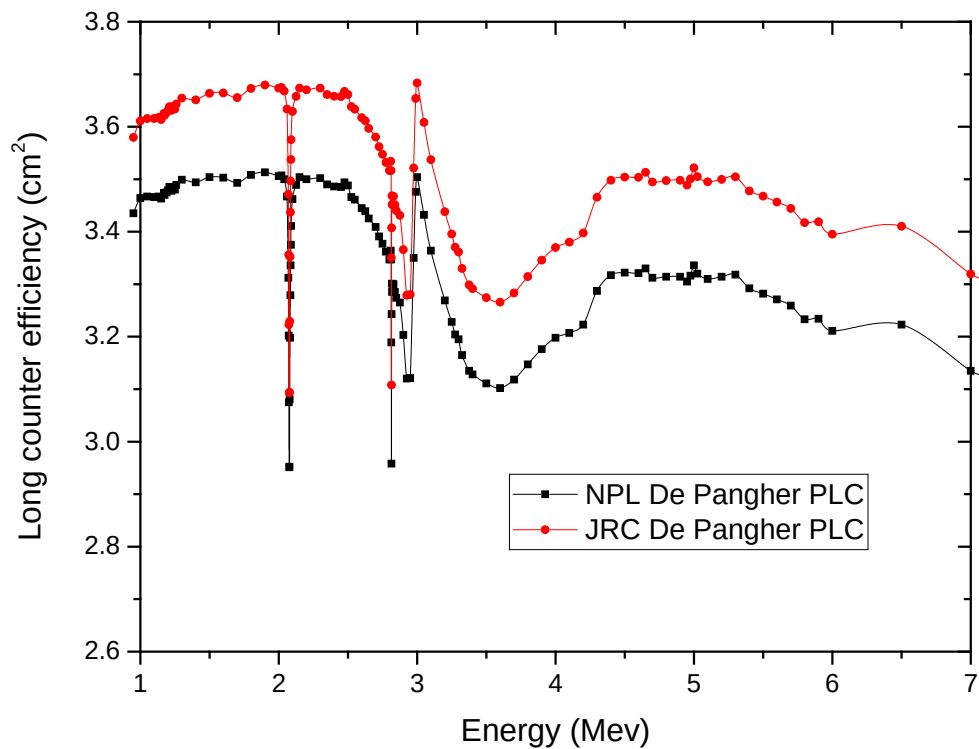


Figure 9. As for Figure 8 but restricted to the energy region from 1 to 7 MeV.

3.3 The long counter effective centre

Measurements of the effective centre of a long can be performed with radionuclide sources, as described in section 3.2.1. They can also be measured using monoenergetic neutrons since the fluence does not need to be known and measurements were performed for the JRC PLC at 565 keV and 16.5 MeV. Figure 10 shows the data analysis for the 565 keV neutron measurements. It was not possible to automate these accelerator-based measurements in the same way as with radionuclide sources, so data were recorded at fewer distances, but good statistics were obtained and reasonable uncertainties for the values of r_0 .

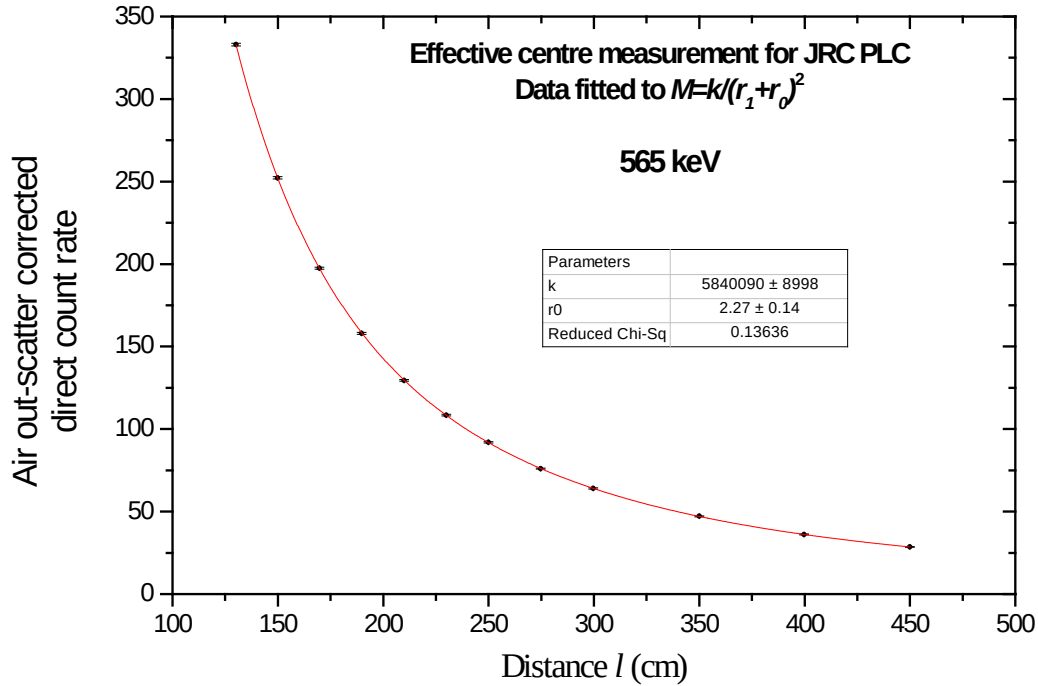


Figure 10. Data analysis of an effective centre measurement for 565 keV neutrons.

The results of all the measurements performed for the JRC PLC are presented in Table 6 where they are compared with the corresponding measurements for the NPL De Pangher and also with calculations of the effective centre. Unlike the efficiency, which is a characteristic of the long counter, and can be calculated directly using MCNP, the effective centre is a characteristic, not of the long counter on its own, but of the long counter plus source combination. The only way it can be calculated is by simulating the experiment used to measure r_0 . Long counter counts are calculated for a range of different distances and the results analysed as if they were experimental data. The approach has advantages in that the system can be modelled in vacuum so that no corrections have to be made for scatter. However, extensive calculations are required, which are time consuming, and care must be taken to avoid correlations which can distort the results⁽⁷⁾. These arise because MCNP begins from the same random number seed unless instructed to use a different one, and calculations which only differ in terms of a change in the source to long counter distance are not completely independent.

Although the average value for the ratios of the JRC measured effective centres divided by the values for the NPL De Pangher is close to one, there are some individual values that are significantly different. This probably does not signify any real difference between the effective centres of the two long counters as a function of energy, but is rather a reflection of the difficulty in measuring this parameter.

Table 6. Effective centre measurements for the JRC and NPL PLCs

Source of neutrons	Energy (MeV)	Long counter effective centre (cm)			Ratio JRC/NPL	
		JRC	Measured	Calculated	Measured	Calculated
$^{241}\text{Am-Li}$	0.53	1.1 ± 1.1	3.4 ± 1.2	1.70 ± 0.20	0.32 ± 0.34	0.65 ± 0.65
$^7\text{Li(p,n)}^7\text{Be}$	0.565	2.27 ± 0.14	1.88 ± 0.24	2.1 ± 1.5	1.21 ± 0.17	1.07 ± 0.76
^{252}Cf	2.2	3.07 ± 0.19	3.08 ± 0.16	3.51 ± 0.16	1.00 ± 0.08	0.87 ± 0.07
$^{241}\text{Am-B}$	2.7	2.8 ± 1.1	4.39 ± 0.84	3.73 ± 0.13	0.64 ± 0.28	0.75 ± 0.30
$^{241}\text{Am-Be}$	4.3	5.53 ± 0.55	4.49 ± 0.18	4.69 ± 0.63	1.23 ± 0.13	1.18 ± 0.20
$\text{T(d,n)}^4\text{He}$	16.5	10.88 ± 0.54	9.92 ± 0.34	7.3 ± 1.5	1.10 ± 0.07	1.44 ± 0.30
Weighted mean =					1.06 ± 0.07	1.10 ± 0.11

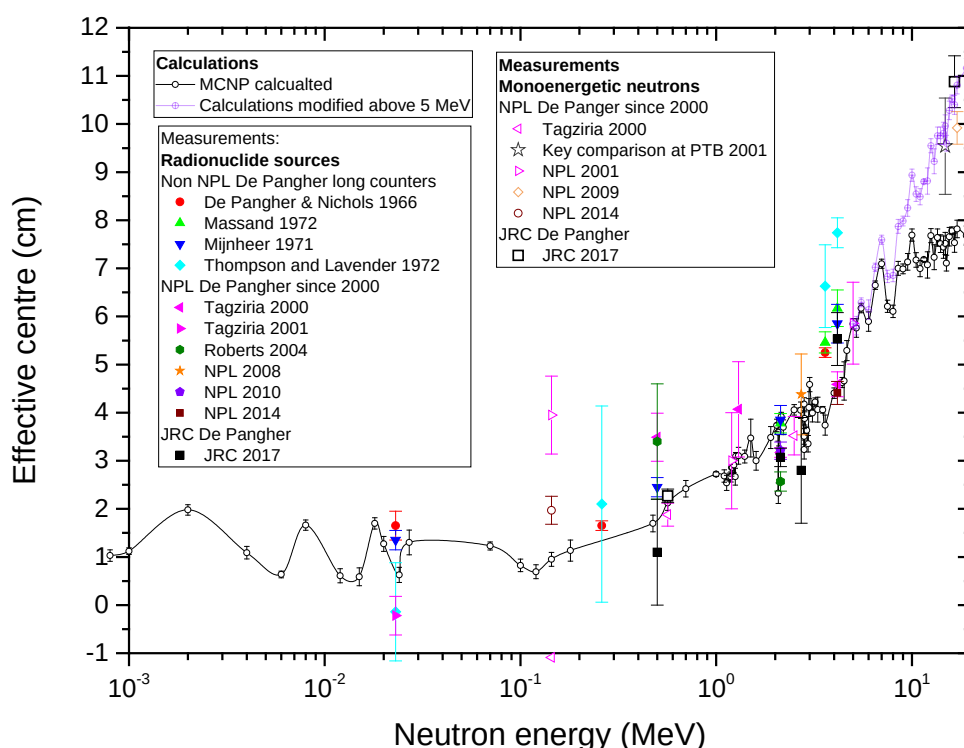


Figure 11. Effective centre measurements and calculations for De Pangher long counters.

In Figure 11 the calculated De Pangher effective centres are compared with a large number of measurements. These have been performed with radionuclide sources and with monoenergetic neutrons by various labs and at various times at NPL. Radionuclide source measurements are plotted at the mean energy of the source neutrons, but it should be remembered that they represent the average effective centre over a broad spectrum of neutrons, and this may be contributing to some of the differences between the measured points and the line joining calculations for monoenergetic neutrons.

The increase in the effective centre distance with neutron energy can be thought of as the peak of the thermal neutron distribution moving deeper into the moderator as the energy of the neutrons increases resulting in the effective point of measurement of these neutrons by the BF_3 moving deeper into the counter.

References for the early measurements shown in Figure 11 are not listed in the Reference section of this report although they are available. Also, some of the NPL measurements have not been formally published. The rationale for including all these measurements in the figure is simply to highlight the fact that the measurements can be dramatically different to the calculations. This is true even for radionuclide sources, which should be the easiest measurements, although there is a tendency for the results to straddle the calculated line.

Despite several investigations, the reason why some measurements diverge from the calculations is not clear. The measurements are rather sensitive to the shadow cone scatter corrections, and it is possible that over-shadowing is distorting the curves of long counter counts versus distance as shown in Figure 6 and Figure 10. Because the number of available shadow cones, and hence solid angles that can be shadowed, is limited, some degree of over-shadowing always occurs at some distances.

Although a number of the measurements unfortunately diverge from the calculations the fact that the majority tend to follow the calculation, and also the fact that they tend to occur roughly equally above and below the line, means that at present the best estimate of the De Pangher effective centre variation with energy is given by the calculations for the energy region up to about 5 MeV. Above that energy the calculations have been modified to pass through the measured points in the vicinity of 15 MeV where the calculations appear to be significantly low.

4 Fluence measurements with the long counter

The basic equation relating the counts M , recorded by a long counter, having an efficiency ε , positioned at a distance l from a source of neutrons, with the fluence $\Phi(d)$ at a distance d along the same line from the source as used in the long counter measurement is:

$$\Phi(d) = \frac{M}{\varepsilon} \frac{(l + r_0)^2}{d^2} \quad (3)$$

Equation (3) excludes much of the complexity inerrant in making these measurements. For example, the measurement environment will involve scattered neutrons so M has to be corrected for in-scatter, this is usually done using shadow cones, and for out-scatter, usually via calculations involving cross sections for the air. (These corrections also have to be made for the measurements with a device positioned at the distance d whose response to neutrons is to be measured.) Because the long counter and a device cannot both be in place at the same time some form of monitoring is needed to relate the two measurements. If the long counter is being used to measure monoenergetic neutrons there will almost inevitably be corrections for contaminant neutrons at other energies. All these corrections are discussed in detail in reference (12).

5 Uncertainties

Reference (12) gives a detailed breakdown of all the uncertainties involved in long counter measurements of neutron fluence. This section addresses the uncertainties in the simplified form, given in equation (3), for the relationship between the fluence and the counts in a long counter, concentrating on the uncertainties in the quantities tabulated in this report, i.e. the efficiency ε , and the effective centre r_0 .

The values recommended for ε and r_0 for the JRC PLC are those tabulated in Appendix 2 and Appendix 3. These are based on calculations for the NPL De Pangher long counter normalised by measurements, and in the case of the efficiency by a conversion factor for the slightly higher efficiency of the JRC PLC compared to the NPL De Pangher. For a number of reasons the uncertainties in these parameters are not easy to quantify precisely. Both parameters are a function of energy, so a single uncertainty at all energies may not be appropriate. They are derived from a combination of calculations and measurements. The measurements do not cover the full range of energies, and the agreement between measurement and calculation is not perfect.

The statistical uncertainties in the calculations are small, values for ε and r_0 being typically 0.2% and 0.2 cm respectively. There are, however, components other than statistics, e.g. for deficiencies in the model, in particular the geometry and material compositions and densities. An attempt to estimate these was made using the measured data and a χ^2 test of the differences between measurements and calculations. The equation used was:

$$\chi^2 / \nu = \sum_{i=1}^n \frac{(C_i - M_i)^2}{(\sigma_{Ci}^2 + \sigma_{Mi}^2)} / (n-1) \quad (4)$$

where C stands for the calculated quantity and M the measured value; σ_C and σ_M are the uncertainties in these values.

Using the values for σ_{Ci} from the statistics in the calculations produced a χ^2 / ν significantly greater than 1. The value of σ_{Ci} was therefore increased until χ^2 / ν was close to unity. For the efficiency the required value of σ_{Ci} was 1.5%, and for the effective centre it was 1.0 cm. These are considered to be much more realistic estimates of the uncertainties than those obtained from the statistics of the calculations alone. An additional component needs to be added to the uncertainty in the efficiency for the factor used to correct for the ratio of the JRC and NPL efficiencies. This was estimated at about 1% resulting in an overall estimated standard uncertainty in the JRC PLC efficiency of about 1.8%.

Deriving the uncertainty in $\Phi(d)$, by applying the formula for combining standard uncertainties from the Guide to the Expression of Uncertainty in Measurement (GUM)⁽¹³⁾ to equation (3), and setting the uncertainties in all quantities except ε and r_0 to zero gave values in the region of 2%. It depends somewhat on the distance l to the long counter since σ_{r_0} adds a large component to the uncertainty in $l + r_0$ at small values of l . Some confirmation of this as a good estimate of the uncertainty in the fluence resulting from the uncertainties in ε and r_0 can be derived from the results of international comparison exercises where NPL have participated with their De Pangher long counter and obtained good agreement with the key comparison reference value^(8,9,10) within uncertainties of this order.

A full analysis of the uncertainties in ε and r_0 , including variations with energy, and combining the uncertainties in both the calculations and the measurement used in deriving the estimated values still remains a goal at NPL. In doing this there is one other aspect that will need to be taken into consideration. The measurements and calculations of the efficiencies and effective centres involve fitting long counter counts as a function of distance using equation (1). The fits are usually performed with the Origin software package using the Levenberg Marquard iteration algorithm. This approach provides information on the degree of correlation between the two fitted parameters k and r_0 . From the form of the equation, with k being in the numerator and r_0 in the

denominator, some degree of correlation in the uncertainties of the fitted values is expected. In fact all the fits undertaken showed a correlation coefficient of between 0.9 and 1.0. The efficiency is derived from k via the relationship $\varepsilon = k / \Phi_c$, so ε and r_0 are correlated. The various contributions that need to be considered in deriving the uncertainties in ε and r_0 mean that the correlation is certainly not as strong as 0.9, but is nevertheless present to some extent. This would result in the overall uncertainty resulting from those in ε and r_0 being less than obtained when assuming the uncertainties to be independent, but the full extent of the effects of these correlations remains to be investigated.

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- 1 A.O. Hanson and J.L. McKibben, *A Neutron Detector Having Uniform Sensitivity from 10 keV to 3 MeV*, *Phys. Rev.* **72** (1947) 673-677.
- 2 J. De Pangher and L.L. Nichols, *A precision long counter for measuring fast neutron flux density*, Pacific Northwest Laboratory report BNWL-260, (1966).
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- 8 J. Chen et al., *International Key Comparison of Neutron Fluence Measurements in Mono-energetic Neutron Fields – CCRI(III)-K10*, *Metrologia* 44 Tech. Suppl. 06005, 2007.
- 9 D.J. Thomas, V.E. Lewis, H. Klein, P.J. Allisy-Roberts, *International Key Comparison of 24 keV Neutron Fluence Measurements (1993-2009) – CCRI(III)-K1*, *Metrologia* 47 Tech. Suppl. 06014, 2010.
- 10 V. Gressier et al., *International Key Comparison of Neutron Fluence Measurements in Monoenergetic Neutron Fields – CCRI(III)-K11*, *Metrologia* 51 Tech. Suppl. Series 06009, 2014.
- 11 International Organization for Standardisation, *International Standard ISO 8529 Part 2, Reference neutron radiations – Calibration fundamentals of radiation protection devices related to the basic quantities characterising the radiation field*, 2000.
- 12 V Gressier, V Lacoste, A Martin and M Pepino, *Characterization of a measurement reference standard and neutron fluence determination method in IRSN monoenergetic neutron fields*, *Metrologia* **51** (2014) 431–440
- 13 BIPM, Joint Committee for Guides in Metrology, *Evaluation of measurement data — Guide to the expression of uncertainty in measurement*, JCGM 100:2008 obtainable from the BIPM web site.

6 Appendix 1 – BF₃ tube information from Centronic

Certificates of conformity and test results provided by Centronic for the two BF₃ counters



CERTIFICATE OF CONFORMITY

Consignee : **NPL Management Ltd.**
National physical Laboratory
Hampton Road
Teddington
Middlesex
TW11 0LW

Certificate No: **GFD170047**
Contract No: **447928**
Sales Order No. **602243/48129**
Date: **10th May 2017**

Identification Marks and/or Serial Number	Description	Qty	Specification/ Part No/or Drawing No.	Issue No.	Works Order No.
1717-037	26EB25/38M + HN TERMINATION (DE PANGHER)	1	F3110260B20801	1	F005554 (101752)

REMARKS:

Certified that the whole of the supplies detailed hereon have been inspected, tested and unless otherwise stated conform in all respects with the requirements of the relevant specifications and the contract.



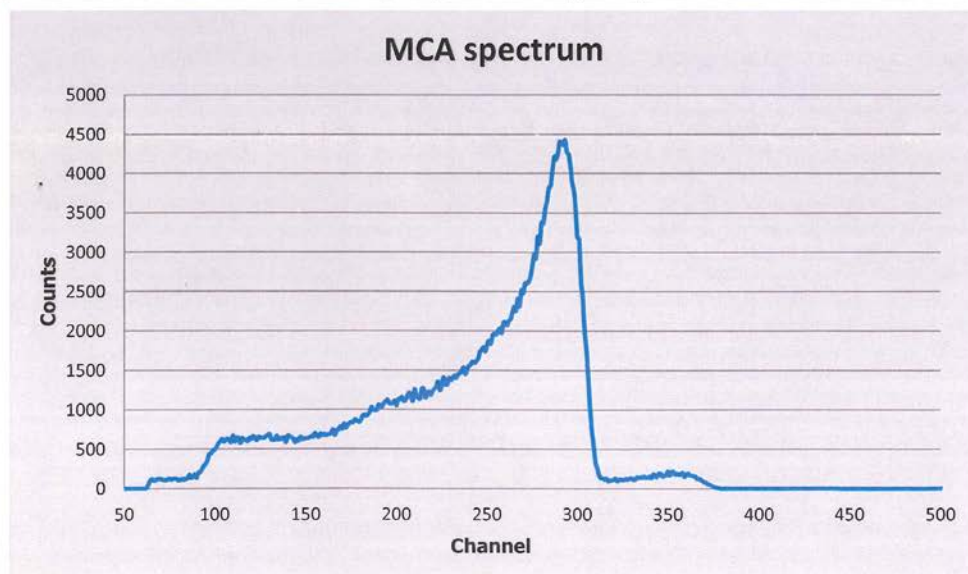
.....Quality Manager
(or his authorised representative)

EOC00130 ISS. 7.

Centronic Limited

Centronic House, King Henry's Drive, Croydon CR9 0BG, England Tel: +44 (0)1689 808000 Fax: +44 (0)1689 841822 www.centronic.co.uk
Registered Office: As above. Registered in England No. 469940

BF₃ Test Results	
Chamber type:	26EB25/38M
Purchase Order Number:	602243
Serial Number:	1717-037
Operating Voltage (V):	1277
Insulation Resistance @ 1000V (Ω):	N/A
Chamber Capacitance (pF):	N/A
Equivalent Value of Calibration Pulse (In Ion Pairs):	2.0×10^6
Head Amplifier Type:	0058
MCA Type:	Ortec 926 MCB
Main Test Amplifier Type:	95/2151-2/6
Main Test Amplifier Gain Setting (dB):	50.5dB
Main Amp Integrating Time Constant Setting (μs):	1μs
Main Amp Differentiating Time Constant Setting (μs):	1μs
Source Type Used:	Am/Be (NGU131)
Chamber resolution (FWHM)	
Peak Channel of Spectrum :	292
Number Of Lower-Numbered Channel at ½ Peak :	263
Number Of Upper-Numbered Channel at ½ Peak :	302
FWHM Resolution :	13.4%
Tested By (including stamp):	Christopher Payne 
Date of Test:	08/05/2017
Quality Assurance sign off:	





CERTIFICATE OF CONFORMITY

Consignee : **NPL Management Ltd.**
National physical Laboratory
Hampton Road
Teddington
Middlesex
TW11 0LW

Certificate No: **GFD170058**
 Contract No: **447928**
 Sales Order No. **602243/ 48238**
 Date: **13th May 2017**

Identification Marks and/or Serial Number	Description	Qty	Specification/ Part No/or Drawing No.	Issue No.	Works Order No.
1724-048	26EB25/38M + HN TERMINATION (DE PANGHER)	1	F3110260B20801	1	W2505603 (102278)

REMARKS:

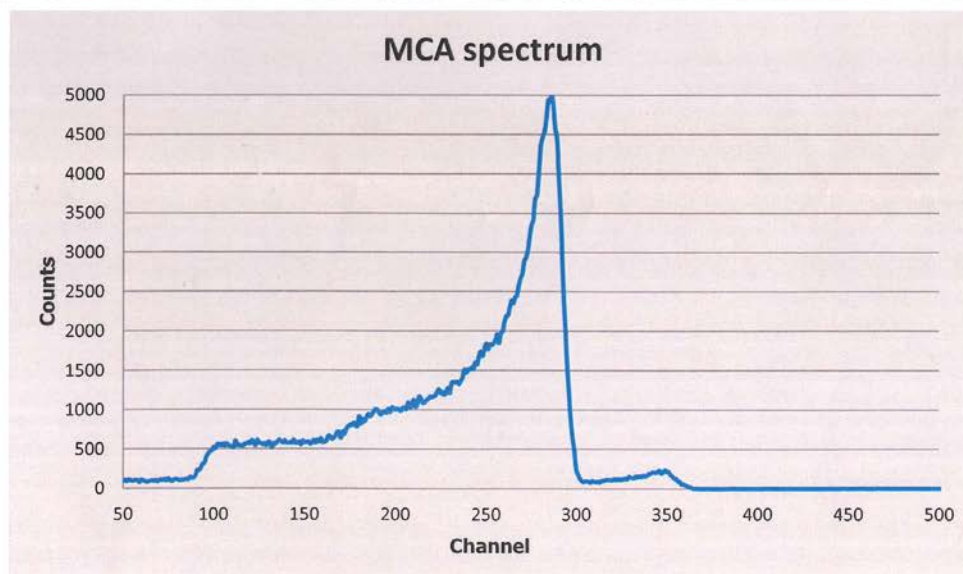
Certified that the whole of the supplies detailed hereon have been inspected, tested and unless otherwise stated conform in all respects with the requirements of the relevant specifications and the contract.

 Quality Manager
 (or his authorised representative)

EOC00130 ISS. 7.

Centronic Limited
 Centronic House, King Henry's Drive, Croydon CR9 0BG, England Tel: +44 (0)1689 808000 Fax: +44 (0)1689 841822 www.centronic.co.uk
 Registered Office: As above. Registered in England No. 469940

BF₃ Test Results	
Chamber type:	26EB25/38M
Purchase Order Number:	602243
Serial Number:	1724-048
Operating Voltage (V):	1267
Insulation Resistance @ 1000V (Ω):	N/A
Chamber Capacitance (pF):	N/A
Equivalent Value of Calibration Pulse (In Ion Pairs):	2.0×10^6
Head Amplifier Type:	0058
MCA Type:	Ortec 926 MCB
Main Test Amplifier Type:	95/2151-2/6
Main Test Amplifier Gain Setting (dB):	50.5dB
Main Amp Integrating Time Constant Setting (μs):	1μS
Main Amp Differentiating Time Constant Setting (μs):	1μS
Source Type Used:	Am/Be (NGU131)
Chamber resolution (FWHM)	
Peak Channel of Spectrum :	285
Number Of Lower-Numbered Channel at ½ Peak :	266
Number Of Upper-Numbered Channel at ½ Peak :	292
FWHM Resolution :	9.1%
Tested By (including stamp):	Lyndon Ouzman
Date of Test:	13/06/2017
Quality Assurance sign off:	



7 Appendix 2 – Efficiency values for the JRC PLC

Efficiency as a function of energy for the JRC PLC derived from the values for the NPL PLC after multiplication by the normalisation function derived in section 3.2.4.

Table 7. JRC De Pangher long counter responses as a function of neutron energy.

Energy (MeV)	Efficiency (cm ²)	Energy (MeV)	Efficiency (cm ²)	Energy (MeV)	Efficiency (cm ²)	Energy (MeV)	Efficiency (cm ²)
0.001	3.592	0.160	3.307	0.900	3.564	2.072	3.356
0.002	3.427	0.180	3.351	0.950	3.580	2.074	3.223
0.003	3.455	0.200	3.356	1.000	3.611	2.076	3.093
0.004	3.447	0.220	3.367	1.050	3.615	2.078	3.094
0.005	3.428	0.240	3.384	1.100	3.616	2.080	3.229
0.006	3.408	0.250	3.393	1.130	3.617	2.082	3.352
0.008	3.275	0.260	3.388	1.150	3.614	2.084	3.437
0.010	3.308	0.280	3.381	1.170	3.626	2.086	3.497
0.012	3.368	0.300	3.383	1.175	3.622	2.088	3.538
0.015	3.358	0.320	3.413	1.190	3.627	2.090	3.575
0.018	3.306	0.340	3.423	1.200	3.631	2.100	3.629
0.020	3.338	0.360	3.440	1.210	3.638	2.125	3.658
0.021	3.316	0.380	3.464	1.225	3.631	2.150	3.674
0.024	3.341	0.400	3.468	1.230	3.638	2.200	3.670
0.027	3.344	0.425	3.454	1.250	3.634	2.300	3.673
0.030	3.309	0.450	3.462	1.260	3.643	2.350	3.661
0.035	3.210	0.475	3.472	1.300	3.654	2.400	3.658
0.040	3.271	0.500	3.474	1.400	3.651	2.450	3.657
0.045	3.296	0.525	3.476	1.500	3.664	2.475	3.667
0.050	3.322	0.550	3.495	1.600	3.664	2.500	3.661
0.055	3.279	0.565	3.505	1.700	3.655	2.525	3.638
0.060	3.310	0.580	3.485	1.800	3.673	2.550	3.633
0.070	3.317	0.600	3.499	1.900	3.680	2.600	3.617
0.080	3.284	0.650	3.498	2.000	3.674	2.625	3.611
0.090	3.247	0.700	3.544	2.020	3.675	2.650	3.597
0.100	3.308	0.750	3.534	2.040	3.668	2.700	3.580
0.120	3.286	0.800	3.542	2.060	3.634	2.725	3.562
0.144	3.295	0.850	3.553	2.070	3.471	2.750	3.547

Table 7. JRC De Pangher long counter response as a function of neutron energy – continued.

Energy (MeV)	Efficiency (cm ²)	Energy (MeV)	Efficiency (cm ²)	Energy (MeV)	Efficiency (cm ²)	Energy (MeV)	Efficiency (cm ²)
2.775	3.532	3.400	3.291	5.800	3.417	11.00	2.737
2.800	3.516	3.500	3.274	5.900	3.419	11.50	2.662
2.810	3.534	3.600	3.266	6.000	3.395	12.00	2.593
2.812	3.516	3.700	3.283	6.500	3.410	12.50	2.543
2.814	3.350	3.800	3.315	7.000	3.319	13.00	2.500
2.815	3.108	3.900	3.346	7.100	3.308	13.50	2.480
2.816	3.407	4.000	3.370	7.200	3.307	14.00	2.457
2.818	3.468	4.100	3.380	7.300	3.298	14.50	2.422
2.820	3.451	4.200	3.397	7.400	3.168	14.80	2.421
2.822	3.452	4.300	3.466	7.500	3.073	15.00	2.414
2.830	3.467	4.400	3.498	7.600	3.012	15.50	2.380
2.840	3.452	4.500	3.504	7.700	2.931	15.54	2.376
2.850	3.440	4.600	3.503	7.800	2.919	16.00	2.354
2.875	3.431	4.650	3.513	7.900	2.957	16.01	2.355
2.900	3.366	4.700	3.495	8.000	2.968	16.50	2.312
2.925	3.279	4.800	3.497	8.100	2.999	17.00	2.273
2.950	3.280	4.900	3.498	8.200	3.070	17.50	2.241
2.975	3.521	4.950	3.489	8.300	3.079	18.00	2.209
2.990	3.654	4.975	3.500	8.400	3.057	18.50	2.197
3.000	3.683	5.000	3.522	8.500	3.045	18.97	2.164
3.050	3.608	5.025	3.505	8.600	3.020	19.00	2.170
3.100	3.537	5.100	3.495	8.700	2.987	19.50	2.144
3.200	3.438	5.200	3.500	8.800	2.959	20.00	2.123
3.250	3.395	5.300	3.504	8.900	2.901		
3.275	3.370	5.400	3.478	9.000	2.837		
3.300	3.361	5.500	3.468	9.500	2.771		
3.325	3.330	5.600	3.457	10.000	2.793		
3.375	3.299	5.700	3.444	10.500	2.749		

8 Appendix 3 – Effective centre values for the JRC PLC

Effective centre as a function of energy for the JRC PLC from values for the NPL PLC. They are based on calculations modified in the region above 5 MeV to fit experimental data.

Table 8. JRC De Pangher long counter effective centres as a function of neutron energy.

Energy (MeV)	Effective centre (cm)	Energy (MeV)	Effective centre (cm)	Energy (MeV)	Effective centre (cm)	Energy (MeV)	Effective centre (cm)
0.00005	2.15	0.180	1.13	2.500	4.06	7.50	6.83
0.00008	1.76	0.475	1.70	2.700	4.05	8.00	6.85
0.00010	1.59	0.565	2.12	2.814	3.51	8.50	7.87
0.00020	1.61	0.700	2.42	2.815	3.23	9.00	7.98
0.00030	1.12	1.000	2.72	2.816	4.18	9.50	8.26
0.00040	1.49	1.100	2.68	2.830	3.88	10.00	8.94
0.00050	1.36	1.130	2.54	2.900	3.63	10.50	8.54
0.00060	1.57	1.170	2.66	2.950	3.35	11.00	8.49
0.00070	1.42	1.190	2.66	2.975	4.11	11.50	8.80
0.00080	1.03	1.200	2.86	3.00	4.58	12.00	8.82
0.0010	1.12	1.210	2.86	3.10	3.99	12.50	9.55
0.0020	1.98	1.230	2.91	3.20	4.22	13.00	9.22
0.0040	1.09	1.250	2.67	3.30	4.06	13.50	9.76
0.0060	0.64	1.260	3.09	3.50	4.06	14.00	9.76
0.0080	1.66	1.300	3.10	3.60	3.74	14.50	9.81
0.0120	0.61	1.400	3.09	4.00	4.41	14.80	9.96
0.0150	0.59	1.500	3.47	4.40	4.63	15.00	9.60
0.0180	1.70	1.600	3.00	4.50	4.66	15.54	10.28
0.0200	1.27	1.900	3.48	4.65	5.29	16.01	10.52
0.0240	0.63	2.040	3.73	5.00	5.85	16.50	10.40
0.0270	1.30	2.070	3.59	5.20	5.81	17.00	10.81
0.0700	1.23	2.078	2.33	5.50	6.29	18.97	11.16
0.100	0.82	2.090	3.16	6.00	6.14	20.00	11.39
0.120	0.69	2.150	3.92	6.50	7.02		
0.144	0.95	2.200	3.70	7.00	7.59		