Fission Chamber Calibration Tests at NRU

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Introduction

As part of the AECL Point Lepreau post-refurbishment process, a significant number of neutron flux scans are scheduled to be performed at low reactor power, in the neutron flux range of 10^9-10^{10} n/cm^2/s (nv). The AECL Applied Physics Branch procured fission chambers for these measurements and, as part of the project, these detectors were planned to be tested at NRU, at L3 beamline of Canadian Neutron Beam Centre (National Research Council Canada). The L3 beamline provides the required flux range and an accessible geometry.

In order to verify the feasibility of testing the Point Lepreau fission chambers at NRU (L3), a pre-test (a 'dry run') has been completed in May 2009 using an existing AECL fission chamber. The scientific and technical personnel from the Applied Physics Branch involved in this experiment were (in alphabetical order): Hutanu Roxana, Johnston James, Jonkmans Guy, Smith Blair, Sur Bhaskar, Yue Shuwei. This report describes the "dry run" experiment and main results. The full-length report can be found in Reference 1.

We should also note here that this work is part of an R&D project, and it is not a qualification testing for safety-related systems and components, and thus it is not subjected to the requirements of Clause 6 of CSA N286.2.

Experimental Set-Up

The fission chamber is an ionization chamber that contains a coating of uranium enriched in ^{235}U. By capturing thermal neutrons, ^{235}U fissions and the resulting high-energy fission products ionize the Ar gas (at 1.2×10^5 Pa pressure) inside the chamber leading to a detectable current.

The AECL fission chamber used during the "dry-run" experiment is a full power fission chamber, designed to function up to a thermal neutron flux of 4×10^{14} n/cm^2/s (=nv) [2]. This fission chamber has a sensitivity to neutrons of $1.67 \cdot 10^{-18}$ A/nv [2]. Although this detector was used at low fluxes, it was not expected that its high power sensitivity would change [3]. The Point Lepreau fission chambers have a similar materials layout, however, they are sensitive to low power thermal fluxes of 10^9-10^{10} nv.

The L3 spectrometer pathway to the NRU reactor core has two channels interconnected to a monochromator cavity, as shown in Figure 1. A 5° bent Al guidetube with the O.D. of ¼" and length of 2.5 meters was used to guide the fission chamber and its associated minerally insulated (MI) cable mainly through one channel, as shown in Figure 1. An Al frame was also designed to support the guidetube in the channel before the monochromator. A small camera (not shown in Figure 1) was attached to one end of the frame. In addition, a gamma sensor (also not shown in Figure 1) was attached to the Al frame in order to monitor any changes in the reactor power for the duration of the experiment.

With the frame in place, the guidetube was carefully inserted into the monochromator cavity so that it does not come in contact with the monochromator crystal. This procedure was successfully monitored using the camera display. A photograph of the camera monitor during the guidetube insertion in the monochromator cavity is shown in Figure 2.

The fission chamber was inserted in the guidetube at known locations using a portable driving system. The MI cable of the fission chamber (~29 m) was wound on the spool. In addition to the driving motors, encoder, the spool and their associated electronics, the driving system included a Keithley 6487 instrument which had two functions: providing a bias voltage to the fission chamber and recording the output current of the detector.

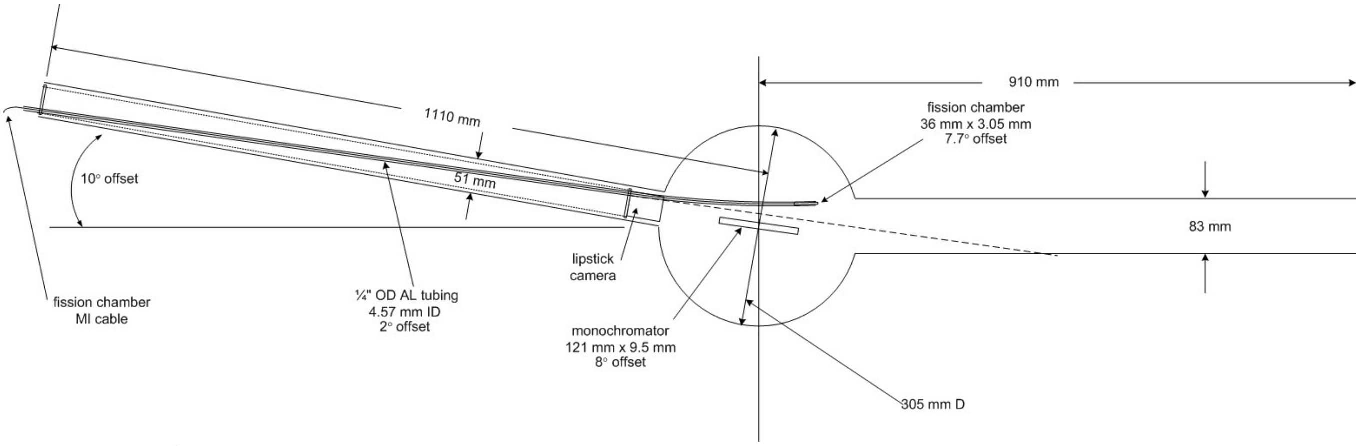


Fig. 1 Diagram of the L3 experiment components

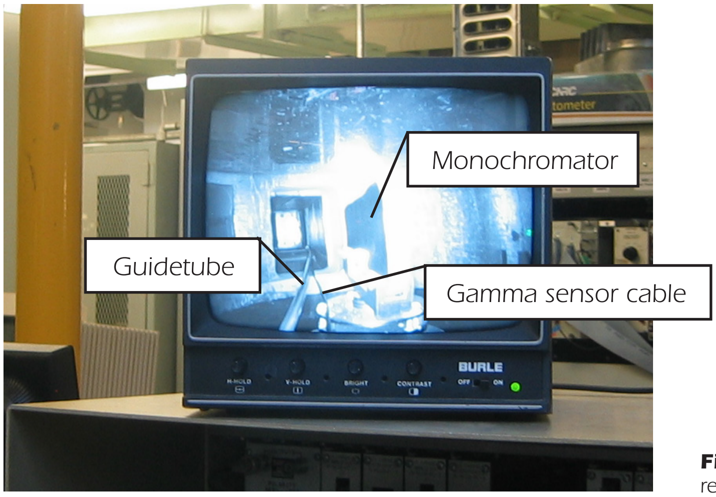


Fig. 2 Camera image of the monochromator crystal and guidetube

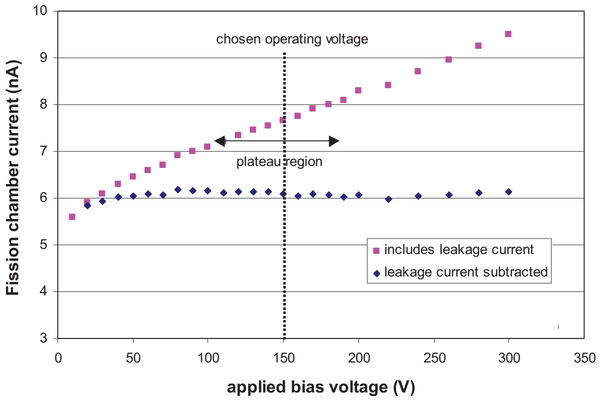


Fig. 3 Fission chamber current with and without the leakage current, respectively, for various bias voltages at the maximum flux location

Measurements

The experiment proceeded in 3 steps:

- ***Voltage bias measurements:***
  The fission chamber was parked at one location and the detector output current was acquired at various bias voltages.
- ***Travelling scans:***
  The data was obtained every 2 cm along the L3 channel (Figure 1), at the operating voltage of the fission chamber. This voltage was obtained from the plateau measurements, as it will be shown in the next sections.
- ***Reference flux measurements by activated Cobalt wire.***

After the fission chamber measurements were completed, a 2.5 meters 0.005" diameter Cobalt wire was attached on an Al wire (for support) and was introduced in the guidetube, in order to obtain the flux profile along the travelling path of the fission chamber. The wire was fully inserted in the guidetube and then it was exposed to neutrons for 1 hour. After the exposure, the Cobalt wire was transferred to Building 145 (Applied Physics Branch) at Chalk River Laboratories for counting, where wire pieces were cut (and weighted) approximately every 1 cm for the first 10 cm length, starting at the highest flux end of the wire. After the first 10 cm, the pieces were cut every 2 cm.

Appendix A includes the calculation for obtaining the thermal neutron flux from the activity of the irradiated Cobalt wire. The neutron flux measurements and calculations were performed and provided by Gregory Morin and Michael Zeller (AECL- Applied Physics Branch).

Results

Bias "Plateau" Measurements

The fission chamber was positioned near the end of the guidetube where the neutron flux was the highest. The plateau measurements are shown in Figure 3 where the fission chamber current was recorded at different bias voltages. A leakage current was observed during the measurement. The magnitude of this current was determined by measuring the detector current at various bias voltages in the absence of a neutron flux. The major source of the leakage current was traced back to a faulty connector at the reel-detector interface. Although the connector could not be repaired during the experiment, at the time of this writing, this problem has been solved.

A plateau region was identified and the fission chamber operating voltage of 150V was chosen in the middle of this plateau. This value is close to the suggested operating voltage (130-140V) of the chamber.

Travelling Scans

After the bias plateau measurements were completed, travelling scans were performed starting from the maximum flux location and during the slow removal of the fission chamber. Figure 4 shows the travelling scan data. In this Figure, the leakage current at the operating voltage of 150V (Figure 3) was subtracted.

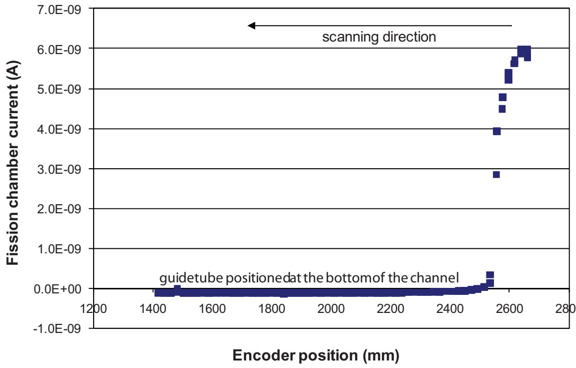


Fig. 4 Fission chamber current profile along the channel

The neutron flux profile confirms that the fission chamber was not centred in the middle of the L3 neutron beam, except at the elevated bent end of the guidetube. Basically, the guidetube was mainly resting against the bottom of the L3 channels. The elevation of the guidetube at the end point was made possible by rotating the guidetube in place until the bent in the guidetube was facing upwards.

Fission Chamber Current Error Estimation

The sources of error for the fission chamber current include: signal from the MI cable, non-linearity effects, and instrumentation error. The first two errors are not well known and one of the goals of the testing of the fission chambers for Point Lepreau at NRU is to estimate the accuracy of the detector linearity as well as its cable contribution to the signal. The instrumentation error is within 1% [4]. Overall, we estimate that these errors can sum up to approximately 10%. As a consequence, the error bars for the fission chamber current can be quite large. For example, for a current of 10 nA, the absolute error is ±1 nA.

Neutron Activation (Cobalt wire) Data

Figure 5 shows the neutron flux profile obtained after the Cobalt wire activation measurements. Note that, as shown in Appendix A, the thermal neutron flux component obtained from the Cobalt wire activation is predominant. The "position" of the X-axis of Figure 5 was calculated based on the position of the Cobalt wire segments relative to the encoder position along the channel.

The percentage error in the thermal neutron flux was estimated as the sum of the largest errors, that is, the wire counting and the wire masses. The error for the wire mass was approximated to be ~10% [5], while the errors resulting from counting statistics are listed in Table 1 [6]. Based on this error, individual absolute errors were thus calculated for each wire segment.

The error for the position (X-axis of Figure) was estimated to be ~ 2%.

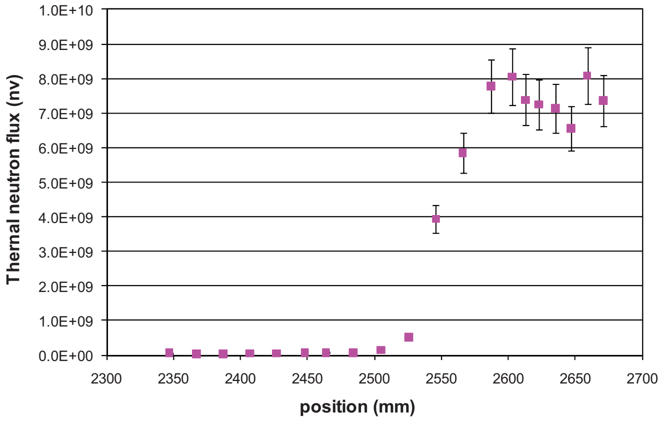


Fig. 5 *Thermal neutron flux profile obtained from the Cobalt wire activation measurement*

Activity [Bq/gram]	Error [%]
12060.70	0.51
13236.70	0.49
10747.10	0.45
11678.30	0.55
11873.70	0.42
12093.60	0.54
13195.10	0.63
12730.60	0.46
9597.42	0.39
6459.16	0.58
840.36	3.81
244.69	6.64
115.16	12.51
121.44	12.80
99.93	16.62
70.89	23.42
76.74	15.02
58.19	13.01
58.25	21.84
96.54	15.94

Table 1.
Activity and the associated errors of the individual cut Cobalt wires [6]

Data Analysis

Figure 6 shows the *calculated* and *measured* thermal neutron fluxes. The *calculated* neutron flux is the thermal neutron flux obtained from the Cobalt wire activation measurements, based on the calculations shown in Appendix A. The *measured* neutron flux was obtained at each location as the ratio of the measured fission chamber current (leakage current at 150V was subtracted) and the detector sensitivity of 1.67×10^{-18} A/nv. In addition, the encoder positions for the *calculated* and *measured* neutron fluxes are shifted by 2 cm to account for the distance between the tip of the fission chamber and its neutron active region.

Figure 6 shows that the measured neutron fluxes using the fission chamber are significantly smaller than the expected fluxes obtained from the Cobalt wire activation data. A number of hypotheses have been raised to explain this discrepancy:

a. A significant decrease in detector sensitivity due to burnup of the active U235 layer. This is highly unlikely considering that the fission chamber has never been irradiated in very high fluxes (in-core) measurements.

b. Deterioration of the insulator material (Al_2O_3) inside the fission chamber due to various environmental effects such as exposure to air, temperature, radiation. In the case of this fission chamber, the manufacturer guarantees proper function of the detector for a minimum of 5 years shelf-life on the premise of proper storage. The fission chamber used in this study was shipped at CRL by the manufacturer in year 2003/2004 [2] and was properly stored by AECL since then. Thus, it is unlikely that the detector's properties changed significantly due to shelf-life/improper storage.

c. Reactor power changes between the fission chamber traveling scan and the Cobalt wire exposure time periods, respectively. No significant changes in the reactor power were found by comparing the REDNET readings, fuel rods power near L3, or the gamma sensor readings.

d. Flux depression/Self-shielding effects caused by the presence of the fission chamber in the neutron flux. Although it is assumed that the manufacturer has accounted for these effects during the factory calibration, the flux depression/self-shielding factors have been estimated in Reference 1. These calculations [1] showed that the self-shielding factors have high values suggesting that self-shielding (and flux depression) does not play an important role in this experiment.

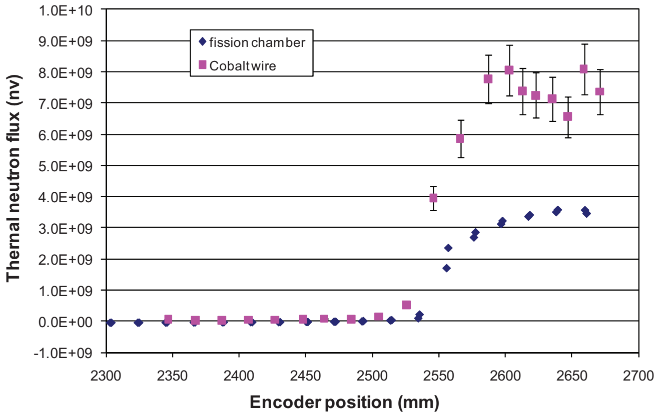


Fig. 6 Measured (fission chamber) and expected (Cobalt wire) thermal neutron flux profiles

Calibration Of The Fission Chamber

Calibration of the fission chamber means to obtain the new sensitivity as the ratio between detector current and the thermal neutron flux. This is shown in Figure 7 which is a plot of the detector current versus the Cobalt wire neutron flux. The data considered for this plot is mainly the high neutron flux data from Figure 6.

Figure 7 indicates that there is a good linearity of the fission chamber only up to about 5×10^9 nv. However, it is difficult to draw a conclusion regarding the overall linearity due to the limited number of available data points.

The slope of the linear fit from Figure 7 yields a new sensitivity of the fission chamber of about 7×10^{-19} A/nv. Although the new sensitivity is ~2.4 times smaller than the manufacturer value of 1.67×10^{-18} A/nv [2], this new value is the acceptable minimum limit for the detector's sensitivity, as shown in Table 2.

As discussed in Section 5, this decrease in sensitivity is not likely to be caused by the burnup effects, extended shelf-life, reactor power changes or self-shielding effects.

Table 2 also shows that this particular fission chamber was calibrated in a 4.31×10^{11} nv neutron flux, which is 2 orders of magnitude higher than the neutron flux available for this experiment. On the other hand, the sensitivity of the detector is not expected to change at $\sim 10^9$ nv fluxes [3].

Using the newly obtained sensitivity of 7×10-19 A/nv, Figure 6 data was re-plotted and it is show in Figure 8. This figure shows this time a very good agreement between the fission chamber and Cobalt thermal neutron fluxes, as opposed to their large disagreement shown by Figure 6. As a consequence, there is a strong possibility that the sensitivity of this high power fission chamber would change at low fluxes. We should underline that, as previously specified in Sections 1 and 2, this experiment is a dry run test for the Point Lepreau fission chambers, which are designed to perform and are expected to have an excellent linearity in low neutron fluxes (5×10^8-5×10^{12} nv).

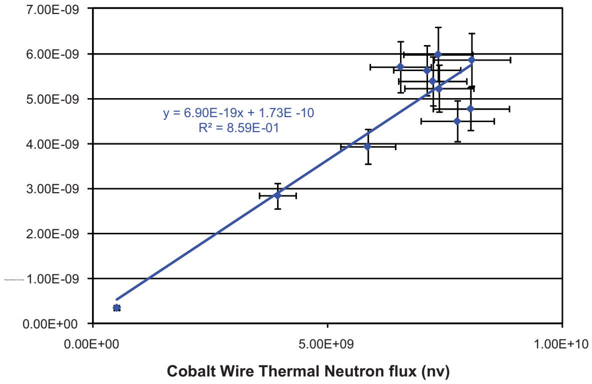
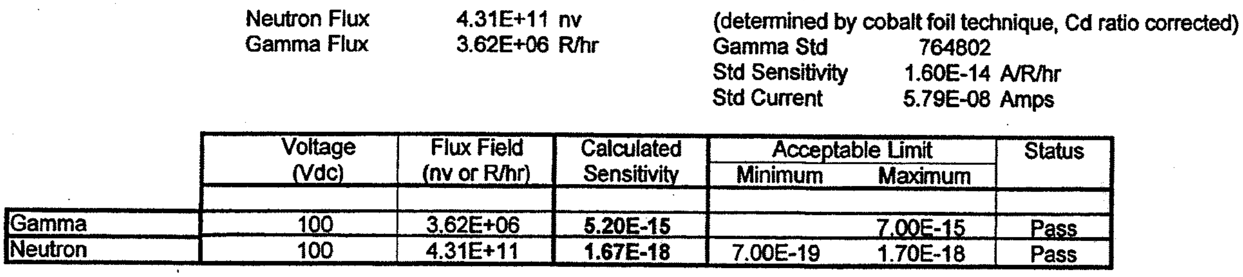


Fig. 7 Calibration plot: fission chamber current versus Cobalt wire thermal neutron flux

Table 2.
Sensitivity Specifications for the Fission Chamber Used in this Study [2]



Neutron Flux 4.31E+11 nv
Gamma Flux 3.62E+06 R/hr

(determined by cobalt foil technique, Cd ratio corrected)
Gamma Std 764802
Std Sensitivity 1.60E-14 A/R/hr
Std Current 5.79E-08 Amps

	Voltage (Vdc)	Flux Field (nv or R/hr)	Calculated Sensitivity	Acceptable Limit		Status
				Minimum	Maximum	
Gamma	100	3.62E+06	**5.20E-15**		7.00E-15	Pass
Neutron	100	4.31E+11	**1.67E-18**	7.00E-19	1.70E-18	Pass

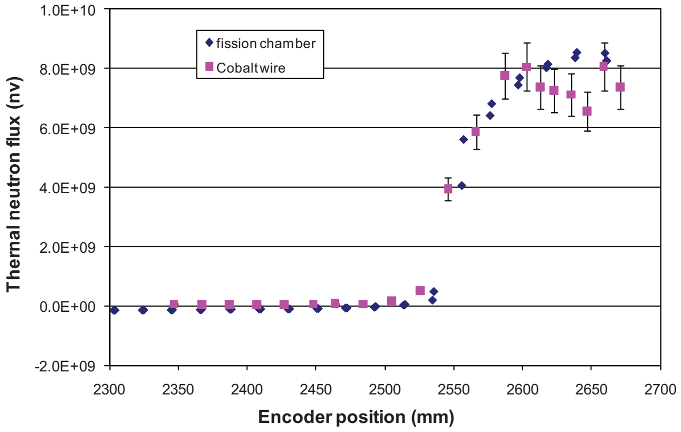


Fig. 8 Measured and expected thermal neutron flux profiles for a detector sensitivity of 7×10^{-19} A/nv

Gamma Contribution

The fission chamber has also a gamma sensitivity of 5.2 × 10 A/Rad/hr, as shown in Table 2. The gamma sensor attached to the guidetube frame recorded a maximum value of approximately 4.5×10^3 Rad/hr near the monochromator. The product between the sensitivity and the measured gamma field yields an approximate gamma current value of 0.02 nA. This current represents a maximum of ~ 0.3% gamma contribution to the total current of the fission chamber (Figure 4- high signal region).

Conclusions and Recommendations

This dry run calibration test was a successful experiment and at the same time, a very good learning experience about what improvements need to be made for the actual final test.

The list below includes the improvements that should be done before the final test:

- A better track of fission chamber/guidetube position changes;
- Mass of the cut cobalt wires should be measured more accurately than 10% in order to better calibrate the fission chamber;
- A new guidetube system that would allow the fission chamber to be in the centre of the L3 beam channel at all times. The neutron flux is significantly higher than near the walls of the beam channel;
- Better insertion system for the Cobalt wire in the guidetube. It was very difficult to introduce the Al wire with the Co wire taped on it in the guidetube;
- Driving system software improvements that will allow faster and more precise position measurements. For example, in the current at each position was obtained for 3 repetitive measurements, which was not desired;
- Minimize the leakage currents in the driving system;
- A long extension of the guidetube to allow for measurements to be performed at a considerable distance from the set-up.

Acknowledgments

The author would like to thank Ronald Rogge (Canadian Neutron Beam Centre, National Research Council Canada), for the support and participation in the experiment. Also, the input provided by Mike Zeller (AECL- Applied Physics Branch) regarding the neutron flux calculations is appreciated.

References

[1] "Fission Calibration Tests at NRU", AECL Unrestricted Technical Document, 153-60520-TD-001 Rev 0, July 2010.
[2] *"Manufacturing, Inspection & Test Data,"*, Certificate of Conformance and Quality Release for WX-33073 In-core Miniature Fission Chamber, Quality Assurance Department, Imaging & Sensing Technology (IST), February 27, 2004.
[3] Mike LaFontaine, Mirion- Imaging & Sensing Technology (IST) Canada Inc., private communication.
[4] Keithley 6487 Picoammeter Specifications.
[5] Michael Zeller, private communication.
[6] Michael Zeller, Cobalt wire data and calculations, email communication.

Appendix A

Derivation of the Neutron Flux, ϕ, by Wire Activation [6]

The relationship between the conventional flux, ϕ, and the Westcott flux, ϕ_W, is given by:

$$\phi = \phi_W \cdot \frac{2}{\sqrt{\pi}} \tag{A.1}$$

The Westcott flux, ϕ_W has the following dependence on the absolute Cobalt wire activation per unit mass, $A_{absolute}$:

$$\phi_W = \frac{A_{absolute}}{\Sigma_W} \cdot \frac{1}{1 - e^{-\lambda \cdot t}} \tag{A.2}$$

Where:

Σ_W is the macroscopic Westcott cross-section

λ is the decay constant of the induced activity for the Cobalt wire

t is the neutron irradiation time

The relationship between $A_{absolute}$ and the measured activity per unit mass of the Cobalt wire, A, is given by:

$$A_{absolute} = \frac{A}{\varepsilon} \tag{A.3}$$

where ε is the counting detector efficiency (number of counts recorded per decay).

The Westcott cross-section, Σ_W, has the following expression:

$$\Sigma_W = N \cdot \sigma_{2200} \cdot (G_{thermal} \cdot g + G_{resonance} \cdot r \cdot (\frac{T}{T_0})^{1/2} \cdot S_0) \tag{A.4}$$

Where:

N is the number of atoms per unit mass of Co^{59}

σ_{2200} is the neutron capture cross-section at a velocity of 2200 m/s

$G_{thermal}$ is the thermal self-shielding factor for the wire

g is the Westcott g parameter for the detector material

$G_{resonance}$ is the resonance self-shielding factor for the wire

S_0 is the Westcott s parameter for the detector material

In equation (A.4), $r \cdot (\frac{T}{T_0})^{1/2}$ is the epithermal index for a neutron spectrum with the temperature T and T_0 is the room temperature. The epithermal index has the expression:

$$r \cdot (\frac{T}{T_0})^{1/2} = \frac{G_{thermal} \cdot (1 - h \cdot R_{Cd})}{G_{resonance} \cdot S_0 \cdot (F \cdot R_{Cd} - 1)/g + R_{Cd} \cdot (1/K - W)} \quad \text{(A.5)}$$

Where:

R_{Cd} is the Cadmium ratio

h is the transmission of the Cadmium filter for thermal neutrons

F is the transmission of the Cadmium filter for resonance neutrons

$1/K$ is approximately the density fraction of the epithermal neutrons transmitted by Cadmium

W is a correction for resonance activation in the wing of resonance below the Cadmium cut-off energy

The $r \cdot (\frac{T}{T_0})^{1/2}$ factor was calculated in this study for a gold foil with R_{Cd} = 14.5, which is the value obtained from measurements at L3 at the monochromator position.

In the case of this experiment [5], it has been found out that the thermal neutron component is dominant compared with resonance neutron component, as indicated by the values of the terms of the equation A.4:

$$G_{thermal} \cdot g = 0.97 \quad \text{(A.6)}$$

$$G_{resonance} \cdot r \cdot (\frac{T}{T_0})^{1/2} \cdot S_0 = 4.5 \times 10^{-3} \quad \text{(A.7)}$$