

**The Australian Primary Standard for**

**Absorbed Dose to Water (Graphite Calorimeter)**

**by**

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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 60Co 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 60Co, 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 103, 5.5 parts in 103, 6.0 parts in 103and 5.9 parts in 103, respectively. This report gives additional information describing the ARPANSA calorimeter and method of realising the absorbed dose for these comparisons.

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# 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. A comparison with the BIPM in 2012 yielded ratios of the 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.

# DESCRIPTION OF ARPANSA GRAPHITE CALORIMETER

## 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.

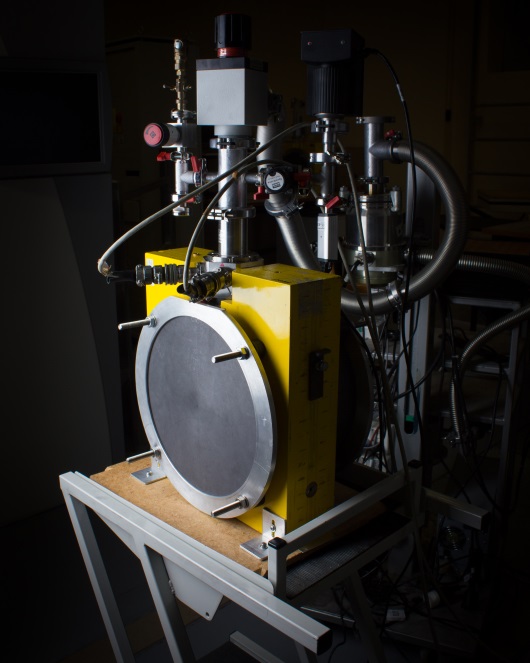


Figure 1: The ARPANSA graphite calorimeter (with build-up plates for 60Co)

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 kΩ. 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.

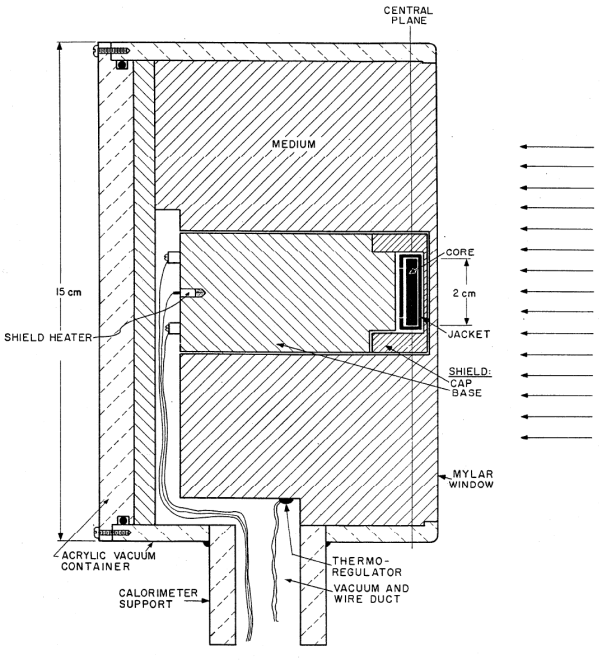


Figure 2: Schematic cross-section of the calorimeter (not to scale)

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.

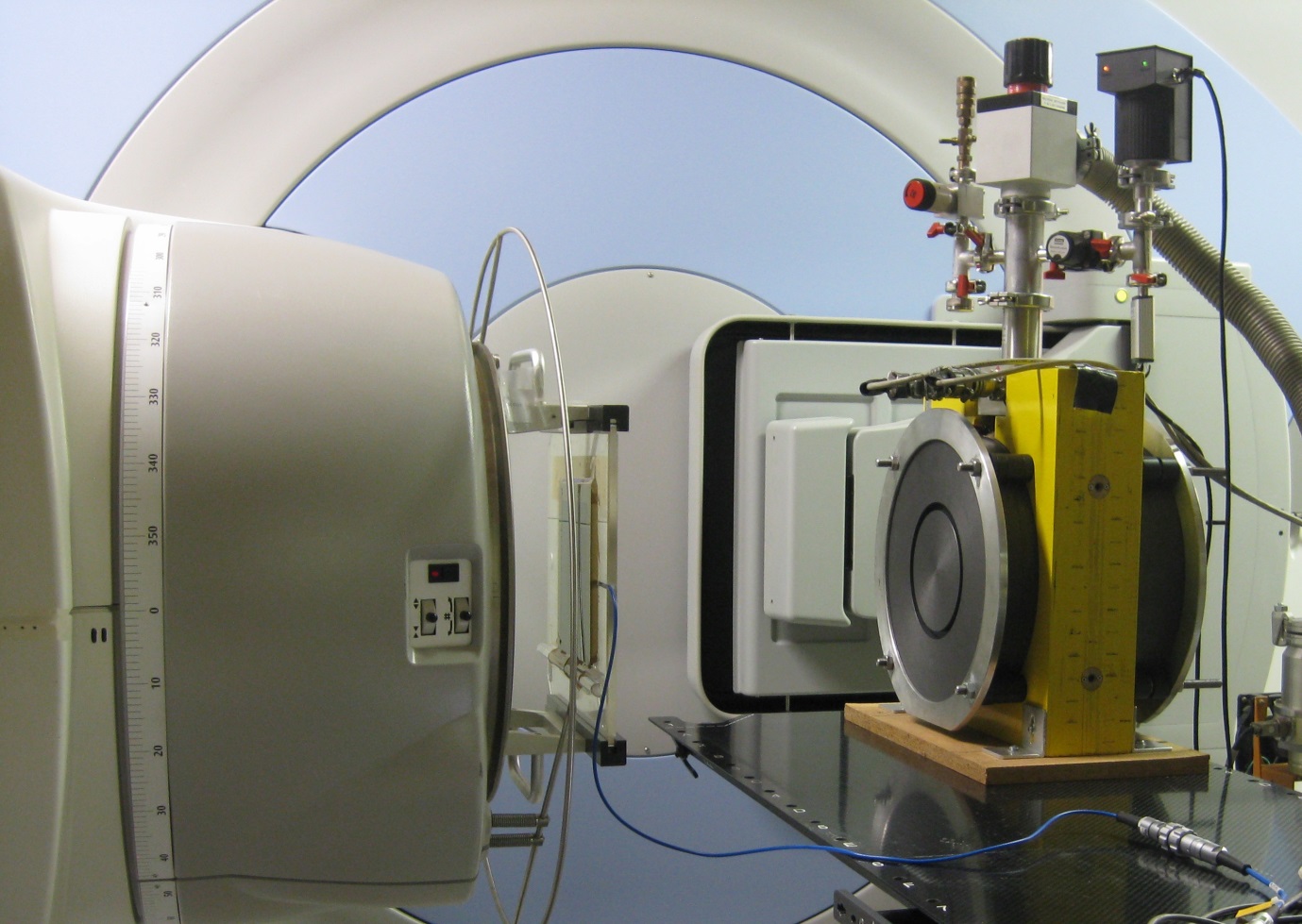


Figure 3: ARPANSA calorimeter positioned in the linac beam

## Calorimeter electronics

A block diagram of the component modules of the calorimeter electronics and their inter-connections 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.

### 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).

### 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 (VC) or this voltage plus the voltage across a very precise (10 kΩ ± 1 Ω) serial resistor (VCRI) and the glow of the LEDs positioned above the switch indicates the corresponding voltages. The 10 kΩ 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.

### 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 µV 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).

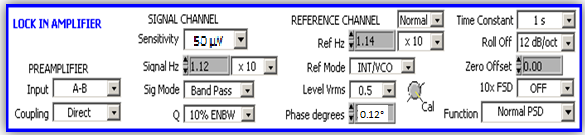


Figure 4: Lock-in-amplifier settings

* 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

### LabVIEWTM 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.

# CALORIMETER measurements

## Calorimeter calibrations

### 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 [ΔV/ (% ΔR/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 (CDVM):

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 × (D1+50,000) / (D1+60,000) ) + 1,000/3 (Ω)

R2= ( 10,000 × (D2+50,000) / (D1+60,000) ) + 1,000/3 (Ω)

ΔR/R = 2 (R2 - R1) / (R2 + R1)

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

CDVM = 100 (ΔR/R) / ΔV × 104 (ppm/V) (1)

**Notes:**

* The DVM calibration factor CDVM is the mean value from three measurements as explained in the procedure (Appendix 9).
* CDVM 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.

### 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 (CECF):

From the entered values of VCRI and VC the current through the core thermistor is given by

IC = (VCRI – VC) / 10,000 (A) (2)

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

Pe = IC VC × 106 (μW). (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 CECF is the ratio of the energy deposited in the core to the percentage change in the resistance of the core thermistor:

CECF = (Pe . te) / (ΔV . CDVM) × 103 (mJ/%), (4)

where Pe is in μW, te is in seconds, ΔV is in V and CDVM is in units of ppm per V. The value of CDVM is around 50 ppm/V and CECF is around -300 mJ/% for C1 mode and -150 mJ/% for C1+C2 mode.

### 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,

VC - voltage across core heating thermistor

VCRI - voltage across the core heating thermistor and standard 10 kΩ resistor.

VJ - voltage across jacket heating thermistor

VJRI - voltage across the jacket heating thermistor and standard 10 kΩ resistor

VS - 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 PC (heating power dissipated in core), PJ (heating power dissipated in jacket), and PS (heat dissipated in shield) are calculated using:

PC = ( (VCRI - VC) / 10,000) VC × 106 (µW) (5)

PJ = ( (VJRI - VJ) / 10,000) VJ × 106 (µW) (6)

PS = (VS 2 / 1,200) × 106 (µW), (7)

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

From the values of PC, PJ and PS the values of √PC, √PJ and √PS 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.

## 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) *Dc* in J/kg is given by

Dcore = cm,core ΔTcore (8)

where:

cm,core is the specific heat capacity of the core (in J kg-1K-1), and

ΔTcoreis 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

Dcore = (ΔV CDVM CECF / mcore) Π ki (9)

where:

Dc is the measured absorbed dose to the core  
ΔV is the measured voltage change due to radiation heating of the core  
CDVM is the DVM calibration factor (ppm%ΔR/R)/V  
CECF is the electrical calibration factor mJ/(%ΔR/R)  
mc is the core mass, and  
Π ki 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.

### 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.

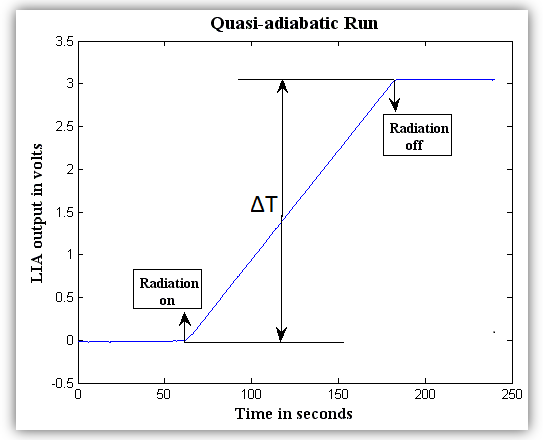


Figure 5: Quasi-adiabatic run for the 10 MV photon beam

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.

### 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.

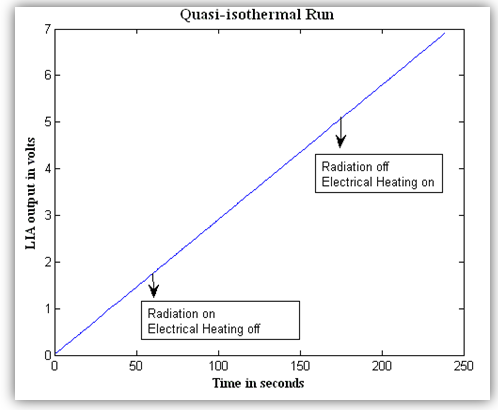


Figure 6: Quasi-isothermal run for the 10 MV photon beam

Dose to the core is given by, DC = (Pe . tR) / mC . Π ki

Where, Pe is the electrical power calculated (see Section 3.1.2), tR is the radiation on time, mC is the mass of the core and Π ki 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 tR 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.

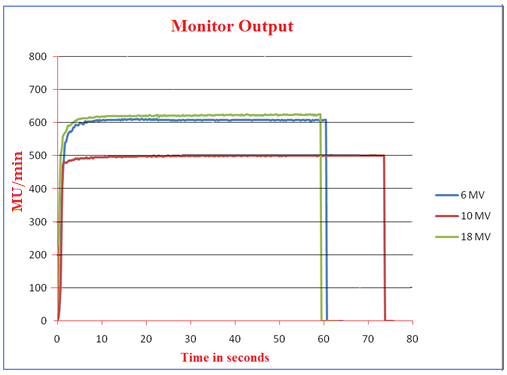


Figure 7: Outputs of internal monitor chamber in linac head during  
irradiations at 6 MV, 10 MV and 18 MV

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, τ = (MBtA – MAtB) / (nMA – MB) (10)

Where, MA is the integrated reading in time tA, MB is the integrated reading in n short exposures of time tB /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 (%ΔR/R). This fractional change is converted to the heating power using the electrical calibration factor and this power (in µW) is denied to the total heating power and hence is added to the actual heating power calculated using the Vcri and Vc 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

# 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.)

1. Separate variables.
2. Find start and stop points of irradiation (in Adiabatic analysis).
3. Give linear polynomial fits to initial drift data and final drift data.
4. Extrapolate to the mid-point of radiation run.
5. Calculate dose and dose-rate.
6. 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.

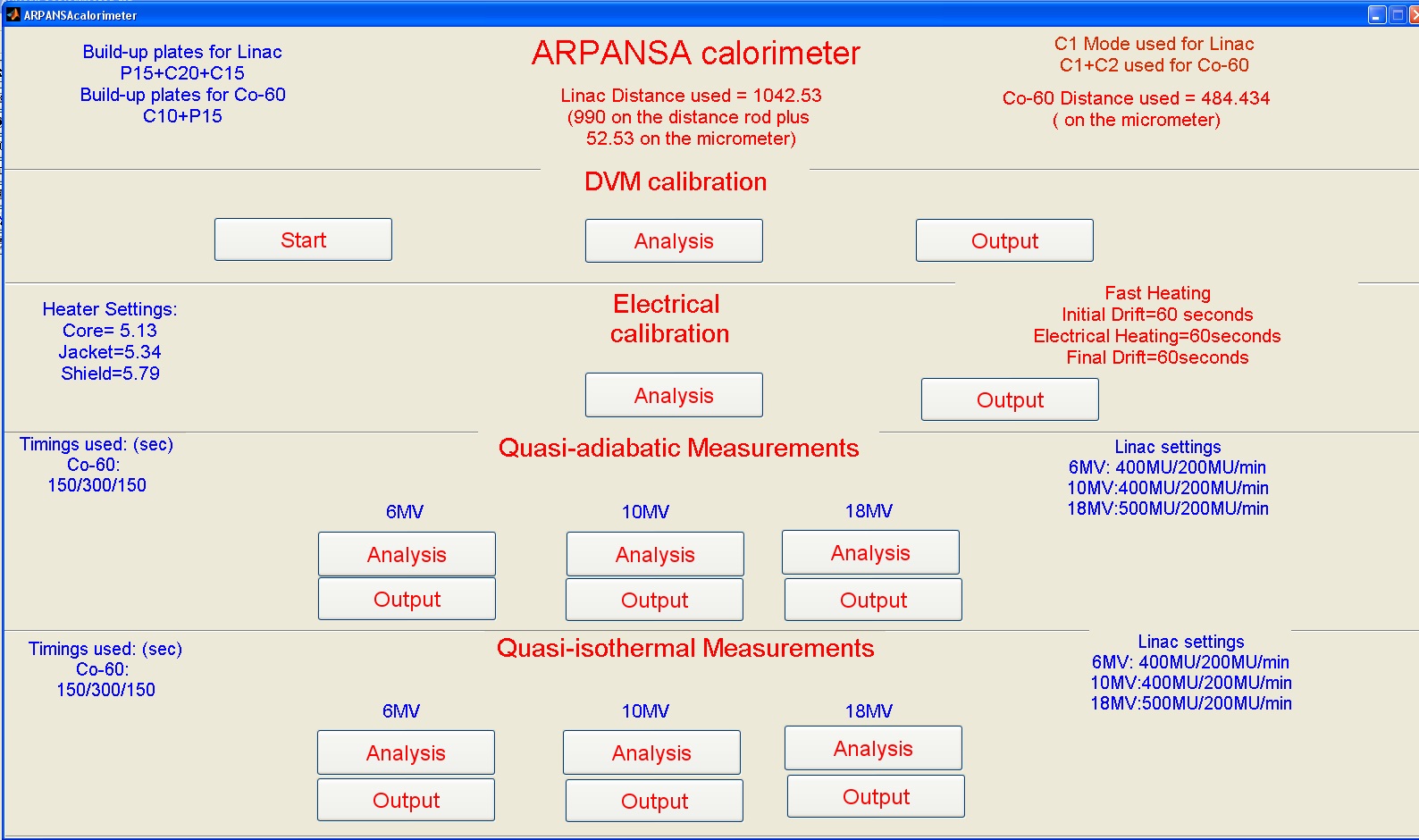


Figure 8: MATLAB GUI for the analysis of calorimetry measurements

# CONVERSION OF GRAPHITE DOSE TO ABSORBED DOSE TO WATER

## 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.



Figure 9: Graphite calorimeter and water phantom geometries used in Monte-Carlo calculations

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 |
| [Dg,core/Dw,core]MC | 0.96157 | 0.94042 | 0.9252 |

![](data:None;base64,)

Figure 10: Calorimeter geometry described in the 2012 BIPM.R1(1)-K6 comparison

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

Dw = Dg,core . [Dw,core/Dg,core]MC . krn,core (11)

where Dg,core is the measured dose to the calorimeter core, [Dw,core/Dg,core]MC is the MC ratio of the absorbed dose to water Dw,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, Dg,core,MC, and krn,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.

## Cavity Ionisation Theory (CIT) Method

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

![](data:None;base64,)

Figure 11: Methodology of conversion of graphite dose to water absorbed dose by CIT method

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

DW / DG = (SW,air . pu,W . QW) / ( SG,air . pu,G . QG) (12)

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

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

SW,air is the restricted stopping power ratio of water to air,

SG,air is the restricted stopping power ratio of graphite to air,

pu,W is the perturbation correction for the ion chamber in water, evaluated at the water reference depth,

pu,G is the perturbation correction for the ion chamber in graphite, evaluated at the graphite reference depth,

QW is the charge measured with ion chamber in water, and

QG is the charge measured with ion chamber in graphite.

DG measured with graphite calorimeter is given by

DG = Dcore kgap krn,core (13)

where, Dcore is the dose measured by the calorimeter, kgap is the correction for vacuum gaps in the calorimeter and krn,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 kgap 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:

ND,g = DG ks kgeom krn,chamber (14)

where ks is the recombination correction, kgeom accounts for a small difference in the depths of the core and chamber and krn,chamber is the radial non-uniformity correction for the chamber length.

For the purposes of comparison with a measured chamber ND,w using the MC method, the equation 12 can be written as:

DW / QW = (DG / QG) (SW,air . pu,W) / ( SG,air . pu,G),

and therefore:

ND,w = ND,g (SW,air . pu,W) / ( SG,air . pu,G). (15)

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

[ND,w / ND,g]Wise= (SW,air . pu,W) / ( SG,air . pu,G) (16)

A cubic spline to the values of [ND,w / ND,g]Wise was used to evaluate the correction at the 6 MV, 10 MV and 18 MV TPR20,10 values. In order to assess the CIT dose conversion method against the direct MC method the ND,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 (ND,w) derived by the two methods for two NE2571 chambers and Table 6 shows the ND,w values and ratios for an NE2611A chamber and the average ratio of ND,w’s for all chambers. It is assumed that the NE2571 chamber is similar enough to the NE2611A chamber that perturbation corrections pu,W and pu,G calculated by Wise can be used.

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

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Beam quality** | **Calorimeter corrections** | | **Chamber corrections** | | | **[ND,w / ND,g]Wise** |
| **kgap** | **krn\_core** | **ks** | **kgeom** | **krn\_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

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Beam quality** | **NE2571, sn 2384** | | | **NE2571, sn 1785** | | | **NE2571 average** |
| **(ND,w)MC** | **(ND,w)CIT** | **(ND,w)CIT / (ND,w)MC** | **(ND,w)MC** | **(ND,w)CIT** | **(ND,w)CIT / (ND,w)MC** |
| 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 by   
MC and CIT methods

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Beam quality** | **NE2611A, sn 152** | | | **Average of 2571 and 2611A chambers** |
| **(ND,w)MC** | **(ND,w)CIT** | **(ND,w)CIT / (ND,w)MC** |
| 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 ND,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 (ND,w)CIT values tending to be higher when compared to (ND,w)MC than the NE2571 chambers. This difference is possibly due to the use of NE2611A perturbation corrections for the NE2571 chamber.

# CORRECTION FACTORS AND UNCERTAINTY ESTIMATES

## Calorimeter corrections

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

Π ki = kt . km . kd . kz . krn,core . kan . kgap (17)

• kt - radioactive source decay

• kd - distance using the inverse square law

• kz - graphite depth using empirical attenuation data

• krn,core - radial non-uniformity to give the central-axis dose

• kan - axial non-linearity in the depth dose through the core

• kgap - vacuum gaps

**Note:**

kt applies in 60Co measurements only.

kt – 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].

kd – 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.

kz – 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.

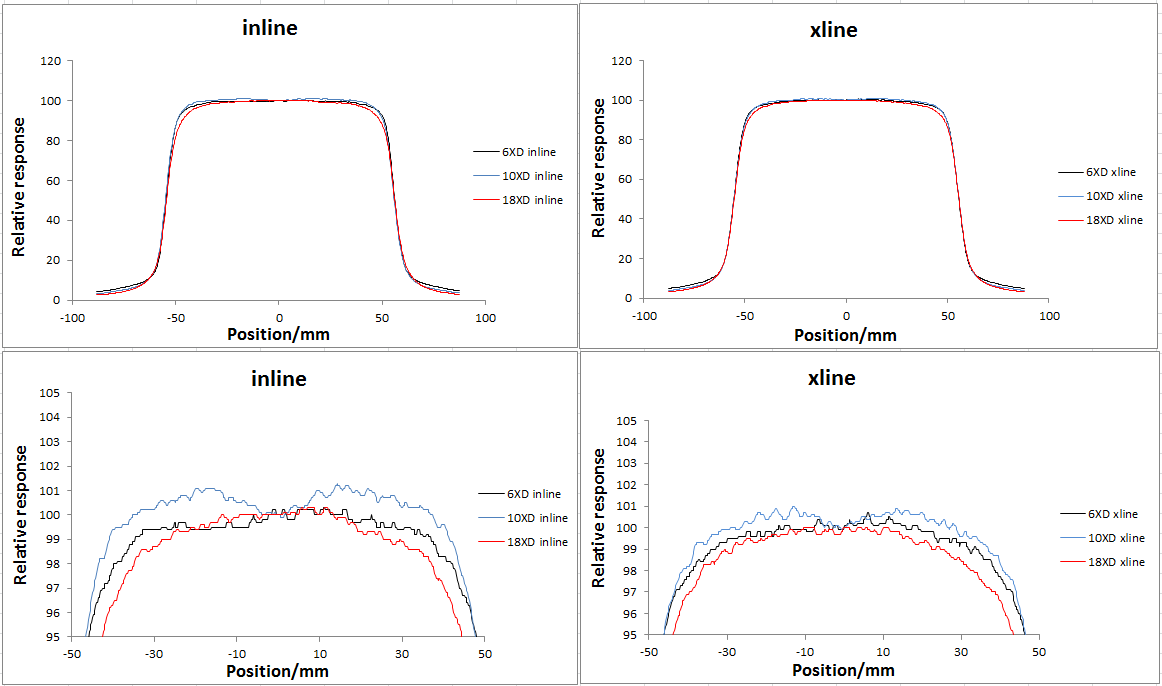
krn,core – Correction factor for the radial non-uniformity of the 60Co beam and linac photon beams over the calorimeter core. This correction factor was evaluated for the 60Co source and found to be close to unity. For linac beams the beam profiles were measured using a scanning ion chamber (Figure 12)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

Table 7: Radial beam non-uniformity corrections for calorimeter

|  |  |
| --- | --- |
| Nominal Accelerating voltage/ MV | krn, core |
| 6 | 1.0000 |
| 10 | 0.9948 |
| 18 | 1.0006 |

kan- 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.

kgap – 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 krn,core. “inline” refers to the GT (Gun-Target) direction and “xline” refers to the orthogonal direction.**

### 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,

mp = mn [1- (ρL /ρn)] / [1- (ρL /ρp)] (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 mp/mn = 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.

### Correction for non-graphite materials:

The effective core mass is the buoyancy corrected graphite mass, corrected for the presence of non-graphite 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.

## 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 CDVM (see Section 3.1.1) and CECF (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:

Dg = (Pe . tR / mc) . Πki (19)

Where, Dg = absorbed dose to graphite

Pe = ((Vcri - Vc)/Ri) Vc – ΔP

tR = Radiation heating-on time

mc = Buoyancy corrected core mass

Πki = kgap . krn

Vc = Vc (measured) - VL

VL = [(Vcri - Vc (measured))/Ri] . RL

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

RL = Resistance of leads (17 ohms)

ΔP = Net voltage of the final minus the initial heating rate slopes \* CDVM \* CECF

CDVM = DVM calibration factor

CECF = 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- | Type A: υ | Type B |
| Vc – core heater voltage |  | 0.05 |
| Vcri – core heater + series R voltage |  | 0.05 |
| Ri – current sense resistance |  | 0.0001 |
| RL – Leads Resistance |  | 0.03 |
| tR – Radiation heating on time |  | 0.1 |
| ΔP – power correction | 0.01:38 |  |
| CDVM – DVM calibration factor | 0.02:38 |  |
| CECF – Electrical calibration factor | 0.03:38 |  |
| Combined % relative standard uncertainty in Dg | | 0.13 |

Table 9 gives the correction factors and the uncertainties in determining the absorbed dose to water at 5 gm/cm2 depth in water irradiated with 60Co beam.

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

|  |  |  |  |
| --- | --- | --- | --- |
| Source of uncertainty | Value | Relative standard uncertainty | |
| **100 si** | **100 uj** |
| *Determination of core (Ḋcore)ARPANSA*  P electrical power  mc mass of the core / g  Repeatability  krn radial non-uniformity | 1.5622  1.0000 | 0.08  0.07 | 0.01  0.05 |
| *Conversion to absorbed dose rate to water by calculation*  [Dw/Dcore]MC conversion from graphite to water | 0.9308 | 0.21 | 0.32 |
| *Uncertainty in (Ḋw ) ARPANSA*  Quadratic summation |  | 0.24 | 0.32 |
| **Combined relative standard uncertainty 0.40** | | | |

Table 10: Uncertainties in the *ND,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 |  |  |  |
| Measured dose to the calorimeter core (*Dg*) | 0.13 | 0.13 | 0.13 |
| Radial non-uniformity corrections for core and chamber | 0.03 | 0.14 | 0.03 |
| Monte Carlo conversion ([*Dg/Dw*]*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 (*kTP*, *ks*, *kpol*, *kelec*) | 0.08 | 0.08 | 0.08 |
| Standard uncertainty of the mean of | 0.05 | 0.05 | 0.05 |
| *Combined uncertainty in determination of transfer standard* | *0.40* | *0.46* | *0.46* |
| Determination of clinical chamber |  |  |  |
| Chamber positioning | 0.11 | 0.09 | 0.08 |
| Current measurement | 0.07 | 0.07 | 0.07 |
| Other corrections (*kTP*, *ks*, *kpol*) | 0.05 | 0.05 | 0.05 |
| Repeatability | 0.10 | 0.10 | 0.10 |
| *Combined uncertainty in determination of clinical chamber* | *0.17* | *0.16* | *0.15* |
| **Combined relative standard uncertainty (k=1)** | **0.44** | **0.49** | **0.49** |

# 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.

Table 11: Results of the 2006 comparison

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Quasi-isothermal mode | | | | | | | Quasi-adiabatic mode |
| **Electrical 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 |
| \* 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.

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

|  |  |  |  |
| --- | --- | --- | --- |
| Beam quality | TPR 20/10 | Dg IAEA / Dg ARPANSA | Dw IAEA / Dw ARPANSA |
| 60Co | 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 |

Note: The DW 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 DW values for the ARPANSA calorimeter have been arrived at using Monte Carlo conversion factors given in Table 3 of Section 5.

# INTERNATIONAL INTERCOMPARISONS

## 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 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 Dw is calculated from

Dw,ARPANSA = Dc . . . . kwin . kair (20)

Where:

Dc = Dose to graphite

= Ratio of primary photon fluences in water and graphite

= Ratio of mass-energy absorption coefficients of water and graphite

= quotients of absorbed dose to collision component of kerma

kwin = correction for the difference in attenuation of the front window of water phantom and water

kair = Correction for air attenuation over the distance between the graphite calorimeter and the water phantom

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

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Transfer chamber | Ḋw,ARPANSA/ (mGy s-1) | IARPANSA / pA | ND,W,ARPANSA/ (Gy µC-1) | Ḋw,BIPM / (mGy s-1) | IBIPM / pA | ND,W, BIPM / (Gy µC-1) | RDW |
| 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 | | | | | | | 1.0024 |

**Note:** Combined uncertainty in the comparison, uc =0.0029, [3]

## 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.

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

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Transfer Chamber** | **ND,w,ARPANSA**  **/ Gy µC−1 pre-BIPM \*** | ***ND,w,BIPM* / Gy µC−1** | **ND,w,ARPANSA**  **/ Gy µC−1 post-BIPM \*** | **ND,w,ARPANSA**  **/ Gy µC−1 overall mean** | ***RD,W*** | ***uR*,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** |

## 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.

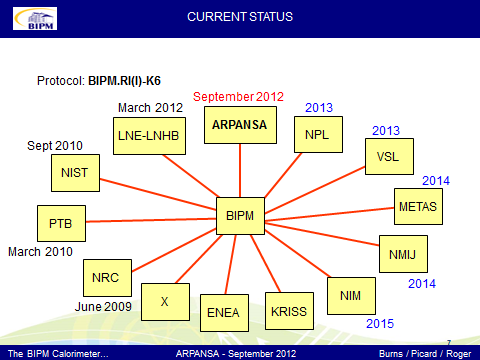


Figure 13: Current Status of BIPM.RI(I)-K-6 comparison (courtesy:BIPM)

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].

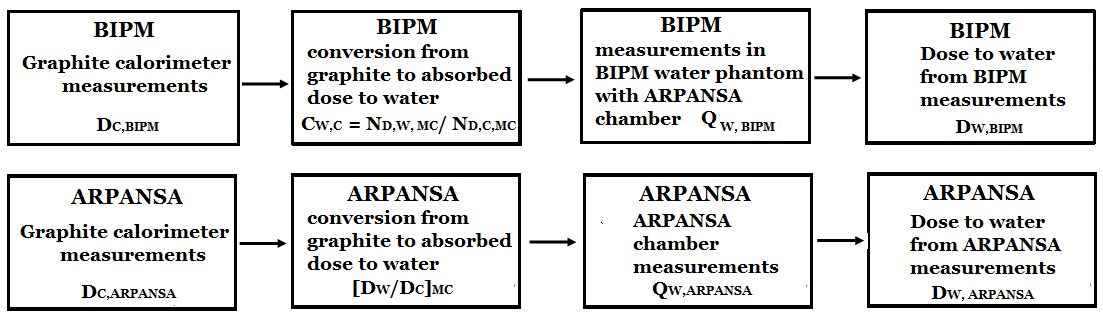
Prior to the BIPM visit in September 2012, a series of calibration were made on the two ARPANSA reference chambers (NE 2571 serial number 1785 and serial number 2384) using the ARPANSA calorimeter. Measurements were made over 6 months in order to establish the stability of the calibration process and 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, DC,BIPM = Measured dose to the core of the BIPM calorimeter

CW,C = BIPM Conversion factor of graphite dose to water absorbed dose

ND,W,MC = Monte Carlo calculated absorbed dose calibration factor for water by BIPM

ND,C,MC = Monte Carlo calculated absorbed dose calibration coefficient for graphite by BIPM

QW, BIPM = Charge measured with ARPANSA chamber in BIPM water phantom

DW,BIPM = Dose to water measured by BIPM methodology

DC,ARPANSA = Measured dose to the core of ARPANSA calorimeter

[DW/DC]MC = ARPANSA Monte Carlo calculated graphite to water dose conversion factor

QW,ARPANSA = Charge measured with ARPANSA chamber in ARPANSA water phantom

DW,ARPANSA = Dose to water measured by ARPANSA methodology

Comparison Ratio, R ARPANSA = DW,ARPANSA / DW,BIPM

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

Table 15: Results of calorimetry measurements

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Nominal operating voltage | 6 MV | | 10 MV | | 18 MV | |
| **A** | **B** | **A** | **B** | **A** | **B** |
| Mean Dg (mGy) | 3085.3 | 3088.8 | 3053.2 | 3057.9 | 3764.7 | 3761.3 |
| MU | 400 | 400 | 400 | 400 | 500 | 500 |
| % ESDM | 0.08 | 0.11 | 0.11 | 0.08 | 0.09 | 0.09 |

**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 | |
| **A** | **B** | **A** | **B** | **A** | **B** |
| ND,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

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

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Nominal operating voltage | 6 MV | | 10 MV | | 18 MV | |
| **A** | **B** | **A** | **B** | **A** | **B** |
| ND,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 |

**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.

Table 18: Preliminary results of the K6 comparison

|  |  |  |  |
| --- | --- | --- | --- |
| ARPANSA Beam | TPR20,10 | Dw, ARPANSA /Dw,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 |

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

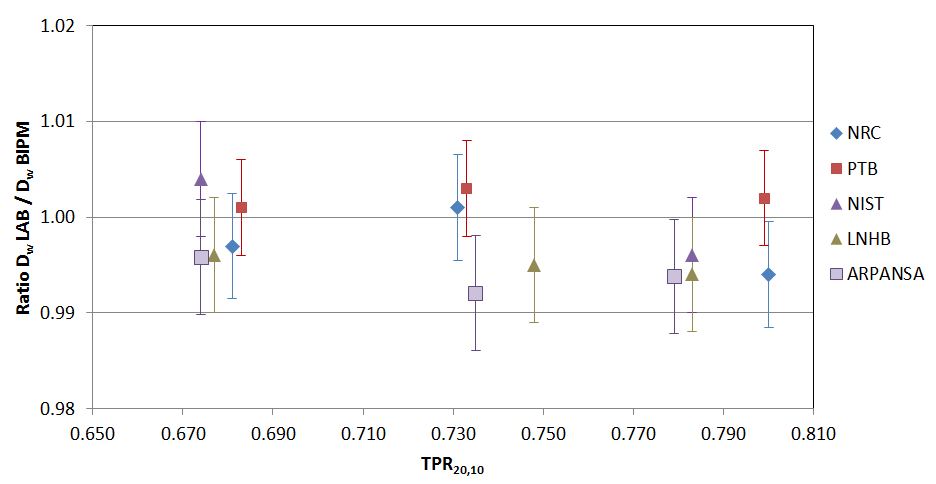


Figure 17: International comparison of Linac dose BIPM.RI(I)-K6

# 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.

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.

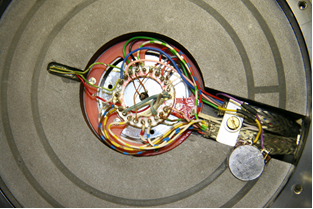


Figure A1.1: Inside the calorimeter

1. The schematic diagram and photo of the calorimeter core-jacket-shield assembly

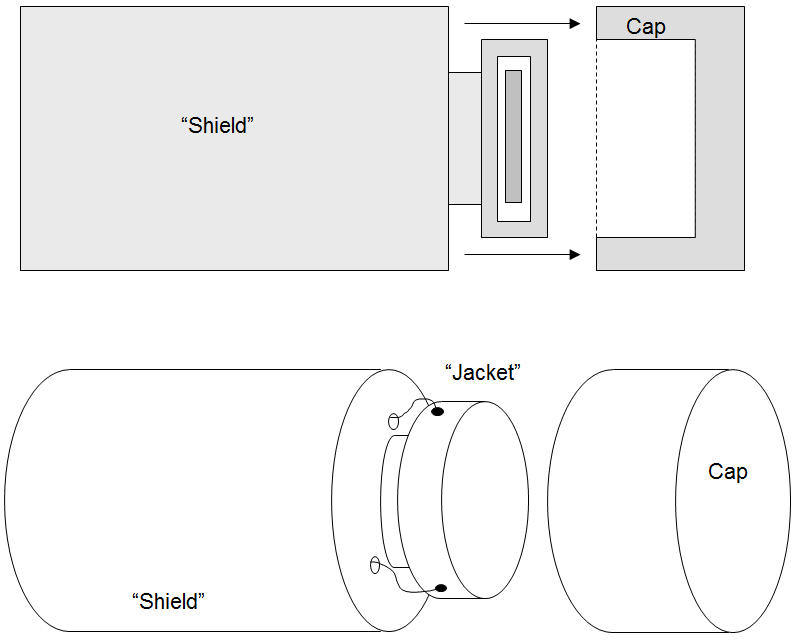
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Figure A2.1: Schematic diagram of the core-jacket-shield assembly

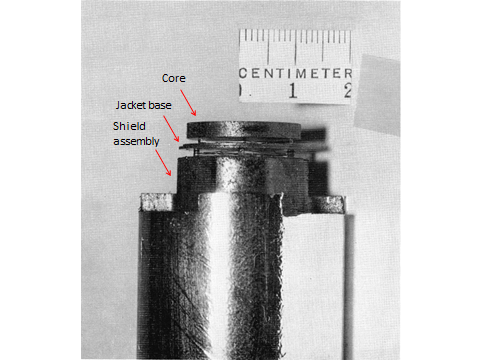
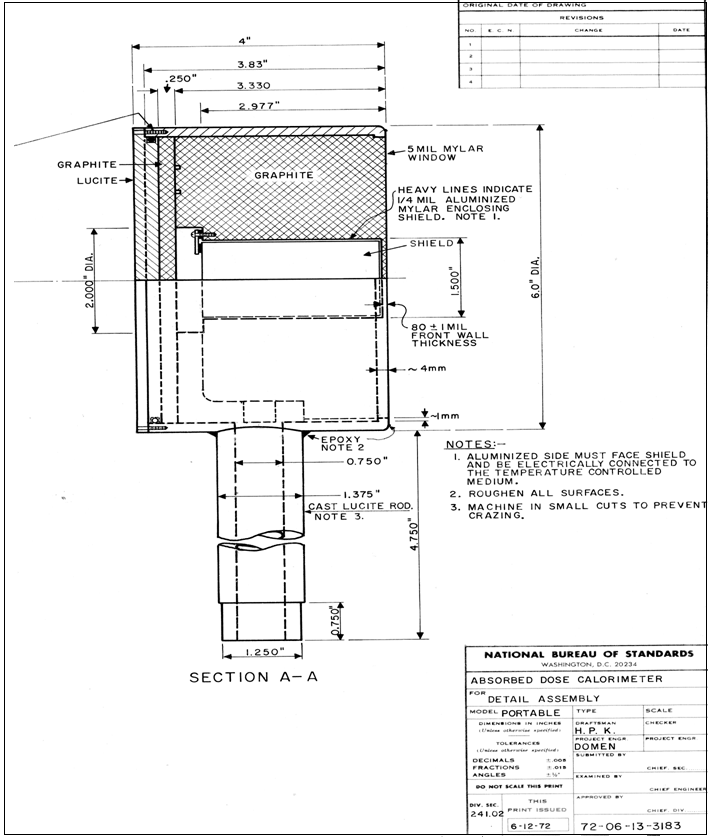
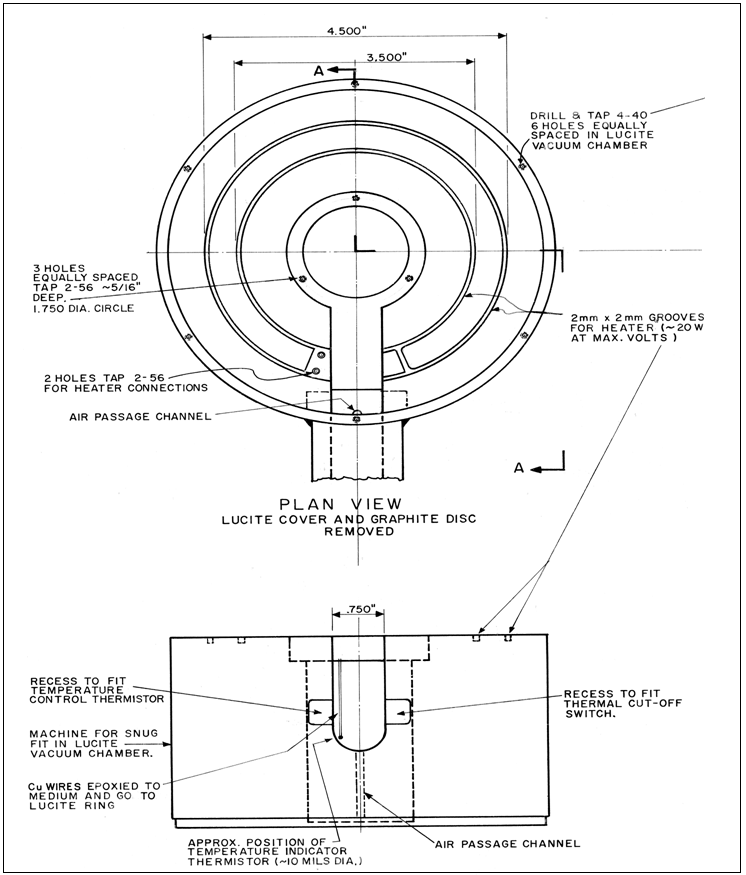
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Figure A2.2: Photo of the core-jacket-shield assembly (Domen calorimeter)

1. Engineering Drawings of the calorimeter

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







1. Build-up plate thicknesses, core materials and thicknesses

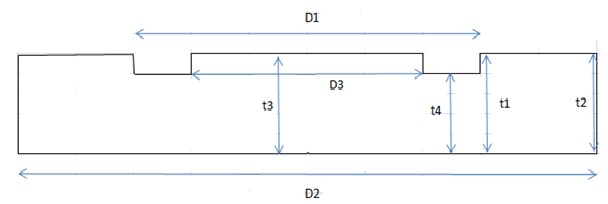
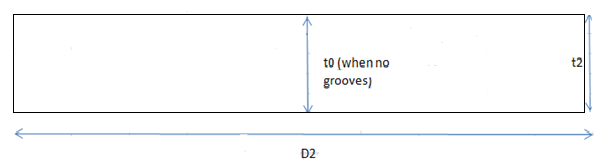


Figure A4.1: Schematic diagrams of build-up plates with and without grooves

**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 |
| I15 | 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 |
| I20 |  | 30.01 |  |  |  | 2.00 | 2.00 |  |  | 1.99 |  |  |  | 1412.6 | 2504.4 | 1.77 |
| I40 |  | 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.

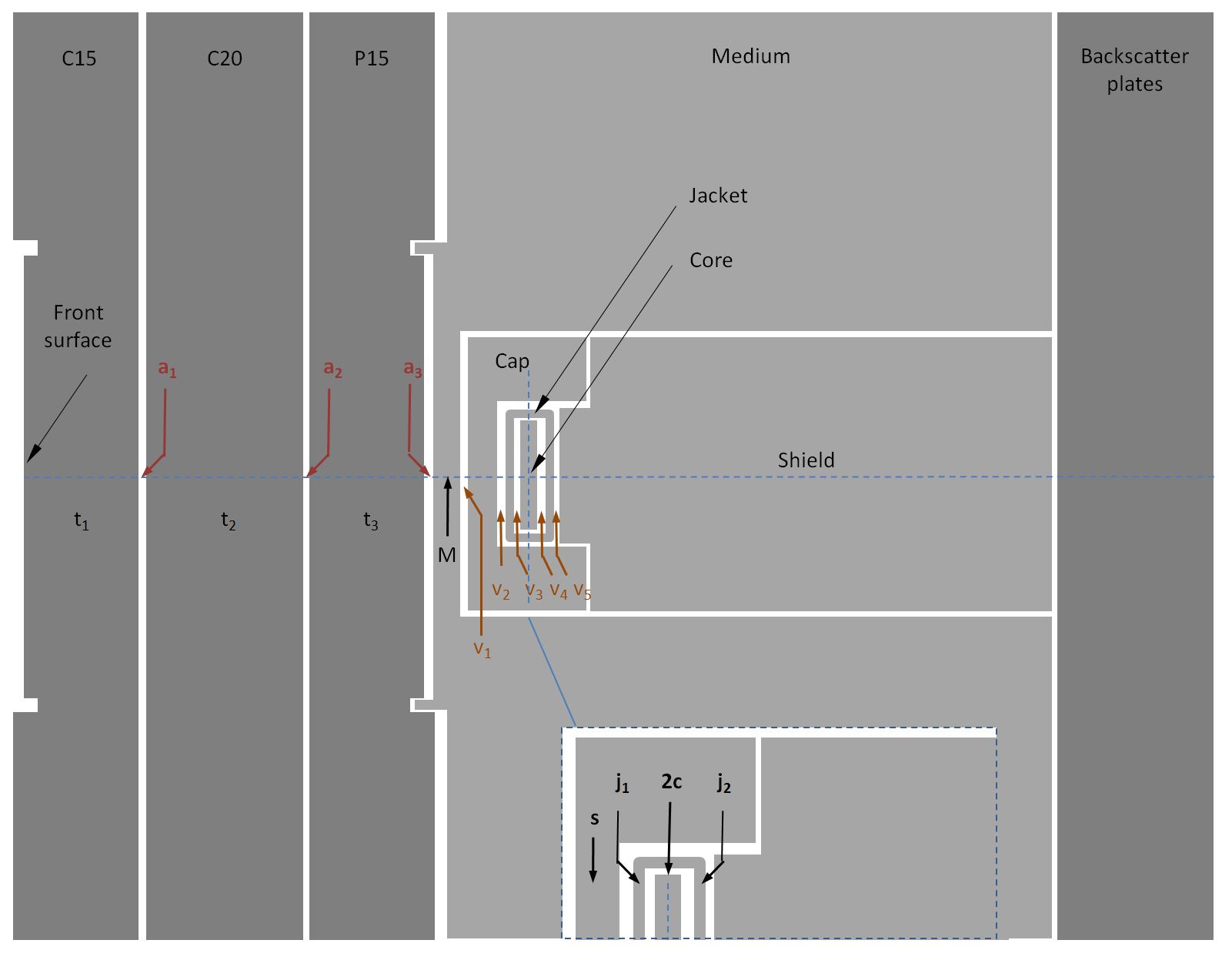
IAEA-K4 data supplied by J Witzani 16 April 2002

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

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Part | Material | Thickness, mm | | |
| **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)

|  |  |  |
| --- | --- | --- |
| Material | Mass, mm | |
| **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** |



Expanded view

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

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

|  |  |  |  |
| --- | --- | --- | --- |
| Material | Symbol | Details | On-axis thickness (cm) |
| Plate 1 | t1 | C15 (reversed) | 1.531 |
| Air gap | a1 |  | 0.05 |
| Plate 2 | t2 | C20 | 1.9815 |
| Air gap | a2 |  | 0.068 |
| Plate 3 | t3 | P15 | 1.486 |
| Air gap | a3 |  | 0.11 |
| Mylar | m |  | 0.0138 |
| Graphite | M | Medium | 0.2 |
| Vacuum | v1 |  | 0.065 |
| Graphite | s | Shield | 0.0744 |
| Vacuum | v2 |  | 0.065 |
| Graphite | j1 | Jacket | 0.0546 |
| Vacuum | v3 |  | 0.055 |
| Graphite | c | Half-core width | 0.1375 |

Table A4.5: Depth calculation (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 |

1. Diagrams of calorimeter electronics

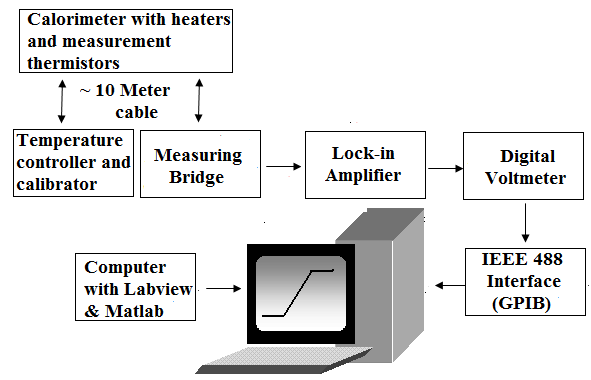
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Figure A5.1: Block diagram of calorimeter electronics

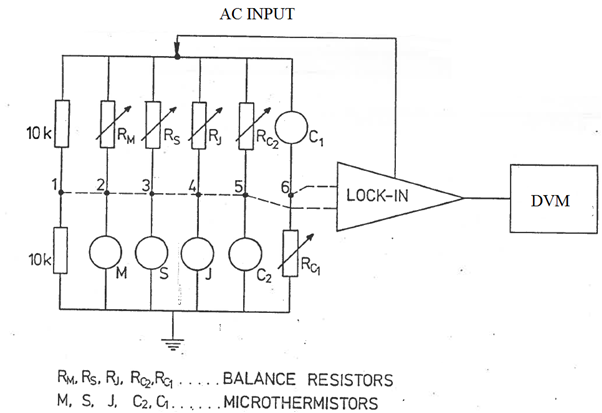
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Figure A5.2: Schematic circuitry of the Wheatstone bridge

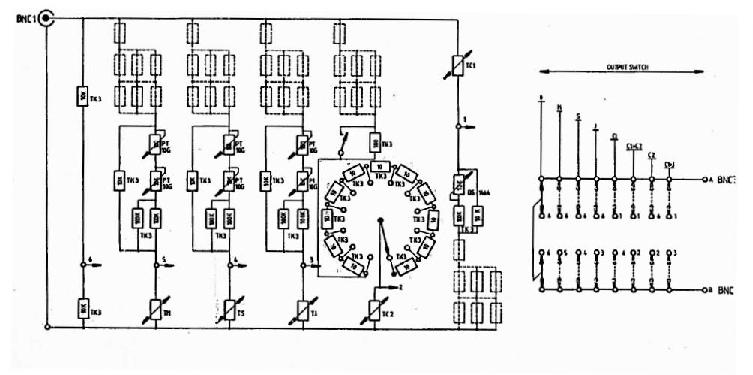


Figure A5.3: Full circuitry of the Wheatstone bridge



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

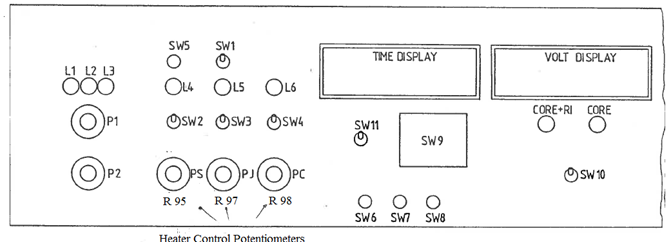


Figure A5.5: Front panel of the temperature controller



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

1. Front panel of the LabVIEWTM program

#### 

1. 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%.

Table A7.1: Results of the calorimeter timer test

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 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 |

**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.

Table A7.2: Results of calorimeter reference resistor measurements

|  |  |  |
| --- | --- | --- |
| Measurement Number | Measured Resistance (Ω) | Deviation from 10 kΩ  (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 |  |

1. Operating procedure of the calorimeter
2. 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.
3. 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.

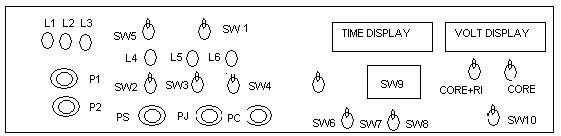


Figure A8.1: Front panel of the temperature controller

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.

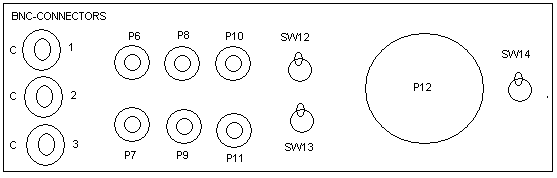


Figure A8.2: Front panel of the calorimeter measuring bridge   
(bottom part of the photograph shown in 5.4)

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).

1. Once the calorimeter has stabilised perform DVM calibration (see Section 3.1.1 for detailed procedure).
2. Perform the electrical calibration and find the calibration factor for core heating. (see Section 3.1.2 for the detailed procedure).
3. 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)
4. 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.

1. 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 µV range) first before changing to higher sensitivity range (50 µV range used).

1. 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 µV 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 LabVIEWTM 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 LabVIEWTM 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 LabVIEWTM 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.

1. 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.

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

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

Select the 50 µV 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.

Start a stop watch and start the LabVIEWTM 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 VCRI and VC 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.

Open the MATLAB GUI titled “Electrical calibration”.

Press the button marked “Analysis”. A new window will open to select the data file for analysis.

Select the data file (e.g. ae130412-1.txt) from the directory and click open. A dialogue box will appear asking for “VCRI” and “VC” 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**

1. Procedure for the calculation of heater settings

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

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

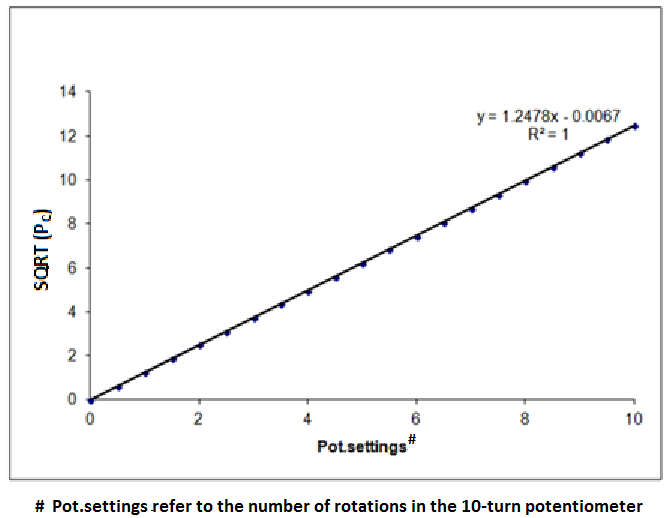
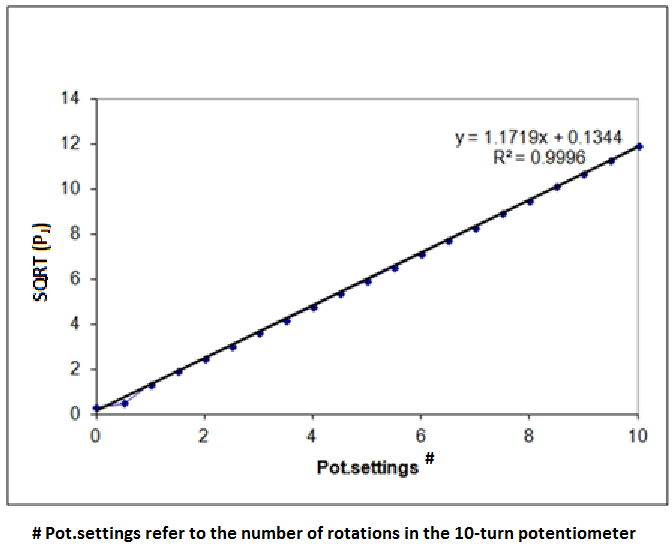


Figure A11.1: Core heater calibration

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FigureA11.2: Jacket heater calibration

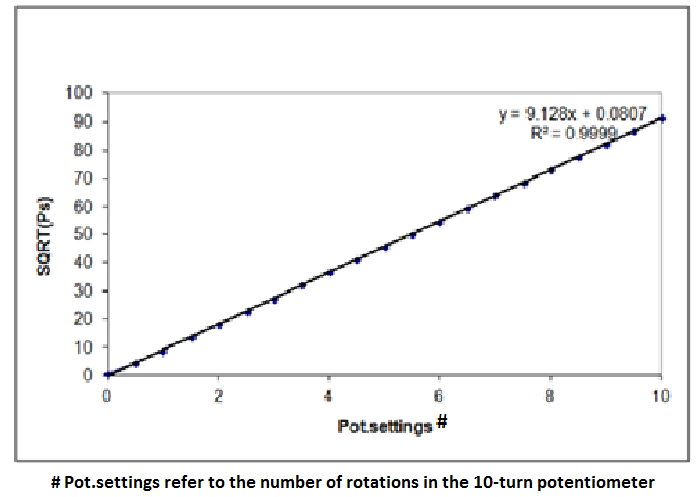


Figure A11.3: Shield heater calibration

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

√PC = A.DC + B (µW) (21)

√PJ = P.DJ + Q (µW) (22)

√PS = R.DS + S (µW) (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

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| A | B | P | 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 (DC), jacket (DJ) and shield (DS) are given by

DC = (√PC – B)/A (24)

DJ = (√PJ – Q)/P (25)

DS = (√PS – S)/R (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 (**Ḋ**) is expressed in mGy/sec, then the desired heating power in µW is given by multiplying the dose rate by the mass of each body,

PC = **Ḋ** (mGy/s) × 1.5622(g) (27)

PJ = **Ḋ** (mGy/s) × 1.56(g) (28)

PS = **Ḋ** (mGy/s) × 107(g) (29)

The dial settings DC, DJ and DS for PC, PJ and PS can be calculated from equations DC = (√PC – B)/A (24), DJ = (√PJ – Q)/P (25) and DS = (√PS – 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.

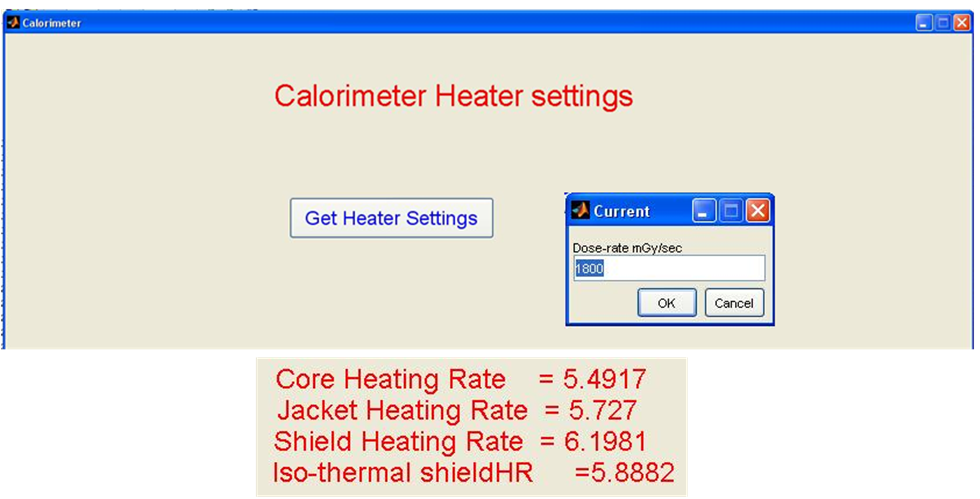


Figure A11.4: Matlab GUI for the calculation of heater settings

1. 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 |
| 60Co (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.

1. Estimation of the specific heat of graphite core from calorimeter measurements

The graphite absorbed dose in calorimetry measurements is given by,

Dcore = Cp . dT (J/kg) (1)

Where, Cp 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,

Dcore = (dV . CDVM . CECF / m) (10-3 J/kg) (2)

From equations (1) and (2),

Cp = dV . CDVM . CECF / dT (J/kg/T) (3)

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

Voltage rise (dV) =3.6298 V

Dose estimated, Dcore =3.084 Gy

DVM calibration Factor (CDVM) = 45.42 (dR/V) × 104

Electrical Calibration Factor (CECF) = 29.22 (10-4 J/dR)

Using these data in equation (3) we get,

Cp = 3.084 / dT. (4)

Fractional change in core thermistor value

dR (%dR/R) = 0.016486552 Ω (5)

The temperature sensitivity of the 10 kΩ 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):

Cp = 729.60 J/kg/K.

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

Cp = 710 J/kg/K.

1. 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 Ǭ 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 Ǭ output signal from IC 74123/1, coinciding with the start of the beam from the linac. Likewise, the leading edge of the Ǭ 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.

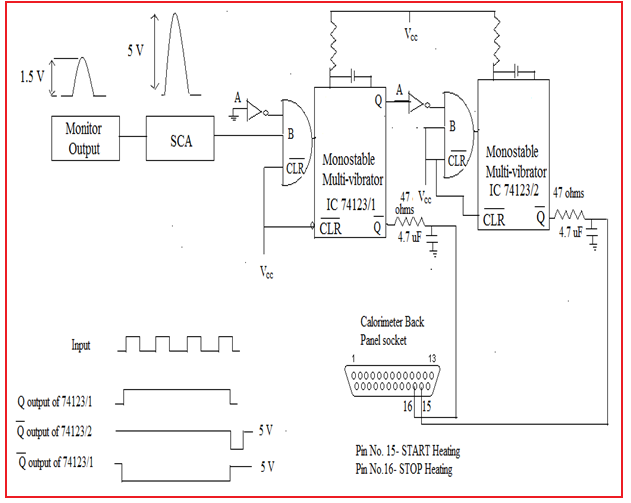


Figure A13.1: Circuit for automatic switching on/off the heaters.

REFERENCES

1. Commonwealth of Australia, "National Measurement Act 1960", Australian Government Publishing Service, 1993.
2. Witzani, K E Duftschmid, Ch Strachotinsky and A Leitner, A Graphite Absorbed Dose Calorimeter In The Quasi-Isothermal Mode Of Operation, Metrologia, 20, 73-79, 1984.
3. Allisy Roberts PJ, Burns DT, Boas JF, Huntley RB and Wise KN, Comparison of the standards for absorbed dose to water of the ARPANSA and the BIPM for 60Co gamma radiation, Rapport BIPM-99/17, October 2000.
4. Robert B Huntley and John F Boas (ARL) and Haitse Van der Gaast (ANSTO) The 1997 determination of the Australian standards of Exposure and Absorbed dose at 60Co, ARPANSA Technical Report ARL/TR 126, 1998.
5. Lye JE, Butler DJ, Franich RD, Harty PD, Oliver CP, Ramanathan G, Webb DV, and Wright T, Direct MC Conversion of absorbed dose to graphite to absorbed dose to water for 60Co radiation, Rad. Prot. Dos. Vol. 155, No. 1, 100-109, 2013.
6. Kessler C, Burns DT, Allisy PJ, Butler D, Lye J and Webb D, Comparison of the standards for absorbed dose to water of the ARPANSA and the BIPM for 60Co γ radiation, Metrologia 49 (06009) 2012.
7. Ramanathan G, Harty P, Lye J, Oliver C, Butler D and Webb D, Establishment of calorimetry based absorbed dose standard for newly installed Elekta Synergy accelerator at ARPANSA, Standards, applications and quality assurance in medical radiation dosimetry (IDOS) Proceedings of an international symposium, Vienna 9-12, November 2010.
8. Picard S, Burns DT, Roger P , Harty PD, Ramanathan G, Lye JE, Wright T, Butler DJ, Cole A, Oliver C, Webb DV, Key comparison BIPM.RI(I)-K6 of the standards for absorbed dose to water of the ARPANSA, Australia and the BIPM in accelerator photon beams, Metrologia, 51,Tech. Suppl., 06006, 2014.
9. Ramanathan G, Butler D, Webb D, Oliver C and Sargent R, The comparison of the ARPANSA and IAEA K-4 graphite calorimeters for the measurement of absorbed dose from 60Co, Proceedings of Absorbed Dose and Air Kerma Primary Standards Workshop, LNHB, Paris, May 2007.
10. Huntley RB et al, The Australian Standard Of Absorbed Dose, in Proceedings of the NPL workshop on recent advances in calorimetric absorbed dose standards, NPL Report CIRM 42 2000.
11. John S. Pruitt, Steve R. Domen and Robert Loevinger, The Graphite Calorimeter as a Standard of Absorbed Dose for Co-60 Gamma Radiation, Journal of Research of the National Bureau of Standards, Vol.86, No.5, September-October, 1981.
12. Andreo P, Burns D T, Hohlfeld K, Huq M S, Kanai T, Laitano F, Smythe V G and Vynckier S Absorbed dose determination in external beam radiotherapy IAEA Technical Report Series No. 398, 2000.
13. Wise K, Monte Carlo methods used to develop the Australian Absorbed Dose Standard, ARPANSA Technical Report 132, 2001.
14. Be M-M, Chiste V, Dulieu C, Browne E, Baglin C, Chechev V, Kuzmenco N, Helmer R, Kondev F, MacMahon D, Lee K B, Table of Radionuclides (Comments on evaluation), Monographie BIPM- 5 Vol. 3, 2006.
15. Allisy-Roberts P.J., Burns D.T., Summary of the BIPM.RI(I)-K4 comparison for absorbed dose to water in 60Co gamma radiation, Metrologia, 42, Tech. Suppl., 06002, 2005.
16. Boutillon M., Perroche A.-M., Ionometric determination of absorbed dose to water for Cobalt‑60 gamma rays, Phys. Med. Biol., 38, 439-454, 1993.
17. Picard S, Burns DT and Roger P, Construction of an Absorbed-Dose Graphite Calorimeter, Rapport BIPM-09/01, May 2009.