

NATIONAL PHYSICAL LABORATORY

Calibration and Monte Carlo Modelling of the NPL Long Counters at 22.8 keV

by

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Abstract

An extensive programme was successfully carried out during the 1995 to 1998 NMS programme to re-calibrate and model by Monte Carlo simulations the characteristics of two NPL long counters that are routinely used to standardise neutron fluences [Ta98,Ta00] for neutron energies above 500 keV. The present work is a continuation of it in that the counters responses and effective centres have been measured and simulated for a neutron energy of 22.8 keV using an antimony-beryllium ($^{124}\text{SbBe}$) photon-neutron source. The neutron source emission rate was measured using the manganese sulphate bath technique. The efficiency and effective centres of both counters have been measured in a low scatter facility at NPL and calculations have been performed using MCNP4C.

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Approved on behalf of Managing Director NPL, by Dr Martyn Sené
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1. INTRODUCTION

At the National Physical Laboratory (NPL), neutron fluences are standardised using the well established long counters [Kn00, DeP66, McT59]. They are neither 100% efficient nor perfectly flat in their response as a function of neutron energy and thus need to be calibrated at as many neutron energies as possible. The solution adopted was to:

- ❖ measure the response with well characterised radioactive neutron sources,
- ❖ predict the response functions by Monte Carlo radiation transport calculations,
- ❖ normalise the predicted response curves using the source measurements.

Over the last few years at the NPL, calculations using the Monte Carlo radiation transport code MCNP have been combined with accurate measurements to characterise the two long counters routinely used to standardise monoenergetic neutron fields in the energy region above 500 keV. New and more accurate response function curves have been produced for both long counters, and these have been reported and published [Ta98, Ta00]. A novel approach using Monte Carlo methods has been developed, validated and used to model the efficiency of the counters and determine more accurately their effective centres, which have always been difficult to establish. Calculations and measurements agree well, especially for the De Pangher long counter for which details of the design and constructional material are well known.

However, similar experimental and computational data for neutron energies below 500 keV were crucially needed in order to extend the improved characterisation of the long counters to lower energies. Within the 1998 to 2001 NMSPU programme at NPL, a project was set up to obtain just such data. Nearly mono-energetic 23 keV neutrons were provided by a spherical antimony-beryllium ($^{124}\text{SbBe}$) photo-neutron source [IS89] that had been activated in a reactor thermal neutron field. Its neutron output had been measured at NPL using the Manganese bath technique [Ax65].

In the following sections, we report on the calibration and Monte Carlo modelling of the long counters for 23 keV neutrons using the $^{124}\text{SbBe}$ source. The NPL has two types of long counters. One type is the De Pangher long counter [DeP66] (see Figure 1-1) with a 38 mm (1½") outer diameter BF_3 tube. The other, built at NPL, is a McTaggart [McT59] type (Figure 1-2) which has a 50 mm (2") outer diameter BF_3 tube for increased efficiency. These counters will be referred to as the De Pangher long counter and the NPL long counter respectively.

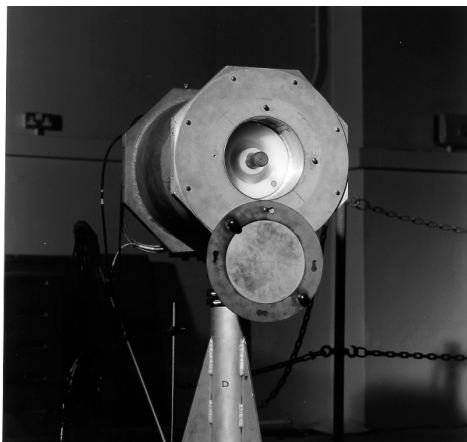


Figure 1-1: The de Pangher long counter with the Cd cover down



Figure 1-2: The NPL long counter

The report contains quite extensive details of how the source was handled. It is unusual for measurements to be made at NPL with such a photo-neutron source where the γ -ray dose rate presents a significant hazard and necessitates careful and well thought out handling techniques. The details are included here as a record of the procedures used in the hope that they will be useful during any future experiments with photo-neutron sources.

2. MEASUREMENTS

2.1 The $^{124}\text{SbBe}$ photo-neutron source

2.1.1 Introduction

A distinct advantage in using photo-neutron (γ, n) sources, in contrast to (α, n) radio-nuclide sources, is the fact that the former produce almost mono-energetic neutron spectra. One of the most popular (γ, n) sources is based on the decay of ^{124}Sb produced by reactor thermal activation of natural Antimony (consisting of 57.3% ^{121}Sb + 42.7% ^{123}Sb) surrounded by a beryllium shell as a target. The threshold energy of the $^9\text{Be}(\gamma, n)$ reaction is $(1661.17 \pm 0.38 \text{ keV})$ and an inspection of the decay scheme of ^{124}Sb shows two relevant groups of γ -ray energies, namely 1690.99 keV and 2090.96 keV with absolute intensities of 0.484 ± 0.006 and 0.057 ± 0.001 per decay respectively. Hence using the laws of energy and momentum conservation one can deduce that the 1690.99 keV and 2090.96 keV γ -rays yield respectively neutron groups of energy:

$$E_n = (22.8 \pm 0.4) + 1.3 \cos \theta_n \text{ keV and } E_n = (378.2 \pm 0.4) + 6.6 \cos \theta_n \text{ keV}$$

where θ_n is the angle between the incident photon and the emitted neutron.

The relative intensity of the high energy group to the low energy group was found [Hu82, IS89] to be 0.030 ± 0.008 . The half-life of ^{124}Sb is 60.20 ± 0.03 days and that of ^{122}Sb , also produced by activation of natural antimony is only 2.7 days. A disadvantage associated with the $^{124}\text{SbBe}$ source is its extremely high photon to neutron ratio which makes it a hazardous source to work with in general and prohibitive for measurements involving devices that are very γ -sensitive.

$^{124}\text{SbBe}$ photon neutron sources of various shapes and sizes have been successfully used in the past by many workers [Ry71, En81, Hu78, Hu82, Le98]. Ryves and Robertson [Ry71] used the $^{124}\text{SbBe}$ source to measure the $^{197}\text{Au}(n, \gamma)^{198}\text{Au}$ cross section at 22.8 keV whereas Hunt [Hu78] used this type of source to calibrate various area survey instruments and long counters and also studied the relative intensity of the secondary group of neutrons emitted by the source [Hu82]. More recently, $^{124}\text{SbBe}$ sources were used, within an international inter-calibration of 24.5 keV neutron fluence measurements [Le98], by the China Institute of Atomic Energy (CAEI) in Beijing and the D I Mendeleyev Institute for Metrology (VNIIM) in St Petersburg Russia.

2.1.2 The design

The $^{124}\text{SbBe}$ source used for the present work consisted of an antimony sphere with radius 0.875 cm surrounded by a spherical shell of beryllium of thickness 0.3 cm. It has the same dimensions as that used by Ryves and Robertson [Ry71] and thus one would expect the same

neutron energy spectrum from both sources. The total weight of the source is 25.89 g, 18.58 g of which are due to the antimony sphere. The spherical shape of the source means that the neutron source emission rate is very isotropic. A short length (10 ± 1 cm) of titanium wire (0.5 mm diameter) was attached to the source via a hole through a small raised section of the beryllium shell (Figure 2-1). A length of cotton wire was attached to a loop at the end of the titanium wire and was used for handling the source in the early stages of the experiments.

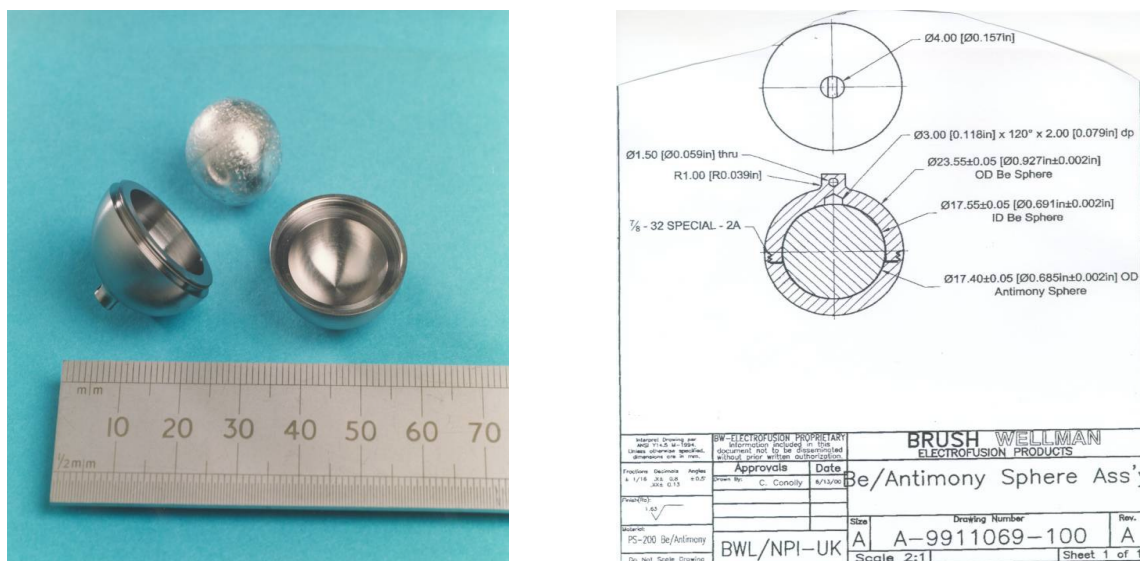


Figure 2-1: The SbBe source used in this work

2.1.3 The Activation

The source was activated at the Nuclear Research Institute Rez Plc reactor in the Czech Republic in a thermal fluence of $10^{13} \text{ cm}^{-2} \text{ s}^{-1}$ and an epithermal fluence of $4.7 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ for a total of 12 hours and 20 minutes. The source was irradiated first for 5 hours on 18 May 2001 starting at 8:33 am and a further irradiation of 7 hours and 20 min was performed on 15th June 2001 from 11:00 am as the neutron output was found to be too low following the first irradiation. The source was allowed to decay for more than ten half lives of ^{122}Sb . Arranged by STRAND transport services, the source was flown to the UK by DHL and was delivered to NPL on 16th July 2001. Details of calculations for the production of ^{124}Sb and ^{122}Sb neglecting epithermal neutrons are given in the appendices.

2.1.4 The transport container and its shielding

The γ -activity of the source being several tens of GBq, adequate shielding was essential for a safe handling and transportation. The container (Figures 2-2 and 2-3) consisted of a 71 cm diameter by 64 cm height orange steel Drumpack 2948 hired from Croft Associates Ltd and a lead pot with a lead plug that were designed and manufactured at NPL and surrounded by high density polystyrene. The cylindrical lead pot was 13 cm in diameter and 22 cm high ensuring that 8.5 cm of lead surrounded the source cavity from all directions (see Figure A-1 in the

appendix). The packaging was modelled using MCNP Monte Carlo code to calculate the photon and neutron attenuation by the shielding.



Figure 2-2: Lowering the drum to the bottom of the Pit



Figure 2-3: Apparatus for removing or storing the source in the lead pot

2.2 The Manganese Bath Measurement

2.2.1 Transferring the source into the manganese bath

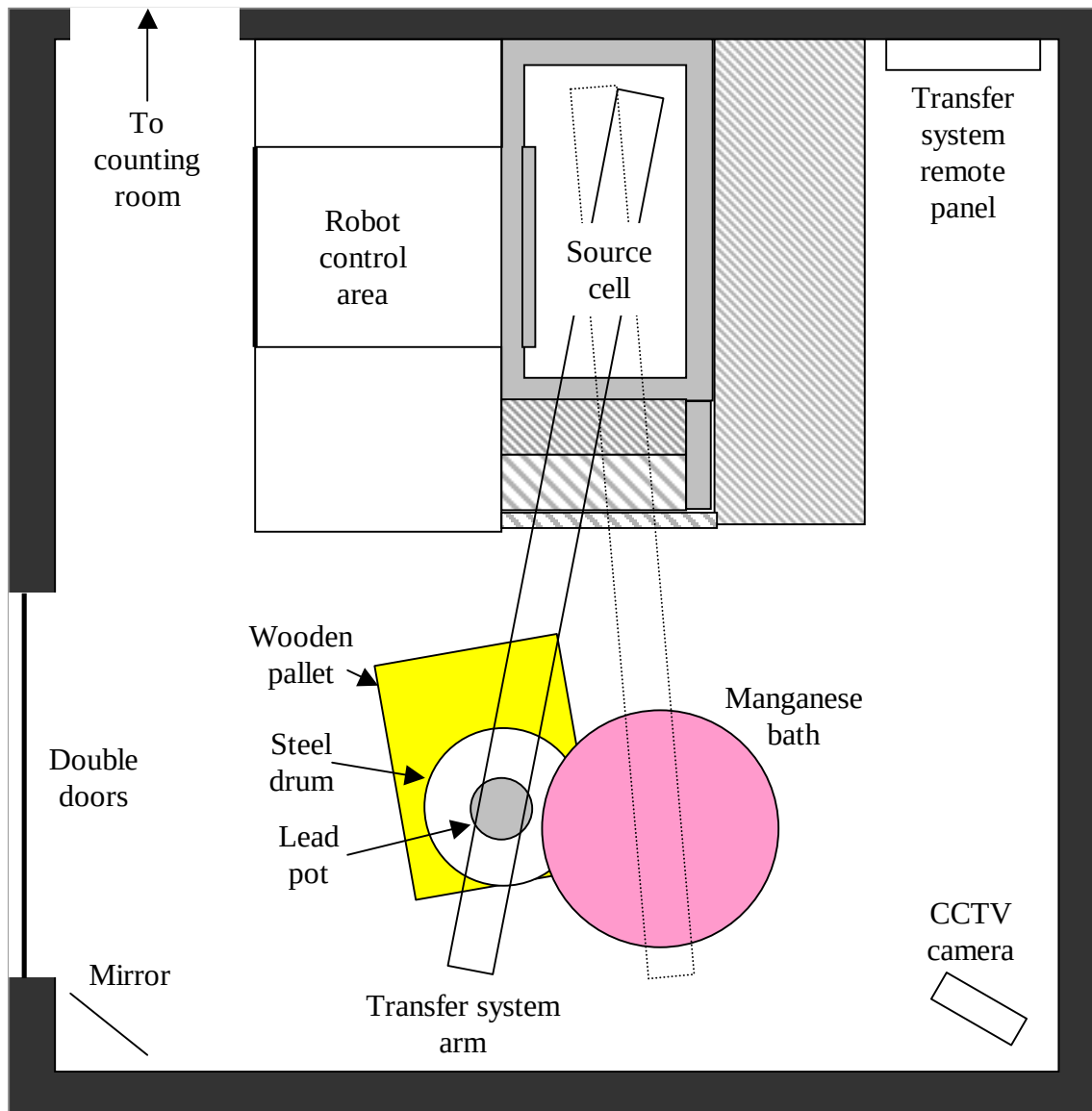
The Manganese Bath method provides an absolute measurement of the total neutron emission rate into 4π sr by measuring the activity induced by the neutrons in a solution of manganese sulphate. The NPL equipment is presently housed in Building 94. For an explanation of the theory of the technique see [Ax65].

The standard source handling procedure is to use long tongs for the transfer of the source from its transport container to the source cell, to place it inside the steel cavity sphere, and to place the lid on the steel cavity. The only operation performed remotely is the transfer of the cavity sphere from the source cell into the bath. As the photon dose rate from the $^{124}\text{SbBe}$ source was too high for it to be handled in this way, it was necessary to devise remote procedures for all stages.

The first step was to remove the small manganese bath from the bath room. This made it possible to bring the drum into building 94 on the pallet, and also to use the source transfer system to remotely transport the source into the source cell (see Figures 2-4 and 2-5). The source transfer arm had to be pulled across to be above the position where the drum would be placed. Vertical motion was provided by an electric winch mounted to the main trolley of the transfer system, which was operated from the counting room (see Figure 2-6).

A length of cotton attached to the source ran up the side of the lead plug. A loop was tied in the cotton as close as possible to the top of the plug and the excess was removed. The hook on the end of the winch was attached to the loop and the lead plug was removed using long tongs. A CCTV camera was set up to look at the source as it left the lead pot and a mirror allowed the

position of the source to be seen from the counting room as it reached the height of the transfer trolley.



Key:

-  Lead
-  Biscuit tins / other neutron shielding
-  Concrete blocks / polythene chips

Figure 2-4: Plan view of bath room of Building 94 (approximately to scale)

Once at the desired height the same transfer system program that is used to remove a source from the bath was run to take the source to a position above the source cell. Two CCTV cameras in the source cell area were used to view the source as it was lowered by the winch. When the source was within the source cell, the bath room was safe to enter.

Two Microbot TeachMover robots on the floor of the source cell (see Figures 2-5 and 2-7) were used to remove the source from the winch hook, to place the source into the cup inside the steel cavity, and lastly to place the lid on top of the cavity. The control panels for the robots were positioned behind 15 cm of lead and visibility was provided by the two CCTV cameras and a lead-glass window. Camera 2 has a narrow field of view and is trained solely on the source cavity, while Camera 1 has a wider field of view and can see both robots. Camera 2 is also positioned higher than Camera 1 to give a different perspective (see Figure 2-8).

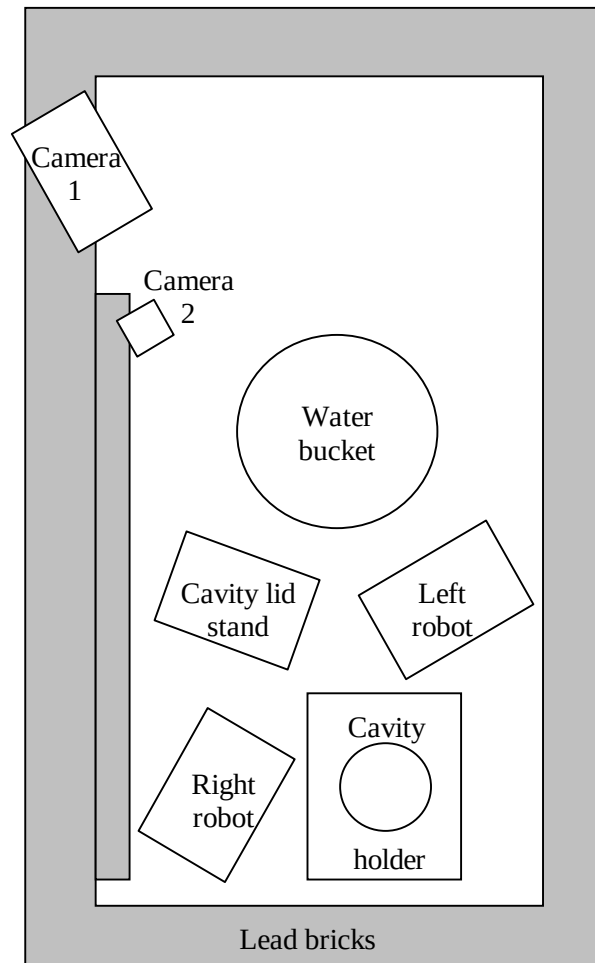


Figure 2-5: Plan view of source cell layout (approximately to scale)

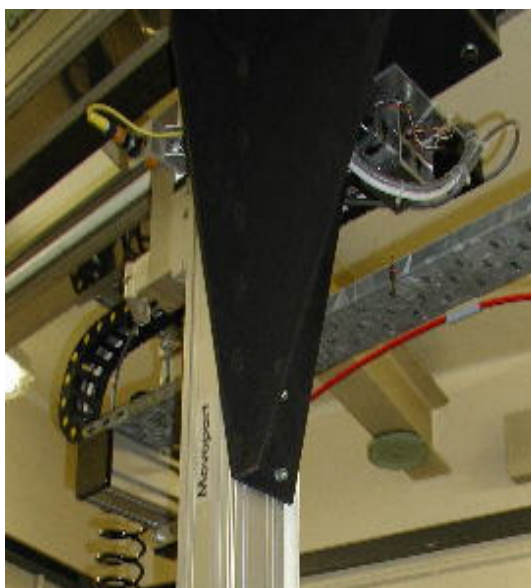


Figure 2-6: Mounting of winch on transfer system trolley



Figure 2-7: View of source cell



Figure 2-8: Locations of CCTV cameras

Care was taken to ensure that the cotton or titanium wire did not lie across the cavity seal and thus prevent the attainment of a good vacuum. The large (133 mm diameter) steel cavity sphere was used to reduce the possibility of this happening.

The transfer rod was attached to the transfer trolley and vacuum system, and the transfer arm was pulled back across to the large tank position. The top of the bath was removed to allow the large cavity to enter. All operations to put the source in the tank were now the same as for a normal manganese bath measurement. As the dose rate in the counting room with the source in the tank was too high to allow access, no effort was made to cover the top of the tank as would normally be the case.

2.2.2 Storage of source between runs

The usual approach to a neutron source emission rate measurement at NPL involves making two measurements with a careful check that both results are consistent. Normally when a source is removed from the bath the vacuum is switched off, the lid of the cavity is removed, and the source lowered into the source storage hole. This is usually done using tongs, but this approach was unacceptable for this source. Another possibility was to perform the operations using the two robots but this would be time consuming and not without risk.

A far easier and safer option was to leave the source in the cavity, under vacuum, and submerge the cavity in a large bucket of demineralised water to prevent the manganese sulphate solution drying on the sphere and also to shield the bath from the source neutrons. A bucket was positioned towards the rear of the source cell and the sphere was lowered into it using the bath room control panel.

2.2.3 Transferring the source back into the drum

This procedure was essentially the reverse of that described in 2.2.1. The transfer arm was pulled across to be over the drum. The robots were used to remove the lid from the cavity, pick up the source, and attach it back onto the winch hook. The source was then raised using the winch and transferred to a position above the lead pot using the same transfer system program that is used to place a source into the bath. The source was then lowered into the pot and the plug inserted using long tongs. Inserting the plug caused the cotton to break so it was not possible to leave a trailing end to aid the removal of the source in Building 47. The top half of the drum was replaced and the source was taken back into the Building 94 shed by forklift truck.

2.2.4 Analysis

The data were processed and analysed in the same way as any other source calibration in the manganese bath. The activity of the manganese sulphate solution was determined using 2 NaI detectors and the readings of these detectors were processed using the Fortran program MNBATH6 (run on the NPL NEWTON mainframe). The program corrects for background, source decay, solution circulation, and dead-time effects, and calculates a value for the saturated count rate at the reference time from each growth and decay cycle count. The final outputs of the program are eight values of the saturated count rate (2 measurement runs x 2 detector channels x growth & decay) together with uncertainties.

The first 18 growth cycles and the last 3 decay cycles of both measurement runs were deleted from the input file as the manganese sulphate solution in the bath had been partially irradiated by the presence of the source in the source cell prior to each measurement. The first measurement consisted of 60 x 1000 s growth cycles and 19 x 1000 s decay cycles, the second of 83 x 1000 s and 19 x 1000 s cycles respectively.

A second Fortran program, SOURCEIMP, is used to calculate the neutron emission rate of the source. In addition to the saturated count rates, information on the counting efficiencies of the detectors and the concentration of the solution is required. The three correction factors (1-O), (1-S), and (1-L) are also inputs to the program and these were calculated using the new MCNP

based system [Ro01] with the $^{124}\text{SbBe}$ energy spectrum of Ryves et al [Ry71] modified to include 3% of neutrons at 378 keV [Hu82].

Saturated count rates from MNBATH6 (referenced to 12 noon GMT on 18.7.01):

Measurement date	Channel 1		Channel 2	
	Growth	Decay	Growth	Decay
18.7.01	248.12 ± 0.07	247.81 ± 0.16	247.89 ± 0.07	248.11 ± 0.16
23.7.01	248.19 ± 0.06	248.10 ± 0.17	247.89 ± 0.06	248.13 ± 0.17

Efficiencies and concentrations extrapolated from linear fits to recent measurements:

Date	Efficiencies		Solution concentration ($N_{\text{H}}/N_{\text{Mn}}$)
	Channel 1	Channel 2	
18.7.01	4.583×10^{-4}	4.576×10^{-4}	33.58
23.7.01	4.583×10^{-4}	4.576×10^{-4}	33.58

(Efficiencies are in terms of counts per decay of ^{56}Mn anywhere in the solution.)

Fraction of thermal neutrons captured in manganese = 0.53768 (from Westcott equation [We58])

Correction factors (calculated using MCNP):

	Percentage of emitted neutrons
Oxygen and sulphur fast capture	0.02
Cavity and source capture	4.81
Bath leakage	0.00

Combined correction factor $\frac{1}{(1-O-S-L)} = 1.0508$

Mean source emission rate from Channel 1 = $1.0582 \times 10^6 \text{ s}^{-1}$

Mean source emission rate from Channel 2 = $1.0597 \times 10^6 \text{ s}^{-1}$

Overall mean emission rate = $1.0584 \times 10^6 \text{ s}^{-1}$

Uncertainty budget:

(Calculated in accordance with UKAS document M3003 [UK97])

Source	Uncertainty (%)	Distribution	Sensitivity	Uncertainty component (%)	Degrees of freedom
Counting	0.1	Normal	1	0.1	∞
Cross-section ratio	0.2	Normal	1	0.2	∞
Efficiency	0.4	Normal	1	0.4	∞
O & S losses	15	Rectangular	0.0002	0.0017	∞
Cavity & source capture	5	Rectangular	0.051	0.15	∞
Leakage	7	Rectangular	0	0	∞
Timing	0.05	Rectangular	1	0.03	∞
Mixing	0.2	Rectangular	1	0.12	∞
Solution concentration	0.1	Normal	1	0.1	9
Background	30	Normal	0.013	0.40	9
Dead-time	15	Normal	0.0009	0.01	9

Combined uncertainty (at 1σ level) = 0.7 % (rounded up to 1 d.p.)

Degrees of freedom = 59.1

Expanded uncertainty (at 2σ level) = 1.3 %

The emission rate of the source at 12 noon GMT on the 18th of July 2001 was therefore $(1.058 \pm 0.014) \times 10^6 \text{ s}^{-1}$.

2.3 The Low Scatter Cell Measurements

2.3.1 Experimental Set-up

Both the De Pangher and the NPL long counters were re-calibrated, in terms of their efficiency and effective centre using the SbBe photo-neutron source. Two measurements for each counter were carried out over a couple of weeks, in a large low-scatter cell at about 40 source to counter distances ranging from 1.3 m to 5 m, from which the efficiency and the effective centre of the counters were evaluated.

The lower level discriminator threshold on the NPL long counter was increased in order to eliminate photon pile up events from the source. This was not a problem for the de Pangher long counter, which has a lower efficiency. Figure 2-9, shows an ungated spectrum compared to a gated one.

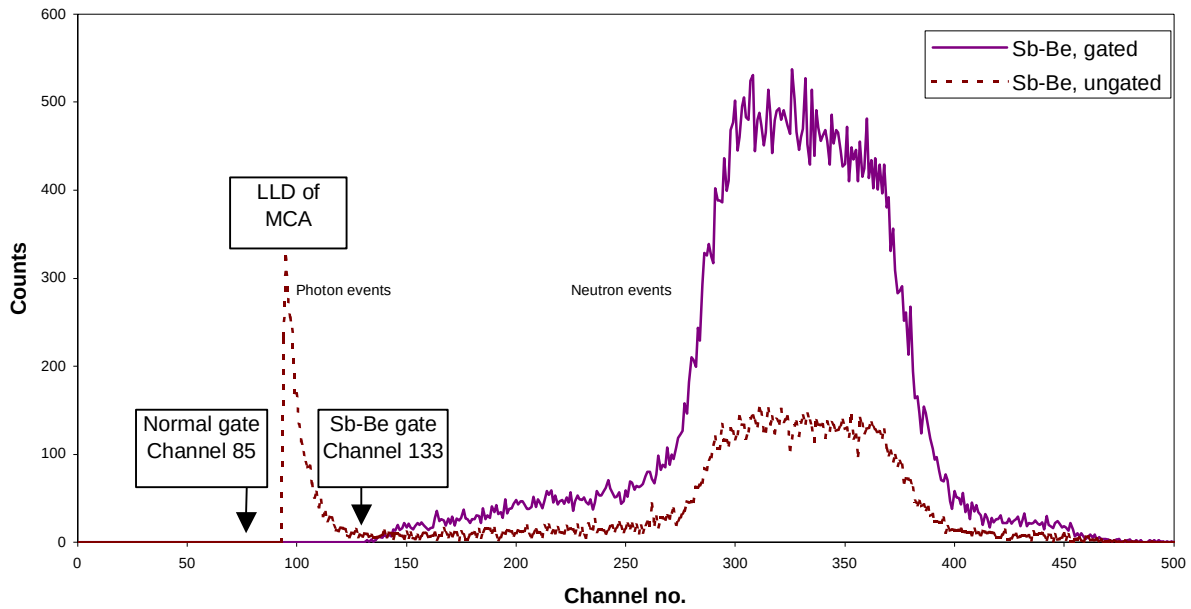


Figure 2-9: Gated and ungated spectra from the NPL long counter with Sb-Be source at near distances (different live-times)

In order to correct for the loss of genuine events caused by a higher threshold, measurements were made with an Am-Be source. A correction factor, equal to 1.0202 ± 0.0009 , was calculated by taking a ratio of count rates with the high and low thresholds. Figure 2-10 shows the spectra with the normal and higher gate settings.

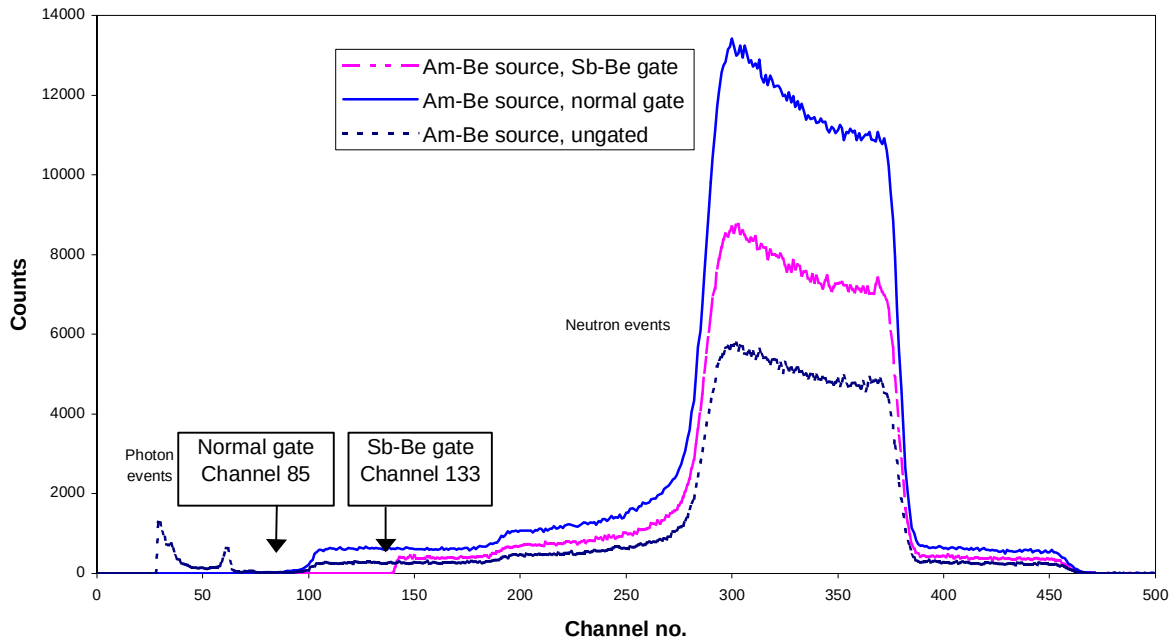


Figure 2-10: Spectra from NPL long counter with Am-Be source (different live times)

With the $^{124}\text{SbBe}$ source fixed in place at the centre of the cell, the counter's position was varied in 5 to 20 cm steps, and the integrated counts were recorded at each of the counter positions. The counter sits on an automatically controlled carriage and can be remotely moved toward or away from the source. The shadow cone technique [Hu76,Hu80, IS98] was used to correct for the scattering of neutrons by the air, the walls, the floors, and the ceiling of the room. Shadow cone number 8 (1), positioned at 9 (12) cm from the source vertical axis was used for source to

counter distances below (above) 250 cm, respectively. Figure 2-11 shows the arrangement of source, shadow cone and NPL long counter.

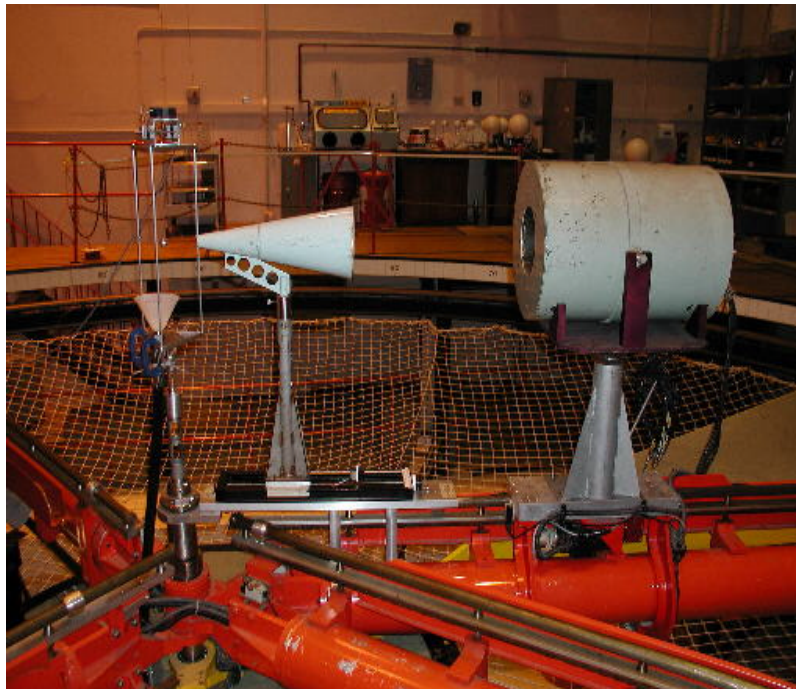


Figure 2-11: Making room scatter measurements with the NPL long counter

2.3.2 Source Handling Procedure

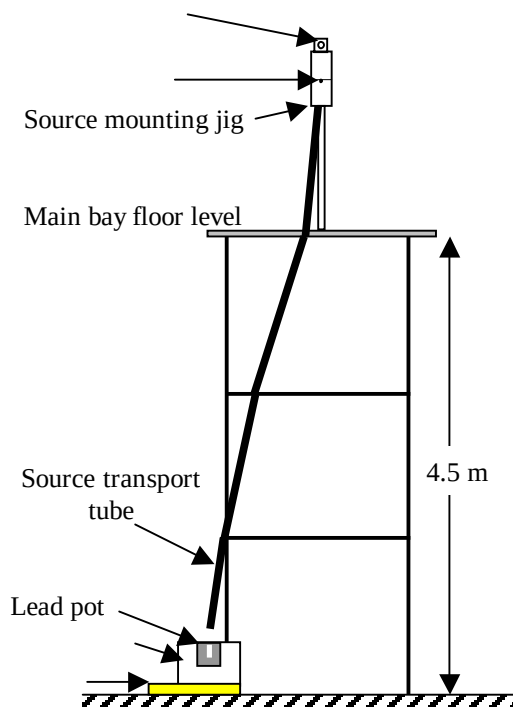


Figure 2-12: Diagram of source mounting & storage apparatus (approximately to scale)

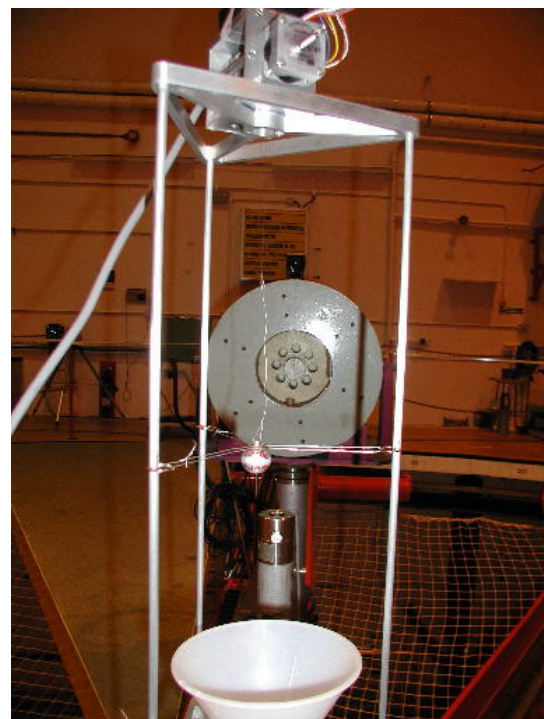


Figure 2-13: Source mounting jig and electric winch with NPL long counter

The drum was lowered to the bottom of the low scatter room, an area known as “the pit” using a crane (as shown in Figures 2-3 and 2-12). Once on the floor, the pallet was slid across to the pit centre stand and the drum was pushed to be in contact with the frame. This enabled the source transport tube to be as straight and as vertical as possible to minimise the likelihood of the source becoming stuck in the tube. Funnels were fitted to both ends of the tube to guide the source.

Firstly the source had to be attached to the winch. As the length of cotton had broken, it was necessary to raise the end still attached to the source using an adhesive pad on the end of a long rod. Great care was taken not to raise the source above the level of the top of the lead pot. Once the loop in the end of the titanium wire was visible the slotted lead plug was placed into the lead pot. The winch fishing line could now be safely attached to loop in the titanium wire.

The same winch that was used in the Manganese Bath was used in the low scatter area. It was mounted to a triangular aluminium jig and was operated from the control room (see Figure 2-13). The position of the source was fixed by a small ring suspended in the centre of the jig by three steel wires. Several CCTV cameras were trained on the jig to observe the location of the source.

Instead of replacing the slotted lead plug each time the source was lowered into the lead pot, to make the area at the top of the pit centre safe a lead brick was slid over the top of the hole. This was quicker and simpler than lining up the slot with the titanium wire and so minimised the dose to staff.

3. DATA ANALYSIS

Details of the analysis procedure were given in references [Ta98] and [Ta00] and thus only the essentials will be repeated here for completeness.

For a point detector and a point source in vacuum one can write that:

$$Cr^2 = \text{Constant} \quad (1)$$

where C is the detector count rate and r is the source to counter distance.

Allowing for scatter and geometry effects, a corresponding expression for a long counter, which is about 50 cm in length and 22 cm in radius, has been suggested by Hunt [Hu76,80, IS98] and is given by:

$$[C_t(r) - C_i(r)]F_a(r) = \frac{K}{(r + r_o)^2} \quad (2)$$

where

$C_t(r)$ and $C_i(r)$ are total and in-scatter measured count rates at a source to detector distance r measured to the front face of the counter moderator.

$F_a(r)$ is the air scatter correction factor (derived from the oxygen and nitrogen cross sections),

r_0 is the effective centre distance into the moderator front face (i.e. a positive value means that the effective centre is within the counter and beyond the moderator front face which is effectively used as reference surface for source to counter distance)

and K is the source-detector characteristic constant.

Rearranging the above expression gives:

$$1/\sqrt{[C_t(r) - C_i(r)]F_a(r)} = \sqrt{1/K}(r + r_0) \quad (3)$$

and it follows that r_0 and K can be obtained by a least squares fit, i.e.,

$$1/\sqrt{[C_t(r) - C_i(r)]F_a(r)} \quad \text{against} \quad r \quad (4)$$

$$\text{with the gradient equal to } \sqrt{\frac{1}{K}} \quad \text{and the intercept equal to } \sqrt{\frac{1}{K}} r_0. \quad (5)$$

Subsequently, the efficiency ε can be evaluated by

$$\varepsilon = \frac{4\pi K}{QF_I} \quad (6)$$

where Q is the source strength, i.e., the total emission rate into 4π steradians, and F_I is the anisotropy factor of the radionuclide source.

The least square fit analysis is carried out using either PCINVFIT, a computer program written by Hunt and adapted to run on a PC, or using the least-squares fitting function within ORIGIN, a commercially available graphics and statistical analysis package. Both ORIGIN and PCINVFIT gave the same results when tested. PCINVFIT calculates the “correct” weights based on all corrections made, the fitting function and the count rates. The weights were used ensuring that χ^2 for each source to counter distance (i.e. $\text{Weight} \times (\text{calculated} - \text{Measured})^2$) was approximately equal to unity and that the overall χ^2 was about equal to N , the number of data points. PCINVFIT also recalculated the fit (i.e. gradient and intercept) for the data with the closest points removed, in succession, until only six points remain. The fit was accepted only if both the gradient and intercept were stable as a function of the range of distances fitted.

4. RESULTS OF EFFICIENCY AND EFFECTIVE CENTRE MEASUREMENTS

4.1 The De Pangher Long Counter

The decay corrected total count rates (i.e. direct + scatter) measured by the de Pangher long counter on two occasions are plotted against the source to detector distance in Figure 4-1. Figure 4-2 shows a comparison of the shadow cone rates obtained from the two measurements whereas in Figure 4-3 is shown the direct counts measured by the de Pangher long counter, after correction for room scatter, versus the source to counter distance. The two measurements

agree well and no problems were found with the data. The above curves were produced for all measurements and provide a good check on the measurements and analysis of the data in general and on the shadow cone correction in particular.

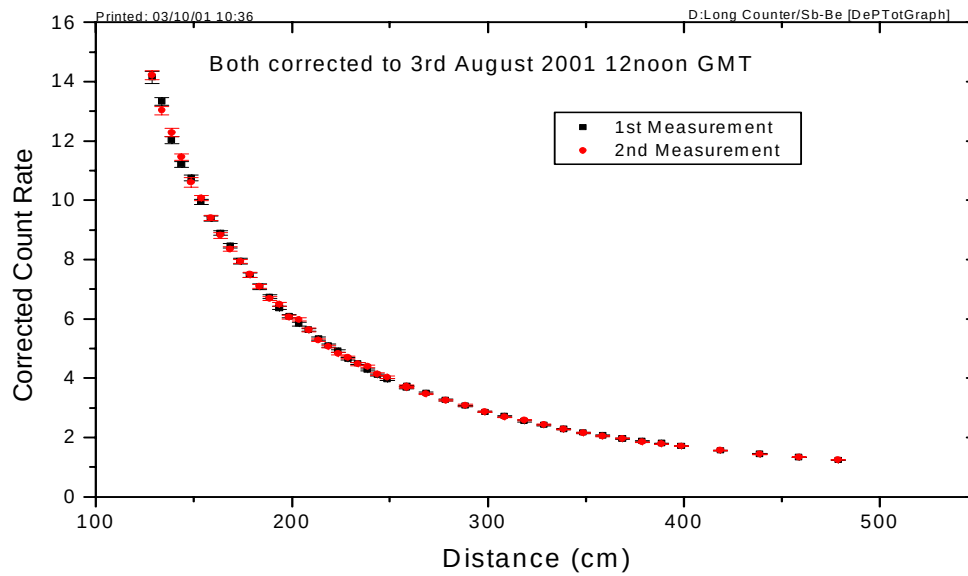


Figure 4-1: Comparison of total (direct+scatter) count rates measured with the de Pangher long counter on two occasions for the SbBe source after decay correction.

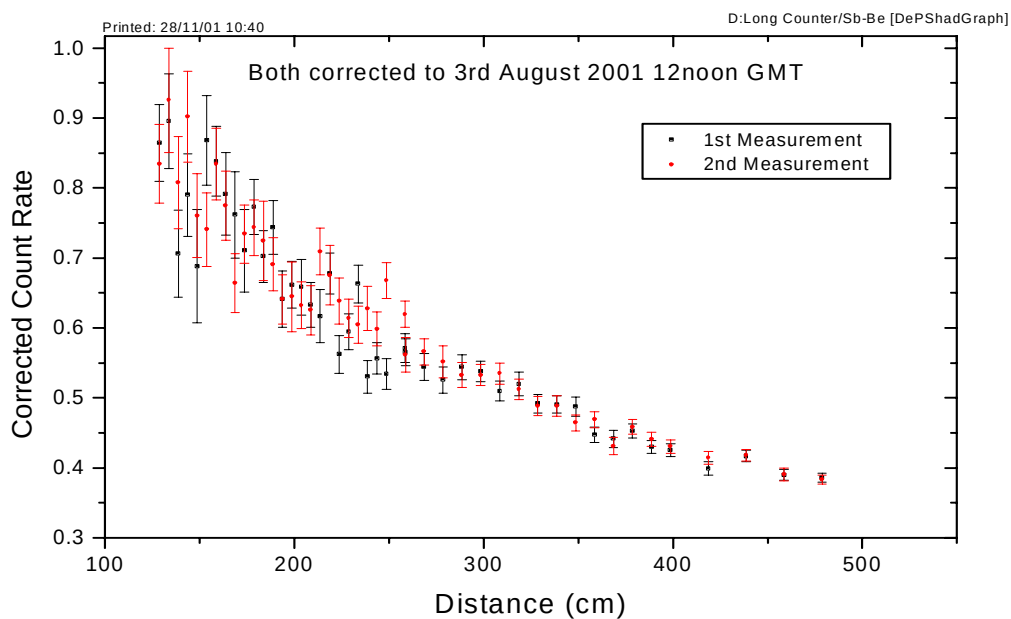


Figure 4-2: Comparison of de Pangher shadow cone rates for the SbBe source from two measurements

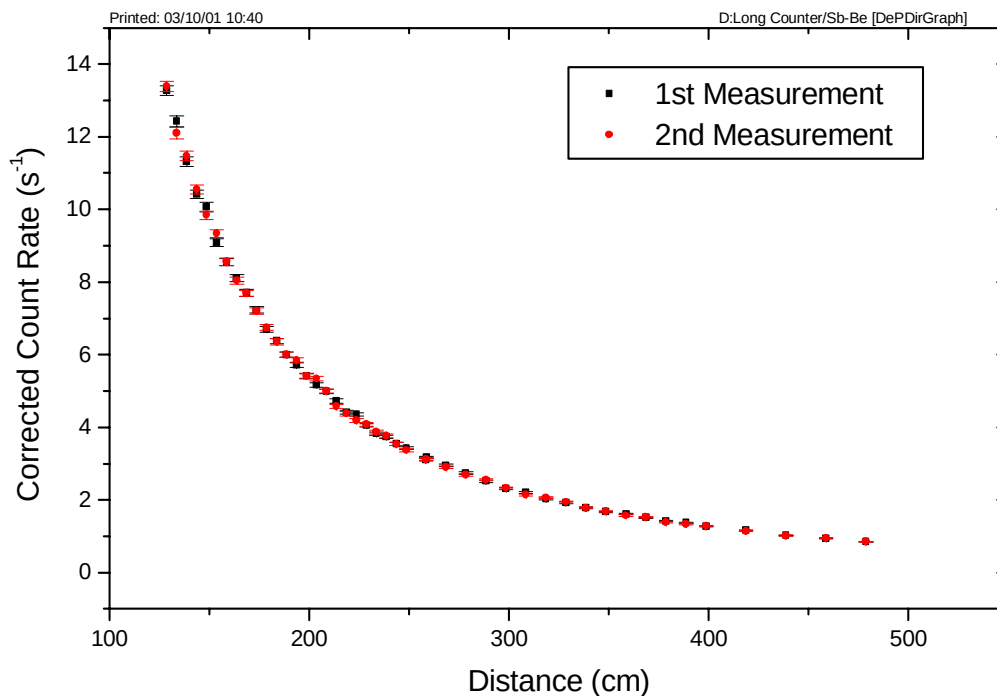


Figure 4-3: The de Pangher direct count rates (corrected for scatter and decay) for the SbBe source

Data obtained with the shadow cone method were analysed as outlined in Section 3, and the results of the two measurements for the De Pangher long counter are shown in Figure 4-4, Figure 4-5 and Table 4-1 using an air attenuation coefficient of $2973 \times 10^{-7} \text{ cm}^{-1}$. The results of Hunt's efficiency measurement is also given in the table for comparison and the rightmost column (1-HT/JH) contains the ratio, in %, of this work's to Hunt's efficiency value. Our mean value for the efficiency of the de Pangher long counter, for SbBe, is $3.26 \pm 0.03 \text{ cm}^2$ whereas Hunt measured $3.35 \pm 0.03 \text{ cm}^2$.

There is reasonable agreement between the two sets of results, although Hunt's result as previously found for ^{252}Cf and $^{241}\text{Am-Be}$ [Ta98], is 2.69% higher than the present results. Our effective centre of the de Pangher long counter, for SbBe, is $r_0 = -0.22 \pm 0.40 \text{ cm}$ compared to $r_0 = 1.69 \pm 0.48 \text{ cm}$ measured by Hunt.

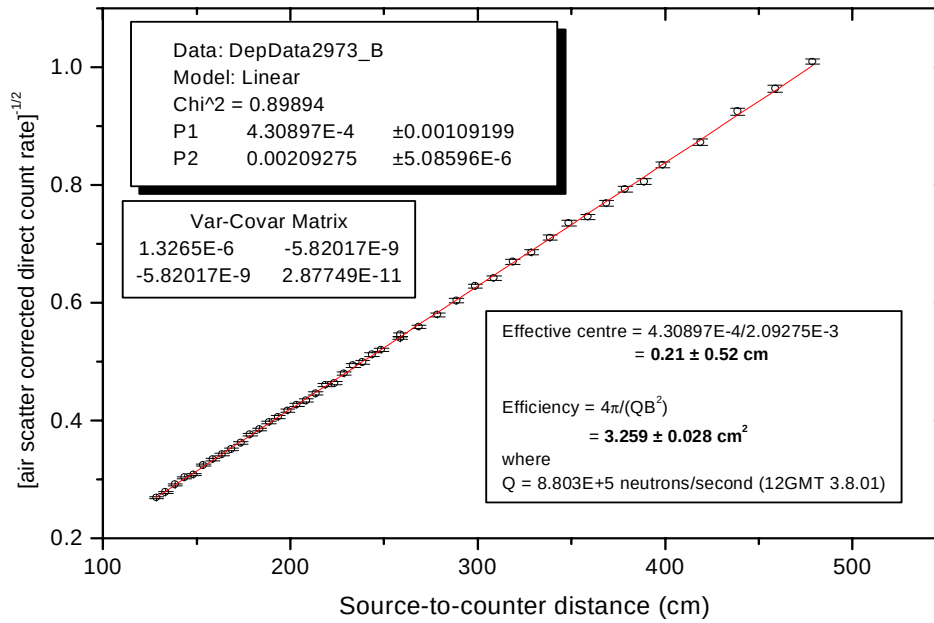


Figure 4-4: The inverse of the square root of the fully corrected count rates of the de Pangher long counter (1st measurement) plotted against source to detector distance

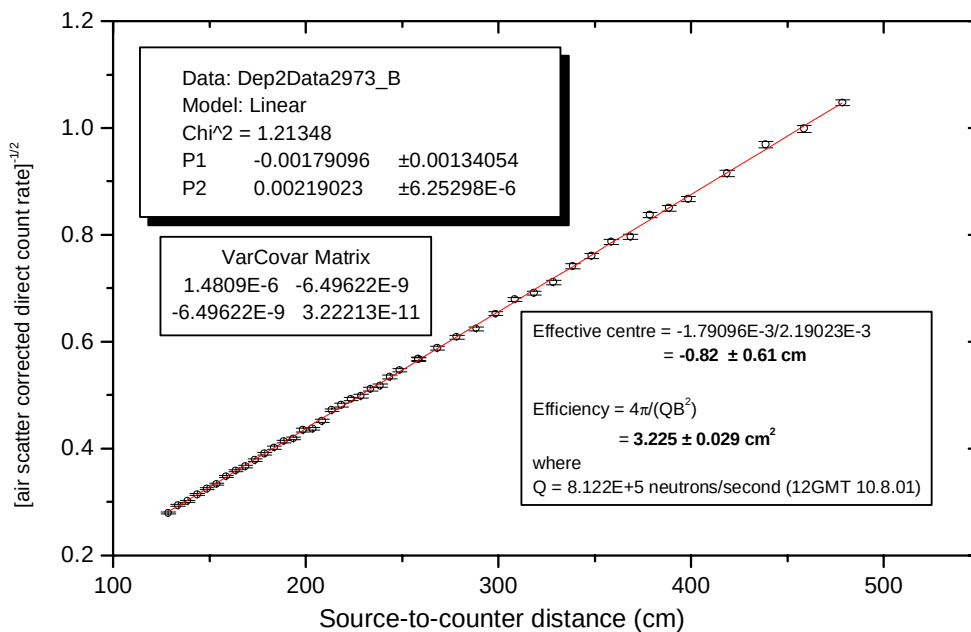


Figure 4-5: The inverse of the square root of the fully corrected count rates of the de Pangher long counter (2nd measurement) plotted against source to detector distance (cm).

Table 4-1: Efficiency and effective centre results from the De Pangher long counter measurements with sources, and a comparison of the present efficiency results (HT) with those of Hunt (JH).

	Effective Centre (cm)	Efficiency (cm ²)		1-HT/JH %
		HT	JH	
1	0.21 ± 0.52	3.22 ± 0.03	3.35 ± 0.07	2.7
2	-0.82 ± 0.61	3.26 ± 0.03		
Aver.	-0.22 ± 0.40	3.24 ± 0.02		

However, it should be noted that a reasonably good agreement is found between Hunt's measurements (JH) and the present ones (HT) if the efficiency is coupled to the effective centre as measured by the same author. From equation (1) and (6) in section 3, one can write that:

$$[C_t(r) - C_i(r)]F_a(r) = \frac{QF_I \varepsilon}{4\pi(r + r_o)^2} \quad (7)$$

It follows that for Hunt's and the present work analysis, the left hand sides of equation (7) should be equal and

$$\left[\frac{QF_I \varepsilon}{4\pi(r + r_o)^2} \right]_{HT} = \left[\frac{QF_I \varepsilon}{4\pi(r + r_o)^2} \right]_{JH} \quad (8)$$

Hence:

$$\frac{\varepsilon_{HT}}{(r + r_{oHT})^2} = \frac{\varepsilon_{JH}}{(r + r_{oJH})^2} \quad (9)$$

where $\varepsilon_{JH}, r_{oJH}$ and $\varepsilon_{HT}, r_{oHT}$ are the efficiency and effective centre measured by Hunt and Tagziria, respectively.

Table 4-2 shows values of the both sides of equation (9) (column labelled HT and JH) as a function of the distance r for Sb-Be measurements. The efficiency and effective centre values are taken from Table 4-1. The fourth column in Table 4-2, equal to 1-JH/HT (in %), shows a reasonably good agreement between the two measurements for the source to counter distances that are usually used and recommended for long counter measurements using the shadow cone technique (i.e. 1.5 to 2 metres).

Table 4-2: Comparison of Hunt's measurements for Sb-Be with the present work using equation 9 as discussed above.

Distance(cm)	Left Side (HT)	Right Side (JH)	1-JH/HT %
75	5.829E-04	5.696E-04	2.3%
100	3.274E-04	3.240E-04	1.0%
150	1.453E-04	1.456E-04	-0.2%
175	1.067E-04	1.073E-04	-0.6%
200	8.166E-05	8.235E-05	-0.8%
250	5.224E-05	5.288E-05	-1.2%
300	3.627E-05	3.681E-05	-1.5%
350	2.664E-05	2.708E-05	-1.7%
400	2.039E-05	2.076E-05	-1.8%

Table 4-3 presents a comparison of the present effective centre results for radionuclide sources with measurements made for the De Pangher long counters by various workers. These include measurements made by Hunt [Hu76, Hu78] with the same counter as used in this work. The remainder of the measurements were for different de Pangher long counters, but, because of the tight manufacturing tolerances applied when constructing this type of long counter [Ma70], every one should have very similar effective centre values. The agreement between the various effective centre values is not, however, particularly good with disagreements well outside the quoted uncertainties. The reasons for the differences between the results of different experimentalists are not clear, although the derived effective centres can be very sensitive to small changes in the data set.

The sensitivity of the effective centre and efficiency of the De Pangher long counter to parameters such as the in-scatter counts and the dead time was previously investigated. It was found, for instance, that an increase of 3 % in the in-scatter counts resulted in a 36% decrease of the effective centre whereas the efficiency decreased by less than 2%. The sensitivity of the effective centre and the efficiency to the dead time of the counting system (a 10 μ s fixed dead time in the present case) was found to be less pronounced. The effective centre is also very dependent on the scatter correction model used in the analysis. It is to be noted that some of the earlier measurements listed in Table 4-3 were analysed using scatter correction models which had not been fully validated and have since been shown not to be appropriate in all calibration rooms.

Table 4-3: The effective centre (cm), for Sb-Be source, as measured by various authors for different de Pangher long counters.

	References	Effective Centre (cm)
Tagziria	This work (2 measurements)	0.21 ± 0.52 -0.82 ± 0.61
Average:		-0.22 ± 0.40
Hunt	Hu76, Hu78	1.69 ± 0.48
Thomson	Th72	-0.14 ± 1.02
De Pangher	DeP66	1.65 ± 0.30
Mijnheer	Mi72	1.35 ± 0.20
Heinzelmann	He73 (2 values from curve)	2.60 4.00

Considering only the NPL measurements for the present counter, modifications to the detector and source support stands at NPL have occurred since Hunt's measurements, but, provided the shadow cone technique correctly subtracts the in-scatter component, these changes should not affect the measurements. The results for the efficiency derived from the analysis are not particularly sensitive to the values deduced for the effective centre and a very reasonable estimate of the efficiency can still be made.

4.2 The NPL Long Counter

As with the de Pangher long counter, two measurements of efficiency and effective centre for the ^{124}Sb -Be source were also made for the NPL long counter. The decay corrected total count rates are plotted against the source detector distance in Figure 4-6. Figure 4-7 shows a comparison of the shadow cone rates obtained from the two measurements and in Figure 4-8, is shown the direct counts measured by the NPL long counter, after correction for room scatter, versus the source to counter distance. Again, the two measurements agree well and no problem with the data was found.

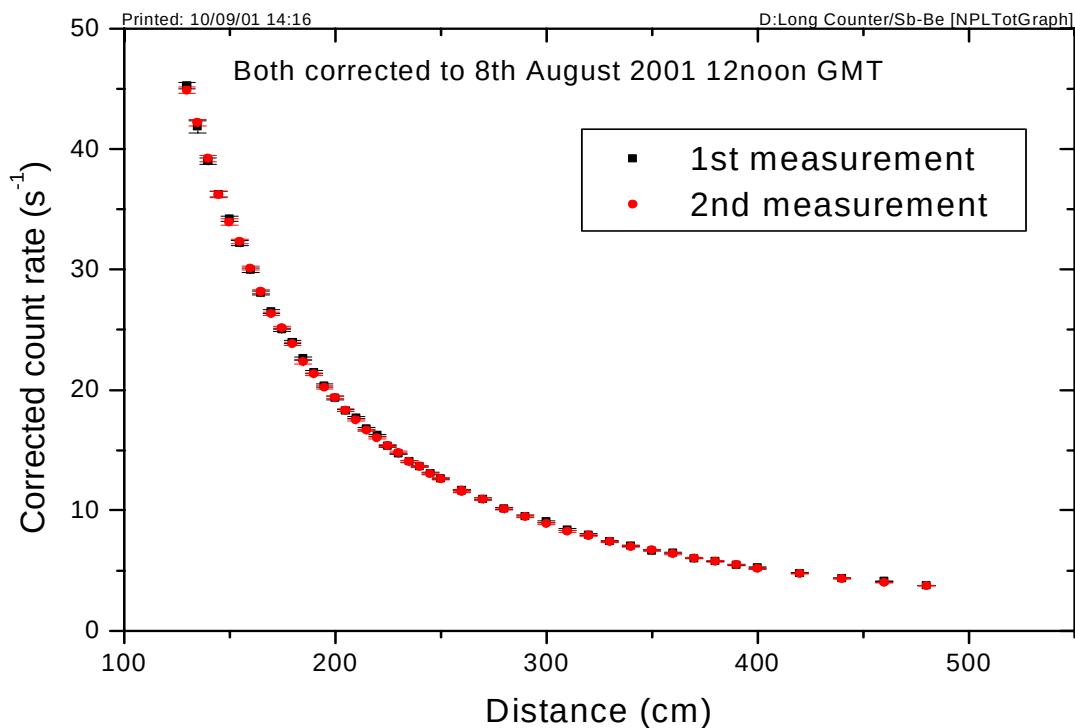


Figure 4-6: Comparison of total (direct+scatter) count rates measured with the NPL long counter on two occasions for the $^{124}\text{SbBe}$ source after decay correction.

Data obtained with the shadow cone method were analysed as outlined in Section 3, and the results of the two measurements for the NPL long counter are shown in Figure 4-9, Figure 4-10 and Table 4-4 using an air attenuation coefficient of $2973 \times 10^{-7} \text{ cm}^{-1}$. The results of Hunt's efficiency measurement [Hu76, Hu78] are also given for comparison and the rightmost column (1-HT/JH) contains the ratio, in %, of this work's to Hunt's efficiency value. Our mean value

for the efficiency of the NPL long counter, for SbBe, is $11.34 \pm 0.07 \text{ cm}^2$ compared to Hunt's value of $11.53 \pm 0.06 \text{ cm}^2$.

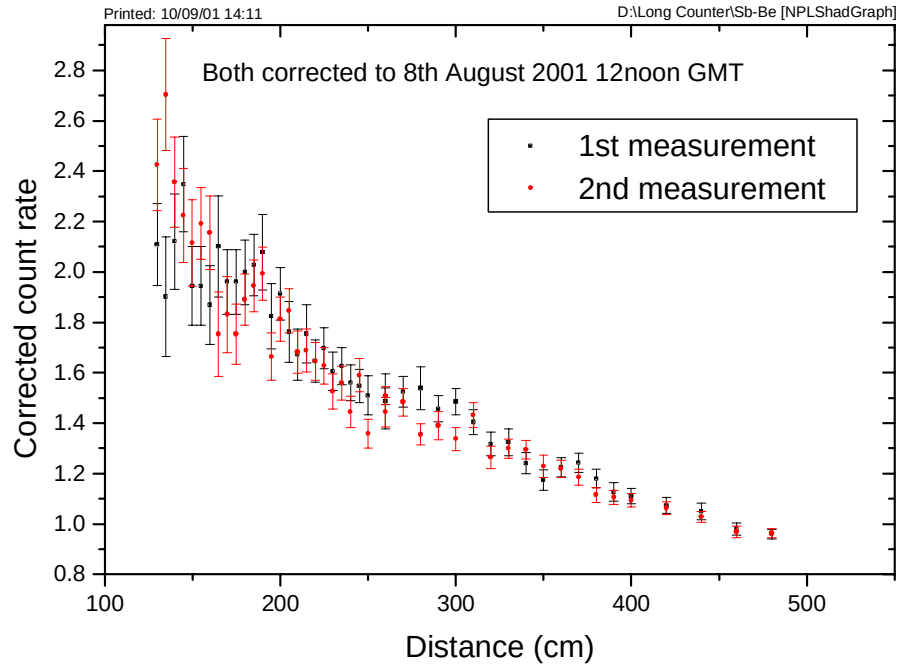


Figure 4-7: Comparison of the NPL long counter shadow cone rates for the SbBe source from two measurements

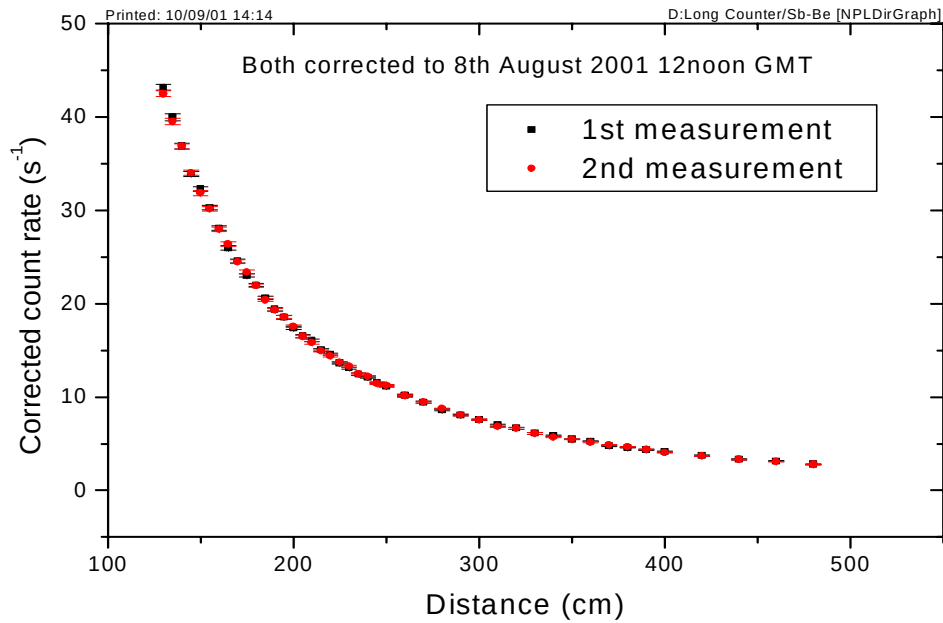


Figure 4-8: The NPL long counter direct count rates (corrected for scatter and decay) for the SbBe source

There is reasonable agreement between the two sets of results, although Hunt's values, as previously found for ^{252}Cf and $^{241}\text{Am-Be}$ [Ta98], are 1.6% higher than the present results. Our effective centre of the de NPL long counter, for SbBe, is -1.26 ± 0.31 cm compared to -0.72 ± 0.44 cm measured by Hunt.

Table 4-4: Efficiency and effective centre results from the NPL long counter measurements with sources, and a comparison of the present efficiency results (HT) with those of Hunt (JH).

	Effective Centre (cm)	Efficiency (cm^2)		1-HT/JH %
		HT	JH	
1	-1.25 ± 0.42	11.36 ± 0.09	11.53 ± 0.06	1.6
2	-1.26 ± 0.47	11.33 ± 0.09		
Mean	-1.26 ± 0.31	11.34 ± 0.07		

However, it should be noted that a reasonably good agreement is found between Hunt's measurements (JH) and the present ones (HT) if the efficiency is coupled to the effective centre as measured by the same author.

Table 4-5 shows values of the both sides of equation (9) (column labelled HT and JH) as a function of the source to counter distance r for $^{124}\text{SbBe}$ measurements. The efficiency and effective centre values are taken from Table 4-4. The last column in the Table 4-5, equal to $1-\text{JH}/\text{HT}$ (in %), shows a reasonably good agreement between the two measurements for the source to counter distances that are usually used and recommended for long counter measurements using the shadow cone technique (1.5 to 2. metres).

Table 4-5 Comparison of Hunt's measurements for $^{124}\text{SbBe}$ with the present work using equation 9 , as discussed in section 3, for the NPL long counter.

Distance(cm)	Left Side (HT)	Right Side (JH)	1-JH/HT %
75	2.086E-03	2.090E-03	-0.2%
100	1.163E-03	1.170E-03	-0.5%
150	5.127E-04	5.174E-04	-0.9%
175	3.758E-04	3.796E-04	-1.0%
200	2.872E-04	2.903E-04	-1.1%
250	1.833E-04	1.855E-04	-1.2%
300	1.271E-04	1.287E-04	-1.3%
350	9.327E-05	9.451E-05	-1.3%
400	7.135E-05	7.232E-05	-1.4%

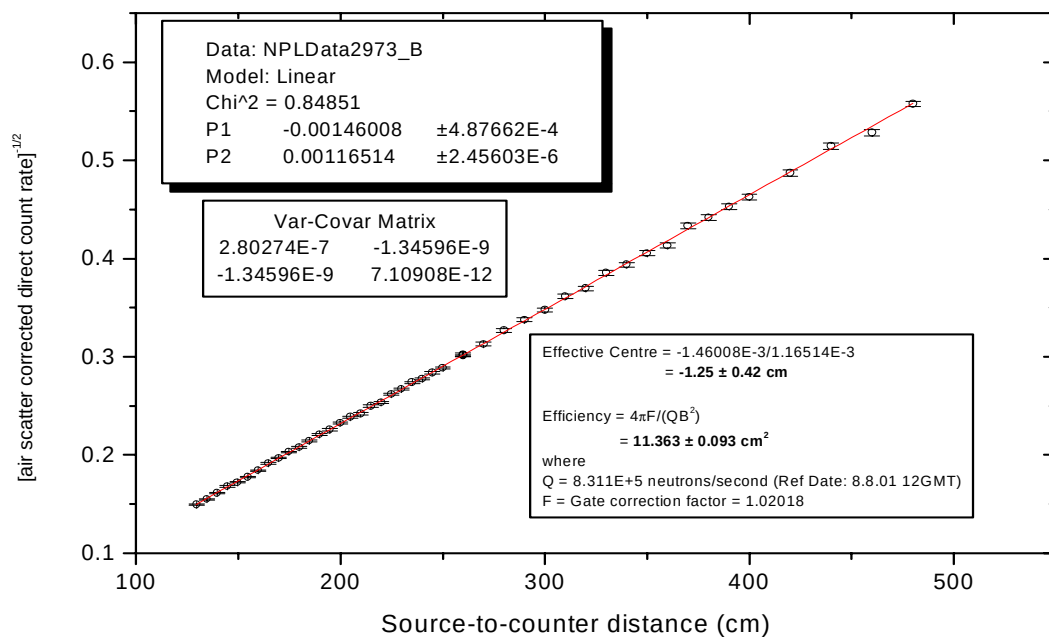


Figure 4-9: The inverse of the square root of the fully corrected count rates of the NPL long counter (1st measurement) plotted against source to detector distance (cm).

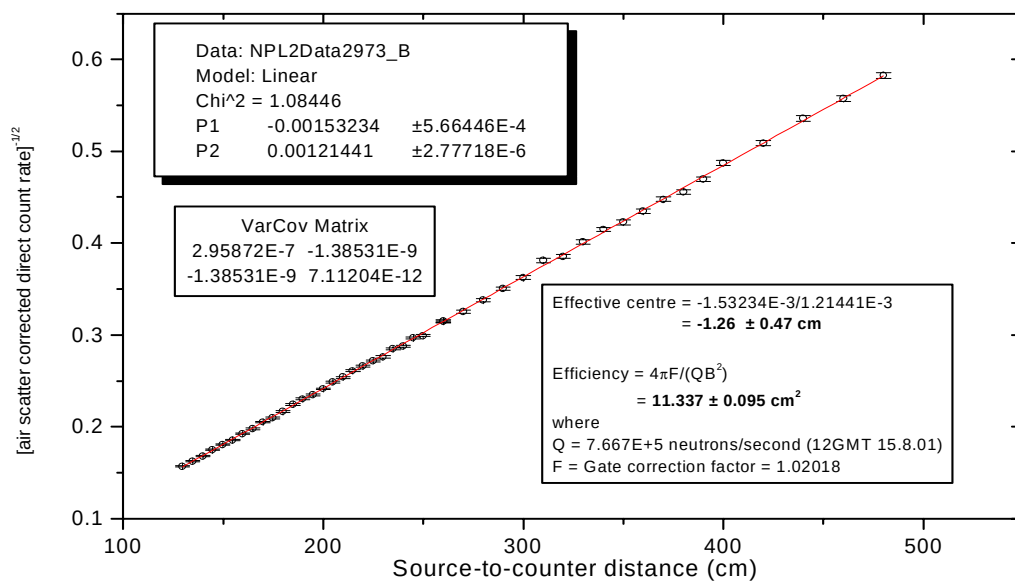


Figure 4-10: The inverse of the square root of the fully corrected count rates of the NPL long counter (2nd measurement) plotted against source to detector distance (cm).

5. MONTE CARLO MODELLING OF THE LONG COUNTERS FOR SbBe

5.1 MCNP Models of the Long Counters

5.1.1 The Geometry

An extensive Monte Carlo modelling of both detectors was carried out using MCNP-4C [Br00]. The models were constructed from engineering drawings supplied by Centronic (for the De Pangher counter) and by the NPL engineering services for the NPL long counter. In addition, the BF₃ tube of the De Pangher long counter was X-rayed to obtain, or confirm, details of the internal construction. Over 55 ‘surface’ cards and 35 ‘cell’ cards were needed to describe the counters, including their BF₃ tubes, in every detail. The space between the source and the front face of the inner polyethylene block, to which the source to counter distance is usually measured, was modelled as being a void. The stand on which the counters sat was not included in the model as it was considered part of the scattering environment and thus taken into account by the shadow cone correction. The eight holes within the NPL long counter wax or the corresponding annular trough for the de Pangher polyethylene were filled with air as they were considered an integral part of the counters.

5.1.2 The Source Definition

The ¹²⁴SbBe neutron source card was of the form:

```
C      Source parallel in x direction, starting at plane 145
sdef   sur=145 erg d1 rad=d2 pos=-10 0 0 axs=1 0 0 dir=1
SC1    SbBe Spectrum (Ryves 1971 + 3% at 378 keV)
SI1    h 0.004 0.007 0.008 0.009 0.010 0.011 0.012 0.0125
        0.013 0.0135 0.014 0.0145 0.015 0.0155 0.016 0.0165 0.017
        0.0175 0.018 0.0185 0.019 0.0195 0.020 0.02025 0.0205
        0.02075 0.021 0.02125 0.0215 0.02175 0.022 0.02225
        0.0225 0.02275 0.023 0.02325 0.0235 0.02375 0.024 0.02425
        0.377 0.379
SP1    d 0.00000 0.00057 0.00110 0.00120 0.00240 0.00367 0.00520
        0.00273 0.00400 0.00413 0.00443 0.00790 0.01010 0.01167
        0.01273 0.01330 0.01357 0.01437 0.01367 0.01557 0.01717
        0.01560 0.01653 0.00923 0.00880 0.00920 0.01050 0.01393
        0.01720 0.06787 0.06070 0.06083 0.06110 0.06550 0.07367
        0.07270 0.08043 0.08047 0.08333 0.03293 0.00000 0.03000
si2    21.75
```

This represents a mono-directional source of energy distribution specified by SI and SP cards, emitted from a plane surface m in the direction of the positive normal to the surface. The position of the point x, y, z (taken a few centimetres from the front face of the counter) is sampled uniformly in area on the surface of radius r (taken equal to the counter’s radius).

A biased point source was used for the effective centre calculation, as follows.

```
C      SOURCE DEFINITION for Effective Centre calculations
C      SbBe energy distribution of Ryves et al.1971)
C      POINT Source on X axis
sdef   pos=-200. 0 0 erg=d1 dir=d2 vec=1 0 0
SI2    as above
SP2    as above
sb2    -31 3.5      $source bias
```

The energy distribution spectrum above is that obtained by Ryves and Robertson [Ry71] by a home made Monte Carlo simulation code to which was added the 378 keV (3%) component discussed in section 2.1. The low energy spectrum shape is show in Figure 5-1.

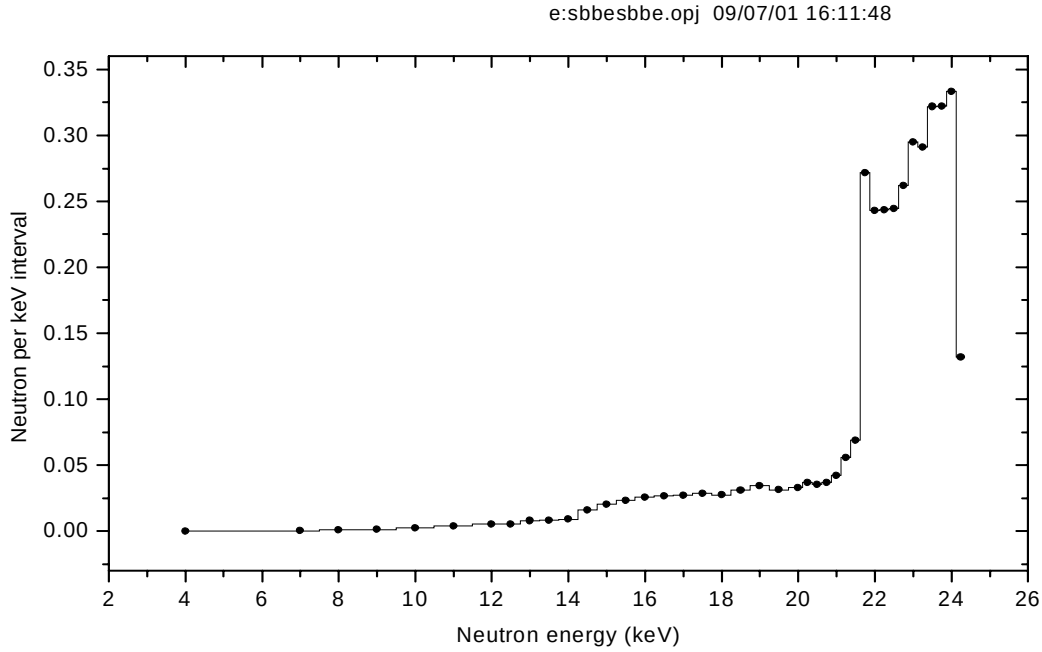


Figure 5-1: Low energy part of the SbBe photo-neutron source spectrum [Ry71]

5.1.3 Tallies

5.1.3.1 Efficiency calculations

MCNP may tally any quantity of the form

$$C \int \phi(E) f(E) dE$$

where C is an arbitrary normalisation scalar, $\phi(E)$ is an energy dependent fluence and $f(E)$ is either a sum or a product of quantities in the cross section libraries, or it can also be a response function provided by the user. The track length estimate tally (F4:n) with a tally multiplier FM4 (-1 3 107) was used to give the α -particle production, through the $^{10}\text{B}(n,\alpha)$ reaction, per cm^3 in the BF_3 active volume per starting particle history. The efficiency of the long counter was subsequently deduced. To obtain the efficiency directly in the MCNP output file, the first factor, (-1) in the tally multiplier, is multiplied by the product of the effective volume and the area of the surface from which the neutron source spectrum is sampled (equal to πr^2).

The neutron source term used for the main calculations of the efficiencies is a surface source, and produces a parallel beam of neutrons incident on the front face of the long counter, an arrangement which ensures an efficient calculation since all the neutrons strike the long counter. A parallel beam can be viewed as being equivalent to a point source at infinity, for which there are no effective centre considerations. Such a model would, however, be impractical for direct

Monte Carlo simulation. In normal usage the long counters are employed to determine the neutron fluence from an almost point source of neutrons at some finite source-to-detector distance. This distance is generally between 1.3 and 5 m at NPL. The parallel beam approach used to calculate the efficiency required has been investigated in previous work [Ta98 and Ta00] and has been fully validated. Thus the justification for the approach will not be repeated here.

5.1.3.2 Effective centre calculations

When using a long counter to measure the fluence from a point source of neutrons it is crucial that the effective centre is known as accurately as possible. Having previously established a good MCNP model for the long counters it was used to mock up a real experiment as depicted in Figure 2-11 but without the shadow cone. The method of determining the effective centre using MCNP, has previously been validated by replacing the long counter with a polyethylene sphere of radius 22 cm (the same radius as the long counter front face) and showing that the effective centre obtained was almost at the centre of the sphere as expected. The point source is fixed in position on the axis of the detector and the counter positioned at varying distances from the source. Both source and counter were assumed to be in vacuum and thus the complications of scatter corrections were avoided. The data analysis is then similar to that carried out for the measurements as described in Section 4 except that the scatter counts, system dead time, and air attenuation are zeroed in the input parameters to PCINVFIT, the least squares fit programme which yields the effective centre.

The quantity tallied for the effective centre calculations, namely tally F14 as written below, is the same as for the efficiency simulations except that, because the source is a point source, the tally multiplier includes only the effective volume of the BF_3 active region, hence giving the alpha production in this volume per starting particle history, not the efficiency.

5.2 Results of calculations for the de Pangher long counter

The tally used to calculate the efficiency of the de Pangher long counter is as follows:

```
f4:n 25                                $TRACK LENGTH ESTIMATE OF CELL 25 FLUX
fm4      -4.010723569E5    3    10    $Tally    multiplier,BF3(N,ALPHA)X-
SEC'N,*eff_V
```

Running for 7.2 million histories, which took 60 minutes on an 800 MHz NT PC, gave the efficiency 3.13 ± 0.10 (Table 5-1) with a 0.35% relative uncertainty. Normalising (3.73%) to all previous measurements with radionuclide sources, excluding $^{124}\text{SbBe}$ [Ta98,Ta00], the calculated efficiency of the de Pangher long counter for $^{124}\text{SbBe}$ is 3.25 ± 0.10 which agrees very well with the present measurements.

Table 5-1: Calculated efficiency (in cm²) of the de Pangher long counter for the ¹²⁴Sb-Be photo-neutron source compared to measurements before and after normalisation to all previous measurements with radionuclide sources [Ta98,Ta00].

	Measured	Calculated (unnormalised)	Calculated (normalised)
HT	3.26 ± 0.02	3.13 ± 0.10	3.25 ± 0.10
JBH	3.35 ± 0.07	--	

To calculate the effective centre of the de Pangher long counter, the following tally card was used as explained above:

```
f14:n 25          $TRACK LENGTH ESTIMATE OF CELL 25 FLUX
fm14 -269.867 3 107 $TALLY MULTIPLIER,BF3(N,ALPHA)X-SEC'N,*eff_V*Pi*25^2
```

The inverse square root of the tally, F14, is plotted in Figure 5-2 as a function of source to counter distance. Either PCINVFIT or the fitting function within ORIGIN was subsequently run to yield, as described above, the calculated effective centre shown in Table 5-2. The simulated effective centres do not agree well with the present measurements. This is more likely to be due to the very sensitive nature of the effective centre measurements and analysis than the calculations themselves where scatter complications are avoided. It was for instance previously reported in reference [Ta00] that a 3% change in scatter rates would yield a 36% change in the effective centre. The calculated effective centre is in agreement with the measurement of Hunt.

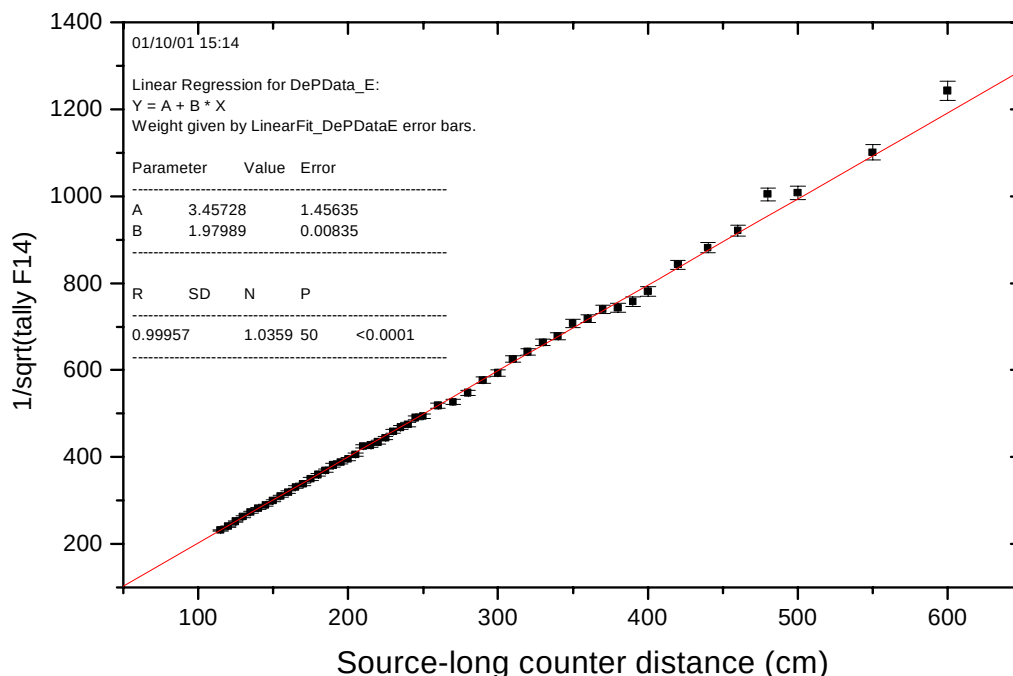


Figure 5-2: Simulation of the effective centre of the de Pangher long counter for the SbBe source

Table 5-2: Effective centre of the De Pangher long counter calculated using MCNP for $^{124}\text{Sb-Be}$ photo-neutron source with and without the high energy peak.

	Measured (cm) - mean	Calculated (cm)
HT Incl. 378keV	-0.22 ± 0.40	1.48 ± 0.74 1.75 ± 0.74
JBH	1.69 ± 0.48	

5.3 Results of calculations for the NPL long counter

The tally used to calculate the efficiency of the de NPL long counter is as follows:

```
f4:n 25                                $TRACK LENGTH ESTIMATE OF CELL 25 FLUX
fm4  -xxxx 3 107  $Tally multiplier,BF3(N,ALPHA)X-SEC'N,*eff_V
```

Running for 3 million histories, which took 60 minutes on an 800 MHz NT PC, gave the efficiency shown in Table 5-4 with a 0.52% relative uncertainty.

In previous work [Ta98, Ta00], calculations were normalised to measurements with four radionuclide sources (^{252}Cf , $^{241}\text{AmBe}$, ^{241}AmF , ^{241}AmB) by a multiplying factor of 11.19 %. This normalisation factor took into account uncertainties in parameters such as the exact pressure of the gas and its effective volume. Using this normalisation factor, one obtains that the normalised calculated efficiency of the NPL long counter for $^{124}\text{SbBe}$ is 10.79 ± 0.06 (see Table 5-3), which is lower than the measured value by 5 %.

Table 5-3: Calculated efficiency (in cm^2) of the NPL long counter for the $^{124}\text{SbBe}$ photo-neutron source compared to measurements.

	Measured	Calculated (Unnormalised)	Calculated (Normalised)
HT	11.34 ± 0.07	9.70 ± 0.05	10.79 ± 0.06
JBH	11.53 ± 0.06		

To calculate the effective centre of the NPL long counter, the following tally card was used as explained above:

```
f14:n 25                                $TRACK LENGTH ESTIMATE OF CELL 25 FLUX
fm14  -xxx 3 107  $TALLY MULTIPLIER,BF3(N,ALPHA)X-SEC'N,*eff_V*Pi*25^2
```

The inverse square root of the tally, F14, is plotted in Figure 5-3 as a function of source to counter distance. Either PCINVFIT or ORIGIN was subsequently run to yield, as described above, the calculated effective centre shown in Table 5-4. Unlike for the efficiency values, the simulated effective centres do not agree well with the present measurements. As noted for the de Pangher, this is more likely to be due to the very sensitive nature of the effective centre measurements and analysis than the calculations themselves where scatter complications are

avoided. It was for instance previously reported in reference [Ta00] that a 3% change in scatter rates would yield a 36% change in the effective centre.

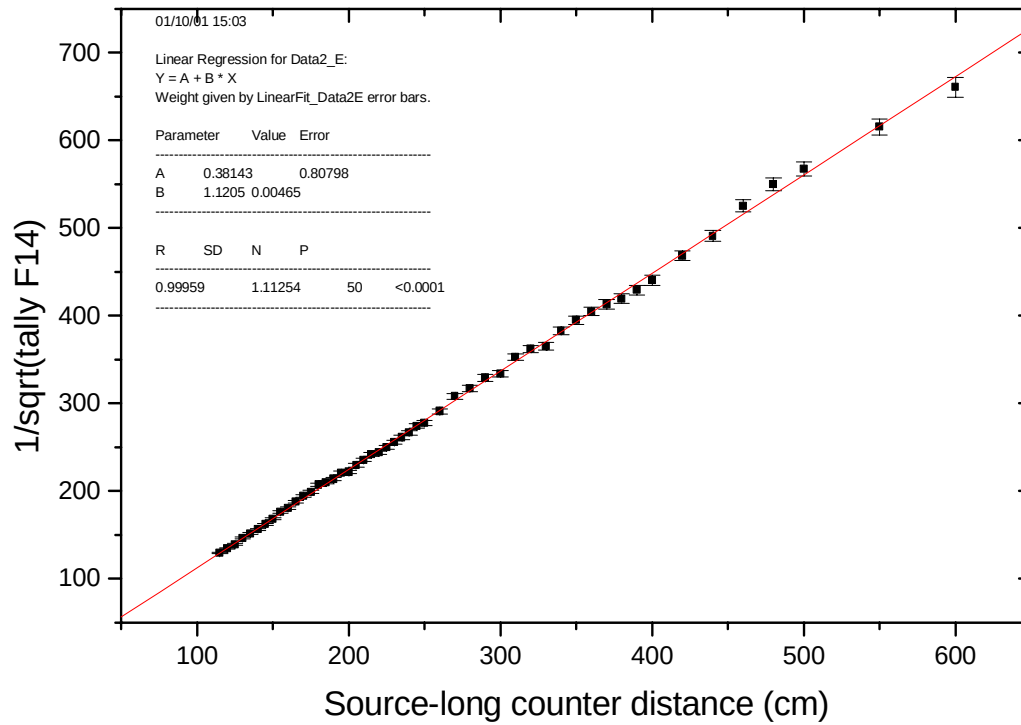


Figure 5-3: Simulation of the effective centre of the NPL long counter for the SbBe source

Table 5-4: Effective centre of the NPL long counter calculated using MCNP for ^{124}Sb -Be photo-neutron source with and without the high energy peak.

	Measured (cm) - mean	Calculated (cm)
HT Incl. 378keV	-1.26 ± 0.45	0.16 ± 0.66 0.34 ± 0.72
JBH	-0.72 ± 0.44	

6. SUMMARY AND CONCLUSIONS

The efficiencies and effective centres, at 22.8 keV using $^{124}\text{SbBe}$ photon neutron source, of two long counters routinely used at NPL have been measured. These have also been calculated using the Monte Carlo N-Particle transport code MCNP-4C. The simulated efficiencies of the de Pangher long counter for $^{124}\text{SbBe}$, after normalisation to all previous radionuclide source measurements agreed extremely well with the present measurements. The normalised calculated efficiency for the NPL long counter is about 5% too low. The simulated effective centres agree less well with the measurements. This is likely to be more due to the very sensitive nature of the effective centre measurements and analysis than the calculations themselves where scatter complications are avoided. It was for instance previously reported in reference [Ta00] that a 3% change in scatter rates would yield a 36% change in the effective centre. Two new projects have now started at NPL in order to investigate the optimum geometry configuration when using shadow cones to correct for scatter and to determine more accurately the effective centres of the long counters by combining measurements and Monte Carlo calculations.

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References:

- [Ax65] Axton, E.J., Cross, P., Robertson, J.C. Calibration of the NPL Standard Ra-Be Photoneutron Source by an Improved Manganese Sulphate Bath Technique, *J. Nucl. Energy*, 1965, **19**, pp 409-22
- [Br00] Judith F Briesmeister, editor, MCNPTM - A General Monte Carlo N-Particle Transport Code, Version 4C, edited by RCICC, Oak Ridge National Laboratory. *LANL Manual LA-13709-M March 2000* ; Forum: mcnp-forum@lanl.gov e-mail: mcnp@lanl.gov or jfb@lanl.gov
- [DeP66] De Pangher, J. and Nichols, L.L A Precision Long Counter for Measuring Fast Neutron Flux Density, *Pacific Northwest Laboratory Report BNWL-260*, 1966.
- [En81] Engdahl, J.C., Knoll, G.F. and Robertson J.C., Absolute Measurement of the ${}^6\text{Li}(n,\alpha){}^3\text{H}$ Cross section at 23 keV, *Nuc. Sci. Eng.*, **78** (1981) 44
- [Ha47] Hanson, A.O. and McKibben, J.L. A Neutron Detector Having Uniform Sensitivity from 10 keV to 3 MeV, *Phys. Rev.* 1947, **72**, 673.
- [He73] Heinzelmann, M. and Rohloff, F. Das Effektive Zentrum des Long-Counters, *Nucl. Inst. & Meths* 1973, **109**, 205.
- [Hu72] Hunt, J.B. and Robertson, J.C. The long counter as a secondary standard for neutron flux density, In *Proceedings of the 1st Symposium on Neutron Dosimetry in Biology and Medicine, Munich*, 1972, Vol. II p 935.
- [Hu76] Hunt, J.B. The calibration and use of long counters for the accurate measurement of neutron flux density, *NPL Report RS 5*, 1976.
- [Hu78] Hunt, J.B. private communication, and various workbooks and files at NPL, 1978
- [Hu80] Hunt, J.B. Harrison, K.G. and Wilson, R. Calibration of a De Pangher long counter and two neutron survey monitors at 21.5 keV, *Nucl. Inst. & Meth.* 1980, **169**, 477.
- [Hu82] Hunt, J.B, The relative intensity of the secondary neutron group emitted by an antimony-beryllium photoneutron source, *Nucl. Inst. & Meth.* 201 (1982) 533
- [IS89] International Organization for Standardization, International Standard, Neutron Reference Radiations for Calibrating Neutron Measurement Devices used for Radiation Protection Purposes, *ISO 8529* , 1st ed. October 1989.
- [IS98] International Organization for Standardization, Draft International Standard, Reference Neutron Radiations: Calibration fundamentals related to the basic quantities characterising the radiation field, *ISO 8529-2.DIS*, 24 February 1998.
- [Kn00] Knoll Glenn F, *Radiation Detection and Measurement*, (John Wiley & Sons) 3rd Edition, 2000.
- [Le98] Lewes, VE, Comparison of 24.5 Neutron Fluence Measurements, NPL report, CIRM16, December 1998, ISSN 1369-6793

- [Ma70] Marshall, T.O. Some Tests on the Consistency of the Performance of Six Precision Long Counters Intended as Secondary Standards for the Measurement of Neutron Flux Densities, *Health Physics* , 1970, **18**, 427.
- [McT59] McTaggart, M.H, A Study of the Neutron Long Counter, *AWRE report NR/A-1/59*, 1959.
- [Mi72] Mijnheer, B.J. Standard Fluxes and Standard Moderating Counters for Neutron Fluence Measurements, 1972, *IKO Amsterdam, Thesis*.
- [Ro01] Roberts, N.J. MCNP Calculations of Correction Factors for Radionuclide Neutron Source Emission Rate Measurements using the Manganese Bath, *NPL Report CIRM 45*, May 2001
- [Ry71] Ryves, T.B. and Robertson J.C., *Journal of Nuclear Energy*, 1971, **25**, p.557
- [Th73] Thomson, I.M.G. and Lavender, A. Calibration of the De Pangher long counter, in *Neutron Monitoring for Radiation Protection Purposes, Proceedings of a Symposium*, Vienna, 11-15 December 1972, Vol. II p 483, Published by the IAEA, 1973.
- [UK97] The Expression of Uncertainty and Confidence in Measurement, M3003, 1st Edition, *United Kingdom Accreditation Service*, 1997
- [We58] Westcott, C.H., Walker, W.H., Alexander, T.K. in: Proceedings of the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, *United Nations, New York*, 1958, **16**, pp70-6

Radioisotope production

¹²⁴Sb

For continuous irradiation at the Rez reactor

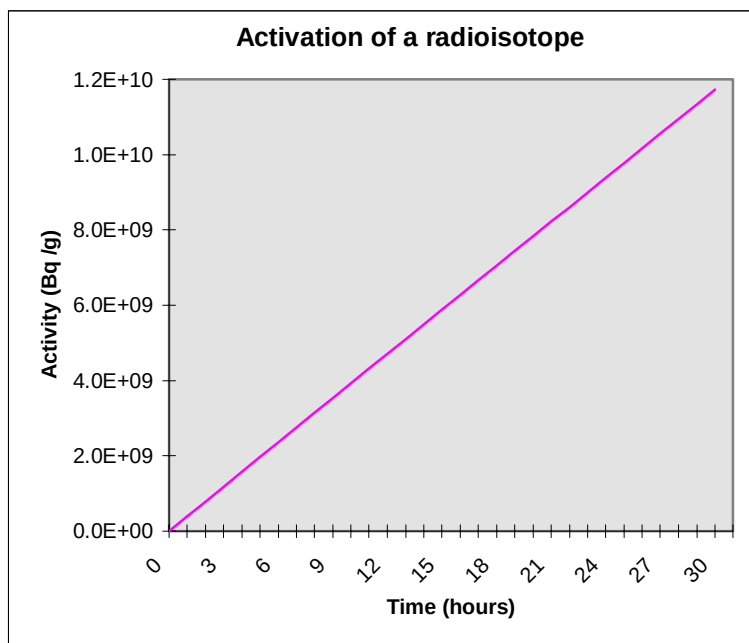
Avogadro's constant	=	6.022E+23	atoms or molecules/mole
Fractional atomic abundance	=	4.270E-01	
Relative atomic mass of target material	=	1.218E+02	g/mole
No. of atoms per gram of target isotope	=	2.112E+21	atoms/g
Cross section for production of isotope	=	4.330E+00	barns
Cross section for destroying the isotope	=	0.000E+00	barns
Half life of the isotope	=	6.020E+01	days
			λ (s ⁻¹) = 1.333E-07
			Λ (s ⁻¹) = 1.333E-07
Neutron fluence	=	1.000E+13	/cm2 /s
Reactor power	=	9.0	

Saturated activity	=	8.231E+11	Bq /g
	For 18.58 g ~	7.3	GBq /hour at the start
	For 18.58 g ~	73	GBq after 10 hours
	For 18.58 g ~	109.3	GBq after 15 hours
	For 18.58 g ~	218	GBq after 30 hours

Time (hours)	Specific activity (Bq /g of Sb)
-----------------	---------------------------------------

0	0.000E+00
1	3.936E+08
2	7.871E+08
3	1.180E+09
4	1.573E+09
5	1.966E+09
6	2.359E+09
7	2.751E+09
8	3.144E+09
9	3.536E+09
10	3.928E+09
11	4.319E+09
12	4.711E+09
13	5.102E+09
14	5.494E+09
15	5.885E+09
16	6.275E+09
17	6.666E+09
18	7.056E+09
19	7.447E+09
20	7.837E+09
21	8.226E+09
22	8.616E+09
23	9.006E+09
24	9.395E+09
25	9.784E+09
26	1.017E+10
27	1.056E+10
28	1.095E+10
29	1.134E+10
30	1.173E+10

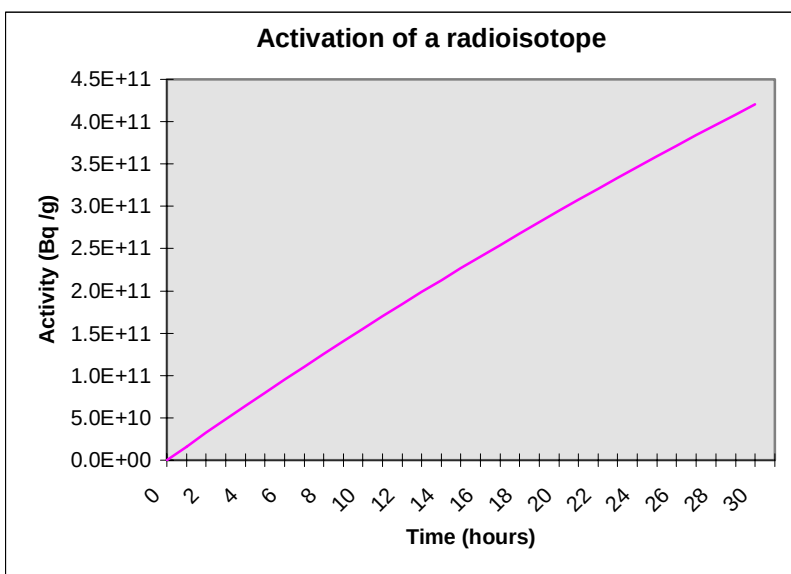
neutrons:	length of irradiation	Ci	1E6 n/s
	Ci after 1hr	0.2	0.2
	Ci after 10hrs	2.0	1.5
	Ci after 15hrs	3.0	2.3
	Ci after 30hrs	5.9	4.5
	assume	1Ci gives 1.3E6n/s	
		GBq	msv/hr
	act. after 30 days cooling; 15hrs irr.	80	20
	inc. 2 GBq of Sb122		



For continuous irradiation at the Rez Reactor

Avogadro's constant	=	6.022E+23	atoms or molecules/mole
Fractional atomic abundance	=	5.730E-01	
Relative atomic mass of target material	=	1.218E+02	g/mole
No. of atoms per gram of target isotope	=	2.834E+21	atoms/g
Cross section for production of isotope	=	6.000E+00	barns
Cross section for destroying the isotope	=	0.000E+00	barns
Half life of the isotope	=	2.700E+00	days λ (s ⁻¹) = 2.971E-06 Λ (s ⁻¹) = 2.971E-06
Neutron fluence	=	1.000E+13	/cm ² /s
Reactor power	=	9.0	
Saturated activity	=	1.530E+12	Bq /g
		For 18.58 g ~	302.5 GBq /hour at the start
		For 18.58 g ~	2884 GBq after 10 hours
		For 18.58 g ~	4214.6 GBq after 15 hours
		For 18.58 g ~	7804 GBq after 30 hours

Time (hours)	Specific activity (Bq /g)
0	0.000E+00
1	1.628E+10
2	3.239E+10
3	4.833E+10
4	6.409E+10
5	7.969E+10
6	9.512E+10
7	1.104E+11
8	1.255E+11
9	1.404E+11
10	1.552E+11
11	1.699E+11
12	1.843E+11
13	1.987E+11
14	2.128E+11
15	2.268E+11
16	2.407E+11
17	2.544E+11
18	2.680E+11
19	2.814E+11
20	2.947E+11
21	3.079E+11
22	3.209E+11
23	3.337E+11
24	3.465E+11
25	3.590E+11
26	3.715E+11
27	3.838E+11
28	3.960E+11
29	4.081E+11
30	4.200E+11



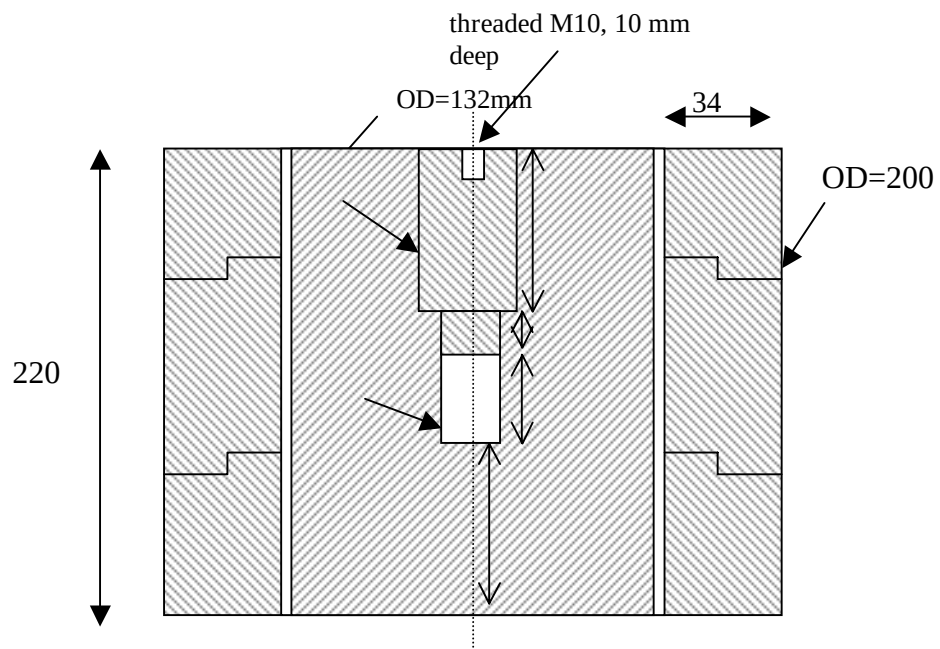


Figure A-1: Lead shielding pot