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Australian Radiation Protection and Nuclear Safety Agency

The Australian Primary Standard for absorbed dose to water (graphite calorimeter)

Ganesan Ramanathan, Peter Harty, Tracy Wright, Jessica Lye, Duncan Butler, David Webb and Robert Huntley

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The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) is the Australian Government's primary authority on radiation protection and nuclear safety. ARPANSA regulates Commonwealth entities using radiation with the objective of protecting people and the environment from the harmful effect of radiation. ARPANSA undertakes research, provides services, and promotes national uniformity and the implementation of international best practice across all jurisdictions.

Abstract

The Australian absorbed-dose-to-water primary standard is a graphite calorimeter procured from the Austrian Research Centres (ARCS, Seibersdorf) in 1991. It was established as the primary standard for ⁶⁰Co gamma rays in 1997.

In 2009 ARPANSA installed an Elekta Synergy Linear Accelerator (linac) and in 2010 the ⁶⁰Co source was replaced with an Eldorado 78 treatment head containing a new ⁶⁰Co source. This report concerns the establishment of the calorimeter on the new ⁶⁰Co source and on the linac beams. It covers technical details of the geometry, modes of operation, analysis, conversion from absorbed-dose-to-graphite to the absorbed-dose-to-water, and the calibration of secondary standard chambers. Appendices give detailed drawings and operating instructions for the ARPANSA calorimeter.

ARPANSA undertook international comparisons of absorbed dose at 60 Co in 2010 and linac beams in 2012. Ratios of the ARPANSA dose to water to that measured by the Bureau International des Poids et Mesures (BIPM) were 0.9973 at 60 Co, 0.9965 at 6 MV, 0.9924 at 10 MV and 0.9932 at 18 MV, with a combined standard uncertainty of 5.3 parts in 10^3 , 5.5 parts in 10^3 , 6.0 parts in 10^3 and 5.9 parts in 10^3 , respectively. This report gives additional information describing the ARPANSA calorimeter and method of realising the absorbed dose for these comparisons.

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1. INTRODUCTION

ARPANSA is authorised to maintain the Australian primary standard of absorbed dose by the National Measurement Institute (NMI), Australia, under Section 8 of the National Measurement Act 1960 [1]. This standard is currently a graphite calorimeter of the Domen design [2]. The calorimeter was purchased from the Austrian Research Centers at Seibersdorf (ARCS, Seibersdorf) in collaboration with Bundesamt für Eich- und Vermessungswesen (BEV), Austria, in 1991. It was established as the primary standard for ⁶⁰Co gamma rays in 1997, when a comparison with the reference standard of the Bureau International des Poids et Mesures (BIPM) gave a ratio of absorbed dose ARPANSA/BIPM [3] of 1.0024 with a combined standard uncertainty of 3.0 parts in 10³.

In March, 2000, electrical problems with the calorimeter prevented its use until it was repaired in 2006 (Appendix 1). During this period the absorbed dose standard continued to be disseminated, with slowly decreasing accuracy, by using the theoretical decay of the ⁶⁰Co source and a suite of thimble chambers to check the absorbed dose rate.

In February 2010, a new 145 TBq ⁶⁰Co source was installed at ARPANSA in an Eldorado 78 therapy treatment head mounted vertically on a custom stand. The repaired calorimeter was re-established as the primary standard for absorbed dose to water with the new ⁶⁰Co source. A new method of converting the absorbed dose measurement from graphite to dose in water was adopted. Previously, the conversion used the photon fluence scaling theorem and was in agreement with cavity ionisation theory [4]. In 2010 ARPANSA used a Monte Carlo calculation of the ratio of dose in the graphite core of the calorimeter to dose in a uniform water phantom. The details and validation of this approach are given in reference [5]. A subsequent comparison of calibration coefficients of reference ionisation chambers at the BIPM and ARPANSA gave a ratio of the absorbed dose to water measured by ARPANSA to that of the BIPM of 0.9973 with a standard uncertainty of 5.3 parts in 10³[6].

In 2010 an Elekta Synergy Linear Accelerator was installed at ARPANSA. This linac can provide seven photon energies from 4 MV to 25 MV and ten electron energies from 4 MeV to 22 MeV. The calorimeter has been established as the primary standard for absorbed dose to water at megavoltage photon energies of 6 MV, 10 MV and 18 MV from the linac [7]. In adapting the calorimeter to work with the linac, modifications to the beam monitoring system and analysis were required to take into account variations in the linac output during the calorimeter irradiation. The method of Monte Carlo calculation was again employed to convert the dose measured by the calorimeter to absorbed dose to water measured by ARPANSA to that of the BIPM of 0.9965 at 6 MV, 0.9924 at 10 MV and 0.9932 at 18 MV, with a combined standard uncertainty of 5.5 parts in 10³, 6.0 parts in 10³ and 5.9 parts in 10³, respectively [8].

ARPANSA has a second calorimeter on loan from the IAEA. This calorimeter has been compared with the ARPANSA calorimeter giving good agreement (0.2%) in ⁶⁰Co at ARPANSA [9]. The agreement between the ARPANSA calorimeter and the IAEA calorimeter at linac energies of 6 MV, 10 MV and 18 MV has been found to be of the same order.

2. DESCRIPTION OF ARPANSA GRAPHITE CALORIMETER

2.1 Calorimeter construction

The ARPANSA calorimeter is a commercial design [10] based on that of Domen [11]. Figure 1 shows the calorimeter in its yellow wooden support and with the vacuum system attached.



Figure 1: The ARPANSA graphite calorimeter (with build-up plates for ⁶⁰Co)

From the outside the calorimeter appears as a solid, uniform graphite cylinder. Circular graphite plates of different thicknesses can be attached to the front of the calorimeter to increase the depth of the sensitive components, and plates can be added behind to increase the overall phantom depth, if required. Internally the calorimeter is separated by small vacuum gaps into thermally isolated bodies. Figure 2 shows a schematic cross-section of the calorimeter.

Radiation is detected by the core: a single graphite disc 20 mm in diameter and 2.75 mm thick. The jacket surrounds the core and has dimensions chosen such that the core and the jacket have approximately the same mass. Holes in the jacket base plate allow for evacuation. The core is mounted on the jacket base plate with polystyrene supports. The jacket is similarly mounted on the larger shield and the shield in turn in the even larger graphite medium. All four of these elements were machined from a single block of high-purity molded graphite, grade ATJ, maximum grain size 0.15 mm, bulk density 1.79 g/cm³, 0.08 % ash. Thermal isolation of these four elements is improved by evacuation of the gaps separating them and by coating the surfaces of the shield and the medium with aluminised Mylar.

Temperature-sensing thermistors are embedded in each of the four components. The core has two thermistors for temperature sensing marked as C1 and C2 and one thermistor for heating. The jacket contains two thermistors: one for temperature-sensing and one for heating. The shield has one sensing thermistor and heater made from a metal-film resistor of nominal value 1.2 k Ω . The medium is heated by wire coils embedded in its rear surface. The different resistor types used for heating the bodies reflects the different power needed to heat these bodies which have significantly different masses.

The temperature of the medium is controlled by a PID circuit in the calorimeter electronics. The set temperature is a few degrees above room temperature and thermal loss to the environment is used as the cooling mechanism for the controller. The temperature is pre-set by coarse and fine potentiometers in the Temperature controller and calibrator unit described in section 2.2.2.



Figure 2: Schematic cross-section of the calorimeter (not to scale)

Figure 3 shows a photo of the calorimeter positioned in the linac beam for measurements.

The schematic diagram and photo of the calorimeter core-jacket-shield assembly with the shield cap and the jacket cap removed are shown in Appendix 2.

Engineering drawings of the calorimeter are shown in Appendix 3.

The details of build-up plate thickness, core mass, non-graphite materials in the core are given in Appendix 4.



Figure 3: ARPANSA calorimeter positioned in the linac beam

2.2 Calorimeter electronics

A block diagram of the component modules of the calorimeter electronics and their interconnections is shown in Appendix 5. The calorimeter electronics consist of the following modules:

- 1. Wheatstone bridge
- 2. Temperature controller
- 3. Lock-in-amplifier and
- 4. Digital Voltmeter

Temperatures in the calorimeter core, jacket, shield and medium are measured using the Wheatstone bridge. The different sensing thermistors can be switched into the sensing arm of the bridge, and the temperature of each body can be measured in this way. A lock in amplifier (LIA) is used to supply the bridge bias voltage and the residual out of balance voltage is registered on the front panel of a Labview program.

Heat is supplied to different bodies by manually setting voltages through potentiometers on the temperature controller. These voltages are applied to heating elements inside the core, jacket, and shield. The temperature of the medium is controlled automatically at a temperature a few degrees above room temperature. Each heater thermistor in the core and jacket is connected through standard resistors and the power delivered to that body is calculated from the measurement of voltage across the resistor and thermistor.

2.2.1 Wheatstone bridge circuitry

The schematic circuitry of the Wheatstone bridge and the complete bridge circuit can be found in Appendix 5. The Wheatstone bridge has one constant arm and five measuring arms. The medium, shield and jacket each have one arm and two arms are for the core (C1 and C2). The measuring arms are selected through a Mode switch which has positions marked as medium, shield, jacket, C1, C1+C2, C2 and C+J. For better sensitivity C1+C2 can be selected. The supply voltage to the bridge is provided by the lock-in-amplifier normally set to 0.5 V at 11.4 Hz (this setting has been found to give better noise rejection).

2.2.2 Temperature controller and calibrator

A photograph and lay-out diagram of the front panel of the temperature controller and calibrator are shown in Appendix 5.

The temperature controller and calibrator unit supplies the heating voltages for the bodies of the calorimeter, namely core, jacket, shield and the medium. It consists of the switches SW1-SW5 as shown in the front panel lay-out diagram. Switch SW1 can be set in 3 positions; High, Off and Low. In position High, the range of voltages is about three times higher than in position Low. The selection of core, jacket and shield can be made by the three switches SW2-SW4. It is possible to heat either core or jacket or shield alone or heat them all together. Push-button SW10 selects the voltage display on the front panel which shows either the voltage across the core heating thermistor (V_c) or this voltage plus the voltage across a very precise (10 k $\Omega \pm 1 \Omega$) serial resistor (V_{CRI}) and the glow of the LEDs positioned above the switch indicates the corresponding voltages. The 10 $k\Omega$ resistor is used to determine the current through the heating thermistor and it is built into an Amphenol plug and mounted on the rear panel of the instrument. The start signal for heating comes from the timer unit which is part of the temperature controller and the optical indication of the heating in the requested body (or bodies) is provided by the three LEDs marked L4-L6 on the front panel. The heating of the shield is powered by a source voltage of +15 V. The heating power can be preset in the selected range (High or Low) by the ten turn potentiometer R95 on the front panel. The heating of jacket and core thermistors important for electrical calibration and quasi-isothermal calorimetry runs need a highly stable voltage to provide constant heating rates. This voltage is generated from by a temperature-stabilised integrated circuit (LM299A) in the temperature controller unit. The fine tuning of the heating voltage can be set for the jacket and the core by the R97 and R98 potentiometers, as shown in the front panel lay-out diagram (Figure A5.4). The heating voltage of shield is set by R95 and medium heater control is adjusted by a coarse potentiometer P1 and fine potentiometer P2. All potentiometers in the temperature controller are 10-turn potentiometers.

2.2.3 Lock-in-amplifier (LIA)

The LIA used is EG&G Model 124-A. The LIA has an EG&G Model 116 Differential Preamplifier module to which the outputs of the Wheatstone bridge circuit are connected. The overall sensitivity is decided by a 21-position switch (can be seen on the top left of the panel of the LIA shown in the photograph in Appendix 5) with full scale ranges varying in a 1-2-5 sequence. The 50 μ V range has been selected in our measurements since this range gives maximum sensitivity without getting saturation.

Figure 4 shows the settings of the various controls on the front panel of the LIA used. These settings are optimum settings and they are set by turning the corresponding controls of the LIA front panel. The LIA produces +/- 20 V output for the full scale reading of the input. The output is connected to a Keithley 199 DVM and then through a GPIB cable to the PC running a LabVIEWTM program (see Section 2.2.4).

LOCK IN AMPLIFIER	SIGNAL CHANNEL	REFERENCE CHANNEL Normal	Time Constant 1 s 💌
	Sensitivity 50 μ V	Ref Hz 1.14 × 10 🗸	Roll Off 12 dB/oct 💌
PREAMPLIFIER	Signal Hz 🛔 1.12 🛛 🗙 10 💽	Ref Mode 🛛 INT/VCO 🖃	Zero Offset 20.00
Input A-B 💌	Sig Mode 🛛 Band Pass 💽	Level Vrms 🛛 0.5 💌 🔍	10x FSD OFF 💌
Coupling Direct 💌	Q 10% ENBW 💌	Phase degrees 0.12°	Function Normal PSD 💌

Figure 4: Lock-in-amplifier settings

- LIA Ref channel is set to 11.5 Hz, 0.5 V rms and 0.12° phase.
- Signal channel is set to 11.45 Hz , Band Pass 10% ENBW
- PSD- Normal 300 ms 12 dB/Octave
- LIA supplies the bridge supply voltage of 0.5 V

2.2.4 LabVIEW[™] data acquisition program

The front panel of the LabVIEWTM program used in calorimetry measurements can be seen in Appendix 6. The program can be accessed with a Matlab GUI described in data analysis (Section 4). The program was developed using LabVIEWTM version 8.2.

Standard tests done on calorimeter electronics and their results are shown in Appendix 7.

The calorimeter operating procedure is given in Appendix 8.

3. CALORIMETER MEASUREMENTS

3.1 Calorimeter calibrations

3.1.1 DVM calibration

The DVM calibration evaluates the unit variation of the LIA output as measured by the DVM for a fractional change in the core thermistor resistance [$\Delta V/$ (% $\Delta R/R$)]. This relationship is then used to form a DVM calibration factor which is used in the evaluation of results in all subsequent electrical calibrations and measurements of absorbed dose.

The procedure for the evaluation of DVM calibration factor is given in Appendix 9.

Calculations to evaluate the DVM Calibration Factor (C_{DVM}):

The MATLAB analysis program takes the drifts before and after the dial changes are made. The drifts are given linear fits and the coefficients of the fits are used for the extrapolation to mid-point of the change to estimate ΔV (change in the DVM output for the change in the dial setting). The D1 and D2 values (see Appendix 9) are converted to the corresponding core thermistor values as shown below.

R1= ($10,000 \times (D1+50,000) / (D1+60,000)) + 1,000/3 (\Omega)$ R2= ($10,000 \times (D2+50,000) / (D1+60,000)) + 1,000/3 (\Omega)$ $\Delta R/R = 2 (R2 - R1) / (R2 + R1)$

For convenience the ratio $\Delta R/R$ is expressed as a percentage, and a factor of 10,000 applied, so that the DVM calibration factor is defined as:

$$C_{\text{DVM}} = 100 \left(\Delta R/R\right) / \Delta V \times 10^4 (\text{ppm/V})$$
(1)

Notes:

- The DVM calibration factor C_{DVM} is the mean value from three measurements as explained in the procedure (Appendix 9).
- C_{DVM} is the same in ⁶⁰Co or linac measurements as it relates the LIA output to the fractional change in the core thermistor resistance causing the change in the output.

3.1.2 Electrical calibration

The electrical calibration is the evaluation of the heating energy per fractional change of the core thermistor resistance. The calibration is performed in quasi-adiabatic mode in which all the bodies (core, jacket and shield) are raised simultaneously in temperature by the same heating power per mass unit.

The procedure for the evaluation of electrical calibration factor is given in Appendix 10.

Calculations to evaluate the Electrical Calibration Factor (C_{ECF}):

From the entered values of V_{CRI} and V_C the current through the core thermistor is given by

$$I_{C} = (V_{CRI} - V_{C}) / 10,000 \text{ (A)}$$
(2)

This current is multiplied by the voltage drop across the core thermistor to get the power dissipated in the core:

$$P_{e} = I_{C} V_{C} \times 10^{6} \,(\mu W). \tag{3}$$

From the heating profile recorded the voltage change ΔV is calculated by the extrapolation of the initial drift and final drift to the mid-point of the voltage change. This voltage is multiplied by the DVM calibration factor to get the fractional change in the core thermistor resistance, and the total energy deposited in the core is obtained by multiplying the power by the time for the time the heaters are on. The electrical calibration factor C_{ECF} is the ratio of the energy deposited in the core to the percentage change in the resistance of the core thermistor:

$$C_{ECF} = (P_{e} \cdot t_{e}) / (\Delta V \cdot C_{DVM}) \times 10^{3} (mJ/\%), \qquad (4)$$

where P_e is in μ W, t_e is in seconds, Δ V is in V and C_{DVM} is in units of ppm per V. The value of C_{DVM} is around 50 ppm/V and C_{ECF} is around -300 mJ/% for C1 mode and -150 mJ/% for C1+C2 mode.

3.1.3 Calibration of heater dial settings

The heater potentiometers located on the panel of the Temperature controller and calibrator (Figure A5.4 in Appendix 5) need to be calibrated so that proper settings can be made for electrical calibration and quasi-isothermal measurements. For this,

V_{C}	-	voltage across core heating thermistor
V_{CRI}	-	voltage across the core heating thermistor and standard 10 $k\Omega$ resistor.
VJ	-	voltage across jacket heating thermistor
V_{JRI}	-	voltage across the jacket heating thermistor and standard 10 $k\Omega$ resistor
V_{S}	-	voltage across the shield heating thermistor

from the banana sockets at the rear panel of the heater calibrator unit were measured for various dial settings. The results are tabulated as shown in Table A11.1 in Appendix 11. The calibration is done with 'Low' heat (Lower heating rate) selected in switch SW1 (Figure A8.1).

From the results, values of P_c (heating power dissipated in core), P_J (heating power dissipated in jacket), and P_s (heat dissipated in shield) are calculated using:

$P_{C} = ((V_{CRI} - V_{C}) / 10,000) V_{C} \times 10^{6} (\mu W)$	(5)
--	-----

$$P_{J} = ((V_{JRI} - V_{J}) / 10,000) V_{J} \times 10^{6} (\mu W)$$
(6)

$$P_{\rm S} = (V_{\rm S}^2 / 1,200) \times 10^6 \,(\mu {\rm W}), \tag{7}$$

where 10,000 and 1,200 refer to the value of heating resistors in ohms.

From the values of P_c , P_J and P_s the values of VP_c , VP_J and VP_s for the potentiometer settings are calculated.

Linear regression plots of square root of the core heating power versus core heater dial settings, square root of the jacket heating power versus the jacket heater dial settings and square root of shield heating power versus the shield heater dial settings respectively are shown in Appendix 11.

The procedure for calculating the heater settings based on the dose-rate using a Matlab GUI is also shown in Appendix 121.

3.2 Calorimeter modes of measurements

Absorbed dose calorimetry is based on the underlying assumption that all of the energy imparted by ionising radiation ultimately appears as a temperature rise in the absorber. Absorbed dose to the core (graphite) D_c in J/kg is given by

$$D_{core} = c_{m,core} \Delta T_{core}$$
(8)

where:

 $c_{m,core}$ is the specific heat capacity of the core (in J kg⁻¹K⁻¹), and ΔT_{core} is the measured temperature change (in K).

The specific heat capacity of the core can be obtained from published values for the material (graphite). However, this method neglects small deviations from the actual value which may occur due to impurities, or the influence of the non-graphite parts of the core such as the measuring thermistors and spacers. In practice it is more accurate to measure the specific heat capacity using an electrical calibration. However, for the ARPANSA calorimeter this procedure is complicated because the core cannot be removed and isolated from the other bodies. Instead, the response of the calorimeter to a known amount of heat is measured, recognising that that this response includes heat losses which might come about because of temperature differentials inside the calorimeter. By calibrating the calorimeter at the same power levels as are delivered with radiation, we can assume that the heat loss is the same in both cases. This calibration also corrects for any variation in the response of the sensing thermistors over time.

The dose is evaluated by measuring the voltage change in the core output due to radiation, and

$$D_{core} = (\Delta V \ C_{DVM} \ C_{ECF} \ / \ m_{core}) \ \Pi \ k_i$$
(9)

where:

 D_c is the measured absorbed dose to the core

 ΔV $\,$ is the measured voltage change due to radiation heating of the core

 C_{DVM} is the DVM calibration factor (ppm% $\Delta R/R$)/V

 C_{ECF} is the electrical calibration factor mJ/(% $\Delta R/R)$

m_c is the core mass, and

 Π $k_i\,$ is the product of correction factors (see Section 6)

The graphite calorimeter is operated in two modes. They are: 1) Quasi-adiabatic and 2) Quasi-isothermal modes.

3.2.1 Quasi-adiabatic mode

In quasi-adiabatic mode, the temperature rise of the core during an irradiation is measured. A similar temperature rise is later induced by electrical heating. The power delivered during the electrical heating is measured using a standard resistor in series with the core thermistor C1. The magnitude of the temperature rise during irradiation and during the electrical heating is used to equate the rate of absorbed dose with that of the electrical power.

The calorimetry run times were chosen to take into account the sensitivity, saturation in the output of the Lock-in-amplifier and timer errors.

In quasi-adiabatic mode, the condition that Tj = Tc where Tj is temperature of jacket and Tc is temperature of core is established by observing the core drift and reducing it to < 30 mV/min by adjusting the medium heating. The mode switch is positioned at C1 for linac measurements and C1+C2 for ⁶⁰Co measurements. In one optimised full run in linac measurements, the initial drift of the core output is recorded for 60 seconds and the radiation beam is brought on at the end of 60 seconds. At the end of the radiation run the final drift is recorded for another 60 seconds. A typical run taken in the quasi-adiabatic mode is shown in Figure 5.



Figure 5: Quasi-adiabatic run for the 10 MV photon beam

During the optimised calorimetric runs at ⁶⁰Co, the initial drift of the core output is recorded for 150 seconds and at the end of the 150 seconds the radiation beam is brought on for 300 seconds. At the end of the radiation run, the final drift is recorded for 150 seconds.

3.2.2 Quasi-isothermal mode

In contrast to quasi-adiabatic mode, in quasi-isothermal mode the temperatures of all the bodies (core, jacket and shield) are increasing at approximately the same rate throughout both electrical and radiation heating. This mode should minimise heat loss errors, as all the bodies have the same (small) temperature differentials throughout the measurement. In this mode the core, jacket and shield they are heated with continuous electrical power before irradiation. The heating powers in the different bodies are chosen in such a way that it is close to the expected heating power of the following irradiation.

In the quasi-isothermal mode of operation since the temperature of the bodies remains at constant equilibrium during irradiation, the temperature dependence of the specific heat of the core and the sensitivity changes of the thermistor have less influence on the absorbed dose determination [2]. The uncertainties in the calorimeter calibration factors (see Section 3) have a direct influence in the estimation of dose in quasi-adiabatic mode as compared to an indirect and negligible influence in the quasi-isothermal mode and hence this is the preferred mode of operation.

The full run in linac measurements is taken by first turning the heaters on for 60 seconds and at the end of this period, the radiation beam is brought on while the heaters are automatically switched off by an electronic circuit, which is described in Appendix 14. At the end of the radiation run the heaters are switched on again by the same circuit. A typical run taken in the quasi-isothermal mode is shown in Figure 6.



Figure 6: Quasi-isothermal run for the 10 MV photon beam

Dose to the core is given by, $D_c = (P_e \cdot t_R) / m_c \cdot \Pi k_i$

Where, P_e is the electrical power calculated (see Section 3.1.2), t_R is the radiation on time, m_c is the mass of the core and Π k_i is the product of the correction factors needed (see Section 6).

During the calorimetric runs at ⁶⁰Co the electrical heating is performed first for 150 seconds and at the end of the electrical heating the radiation beam is brought on for 300 seconds after which the electrical heating is performed for another 150 seconds.

Adjustment of shield heating rate:

The shield is about 70 mm long and so the rear part will have an attenuated dose-rate compared to the core during irradiation. The shield heating is set so that when the radiation is turned on and electrical heating off, the shield temperature rises at the same rate. This means that the shield is set to a slightly lower power than the jacket and core, as the average heating of the shield is lower due

to attenuation and inverse square law. The MC results to adjust the shield electrical heating rate to match with the radiation heating rate is shown in Appendix 12.

Corrections for radiation-on time:

In linac measurements, the dose-rate ramps up for the first 1-2 seconds before it becomes steady. The dose-rate profiles recorded from the internal monitor chamber output is shown in Figure 7. During data analysis (Section 4), these profiles are used to calculate the dose-rate weighted radiation-on times. This is important in quasi-isothermal analysis in which the electrical heating power is equated to the radiation heating power giving the dose-rate. For the quasi-adiabatic mode, we do not expect the total temperature rise to depend on small variations in dose rate, and so there should be no effect.

The total number of monitor units (MU) from the internal linac monitor chamber is used to deliver approximately the same amount of radiation in each exposure. An external monitor chamber (PTW Model 786 with added 3 mm buildup and positioned in the linac shadow tray) is used to correct for any changes in the internal monitor during the day, and a thimble chamber check was also implemented after 2012 to correct for larger day to day variations. In this case a 2571 chamber is position on the central axis at the start of the day, and removed for measurements.

The output profiles shown in Figure 7 are used to calculate the radiation time t_R corresponding to the same number of monitor units if the beam were to have been delivered at a constant dose rate. This quantity is used in the analysis of the quasi-isothermal measurements.



Figure 7: Outputs of internal monitor chamber in linac head during irradiations at 6 MV, 10 MV and 18 MV

In ⁶⁰Co measurements, the radiation-on time is corrected for timer error of the control unit which is evaluated as per the procedure given in IAEA TRS-398 [12].

The timer error is given by,

Timer error,
$$\tau = (M_B t_A - M_A t_B) / (nM_A - M_B)$$
 (10)

Where, M_A is the integrated reading in time t_A , M_B is the integrated reading in n short exposures of time t_B /n each (2 ≤ n ≤ 5). The timer error evaluated in August 2013 was +0.3 seconds.

Correction for drift during irradiation:

This correction is worked out by making linear fits to the initial heating drift and the final heating drift and extrapolating them to the mid-point of the radiation run. The difference between the two extrapolated values gives ΔV which is multiplied by the DVM calibration factor to get the fractional change in the core thermistor resistance (% $\Delta R/R$). This fractional change is converted to the heating power using the electrical calibration factor and this power (in μ W) is denied to the total heating power and hence is added to the actual heating power calculated using the V_{cri} and V_c values recorded during the electrical heating.

Electronic circuitry for automatic switching-off/on of heaters

The electronic circuitry used for automatic switching-off/on of heaters is shown in Appendix 14. When run in quasi-isothermal mode, it is necessary to electrically heat the calorimeter before and after the radiation heating. The heating is provided by thermistors powered from the calorimeter electronics. To achieve the correct START/STOP timing for the heating, an electrical circuit was constructed, as in Figure A13.1. The circuit uses the 1.5 V signals from the linac's monitor chamber output (labelled AUX 1 on the linac output panel) and amplifies them to 5V. These signals come at a frequency which depends on dose rate from the linac, as Table 1.

Table 1: Pulse-rates for various beam-rates

Energy	Beam rate	Pulse Rate
6 MV	400 MU/min	400 Hz
10 MV	375 MU/min	200 Hz
18 MV	500 MU/min	200 Hz

Calorimetry measurements as a function of dose-rates:

Table 2 gives the results of calorimetric measurements at various dose-rates. The dose-rate dependence was less than 0.1% (the statistical uncertainty). This result supports the conclusion that heat loss differences between radiative and electrical heating do not influence the measurement.

At dose rates above 200 MU/min, timing errors resulted in worse reproducibility of measurements. Hence, 200 MU/min was the dose rate chosen for calorimeter runs used for the calibration of ion chambers.

Table 2: Results of calorimetric measurements at various dose-rates

Nominal Accelerating Voltage / MV	200 MU/min	100 MU/min	% change relative to 200 MU/min	50 MU/min	% change relative to 200 MU/min
6	1220.84	1220.10	-0.06	1221.86	0.08
10	1505.09	1505.85	0.05	1505.44	0.02
18	1752.44	1751.96	-0.03	1754.17	0.10

Note: 200 MU/min is the normal dose-rate used for calorimetry

4. DATA ANALYSIS

Calorimetry data analysis is performed using MATLAB scripts. A special GUI has been developed to make the analysis simple, user-friendly and semi-automatic as shown in Figure 8. The sequence of the measurements with all the relevant details are from top to bottom as shown in the GUI and the steps in the analysis are as follows:

1. Import the data file (by pressing the Analysis button a selection window opens for the directory and the file).

(The following steps are done automatically by the Matlab script once the file selection is done.)

- 2. Separate variables.
- 3. Find start and stop points of irradiation (in Adiabatic analysis).
- 4. Give linear polynomial fits to initial drift data and final drift data.
- 5. Extrapolate to the mid-point of radiation run.
- 6. Calculate dose and dose-rate.
- 7. Write-out the output data and transfer the figures of full run and the fits to the initial drift and final drift to an excel data sheet for follow-up and archival purposes and pressing the Output button in the GUI retrieves the corresponding excel spreadsheet.



Figure 8: MATLAB GUI for the analysis of calorimetry measurements

5. CONVERSION OF GRAPHITE DOSE TO ABSORBED DOSE TO WATER

5.1 Monte Carlo Method

The graphite calorimeter provides a measurement of absorbed dose to graphite which needs to be converted to absorbed dose to water. At ARPANSA, this is done using a Monte Carlo (MC) conversion method, where the calorimeter and the water tank used for ionisation chamber measurements are modelled in the linac beams using EGSnrc [5]. The reference position for the calorimeter is 1042.53 mm from the linac source to the surface of the front build-up plate. Dose is calculated in the calorimeter core. An unscaled geometry of the calorimeter used in MC calculations is shown in Figure 9. The tank reference position is 1000 mm from the linac source to the surface of the front window. The front window is modelled as polycarbonate with a thickness of 2.4 mm (density 1.2 g/cm²) and the physical depth of the chamber was 99.52 mm from the outside window surface (corresponding to a water-equivalent depth of approximately 10 g/cm² including the front window) for all the linac beam qualities. Dose is calculated in a voxel with a radius of 10 mm and depth of 2.75 mm (the same size and shape as the calorimeter core) centred at the reference depth. The geometries used in the simulation are shown side by side in Figure 9.





The MC correction factor is given by the ratio of the calculated doses in the calorimeter and water phantom. The correction factors have been calculated for the three linac beam qualities and are shown in Table 3.

Table 3: MC calculated dose to water conversion factors as used in the 2012 BIPM.RI(I)-K6 comparison with geometry described in Figure 10

Beam Quality	6 MV	10 MV	18 MV
$[D_{g,core}/D_{w,core}]_{MC}$	0.96157	0.94042	0.9252





The absorbed dose to water at the reference depth, D_w , is given by:

$$D_{w} = D_{g,core} \cdot [D_{w,core}/D_{g,core}]_{MC} \cdot k_{rn,core}$$
(11)

where $D_{g,core}$ is the measured dose to the calorimeter core, $[D_{w,core}/D_{g,core}]_{MC}$ is the MC ratio of the absorbed dose to water $D_{w,core,MC}$ at the reference depth (calculated over a volume identical to that of the calorimeter core) to the absorbed dose to the graphite calorimeter core, $D_{g,core,MC}$, and $k_{rn,core}$ is the correction for radial non-uniformity of the beam to the central axis dose. The non-uniformity correction is calculated by integrating measured beam profiles over the 2 cm core diameter.

5.2 Cavity Ionisation Theory (CIT) Method

The methodology of conversion from graphite dose to water absorbed dose by CIT method is shown in Figure 11.





The dose to water is related to dose to graphite by,

$$D_W / D_G = (S_{W,air} \cdot p_{u,W} \cdot Q_W) / (S_{G,air} \cdot p_{u,G} \cdot Q_G)$$
 (12)

where: D_W is dose to water at the reference depth in water,

 D_G is dose to graphite at the reference depth in graphite,

 $S_{W,\text{air}}$ is the restricted stopping power ratio of water to air,

 $S_{G,\text{air\,}}$ is the restricted stopping power ratio of graphite to air,

- $p_{u,W}$ is the perturbation correction for the ion chamber in water, evaluated at the water reference depth,
- $p_{u,G}\,$ is the perturbation correction for the ion chamber in graphite, evaluated at the graphite reference depth,
- $Q_{W} \,$ is the charge measured with ion chamber in water, and
- \mathbf{Q}_{G} is the charge measured with ion chamber in graphite.

 D_{G} measured with graphite calorimeter is given by

$$D_{G} = D_{core} k_{gap} k_{rn,core}$$
(13)

where, D_{core} is the dose measured by the calorimeter, k_{gap} is the correction for vacuum gaps in the calorimeter and $k_{rn,core}$ is the radial non-uniformity correction for the core radius. The gap correction

is determined by MC modelling with the vacuum and air gaps and Mylar foils removed from the calorimeter model. The calorimeter is positioned at an SSD of 104.253 cm from the source and contains 0.432 cm of gaps including Mylar foils. The gap correction is modelled as solid graphite with an SSD of 104.685 cm and the core in the same position as the original model. The factor k_{gap} is given as the ratio of the dose to the core in the absence of gaps to the dose to the core with gaps included.

An ion chamber is calibrated in a graphite phantom with the centre of the chamber at the reference point, C', and the graphite depth approximately equal to the calorimeter core depth. A 4 cm thick graphite plate is attached to the front of the graphite phantom with an actual graphite depth of 5.522 cm. The calibration factor of the chamber in graphite is:

$$N_{D,g} = D_G k_s k_{geom} k_{rn,chamber}$$
(14)

where k_s is the recombination correction, k_{geom} accounts for a small difference in the depths of the core and chamber and $k_{rn,chamber}$ is the radial non-uniformity correction for the chamber length.

For the purposes of comparison with a measured chamber $N_{D,w}$ using the MC method, the equation 12 can be written as:

$$D_W / Q_W = (D_G / Q_G) (S_{W,air} \cdot p_{u,W}) / (S_{G,air} \cdot p_{u,G}),$$

and therefore:

$$N_{D,w} = N_{D,g} (S_{W,air} \cdot p_{u,W}) / (S_{G,air} \cdot p_{u,G}).$$
(15)

The perturbation correction, p_u , is given by $p_u = p_{wall} p_{dis} p_{cel}$ where p_{wall} is the correction due to the disparity between the ion chamber wall material and the phantom material, p_{dis} is the correction due to displacement of the phantom material by the presence of the chamber and p_{cel} is the correction due to the non-air equivalence of the central electrode of the chamber. The value of p_{cel} is the same in both phantom materials and so they cancel in the ratio. The value of $p_{wall,G}$ is unity since the phantom and wall materials are the same for a graphite-wall chamber. Hence the ratio of perturbation corrections, $p_{u,W}/p_{u,G}$, is reduced to $(p_{wall,W} p_{dis,W})/p_{dis,G}$.

Keith Wise calculated values of restricted stopping power ratios and perturbation corrections at the relevant reference depths in graphite and water for an NE2611A ion chamber [13]. The ratios of restricted stopping power ratios and perturbation corrections were combined as the ratio of calculated calibration factors such that

$$[N_{D,w} / N_{D,g}]_{Wise} = (S_{W,air} \cdot p_{u,W}) / (S_{G,air} \cdot p_{u,G})$$
(16)

A cubic spline to the values of $[N_{D,w} / N_{D,g}]_{Wise}$ was used to evaluate the correction at the 6 MV, 10 MV and 18 MV TPR_{20,10} values. In order to assess the CIT dose conversion method against the direct MC method the $N_{D,w}$ values for each method were compared. Table 4 provides a summary of the corrections used to achieve the calibration factor.

Table 5 gives the ratios of water calibration factors $(N_{D,w})$ derived by the two methods for two NE2571 chambers and Table 6 shows the $N_{D,w}$ values and ratios for an NE2611A chamber and the average ratio of $N_{D,w}$'s for all chambers. It is assumed that the NE2571 chamber is similar enough to the NE2611A chamber that perturbation corrections $p_{u,w}$ and $p_{u,G}$ calculated by Wise can be used.

Table 4: Corrections used to calibrate an NE2611A chamber in a graphite phantom

Beam	Calorimeter	corrections	Cha	[N _{D.w} / N _{D.g}] _{Wise}		
quality	k_{gap}	k _{rn_core}	k _s	k _{geom}	k _{rn_chamber}	- /
6MV	1.0087	1.0000	1.0044	1.0036	0.9992	1.142
10MV	1.0055	0.9948	1.0068	1.0032	0.9953	1.145
18MV	1.0041	1.0006	1.0081	1.0029	1.0009	1.145

Table 5: Absorbed dose to water calibration for NE 2571 chamber derived by MC and CIT methods

Room	N	E2571, sn 238	34	NE2571, sn 1785			NE2571	
quality	(N _{D,w}) _{MC}	(N _{D,w}) _{CIT}	(N _{D,w}) _{CIT} / (N _{D,w}) _{MC}	(N _{D,w}) _{MC}	(N _{D,w}) _{CIT}	(N _{D,w}) _{сіт} / (N _{D,w}) _{МС}	average	
6MV	44.66	44.67	1.000	45.17	45.25	1.002	1.001	
10MV	44.14	44.20	1.001	44.69	44.78	1.002	1.002	
18MV	43.61	43.65	1.001	44.19	44.19	1.000	1.001	

Table 6: Absorbed dose to water calibration for NE 2611A chamber derived byMC and CIT methods

		Average of 2571			
Beam quality	(N _{D,w}) _{MC}	(N _{D,w}) _{CIT}	(N _{D,w}) _{CIT} / (N _{D,w}) _{MC}	and 2611A chambers	
6MV	103.09	103.68	1.006	1.003	
10MV	101.41	101.90	1.005	1.003	
18MV	100.19	100.79	1.006	1.002	

The MC and CIT methods agree to better than 0.6% for NE2611A chambers and better than 0.2% for NE2571 chambers. The combined relative standard uncertainty in the ratio of $N_{D,w}$ values obtained by CIT and MC methods is 0.62% at 6 MV and 0.65% at the 10 MV and 18 MV beam qualities. There is a trend in the chamber results with the NE2611A $(N_{D,w})_{CIT}$ values tending to be higher when compared to $(N_{D,w})_{MC}$ than the NE2571 chambers. This difference is possibly due to the use of NE2611A perturbation corrections for the NE2571 chamber.

6. CORRECTION FACTORS AND UNCERTAINTY ESTIMATES

6.1 Calorimeter corrections

The calorimeter corrections (used in conversion from graphite absorbed dose to water absorbed dose by Cavity Ionization Theory) are:

$$\Pi k_{i} = k_{t} \cdot k_{m} \cdot k_{d} \cdot k_{z} \cdot k_{rn,core} \cdot k_{an} \cdot k_{gap}$$
(17)

- k_t radioactive source decay
- k_d distance using the inverse square law
- k_z graphite depth using empirical attenuation data
- k_{rn,core} radial non-uniformity to give the central-axis dose
- k_{an} axial non-linearity in the depth dose through the core
- k_{gap} vacuum gaps

Note:

 k_t applies in ⁶⁰Co measurements only.

 k_t – The calorimeter measurements were corrected to the reference date and time of 2010-06-07 at 12:00 Australian Eastern Daylight time. The half-life of ⁶⁰Co was taken as 1925.21 d, σ =0.3d [14].

 k_d – All measurements are corrected to a reference distance of 1050 mm for ⁶⁰Co and 1100 mm for linac measurements. The correction for any deviation is applied in MC modelling reported in the earlier section.

 k_z – The desired reference depth is not achieved exactly with the available combination of graphite build-up plates. Thus, a correction is needed and this correction also is applied in MC modelling reported.

 $k_{rn,core}$ – Correction factor for the radial non-uniformity of the ⁶⁰Co beam and linac photon beams over the calorimeter core. This correction factor was evaluated for the ⁶⁰Co source and found to be close to unity. For linac beams the beam profiles were measured using a scanning ion chamber (Figure 12) and the scans used to arrive at the correction factors shown in Table 7 by averaging over the core dimensions.

Nominal Accelerating voltage/ MV	k _{rn, core}
6	1.0000
10	0.9948
18	1.0006

 Table 7: Radial beam non-uniformity corrections for calorimeter

 k_{an} - Correction factor for the axial non-uniformity of the ⁶⁰Co beam and linac photon beams over the calorimeter core. The correction factor used is 1.000 as there is axial symmetry.

 k_{gap} – The difference between the absorbed dose-rate at the centre of the calorimeter core and that at the same position in a solid graphite phantom. This correction is included in the MC simulation of the calorimeter reported in the earlier section.



Figure 12: Linac photon beam profiles used in the calculations of k_{rn,core.} "inline" refers to the GT (Gun-Target) direction and "xline" refers to the orthogonal direction.

6.1.1 Buoyancy correction to the core mass:

When the calorimeter core is weighed, the standard weights and the specimen both displace air, and therefore both experience a buoyancy force. When the sample density differs significantly from that of the standard weights, these buoyancy forces differ.

The buoyancy correction is given by,

$$m_{p} = m_{n} \left[1 - (\rho_{L} / \rho_{n})\right] / \left[1 - (\rho_{L} / \rho_{p})\right]$$
(18)

where the subscripts L= air, p=sample, and n= standard weights

For a typical air density of 1.2 kg/m³, a graphite sample density of 1800 kg/m³, and a standard brass weights density of 8000 kg/m³, this gives $m_p/m_n = 1.00051$.

The buoyancy corrected core mass of ARPANSA calorimeter = 1.5622 g.

The buoyancy corrected core mass of IAEA calorimeter (see Section 7) = 1.46852 g.

6.1.2 Correction for non-graphite materials:

The effective core mass is the buoyancy corrected graphite mass, corrected for the presence of nongraphite materials (epoxy, polystyrene, thermistors, lead wires) which absorb energy from the radiation beam at a different rate from graphite, and contribute to the heating of the core. This correction can be evaluated using the mass energy absorption coefficient and stopping power ratios to calculate the "effective graphite mass" of the non-graphite materials. However, for small total impurity mass, as in the present case, the simple total mass of the core including impurities is very close (0.02%) to the weighted total mass, so the exact weighting scheme chosen is not particularly important. The scheme of correction for non-graphite materials based on their specific heat capacities is chosen and used. The core composition is shown in Appendix 4.

6.2 Uncertainty Estimates

Uncertainties in the quasi-adiabatic measurements are inherently higher since the estimation of the graphite absorbed dose is more sensitive to the calorimeter calibration factors C_{DVM} (see Section 3.1.1) and C_{ECF} (see Section 3.1.2) than in the quasi-isothermal mode and hence the uncertainties in the quasi-isothermal measurements are presented here. The equation describing the quasi-isothermal measurements is:

$$D_{g} = (P_{e} \cdot t_{R} / m_{c}) \cdot \Pi k_{i}$$
 (19)

Where, D_g = absorbed dose to graphite

$$P_e = ((V_{cri} - V_c)/R_i) V_c - \Delta P$$

- t_R = Radiation heating-on time
- m_c = Buoyancy corrected core mass

$$\Pi \mathbf{k}_{i} = \mathbf{k}_{gap} \cdot \mathbf{k}_{rn}$$

 $V_c = V_c$ (measured) - V_L

 $V_L = [(V_{cri} - V_c \text{ (measured))}/R_i] . R_L$

R_i = Current sense resistor (nominally 10,000 ohms)

 R_L = Resistance of leads (17 ohms)

 ΔP = Net voltage of the final minus the initial heating rate slopes * C_{DVM} * C_{ECF}

 C_{DVM} = DVM calibration factor

 C_{ECF} = Electrical calibration factor

Table 8 gives the uncertainty budget.

Table 8: Uncertainties in the absorbed dose to graphite due to measurement factors of Linac photon energies

Percentage relative standard uncertainties of type-	Туре А: υ	Туре В
V _c – core heater voltage		0.05
V _{cri} – core heater + series R voltage		0.05
R _i – current sense resistance		0.0001
R _L – Leads Resistance		0.03
t_R – Radiation heating on time		0.1
ΔP – power correction	0.01:38	
C_{DVM} – DVM calibration factor	0.02:38	
C_{ECF} – Electrical calibration factor	0.03:38	
Combined % relative standard uncertainty in D_g		0.13

Table 9 gives the correction factors and the uncertainties in determining the absorbed dose to water at 5 gm/cm^2 depth in water irradiated with ⁶⁰Co beam.

Source of uncertainty	Value	Relative standard uncertainty			
		100 si	100 uj		
Determination of core (D _{core})ARPANSA					
P electrical power		0.08			
m_c mass of the core / g	1.5622		0.01		
Repeatability		0.07			
k _m radial non-uniformity	1.0000		0.05		
Conversion to absorbed dose rate to water by calculation [D _w /D _{core}] _{MC} conversion from graphite to water	0.9308	0.21	0.32		
Uncertainty in (Dw) ARPANSA					
Quadratic summation		0.24	0.32		
Combined relative standard uncertainty		0.40			

Table 9: Uncertainties in the determination of absorbed dose to water based oncalorimetry measurements at ⁶⁰Co energies [6]

Table 10: Uncertainties in the $N_{D,W,QARP}$ of a clinical ion chamber calibrated in a megavoltage beam based on calorimetry measurements

Source of uncertainty	6 MV	10 MV	18 MV
Determination of transfer standard $N_{D, w, \mathcal{Q}_{ARP}}$			
Measured dose to the calorimeter core (D_g)	0.13	0.13	0.13
Radial non-uniformity corrections for core and chamber	0.03	0.14	0.03
Monte Carlo conversion ($[D_g/D_w]_{MC}$)	0.33	0.37	0.40
Positioning and depth of chamber	0.17	0.17	0.17
Chamber drift	0.03	0.03	0.03
Other corrections (k_{TP} , k_s , k_{pol} , k_{elec})	0.08	0.08	0.08
Standard uncertainty of the mean of $N_{\scriptscriptstyle D,w,\mathcal{Q}_{\scriptscriptstyle A\!R\!P}}$	0.05	0.05	0.05
Combined uncertainty in determination of transfer standard $N_{\rm D,w,Q_{\rm ARP}}$	0.40	0.46	0.46
Determination of clinical chamber $N_{D,w,\mathcal{Q}_{ARP}}$			
Chamber positioning	0.11	0.09	0.08
Current measurement	0.07	0.07	0.07
Other corrections (k_{TP} , k_s , k_{pol})	0.05	0.05	0.05
Repeatability	0.10	0.10	0.10
Combined uncertainty in determination of clinical chamber $N_{\rm D,w,Q_{\rm ARP}}$	0.17	0.16	0.15
Combined relative standard uncertainty (k=1)	0.44	0.49	0.49

7. COMPARISON WITH THE IAEA GRAPHITE CALORIMETER

In March 2000, while setting the heater setting in the ARPANSA calorimeter, the jacket was found to be drifting down at a fast rate of ~350 nV/min. This required replacement of the jacket thermistors in the ARPANSA calorimeter. In 2002, IAEA loaned their K-4 calorimeter which is also based on the Domen design. In 2006, the IAEA calorimeter along with ARPANSA calorimeter was repaired (a cold solder joint) and comparative measurements were made in the ⁶⁰Co beam. The agreement between the two calorimeters was within 0.2%. Table 11 gives the results of the comparison.

	Quasi-isothermal mode										
	E	ectrical C.	F	Dose to	Graphite	rate*	Deviation [#]				
	mJ/%	%sd	%Esdm	mGy/s	%sd	%Esdm	%	mGy/s			
ARPANSA	145.4	0.6	0.2	3.1563	0.5	0.1	0.12	3.1538			
IAEA	115.4	0.3	0.1	3.1517	0.4	0.1	-0.09	3.1478			

Table 11: Results of the 2006 comparison

* Dose-rates are normalised by applying the decay correction to the starting date 1/9/2006

% deviations are from the measured dose rate to the decay corrected dose rate relative to 15/3/1997

A similar comparison was done at linac photon energies in which the dose to graphite measured by both the calorimeters was compared in 2012. Table 12 gives the results.

Beam quality	TPR _{20/10}	D _g IAEA / D _g ARPANSA	D _w IAEA / D _w ARPANSA
⁶⁰ Co	0.576	1.0020	1.0022
6X	0.673	1.0033	1.0000
10X	0.734	1.0035	1.0018
18X	0.777	1.0028	0.9993

Table 12: Results of the comparison for linac MV photons and ⁶⁰Co

Note: The D_w values for IAEA calorimeter in the last column of Table 12 have been arrived at using Monte Carlo conversion factors of 0.9986 for 6 MV, 0.9976 for 10 MV and 1.0005 for 18 MV and the D_w values for the ARPANSA calorimeter have been arrived at using Monte Carlo conversion factors given in Table 3 of Section 5.

8. INTERNATIONAL INTERCOMPARISONS

8.1 Comparison with BIPM 1997

The Australian absorbed dose standard was compared with the BIPM reference standard at ⁶⁰Co in 1997 [3]. The Australian standard was the ARPANSA calorimeter and the subsequent conversion from absorbed dose to graphite to absorbed dose to water was done using the photon fluence scaling theorem (also called 'dose ratio method'). The methodology adopted and the results obtained are as follows.

In the "dose ratio" method, the photon fluence scaling is used to determine Ψ_c^w for a point source of radiation by scaling down the phantom dimensions, measurement depths and distances from the source in the inverse ratio (0.61958) of the electron densities of water and graphite (using the tabulated value of water density at 20° C, 0.99822 g.cm⁻³, the measured graphite bulk density; 1.79 g.cm⁻³ and the Z/A ratios). The dose to water D_w is calculated from

$$D_{w,ARPANSA} = D_c \cdot \Psi_c^w \cdot (\mu_{en}/\rho)_c^w \cdot \beta_c^w \cdot k_{win} \cdot k_{air}$$
(20)

Where:

D_c = Dose to graphite

 Ψ_{c}^{w} = Ratio of primary photon fluences in water and graphite

 $(\mu_{en}/\rho)_c^w$ = Ratio of mass-energy absorption coefficients of water and graphite

 β^w_c = quotients of absorbed dose to collision component of kerma

 $k_{win}\,$ = $\,$ correction for the difference in attenuation of the front window of water phantom and water

 k_{air} = Correction for air attenuation over the distance between the graphite calorimeter and the water phantom

Transfer chamber	Ď _{w,ARPANSA} / (mGy s ⁻¹)	I _{arpansa /} pA	_{RPANSA /} N _{D,W,ARPANSA} / Ď _{w,BIPM} / pA (Gy µC ⁻¹) (mGy s ⁻¹)		I _{ВIРМ} / pA	Ν _{D,W, BIPM} / (Gy μC ⁻¹)	R _{DW}		
NE2561/070	4.679	45.751	102.27	4.617	45.260	102.01	1.0025		
NE2561/ 328	4.679	45.397	103.07	4.617	44.896	102.84	1.0022		
Mean values									

Table 13: The calibration factors and the results of the comparison

Note: Combined uncertainty in the comparison, $u_c = 0.0029$, [3]

8.2 BIPM.RI(I)-K4 comparison (2009)

An indirect comparison of the standards for absorbed dose to water of the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), Australia and of the Bureau International des Poids et Mesures (BIPM) has been carried out in ⁶⁰Co radiation at the BIPM in June 2010. This absorbed dose to water comparison replaced the indirect comparison made between the two laboratories in 1997 [15].

The absorbed dose to water is determined at ARPANSA using a graphite calorimeter with a calculated dose conversion factor from graphite to water using Monte Carlo methods. The BIPM primary standard is a parallel-plate graphite cavity ionisation chamber [16]. The comparison was undertaken using two ionisation chambers belonging to ARPANSA as transfer standards. The result of the comparison is given in terms of the mean ratio of the calibration coefficients of the transfer chambers determined at the two laboratories under the same reference conditions.

Transfer Chamber	N _{D,w,ARPANSA} / Gy μC ⁻¹ pre-BIPM *	<i>N_{D,w,BIPM}</i> / Gy μC ⁻¹	N _{D,w,ARPANSA} / Gy μC ⁻¹ post-BIPM *	N _{D,w,ARPANSA} / Gy μC ⁻¹ overall mean	R _{D,W}	и_{к,NMI}
NE 2561-328	103.061	103.282	102.971	103.016	0.9974	0.0053
NE 2571-3075	45.174	45.274	45.134	45.154	0.9973	0.0053
				Mean values	0.9973	0.0053

Table 14: The calibration factors and the results of the comparison

8.3 BIPM.RI(I)-K6 comparison (2013)

In order to establish dosimetry equivalence in absorbed dose to water based on calorimetry, BIPM in 2008, initiated a Key comparison; BIPM.RI(I)-K6, using their graphite calorimeter. As of 2013, the BIPM has completed comparisons with NRC (Canada), NIST (U.S.A), PTB (Germany), LNHB (France) and ARPANSA. Figure 13 shows the current status of the K6 comparison.



Figure 13: Current Status of BIPM.RI(I)-K-6 comparison (courtesy:BIPM)

In September 2012, BIPM visited ARPANSA bringing their calorimeter system and undertook a direct comparison with the ARPANSA standard. Figure 14 shows the methodology of the comparison.

The details of the BIPM graphite calorimeter have been published in the literature [17].

Prior to the BIPM visit in September 2012, a series of calibration were made on the two ARPANSA reference chambers (NE 2571 serial number 1785 and serial number 2384) using the ARPANSA calorimeter. Measurements were made over 6 months in order to establish the stability of the calibration process and to evaluate Type A uncertainties. Table 15, Table 16 and Table 17 give the calorimetry results and the results of the reference chamber measurements.



Figure 14: Methodology of comparison (courtesy: BIPM)

In the figure, $D_{C,BIPM}$ = Measured dose to the core of the BIPM calorimeter

 $C_{W,C}$ = BIPM Conversion factor of graphite dose to water absorbed dose $N_{D,W,MC}$ = Monte Carlo calculated absorbed dose calibration factor for water by BIPM $N_{D,C,MC}$ = Monte Carlo calculated absorbed dose calibration coefficient for graphite by BIPM $Q_{W,BIPM}$ = Charge measured with ARPANSA chamber in BIPM water phantom $D_{W,BIPM}$ = Dose to water measured by BIPM methodology $D_{C,ARPANSA}$ = Measured dose to the core of ARPANSA calorimeter $[D_W/D_C]^{MC}$ = ARPANSA Monte Carlo calculated graphite to water dose conversion factor $Q_{W,ARPANSA}$ = Charge measured with ARPANSA chamber in ARPANSA water phantom $D_{W,ARPANSA}$ = Dose to water measured by ARPANSA methodology

Comparison Ratio, $R_{ARPANSA} = D_{W,ARPANSA} / D_{W,BIPM}$

The comparison ratios for the three energies namely 6 MV, 10 MV and 18 MV are shown in Table 15.

Nominal operating voltage	6	MV	10	MV	18 MV		
	А	В	А	В	Α	В	
Mean D _g (mGy)	3085.3	3088.8	3053.2	3053.2 3057.9		3761.3	
MU	400	400	400	400	500	500	
% ESDM	0.08	0.11	0.11	0.08	0.09	0.09	

Table 15: Results of calorimetry measurements

Note: A Measurements made during April to September, 2012 before BIPM visit

B Measurements made on 24/10/2012 after BIPM visit

All measurements were made with 200 MU/min

Figure 15 and Figure 16 show the results of ARPANSA reference chamber measurements made before the BIPM visit during April to September 2012 and after the BIPM visit on 24-10-2012.

Table 16: Reference chamber measurements (NE 2571, serial number 2384)

Nominal operating voltage	6	MV	10	MV	18 MV		
	А	В	А	В	А	В	
N _{D,W} (mGy/nC)	44.74	44.69	44.18	44.18	43.63	43.64	
MU	400	400	400	400	500	500	
% ESDM	0.08	0.1	0.11	0.1	0.09	0.1	

Note: A Measurements made during August to September 2012 before BIPM visit B Measurements made on 24/10/2012 after BIPM visit All measurements were made with 200 MU/min

(NE 2571, Serial humber 1785)											
Nominal operating voltage	6	MV	10	MV	18 MV						
	А	В	А	В	А	В					
N _{D,W} (mGy/nC)	45.36	45.31	44.80	44.80	44.25	44.25					
MU	400	400	400	400	500	500					
% ESDM	0.06	0.1	0.04	0.1	0.04	0.1					

Table 17: Reference chamber measurements (NE 2571, serial number 1785)

Note: A Measurements made during August to September, 2012 before BIPM visit B Measurements made on 24/10/2012 after BIPM visit

All measurements were made with 200 MU/min



Figure 15: ARPANSA reference chamber measurements before and after BIPM visit



Figure 16: ARPANSA reference chamber measurements before and after BIPM visit Table 18 shows the preliminary results of the K6 comparison.

ARPANSA Beam	TPR _{20,10}	D _{w, ARPANSA} /D _{w,BIPM}	Combined standard u _c (%)
6 MV	0.673	0.996	0.6
10 MV	0.734	0.992	0.6
18 MV	0.777	0.993	0.6

Table 18: Preliminary results of the K6 comparison

Figure 17 shows the results of International comparison linac dose BIPM.RI(I)-K6





9. SUMMARY AND CONCLUSIONS

The ARPANSA graphite calorimeter has been established as the primary standard for absorbed dose as required by the National Measurement Act 1960. It has been established with the newly installed ⁶⁰Co source and the Elekta Linac photon beams of nominal energies 6 MV, 10 MV and 18 MV. The calorimetry measurements at ⁶⁰Co have been validated by intercomparison with BIPM through the use of transfer chamber measurements. The linac measurements have been validated by the BIPM.RI(I)-K6 comparison.

The Monte Carlo method of conversion of the graphite absorbed dose measured by the calorimeter to the water absorbed dose has been validated by depth dose measurements in graphite and water. Two ARPANSA NE 2571 Farmer chambers have been regularly calibrated against the calorimeter. The chambers were calibrated in water using reference conditions of 100 cm source-surface distance and 10 cm depth, with a 10 x 10 cm field size, as recommended in the IAEA TRS-398 code of practice. The absorbed dose to water calibration factors of the chambers over a period of more than a year have remained stable within 0.1%. These chambers will be used as the basis for a calibration service by ARPANSA in which ionisation chambers will be calibrated directly using megavoltage linac beams.

Appendix 1 Details of calorimeter failure and repair

In March 2000, it was observed that the jacket heating thermistor had a bad connection inside the calorimeter or had 'gone high'. It was also observed that the jacket heating thermistor was not stable. So, it was concluded that there may be a dry/high resistance joint on the inside of the vacuum feed-through. Remediation measures attempted were i) to raise the jacket heater voltage to get the same heating power as earlier, ii) to use jacket measuring thermistor as heater without measuring the jacket temperature and relying upon the earlier power setting. These measures were not satisfactory due to the instability of the jacket thermistors.

Subsequently in 2006, the calorimeter was opened, the shield assembly containing the core and the jacket was removed after removing the shield cap. New ultra-small VECO thermistors were fixed to the wall of the jacket after drilling a small wedge and the thermistors were glued with epoxy glue. The thermistor lead wires were insulated with a coating of nail polish and the calorimeter reassembled. In the calorimeter electronics, the jacket bridge circuitry was adjusted to the new value of the thermistor resistance.



Figure A1.1: Inside the calorimeter

Appendix 2 The schematic diagram and photo of the calorimeter corejacket-shield assembly





Figure A2.1: Schematic diagram of the core-jacket-shield assembly



Figure A2.2: Photo of the core-jacket-shield assembly (Domen calorimeter)

Appendix 3 Engineering Drawings of the calorimeter

These drawings are from the original Domen calorimeter. The ARPANSA calorimeter has been fabricated based on this design.









Appendix 4 Build-up plate thicknesses, core materials and thicknesses

Figure A4.1: Schematic diagrams of build-up plates with and without grooves

- **Note:** t3 used for grooved plates (where t3 is slightly less than t1 and t2 because extra room has been allowed for Mylar foil)
- **Note:** When stacking plates, we usually use t2 for the thickness (as this is generally the largest number)

Table A4.1: Dimensions, masses and densities of build-up plates as measured at ARPANSA

Block	D1	D2	D3	R1	R3	t1	t2	t3	t4	t0	V1	V2	V3	v	Mass	Density
l15	15.2	30.00	13.35	7.60	6.67	1.56	1.55	1.49	0.49		816.1	208.7	20.4	1045.3	1869.9	1.79
120		30.01				2.00	2.00			1.99				1412.6	2504.4	1.77
140		30.00				3.99	4.00			3.99				2821.8	4989.7	1.77
C15	15.2	29.98	13.40	7.60	6.70	1.58	1.59	1.53	0.53		831.7	215.9	21.5	1069.1	1907.4	1.78
P15	15.2	29.98	13.40	7.60	6.70	1.54	1.55	1.49	0.49		809.3	209.6	19.6	1038.4	1859.1	1.79
C10		29.99				0.99	1.00			0.97				697.3	1246.6	1.79
C20		30.00				1.99	2.00			1.98				1408.7	2520.3	1.79
C40		30.00				4.01	4.01			4.00				2831.0	5071.2	1.79
P10		29.99				0.99	1.00			0.98				699.5	1250.4	1.79
P20		30.00				2.00	2.00			1.98				1410.1	2523.8	1.79
P40		30.00				4.00	4.01			4.00				2829.0	5078.8	1.80
C15 (2)	15.2	29.99	13.40	7.60	6.70	1.58	1.59	1.53	0.53		830.9	215.1	21.3	1067.3	1907.4	1.79
P80						8.00	8.00			8.00						

Core composition materials and thicknesses:

ARPANSA data taken from Operator's Manual supplied by ARCS/OMH, December 1990.

IAEA-K4 data supplied by J Witzani 16 April 2002

Table A4.2: Materials and their thickness from the front Mylar-window to the core centre

Dout	Matarial	Thickness, mm		
Part	wateria	IAEA - K4	ARPANSA	
Front Window	Mylar®	0.13	0.138	
Medium	Graphite	2.0	2.0	
Gap	Vacuum	0.5	0.65	
Shield	Graphite	1.0	0.744	
Gap	Vacuum	0.5	0.65	
Jacket	Graphite	0.75	0.546	
Gap	Vacuum	0.5	0.55	
Core	Graphite	1.37	1.375	
Foils and layers on medium, shield and jacket	Mylar [®] and Epoxy resin	0.1	not stated	
Sum	-	6.85	6.65	

Table A4.3: Core mass (thermally attributable)

Matarial	Mass, mm		
Widterid	IAEA - K4	ARPANSA	
Graphite	1462.8	1557.69	
Mylar, Epoxy, Thermistors	3.4		
Mylar, Epoxy		1.43	
Polystyrene rods (for core suspension)	0.75	1.39 / 2 = 0.69	
Copper wires	0.72		
Thermistors, Copper wires		1.24	
Resistance wire		0.12	
Sum	1467.7	1561.17	
Buoyancy corrected		1562.20	



Figure A4.2: Schematic diagrams of build-up plates on ARPANSA calorimeter for MV photon measurements

Material	Symbol	Details	On-axis thickness (cm)
Plate 1	t ₁	C15 (reversed)	1.531
Air gap	a_1		0.05
Plate 2	t ₂	C20	1.9815
Air gap	a ₂		0.068
Plate 3	t3	P15	1.486
Air gap	a ₃		0.11
Mylar	m		0.0138
Graphite	М	Medium	0.2
Vacuum	V ₁		0.065
Graphite	S	Shield	0.0744
Vacuum	V ₂		0.065
Graphite	j ₁	Jacket	0.0546
Vacuum	V ₃		0.055
Graphite	С	Half-core width	0.1375

Table A4.4: On-axis distances (ARPANSA calorimeter)

Physical distance from front of calorimeter to centre of core	5.8968	cm
Total thickness of air between front and core	0.228	cm
Total thickness of vaccuum between front and core	0.185	cm
Total air + vacuum gaps	0.413	cm
Total thickness of air between front and core	0.228	cm
Total thickness of vaccuum between front and core	0.185	cm
Total thickness of Mylar and foils	0.0188	cm
Total air + vacuum	0.413	cm
Total graphite + mylar	5.4838	cm
Total graphite after gap correction (Mylar,air,vac=gap)	5.465	cm
Reference distance	110.000	cm
Calculated SSD for 110 cm SDD	104.103	cm
SSD actually used	104.253	cm
Actual SDD	110.150	cm

Table A4.5: Depth calculation (ARPANSA calorimeter)

Appendix 5 Diagrams of calorimeter electronics



Figure A5.1: Block diagram of calorimeter electronics



Figure A5.2: Schematic circuitry of the Wheatstone bridge



Figure A5.3: Full circuitry of the Wheatstone bridge



Figure A5.4: Photograph of the Temperature controller and calibrator



Figure A5.5: Front panel of the temperature controller



Figure A5.6: Photograph of the Lock-in-amplifier

Appendix 6 Front panel of the LabVIEW[™] program



Appendix 7 Standard tests on the calorimeter electronics

Test of the calorimeter timer

The ARPANSA Calorimeter timer was tested with Agilent 53132A counters (two in parallel). The start of the calorimeter timer starts the heaters and the heater voltage, which is available from banana sockets in the back panel of the calorimeter, was used to trigger the counters on and off. The counters were operated in the time interval mode T1:T2 with common: "On" and Auto trigger: "Off". The following settings were used in the counters.

Time interval mode T1:T2 Common: ON Auto trigger: OFF Trigger level: 0.1 V Sensitivity: LO

The results are shown in Table A7.1 below. It can be seen that the largest deviation from the set time is 0.007%.

Calorimeter time set (seconds)	Measured with Agilent counter (IRS No.98 [*]) (seconds)	% error	Measured with Agilent counter (IRS No.99 [*]) (seconds)	% error
20	19.9987	0.007	19.9987	0.007
50	49.9964	0.007	49.9969	0.006
100	99.9943	0.006	99.9941	0.006
200	199.9888	0.006	199.9883	0.006
500	499.9717	0.006	499.972	0.006
600	599.9665	0.006	599.9674	0.005
999.9	999.9	0	999.8455	0.005

Table A7.1: Results of the calorimeter timer test

Note: * Refers to ARPANSA internal equipment numbering system

Measurement of 10 kohm standard resistor

In the calorimeter reference resistor measurements, the standard Guildline 10 kohm resistor was first checked with an HP 3458A (s/n 2823A24732) multimeter in 4-wire resistance mode and then replaced with the calorimeter reference resistor. The Guildline resistor had a calibrated value of 10000.154 ohm (calibrated 7 November 2002, reference CSIRO NML RN45295) with an uncertainty of 0.4 ppm at k=1.96. The measured value using the 4-wire technique was 10000.158 ohms with a standard deviation of 0.013 ohms.

Then the Guildline resistor was replaced by the calorimeter reference resistor and the measurements are recorded below.

Calorimeter reference resistor measurements

The results of the 4-wire measurements of the calorimeter reference resistor are shown in Table A7.2 below.

Measurement Number	Measured Resistance (Ω)	Deviation from 10 k Ω (Ω)
1	9999.902	-0.098
2	9999.900	-0.100
3	9999.904	-0.096
4	9999.904	-0.096
5	9999.897	-0.103
6	9999.893	-0.107
7	9999.895	-0.105
Average	9999.899	-0.101
Standard Deviation	0.004	
Experimental Standard Deviation of the Mean	0.002	

Table A7.2: Results of calorimeter reference resistor measurements

Appendix 8 Operating procedure of the calorimeter

- 1. Apply vacuum (10^{-4} to 10^{-5} mbar) to the calorimeter. The vacuum system consists of a turbo pump and control unit, backed by a rotary oil pump. After switching on the rotary pump wait till the pressure reading on the meter drops to $< 10^{-2}$ mbar. Open slowly the valve on top of the calorimeter and ensure that pressure remains $< 10^{-2}$ mbar and start the turbo pump. It will take a few hours before the vacuum settles down to a 10^{-4} to 10^{-5} mbar level.
- 2. Switch on the mains power and the Wheatstone bridge supply and allow for thermal equilibrium of the core, jacket and shield. It may take several hours to stabilise. Figure A8.1 shows the front panel of the temperature controller.



Figure A8.1: Front panel of the temperature controller

Referring to Figure A8.1 set P1 to zero. Starting from 20° C the working temperature of the medium will be reached within a few hours.



Figure A8.2: Front panel of the calorimeter measuring bridge (bottom part of the photograph shown in 5.4)

Referring to Figure A8.2, balance the shield by keeping the mode switch (SW14) on S and turn P8 (coarse) and P9 (fine).

Balance jacket: Keep mode on J (SW14) and turn P10 (coarse) and P11 (fine).

Balance core thermistor C2: switch 0 or 100 (SW12), then fine adjustment 0,10 etc., using SW13).

Balance core thermistor C1 or C1+C2 - adjust using the big dial P12 (large inner dial is 1000 Ω).

3. Once the calorimeter has stabilised perform DVM calibration (see Section 3.1.1 for detailed procedure).

- 4. Perform the electrical calibration and find the calibration factor for core heating. (see Section 3.1.2 for the detailed procedure).
- 5. Calculate the dial setting for the jacket, core and shield heaters for the expected radiation heating based on the current dose-rate and set the dials accordingly. (see Section 3.1.3 for the detailed procedure)
- 6. Balance the shield, jacket and core.
 - (a) For quasi-adiabatic measurements, see Section 3.2.1 for details.
 - (b) For quasi-isothermal measurements, see Section 3.2.2 for details.
- 7. Perform analysis.

Notes:

- The heating drift of a body (core, jacket or shield) can be reduced by additional heating of that body or by decreasing the temperature of its surrounding body.
- The cooling drift of a body can be reduced by increasing the temperature of its surrounding body.
- The drift is identified as heating or cooling by the increase or decrease of the output respectively by convention.
- Balancing shield, jacket and core is done at a lower sensitivity (e.g. 100 μ V range) first before changing to higher sensitivity range (50 μ V range used).

Appendix 9 Procedure for the evaluation of DVM calibration factor

The procedure adopted is:

- 1. Select the mode of core output measurement ('C1' for Linac measurements involving higher dose-rates and 'C1+C2' for ⁶⁰Co measurements of lower dose-rates).
- 2. Select 50 μ V range on the LIA and observe the drift in the output. If the drift is < 30 mV/min it is acceptable and if it is more than 30 mV/min reduce the drift by using methods given in Appendix 8.
- 3. If the drift is acceptable, start a stop watch and start the LabVIEW[™] program "calorimeter.vi" and enter the file name as e.g." ad130412-1.txt" (file naming convention is 'a' for ARPANSA calorimeter, 'd' for DVM calibration and numbers giving year-month-day-run number). Start recording the drift. Note the dial reading of dial P12 shown in Figure A8.2 as 'D1'.
- 4. At the end of 60 seconds change the dial P12 by 100 ohms and continue to record the output until 130 seconds has elapsed from the start. Note the dial reading of dial P12 as 'D2'.
- 5. Put the dial reading of dial P12 to 'D1' and balance the bridge output. Note the new dial reading of dial P12 as "D1" again.
- 6. Start a stop watch and start the LabVIEW[™] program "calorimeter.vi" again and enter the file name as e.g. "ad130412-2.txt". Start recording the drift and at the end of 60 seconds change the dial P12 by 200 ohms so that the output is doubled and continue to record the output until 130 seconds has elapsed from the start. Note the dial reading of dial P12 as 'D2'.
- 7. Put the dial reading of dial P12 to 'D1'from step 5 and balance the bridge output. Note the new dial reading of dial P12 as "D1" again.
- 8. Start a stop watch and start the LabVIEW[™] program "calorimeter.vi" again and enter the file name as e.g. "ad130412-3.txt". Start recording the drift and at the end of 60 seconds change the dial P12 by 300 ohms so that the output rises by three times and continue to record the output until 130 seconds has elapsed from the start. Note the dial reading of dial P12 as 'D2'.
- 9. Open the Matlab GUI titled "DVM calibration".
- 10. Press the button marked "Analysis". A new window will open to select the data file for analysis.
- 11. Select the data file (e.g. ad130412-1.txt) from the directory and click open. A dialogue box will appear asking for "D1" and "D2" values. Enter the respective values and click OK. The file directory will open again and repeat the analysis for files (e.g. ad130412-2.txt and ad130412-3.txt) and enter the corresponding D1 and D2 values. At the end of the analysis of all the three files the results of DVM calibration values and their mean will be displayed.
- **Note:** The values of 100 ohms, 200 ohms and 300 ohms are chosen so as to ensure adequate sensitivity and statistical accuracy in the measurements.

Appendix 10 Procedure for the evaluation of electrical calibration factor

The procedure adopted for electrical calibration is:

 Set the heater control potentiometers PS, PJ and PC (Ref. Figure A8.1) to calculated values of 5.75, 5.37 and 5.13 respectively. These settings are the same for ⁶⁰Co and Linac measurements excepting that the heating rates are chosen as Low for ⁶⁰Co and High for Linac measurements by flipping the switch SW1 shown in Figure A8.1. The run timings are as shown in Table A10.1.

Steps	Timings (seconds)	
	⁶⁰ Co	Linac
Initial Drift (no heating)	120	60
Heating	120	60
Final Drift (no heating)	120	60

Table A10.1: Timings used for a run of electrical calibration

- 2. Select the 50 μ V range in the LA and observe the drift in the output. If the drift is < 30 mV/min it is acceptable and if it is more than 30 mV/min reduce the drift by using methods given in Appendix 8.
- 3. Start a stop watch and start the LabVIEW[™] program "calorimeter.vi" again and enter the file name as e.g. "ae130412-1.txt". Start recording the drift and at the end of 60 seconds start the heaters and note the values of V_{CRI} and V_c by operating the switch SW10 and reading the digital display above the switch and the LED indicators marked Core+RI and Core respectively (refer to fig.A8.1). At the end of heating continue the recording to collect the drift for another 60 seconds.
- 4. Open the MATLAB GUI titled "Electrical calibration".
- 5. Press the button marked "Analysis". A new window will open to select the data file for analysis.
- 6. Select the data file (e.g. ae130412-1.txt) from the directory and click open. A dialogue box will appear asking for " V_{CRI} " and " V_{C} " values. Enter the respective values and click OK.

Figure A10.1 shows the electrical calibration factors evaluated during 2011-2014 as a function of the core thermistor resistances during this period.



Figure A10.1: Summary of ECFs measured during 2011-2014

Appendix 11 Procedure for the calculation of heater settings

Potentiometer setting	Vc	Vcri	Vj	Vjri	Vs
0	0.0003	0.0006	0.0336	0.069	0.0286
50	0.0586	0.121	0.0817	0.167	0.165
100	0.12	0.249	0.133	0.272	0.306
150	0.182	0.378	0.188	0.385	0.472
200	0.241	0.5	0.243	0.497	0.625
250	0.301	0.624	0.298	0.611	0.79
300	0.36	0.747	0.355	0.729	0.943
350	0.421	0.872	0.411	0.843	1.111
400	0.48	0.995	0.468	0.958	1.264
450	0.542	1.123	0.527	1.08	1.427
500	0.601	1.245	0.58	1.19	1.582
550	0.661	1.37	0.64	1.311	1.744
600	0.72	1.493	0.696	1.428	1.898
650	0.781	1.62	0.754	1.547	2.064
700	0.841	1.745	0.81	1.663	2.218
750	0.903	1.873	0.87	1.785	2.379
800	0.963	1.998	0.927	1.902	2.533
850	1.024	2.126	0.986	2.025	2.689
900	1.081	2.244	1.042	2.139	2.848
950	1.143	2.373	1.1	2.259	3.009
1000	1.203	2.497	1.16	2.384	3.164

Table A11.2: Heater voltages as a function of potentiometer settings

Linear regression plots of square root of the core, jacket and shield heating power versus heater dial settings:



Figure A11.1: Core heater calibration



FigureA11.2: Jacket heater calibration



Figure A11.3: Shield heater calibration

Using the fit coefficients from the plots the dial setting for the desired heating rate is calculated as follows.

$$vP_{c} = A.D_{c} + B \quad (\mu W)$$
(21)

$$vP_{J} = P.D_{J} + Q \quad (\mu W)$$
(22)

$$VP_{s} = R.D_{s} + S \quad (\mu W)$$
(23)

The coefficients A, B, P, Q, R and S are listed in Table A11.1.

Table A11.1: Coefficients for the calculation of heater dial settings

А	В	Р	Q	R	S
1.2478	-0.0067	1.1719	0.1344	9.128	0.0807

Using the coefficients from Table A11.1 the heater dial settings for core (D_c) , jacket (D_J) and shield (D_S) are given by

$$D_{\rm C} = (\sqrt{P_{\rm C}} - B)/A \tag{24}$$

$$D_{J} = (\sqrt{P_{J}} - Q)/P \tag{25}$$

$$D_{\rm S} = (V P_{\rm S} - S)/R \tag{26}$$

Note: The potentiometers are 10-turn types and a dial setting of 5.3 means 5 rotations and 30 divisions.

If the dose-rate (\dot{D}) is expressed in mGy/sec, then the desired heating power in μ W is given by multiplying the dose rate by the mass of each body,

$P_{c} = \dot{D} (mGy/s) \times 1.5622(g)$	(27)
P _J = Ď (mGy/s) × 1.56(g)	(28)
P _s = ḃ (mGy/s) × 107(g)	(29)

The dial settings D_c , D_J and D_s for P_c , P_J and P_s can be calculated from equations $D_c = (vP_c - B)/A$ (24), $D_J = (vP_J - Q)/P$ (25) and $D_s = (vP_s - S)/R$ (26) respectively.

Procedure for getting the heater settings corresponding to dose-rate:

- 1. Select the MATLAB GUI titled 'Heater settings'.
- 2. Press the button marked 'Get Heater Settings'
- 3. Enter the dose-rate in mGy/sec in the dialog box marked 'current'.
- 4. Note the heater settings.

Calorimeter	Calorimeter Heater settings Get Heater Settings	
	Core Heating Rate = 5.4917 Jacket Heating Rate = 5.727 Shield Heating Rate = 6.1981 Iso-thermal shieldHR =5.8882	

Figure A11.4: Matlab GUI for the calculation of heater settings

Appendix 12 Adjustment of shield heating rate



Figure A12.1: Geometry to calculate the ratio of core to shield dose

The ratios calculated for ⁶⁰Co and Linac energies corresponding to 6MV, 10MV and 18MV are shown in Table A12.1.

Table A12.1: Ratios of MC calculated shield dose to core dose

Photon energy	shield dose / core dose
⁶⁰ Co (1.25 MeV)	0.785
6 MV	0.812
10 MV	0.837
18 MV	0.856

So, when the core, jacket and shield heaters are turned off, the shield has a slightly slower cooling rate than core and jacket. In the MATLAB GUI the Iso-thermal shield heating rate based on this calculation is also displayed.

Appendix 13 Estimation of the specific heat of graphite core from calorimeter measurements

The graphite absorbed dose in calorimetry measurements is given by,

$$D_{core} = C_p \cdot dT (J/kg)$$
(1)

Where, C_p is the specific heat capacity of the graphite core and dT is the temperature rise due to radiation absorption.

The graphite absorbed dose to the core in ARPANSA calorimeter is estimated based on an electrical calibration (see Appendix 10) and is given by,

$$D_{core} = (dV . C_{DVM} . C_{ECF} / m) (10^{-3} J/kg)$$
 (2)

From equations (1) and (2),

$$C_{p} = dV \cdot C_{DVM} \cdot C_{ECF} / dT \quad (J/kg/T)$$
(3)

From a quasi-adaibatic run of the calorimeter measurements, the following data has been used in the calculations for C_p .

Voltage rise (dV) =3.6298 V Dose estimated, D_{core} =3.084 Gy DVM calibration Factor (C_{DVM}) = 45.42 (dR/V) × 10⁴ Electrical Calibration Factor (C_{ECF}) = 29.22 (10⁻⁴ J/dR)

Using these data in equation (3) we get,

$$C_p = 3.084 / dT.$$
 (4)

Fractional change in core thermistor value

$$dR (%dR/R) = 0.016486552 \Omega$$
 (5)

The temperature sensitivity of the 10 k Ω VECO micro-bead thermistor used in the ARPANSA calorimeter core is given in the specification as -3.9 % dR/ K

The temperature rise in the calorimeter core due to radiation absorption was dT = 0.004227321 K. Hence, from equation (4):

$$C_p = 729.60 \text{ J/kg/K}.$$

From earlier measurements on the specific heat capacity of the core,

$$C_p = 710 \text{ J/kg/K}.$$

Appendix 14 Circuit for automatic switching on/off the heaters

The circuit converts the train of pulses into one rectangular pulse (Q output of IC 74123/1), and the inverse \bar{Q} is used as a STOP signal into the calorimeter electronics back panel socket, as in Figure A13.1. The electronic heating is stopped when the voltage on pin number 16 drops from 5V to 0V, which is delivered by the leading edge of the \bar{Q} output signal from IC 74123/1, coinciding with the start of the beam from the linac. Likewise, the leading edge of the \bar{Q} output of IC 74123/2 provides a START signal into pin 15, coinciding with the end of the beam from the linac. In this way there is a seamless transition between electrical heating, radiation heating and back to electrical heating, with no delays or human intervention required.



Figure A13.1: Circuit for automatic switching on/off the heaters.

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