

A Status report on the NPL Water Calorimeter

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Centre for Ionising Radiation Metrology

December 1998

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ABSTRACT

At present, the primary standard at NPL for the measurement of absorbed dose in high energy photon beams is a graphite calorimeter. However, the quantity of interest in radiation dosimetry is absorbed dose to water. Therefore, a new absorbed dose to water standard based on water calorimetry has been developed for use in high energy photon and electron beams. The calorimeter operates at 4 °C, with temperature control being provided by a combination of liquid and air cooling. The sealed glass inner vessel of the calorimeter has been designed to minimise the effect of non-water materials on the measurement of absorbed dose. In particular, great care was taken in the design and construction of the temperature sensing thermistor probes so that glass is the only material in contact with high purity water inside the vessel. Measurements of absorbed dose to water made in 6, 10, and 19 MV photons, and 16 MeV electrons agreed, within the measurement uncertainties, with those determined by graphite calorimetry. Initial tests have confirmed the feasibility of the calorimeter design although further work is required before the calorimeter can be used as a primary standard.

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ISSN 1369-6793

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by J Hunt, Head of Centre, Centre for Ionising Radiation Metrology

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1. INTRODUCTION

Radiotherapy treatment uses ionising radiation to destroy cancerous tissue, the aim being to kill the tumour whilst leaving the surrounding tissue as undamaged as possible. In order for this to be the case, one requirement is that the absorbed dose (the mean energy deposited per unit mass) delivered to the target volume should be known with an uncertainty of less than $\pm 5\%$ ¹ and in some cases to within $\pm 3\%$ ². The determination of this dose involves a number of factors, one of which is having accurate knowledge of the ionising radiation output of the treatment device, for example, a linear accelerator, and the resultant absorbed dose imparted by the radiation at various known depths in a medium. Measurements of treatment device output are made typically in a water phantom using an ionisation chamber calibrated in terms of absorbed dose to water.

1.1 AIM OF PROJECT

The aim of this project is to design and build a water calorimeter for use in medium and high energy X-rays and 16 MeV electrons which will enable ionisation chambers to be calibrated directly in terms of absorbed dose to water. The present UK primary standards for both high energy X-rays and electrons at radiotherapy level dose-rates are graphite calorimeters. The high energy X-ray calorimeter has been in use at the National Physical Laboratory (NPL) since 1988^{3,4}. It was built to a design by Domen⁵, and measures absorbed dose to graphite. An electron calorimeter has been in use at NPL since 1988^{6,7} capable of absorbed dose to graphite measurements at high electron dose-rates. However, it is only recently that a new design of electron graphite calorimeter has been built enabling absorbed dose measurements to be made at therapy level dose-rates and doses⁸. This calorimeter forms the measurement base for a new calibration service for electron beam radiotherapy which gives users ion chamber calibration factors in terms of absorbed dose to water^{9,10}. Using the present primary standard graphite calorimeters to calculate absorbed dose to water has an obvious disadvantage in that the calorimeters actually measure absorbed dose to graphite. This has to be converted from absorbed dose to graphite to absorbed dose to water which introduces significant uncertainties¹⁰. It would be advantageous if absorbed dose to water was measured directly, using a water calorimeter, since this would avoid introducing such uncertainties.

1.2 THE BASICS OF WATER CALORIMETRY

A calorimeter is a device used to measure heat input by measuring the temperature rise in a known mass of material such as water. For absorbed dose to water calorimetry, the relationship between absorbed dose to the water D_w and the measured temperature rise ΔT is given by

$$D_w = \frac{c_p \Delta T}{1 - k_{HD}} \quad (1)$$

where c_p is the specific heat capacity of the water and k_{HD} is the heat defect (see section 5.1 for more detailed information on the heat defect). The heat defect, which can be positive (endothermic) or negative (exothermic), is given by

$$k_{HD} = \frac{E_{\checkmark} - E_{\bullet}}{E_{\checkmark}} \quad (2)$$

where E_a is the energy absorbed and E_h is the energy appearing as heat. Equation (1) is true when the measuring element is thermally isolated so that processes such as heat conduction and convection do not affect the temperature at the measurement point.

The calorimeter which first demonstrated the potential of water calorimetry was designed and built by Domen¹¹ (**Figure 1**). Domen based his design on the simple fact that, when irradiated by a beam facing vertically downward, the water temperature decreases with increasing depth (apart from the initial buildup region), so at depths beyond the peak of the depth dose distribution, the water is stable with respect to convection. Additionally, water, unlike graphite, has a very low thermal diffusivity, so that the energy deposited by the radiation tends to stay

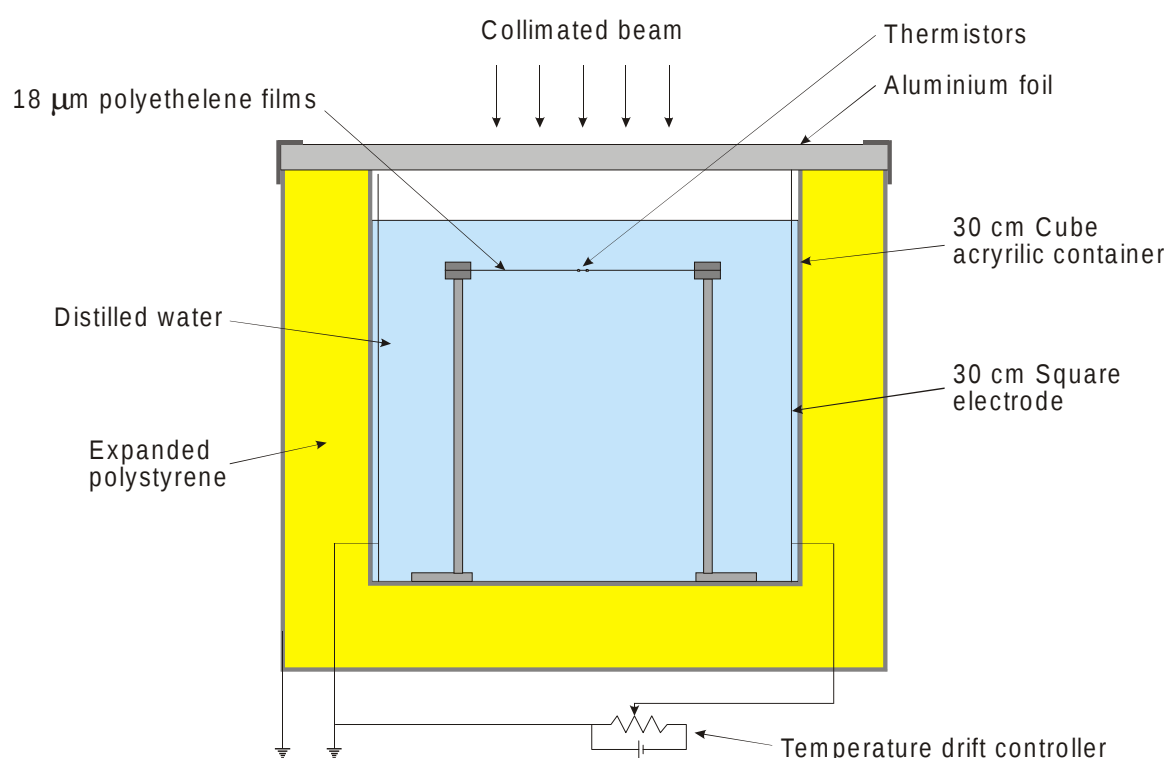


Figure 1 Domen's original calorimeter

where it is, enabling dose measurements to be made at a point. In comparison, graphite calorimeters, such as the present NPL primary standard X-ray graphite calorimeter, require complex thermal isolation systems to enable measurements to be made of dose at a point (actually an average dose over a depth of between 2 and 3 mm).

Domen's calorimeter consisted of a 30 cm by 30 cm by 30 cm (single distilled and open to the atmosphere) water phantom encased in expanded polystyrene for thermal isolation from the surroundings. Two thermistors sandwiched between two polyethylene films comprised the temperature sensors. The measurement depth was varied by changing the water level in the phantom. Using this calorimeter^{11,12} Domen found that (i) the measured temperature change was sensitive to thermistor power and, (ii) the absorbed dose to water assuming a zero heat defect was 3.5% higher than that obtained using graphite calorimetry.

Domen's calorimeter was subsequently duplicated by a number of groups^{13,14,15,16}, and on the whole his original observations were confirmed. Most of these measurements pointed to a

systematic error with the calorimeter, the most likely cause being the unknown heat defect of the systems used.

1.3 MAIN REQUIREMENTS FOR THE NPL WATER CALORIMETER.

The main requirements of the water calorimeter to be built at NPL were that it could be used at (i) measurement depths of 2 cm (medium energy X-rays), 3.3 cm (16 MeV electrons)¹⁷ and 5 cm and 7 cm (high energy X-rays), (ii) dose-rates of between 0.1 Gy/min (medium energy X-rays) and 25 Gy/min (16 MeV electrons), and (iii) have a stable known heat defect.

1.4 RECENT PURE WATER CALORIMETERS

A number of water calorimeters have been designed over the two decades since Domen's original design of 1980. One of the first calorimeters in which water quality was controlled was that of Schulz *et al*^{18,19}. Their main aim was to develop a water calorimeter that could serve as a reference standard. Another calorimeter in which water quality was carefully controlled was that developed by Ross *et al*^{20, 21, 22}. However, this calorimeter operated on a different principle to most other water calorimeters as it did not attempt to measure dose at a point, but rather to measure the relative response of various aqueous systems. A more recent calorimeter, in which the water quality is controlled is that of Domen²³, based on his original design, but modified to allow the control of water quality. Palmans and Seuntjens²⁴ also constructed a water calorimeter based on Domen's design but modified so that it operated at 4 °C. Each of these designs was examined to determine what were the advantages and disadvantages of using each type for use at NPL in high energy photon and electron beams.

1.4.1 Comparison of various water calorimeters

The following points were examined (see **Table 1** and **Table 2**):

i. Water temperature and control.

As a calorimeter operates by measuring a temperature rise, some form of temperature control is required, whether it be passive (insulation only) or active (external heating and cooling).

ii. Thermistor temperature sensing probes and associated electronics.

One of the most important components in a calorimeter: the probes need to be small and the electronics sensitive but low noise.

iii. Core type and water purity.

Core vessels are used to isolate the high purity water from the surrounding phantom medium. They should be made out of a material that will not leach impurities in the water, and be large enough such that heat conduction from it's walls to the measurement point does not introduce a large uncertainty in the temperature measurement.

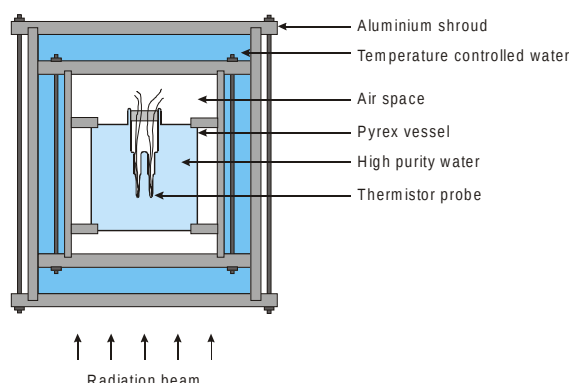
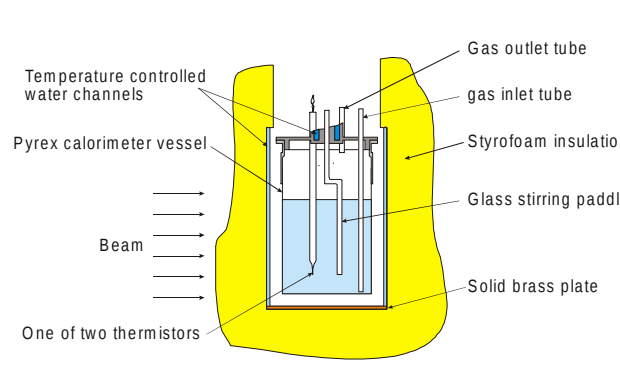
	Schulz, Wu and Weinhaus (1987,88,91)	Ross, Klassen, Shortt and Smith (1984,88,89,94)
	 Aluminium shroud Temperature controlled water Air space Pyrex vessel High purity water Thermistor probe Radiation beam	 Gas outlet tube gas inlet tube Styrofoam insulation Pyrex calorimeter vessel Glass stirring paddle Solid brass plate One of two thermistors Beam Temperature controlled water channels
i	Outer shroud water temperature controlled to $4\text{ }^{\circ}\text{C} \pm 0.1\text{ mK}$ using water supplied at a rate of 5 l/min	Outer shroud water temperature controlled to $21\text{ }^{\circ}\text{C} \pm 0.5\text{ mK}$ using water supplied at a rate of 0.4 l/min
ii	Two $5\text{ k}\Omega$ at $4\text{ }^{\circ}\text{C}$ thermistors secured using silicone grease inside 0.7 mm diameter glass tubing, itself an integral part of the core vessel. Originally separate from the core, but were later joined to the core to prevent impurity ingress. Battery powered DC Wheatstone bridge with thermistors in opposite legs. Output detected by a nanovoltmeter. System calibrated over the range $2\text{--}7\text{ }^{\circ}\text{C}$ at power levels of $15\text{--}200\text{ }\mu\text{W}$. Used at $100\text{ }\mu\text{W}$ for calorimetry, corrected to zero power.	Two $10\text{ k}\Omega$ at $21\text{ }^{\circ}\text{C}$ thermistor probes, each being made up of six thermistor beads in series over a length of 10 mm. Two DC Wheatstone bridges (one for each probe). Output detected by a nanovoltmeter. System calibrated over a $10\text{ }^{\circ}\text{C}$ range against a PRT (1 mK resolution, 5 mK accuracy). Probe power dissipation $18\text{ }\mu\text{W}$ ($3\text{ }\mu\text{W}$ per bead).
iii	10 cm by 10 cm cylindrical glass cores (one each for 3 cm and 10 cm measurement depths), of wall thickness $\sim 3\text{ mm}$ (50 mm by 0.86 mm window for 3 cm core). Radiation enters through flat end of cylinder. Water purified using commercial ion exchange system, and bubbled with gases prior to filling the vessel.	10 cm by 5 cm cylindrical glass core of wall thickness 0.18 mm. Contents stirred with glass paddle. Radiation enters through curved side of cylinder. Water purified by passing through a charcoal filter, a Millipore reverse osmosis unit and a Millipore UV unit. The water could be bubbled in the core vessel.
iv	Glass, 60 mm ² of Teflon.	Glass.
v	10 cm and 3.1 cm.	Dose at a point not measured.
vi	As the core vessel is large, it's glass walls should only have a small effect on the dose and temperature at the measurement point. However the air space surrounding the core (originally to be water filled) and the aluminium shroud make the whole calorimeter in-homogenous. Schulz <i>et al</i> used a separate dummy core for chamber measurements which take these phantom in-homogeneities into account.	The brass shroud around the vessel makes this set-up in-homogenous. However, this system was developed for measuring the relative response of various aqueous systems for which phantom homogeneity was not critical.
vii	For O_2 ratio of 0.987 ± 0.001 For N_2 ratio of 1.002 ± 0.001	For 50:50 H_2/O_2(with gas space) ratio of 1.024 ± 0.005 For H_2 only ratio of 1.000 ± 0.005

Table 1 Comparison of four different calorimeter designs (1)

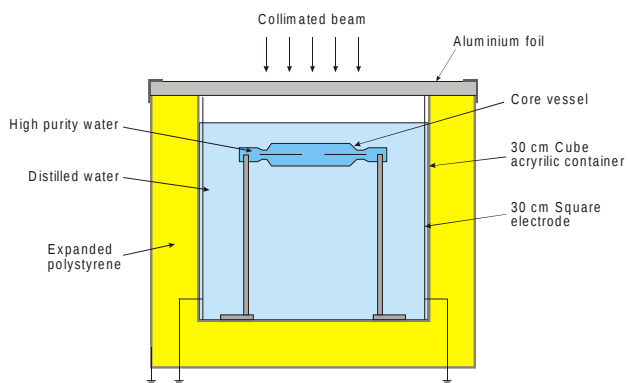
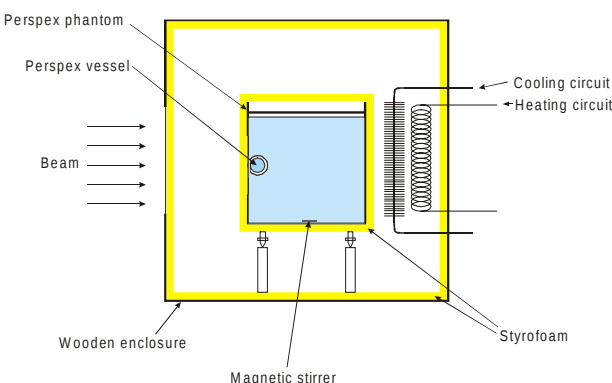
	Domen (1994)	Palmans and Seuntjens (1994)
		
i	Passive control only at 21 °C (room temperature). Thermal inertial of water maintains stability.	Outer shroud air controlled at 4 °C ± 0.1 mK using a combination of water cooling and electrical heating.
ii	Two 3.3 kΩ at 22 °C thermistor beads embedding in epoxy at the end of glass capillaries of total diameter ~ 0.4 mm. Battery powered DC Wheatstone bridge with thermistors in opposite legs. Output measured by nanovoltmeter. System calibrated over the range 15-29 °C. Probe power dissipation typically between 9-30 μW.	Two probes constructed to ‘Domen’ design, but using larger 0.8 mm diameter glass capillaries. Single arm AC bridge with two thermistors in one half. Bridge output connected to a lock-in amplifier. Amplifier output measured by a precision voltmeter. Probes calibrated over the range 2-7 °C using a separate DC system.
iii	11 cm by 3.3 cm cylindrical glass core of wall thickness between 0.25 and 0.33 mm. Radiation enters through curved side of cylinder. The water was prepared using a filter, deioniser, and an organic absorber. Gasses were bubbled through prior to filling the vessel.	15 cm by 4 cm cylindrical acrylic core of wall thickness 0.5 mm. Radiation enters through curved side of cylinder. The water was prepared distilling 6 times. Gasses were bubbled through prior to filling the vessel.
iv	Glass, platinum wire (for electrical grounding) 5 mm ² of low density polyethylene, epoxy (from probes).	Acrylic, glass, epoxy (from probes)
v	Any depth greater than ~ 2 cm.	Any depth greater than ~ 2.5 cm.
vi	The core vessel is surrounded by once-distilled water, making the phantom essentially homogenous, except for the glass of the core vessel itself.	The core vessel is surrounded by once-distilled water, making the phantom essentially homogenous, except for the acrylic of the core vessel itself.
vii	N₂/H₂ ratio of 1.001 ± 0.001 (random uncert. only) H₂/O₂ showed large variable changes in response	Combined (weighted) H ₂ and Ar results 0.995 ± 0.007

Table 2 Comparison of four different calorimeter designs (2)

iv. Materials in contact with the high purity water

Ideally, nothing would be in contact with the high purity water. However, this is not possible, so the next best thing would be for only non-contaminating easy to clean materials such as glass to be in contact. In practise, there is also likely to be Teflon present (often used to seal the openings to the core vessels).

v. Measurement depths available.

The NPL requirements are measurement depths of 2, 3.3, 5 and 7 cm. One design of calorimeter may be ideally suited for use at one of these measurement depths, but not at others.

vi. Phantom homogeneity.

The core, phantom and enclosure will all affect the dose at the point of measurement by perturbing X-ray/electron beam. This effect should be minimised.

vii. Results

Results of calorimeter to ion chamber ratio (or calorimeter to calorimeter) measurements for various aqueous solutions.

1.4.2 Summary of various calorimeter designs

Table 3 summarises the advantages and disadvantages of various calorimeter designs.

1.5 THE IDEAL WATER CALORIMETER

The ideal water calorimeter would consist of a mass of pure water with a zero heat defect, into which an infinitesimally small temperature sensor was placed. It would be thermally isolated from its surroundings, there would be no heat flow or convection in the water that would upset the temperature stability of the system, there would be no containment vessel which could contaminate the water or affect the temperature stability and no chemical impurities in the water that would result in a heat defect.

1.5.1 NPL design calorimeter

It is not possible to build the ‘ideal water calorimeter’. Unless water in the form of ice²⁵ is used as the absorbing medium, it has to have some kind of containment vessel, and temperature sensors are of finite size. However, it is possible to virtually eliminate convection, provide good thermal isolation, and with careful preparation, have an aqueous solution with known constant heat defect.

Briefly, the NPL design calorimeter consists of:

- A temperature controlled water phantom and enclosure. It operates at 4 °C to eliminate convection, using a combination of a water and air cooled shroud, as this results in a more compact calorimeter (see section 2).
- A glass calorimeter vessel. This sits in the water phantom and contains the high purity water (see section 3).

- Two temperature sensing probes and associated electronics. The probes pass through the walls of the calorimeter vessel into the high purity water to measure the rise in temperature due to the incident radiation (see section 4).

Each of these components is described in detail in the following sections of this report.

	Advantages	Disadvantages
SCHULZ <i>et al</i>	Temperature controlled at 4 °C (eliminates convection). Has large diameter glass core. Flat beam entrance window. Only Teflon non glass material in contact with high purity water.	Thick walled (3 mm) core Bulky thermistor probe mountings with no fine positioning adjustment. Non homogenous phantom due to air around core vessel.
ROSS <i>et al</i>	Temperature controlled. Thin walled glass core. Removable thin thermistor probes giving two temperature plots for each irradiation. No non-glass materials in contact with high purity water.	Temperature control is at 21 °C. Dose is not measured at a point. The beam entrance window is the cylindrical side of the glass core. The phantom is non homogenous (brass, air, glass present).
DOMEN	Thin walled glass core. Two removable, thin thermistor probes. Homogenous phantom	No active temperature control with room temperature operation only. Small diameter glass vessel with cylindrical beam window. Epoxy in contact with high purity water.
PALMANS <i>et al</i>	Temperature controlled at 4 °C (eliminates convection). Two removable thin thermistor probes Homogenous phantom	Acrylic core vessel with cylindrical beam entrance window. Epoxy and acrylic in contact with high purity water.

Table 3 Advantages and disadvantages of various calorimeter designs

2. WATER PHANTOM AND ENCLOSURE

The aim of this part of the project was to build a shroud or enclosure to enable the calorimeter vessel to be maintained at a temperature of $4\text{ }^{\circ}\text{C} \pm 0.05\text{ }^{\circ}\text{C}$. The reason for operating at $4\text{ }^{\circ}\text{C}$ is that, at this temperature, the likelihood of convection being set up in water is greatly reduced²⁶. If we consider a small element of water, convection will take place when the upward buoyancy force on the element overcomes the drag force due to the viscosity of the fluid. For water, the thermal expansivity, and therefore the change in buoyancy, passes through a minimum at $4\text{ }^{\circ}\text{C}$. Therefore, as we move away from $4\text{ }^{\circ}\text{C}$, the likelihood of convection being set up increases considerably. For example, at $20\text{ }^{\circ}\text{C}$, the thermal expansivity of water is 250 times what it is at 3.95 and $4.05\text{ }^{\circ}\text{C}$. In addition to maintaining the temperature to within the $0.05\text{ }^{\circ}\text{C}$ limit, the maximum temperature gradient in the calorimeter vessel has to be carefully controlled. The temperature rise in water for an absorbed dose of 2 Gy is approximately 0.5 mK . For the background temperature drift over the time of the measurement, typically 10 minutes, to be less than 10% of the temperature rise due to the irradiation, we need a drift rate of less than $5\text{ }\mu\text{K/min}$.

The following sections describe the design and construction of the water phantom, the temperature controlled enclosure, the electronic control systems, and the vessel positioning jig.

2.1 WATER PHANTOM

The system is based around a 25 cm square X-ray phantom that is fixed inside a larger 36 cm square phantom, both phantoms being made out of Perspex. Temperature controlled refrigerant (a mix of water and anti-freeze) circulates around the space between the phantoms at a rate of 6 litres per minute, while the inner phantom is filled with stationary single distilled water (the glass calorimeter vessel is suspended in this stationary water).

Four sides of the inner phantom are therefore shielded against external influences by the temperature controlled refrigerant circulating around the inner phantom, while the other two sides (the top and front) are shielded by a flow of temperature controlled air (see next section for more details).

2.2 TEMPERATURE CONTROLLED ENCLOSURE

An enclosure was designed and built to insulate the phantom from any external temperature variations (see **Figure 2**). A combination of liquid refrigerant and air temperature control is used which has an advantage over just an air control system, such as that of Palmans and Seuntjens²⁴, of being more compact.

The temperature of the circulating air is controlled by a heating/cooling process in the rear section of the enclosure (see section 2.3.2 for more detailed information). After being chilled, the air is directed over the top and down the front of the phantom by the Perspex baffle, and then returns by passing around the outside of the baffle, back into the rear section of the enclosure once again, to be chilled. The expanded polystyrene, which lines the inside of the enclosure and is between 2 and 6 cm thick depending on position, helps to isolate the circulating air and water from any external temperature variations. Outside this, in the main section, is Mu-metal sheet which shields the temperature measurement system from electrical and magnetic (EMF) interference. The whole system is held together by an outer casing of 18 mm MDF. The top and

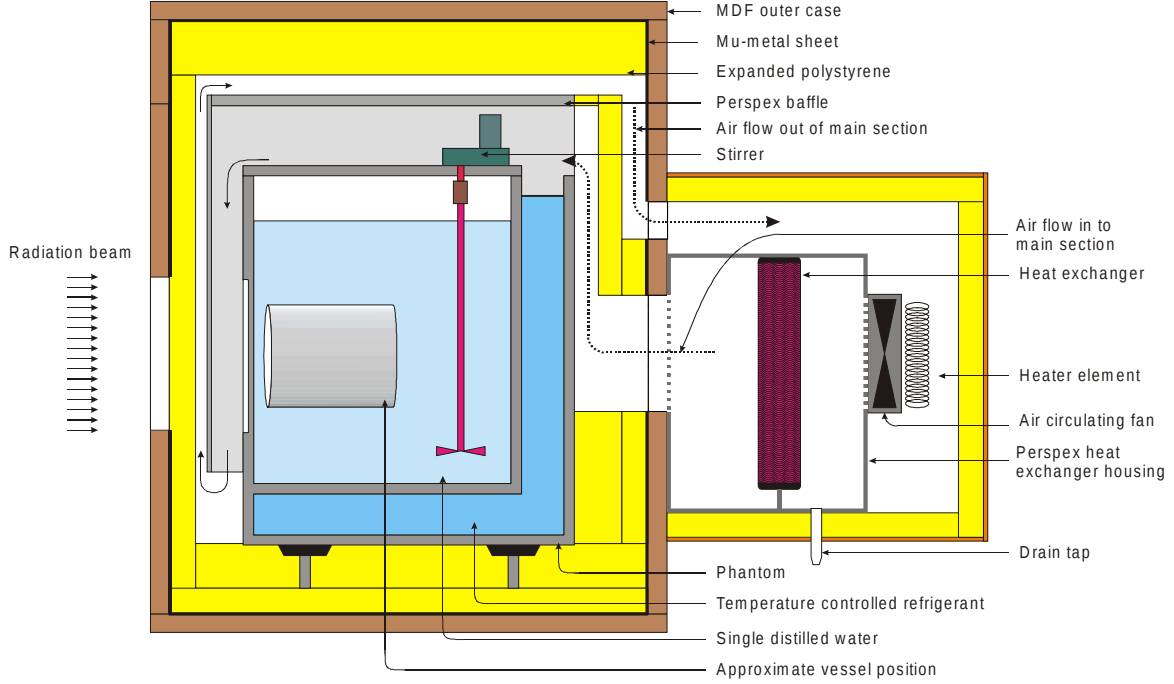


Figure 2 Schematic diagram of temperature controlled enclosure

front of this outer casing are removable to allow easy access to the interior. The front of the case also has a 15 cm diameter hole cut out of it so that the incident radiation beam is not impeded.

2.3 TEMPERATURE CONTROL SYSTEM AND ELECTRONICS

The temperature in the enclosure is controlled by two independent systems, one for the control of the liquid refrigerant, and one for the control of the circulating air.

2.3.1 Refrigerant temperature control system

A schematic diagram of this control system is shown in **Figure 3**. The refrigerant is pumped from the phantom, through a flow cooler and a reservoir containing a 1 kW heating element, then back into the phantom. Its temperature is sensed by two thermistor temperature probes, each connected to its own DC Wheatstone bridge, the outputs of which are calibrated in terms of temperature, and measured using two digital voltmeters (DVM) under the control of a computer. These temperatures are used to determine the amount of heating that has to be applied by the 1 kW heating element using the formula

$$V_h = G \times \left(T_{set} - \frac{(T_{r1} + T_{r2})}{2} \right) + \overline{V}_h \quad (3)$$

where V_h is the voltage applied to the heating control unit from a computer controlled power supply unit (PSU), $\overline{V}_h$ is a running mean of the last sixty values of V_h , T_{set} is the set or required refrigerant temperature, T_{r1} and T_{r2} are the measured refrigerant temperatures, and G is the system gain. V_h can vary from 0 to 30 VDC. This is converted by the heating control unit into pulsed 240 VAC (i.e., 0 VDC = 100% off, 15 VDC = 50% on 50% off, 30 VDC = 100% on).

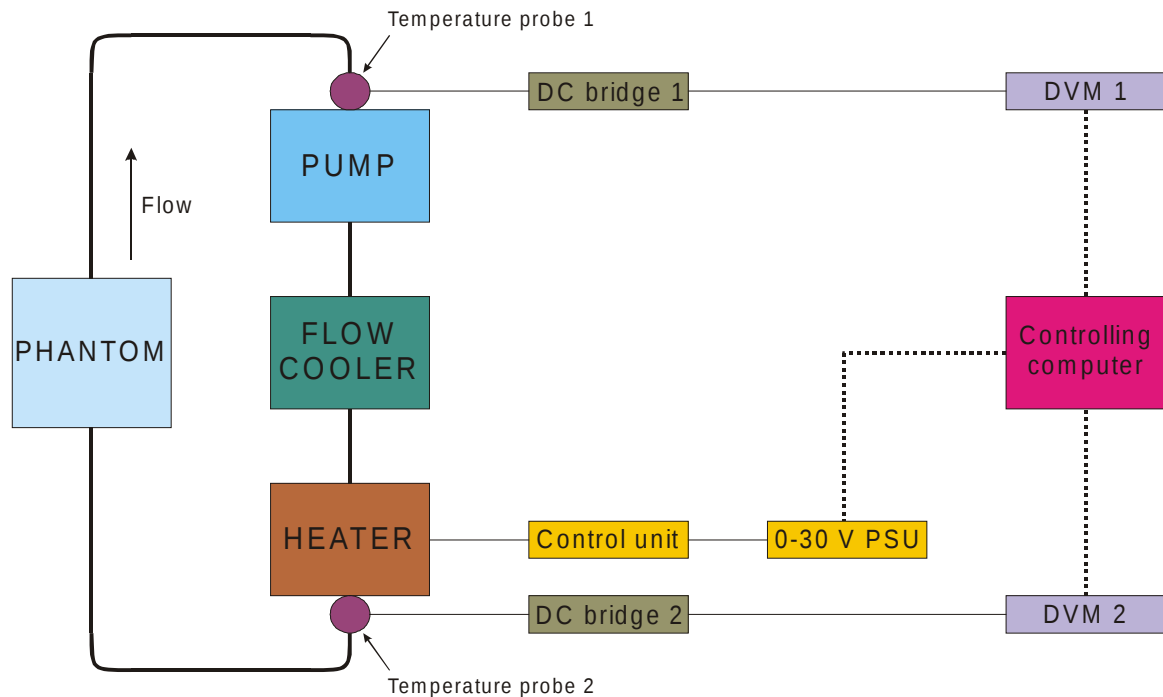


Figure 3 Schematic diagram of refrigerant control system

2.3.2 Air temperature control system

A schematic diagram of this control system is shown in **Figure 4**. The air is circulated around the enclosure, passing over the heater element, the fan, the heat exchanger (cooling element), and finally the temperature probe before being returned to the enclosure. The thermistor

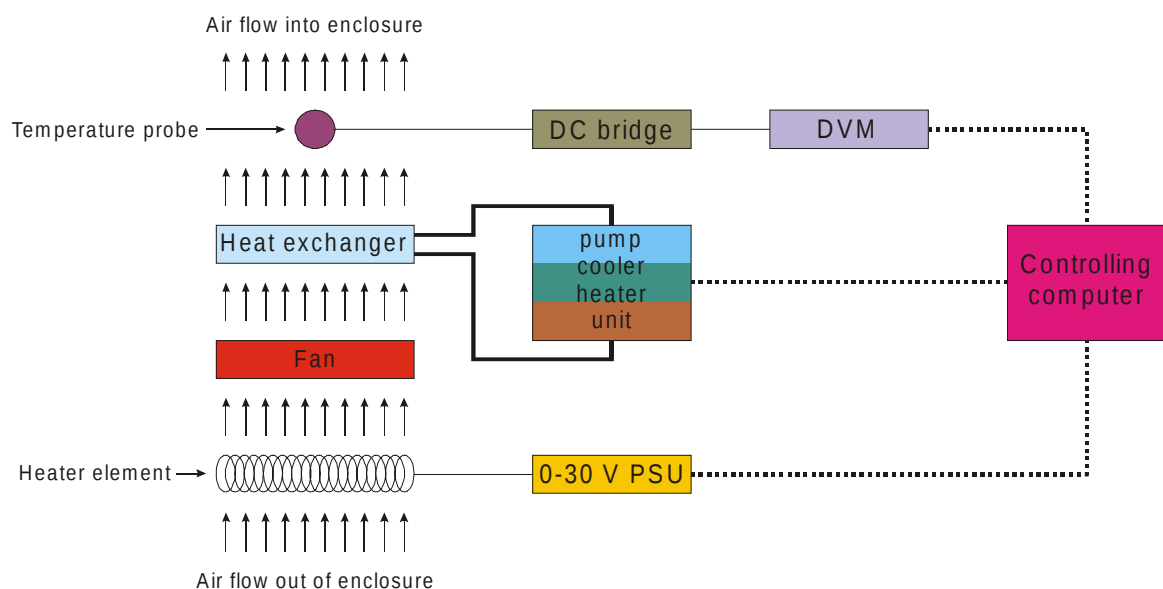


Figure 4 Schematic diagram of the air control system

temperature probe is connected to its own DC Wheatstone bridge, the output of which is calibrated in terms of temperature, and measured using a digital voltmeter (DVM) under the

control of a computer. This temperature is used to determine the amount of heating that has to be applied by the 0-30 V PSU to the heating element using the formula (very similar to that for the refrigerant control)

$$V_h = G \times (T_{set} - T_a) + \overline{V_h} \quad (4)$$

where, as previously, V_h is the voltage applied to the heating element from the computer controlled PSU, $\overline{V_h}$ is a running mean of the last sixty values of V_h , T_{set} is the set or required air temperature, T_a is the measured air temperature, and G is the system gain. In order for the system to be able to cope with large variations in external temperature, the temperature of the heat exchanger's refrigerant is varied over the range -2 °C to 4 °C according to the formula

$$\begin{aligned} &\text{If } V_h > 25 \text{ then } T_{refrigerant} = T_{refrigerant} + 0.1 \\ &\text{else} \\ &\text{If } V_h < 5 \text{ then } T_{refrigerant} = T_{refrigerant} - 0.1 \end{aligned} \quad (5)$$

2.4 ENCLOSURE STABILITY

The temperature stability of the liquid refrigerant and air is shown in **Figure 5** for a 'worst case scenario' (in a room with very poor temperature control). While the external room temperature fluctuates by ± 1 °C (one standard deviation), the control air fluctuates by just ± 4 mK, and the refrigerant (as it enters the phantom) by ± 40 mK. A more realistic comparison can be obtained by testing the system in the LINAC X-ray exposure room, which has a temperature stability of approximately ± 0.1 °C. In this case the control air temperature fluctuates by ± 3 mK, the refrigerant, as it enters the phantom, by ± 11 mK, and the refrigerant, as it leaves the phantom by ± 0.2 mK.

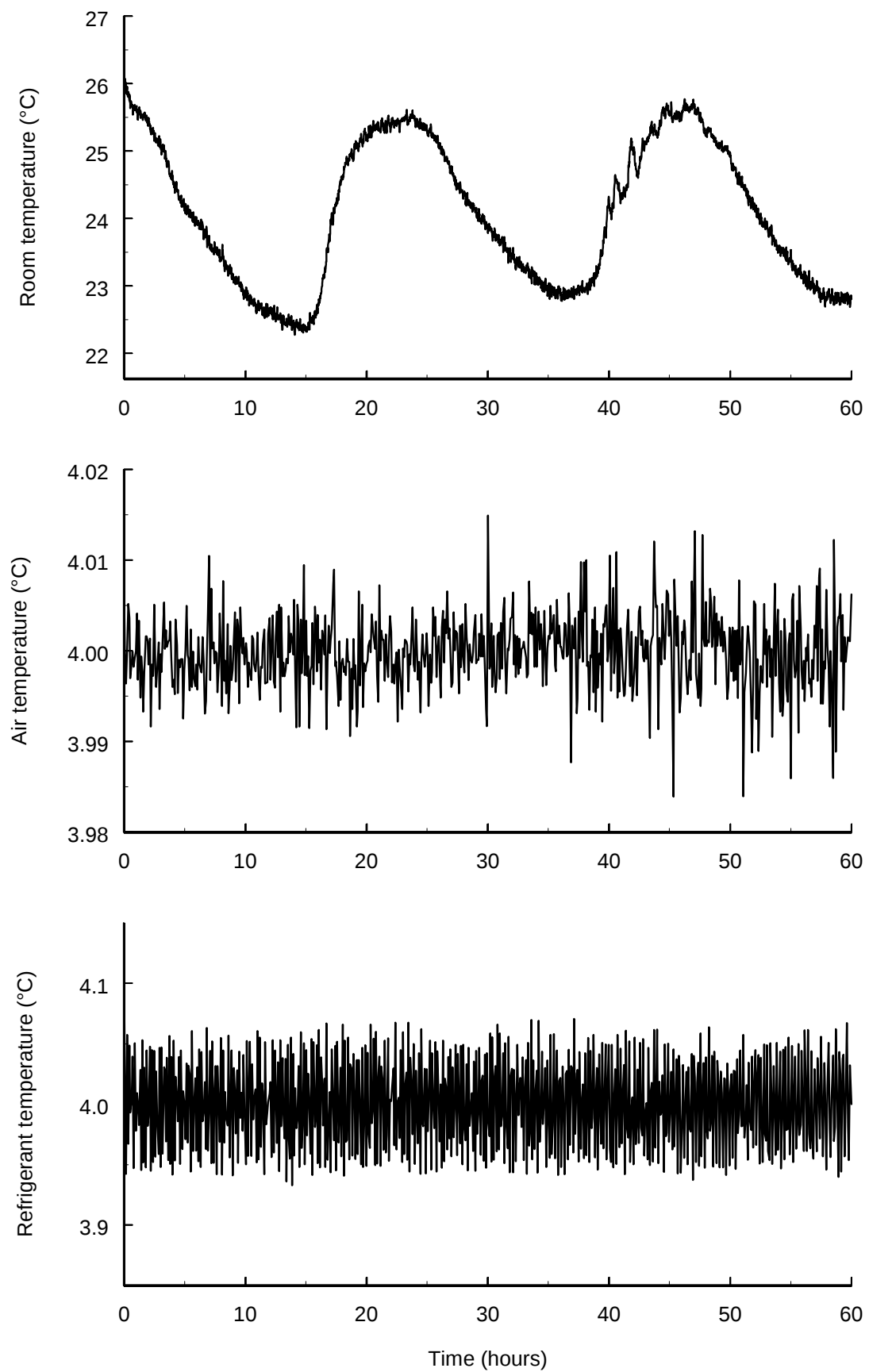


Figure 5 Temperature stability of enclosure (worst case)

2.5 VESSEL POSITIONING JIG

A positioning jig is used to hold the various calorimeter vessels (described in detail in the next section) at the correct measurement depth as shown in **Figure 6** and **Figure 7** with an estimated accuracy of ± 0.2 mm. Briefly, the vessel clamp is fixed to a sliding horizontal carriage by supports *A* and *B*, and the linear shafting that supports the carriage is fixed securely onto the front and rear walls of the water phantom. Supports *A* and *B* and the carriage are made out of Perspex, the vessel clamp out of Victrex Peek (a radiation tolerant plastic), the linear shafting of stainless steel, and the support blocks of aluminium.

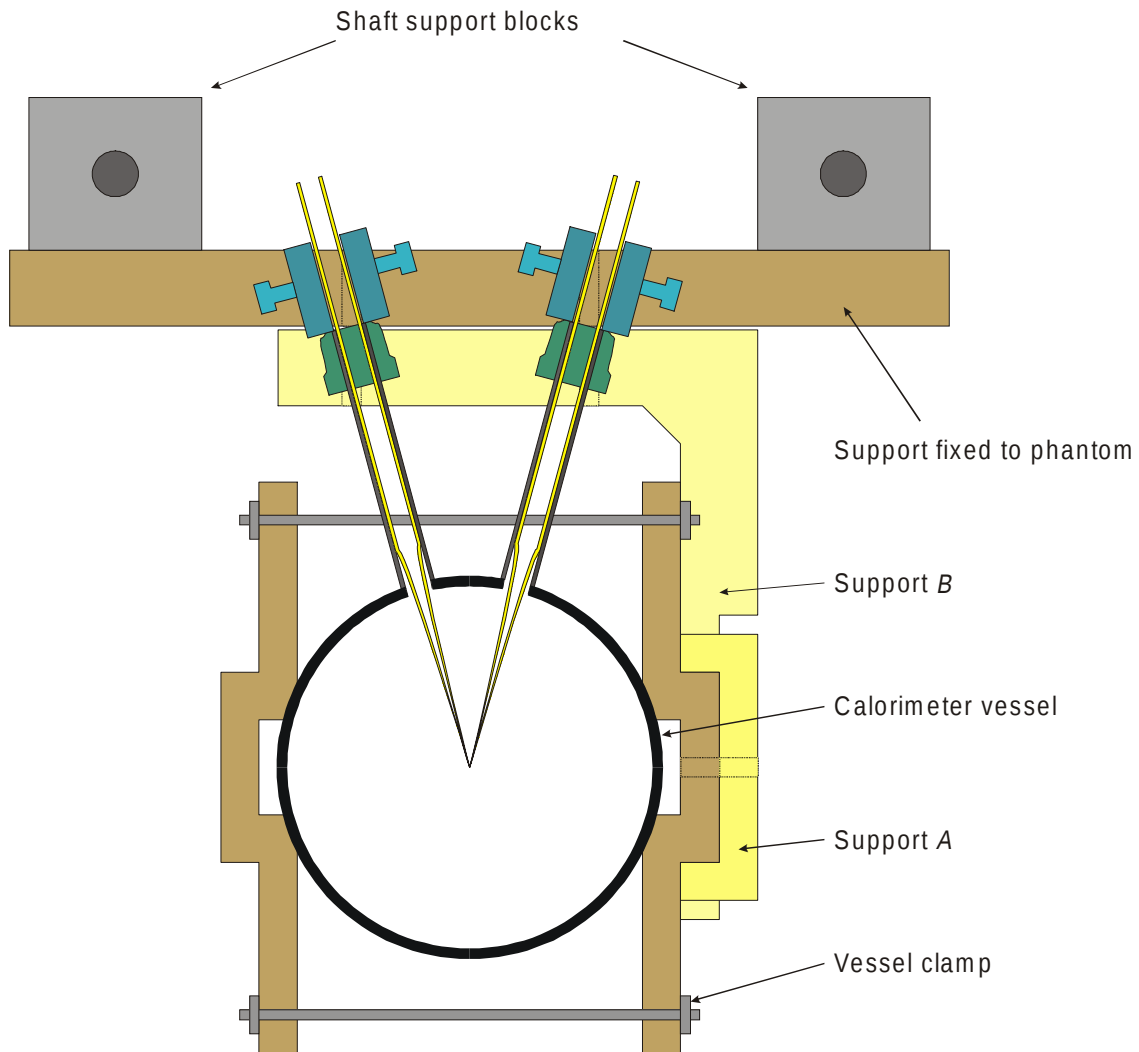


Figure 6 Positioning jig - front view

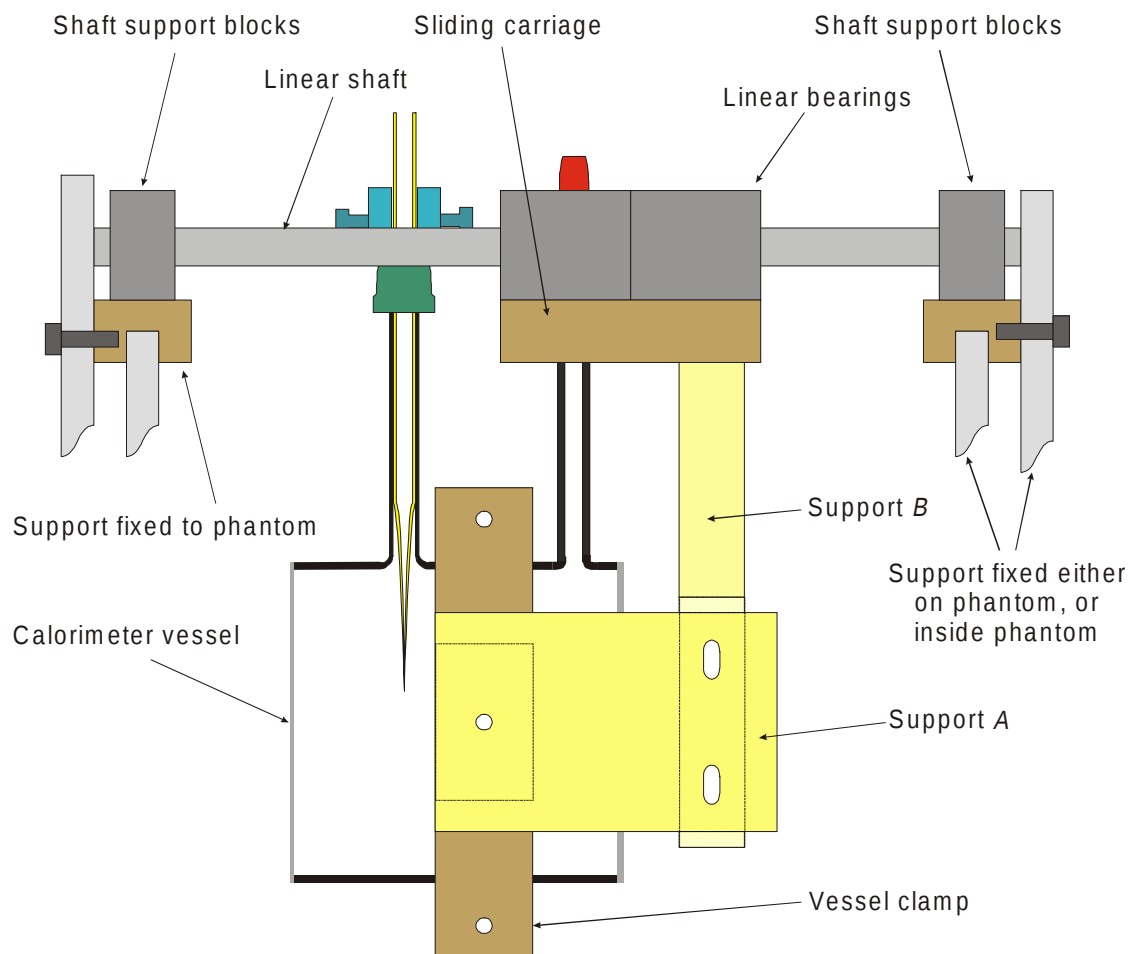


Figure 7 Positioning jig - side view

3. THE CALORIMETER VESSEL

When designing a calorimeter vessel, the following three points need to be given careful consideration:

- i. The range of measurement depths required - in this case, 2 cm for medium energy X-rays, 5 cm for 4 MV to 10 MV X-rays, 7 cm for 10 MV to 19 MV X-rays, and 3.3 cm for 16 MeV electrons.
- ii. The FWHM diameter of the radiation beam - in this case 5.6 cm for medium energy X-rays, 11.6 cm for high energy X-rays, and 20 cm for 16 MeV electrons. If the vessel diameter is much larger than this then the water contained inside it will not be uniformly irradiated. This may cause problems when trying to calculate the heat defect of the system.
- iii. The quantity and position of non-water materials used in its construction which may effect the temperature profile in the vessel, and the water purity.

There are four NPL calorimeter vessels, one for each measurement depth. They are made of glass, a material that can be easily cleaned with chromic acid. The front and rear walls of the vessels are very thin and uniform, and are positioned as far as possible (subject to constraint (ii)) from the measurement point, so that heat build up in them has little effect on the temperature at the measurement point. Their dimensions were optimized by heat-flow modelling, described in detail in section 6.

3.1 4 TO 10 MV X-RAY VESSEL

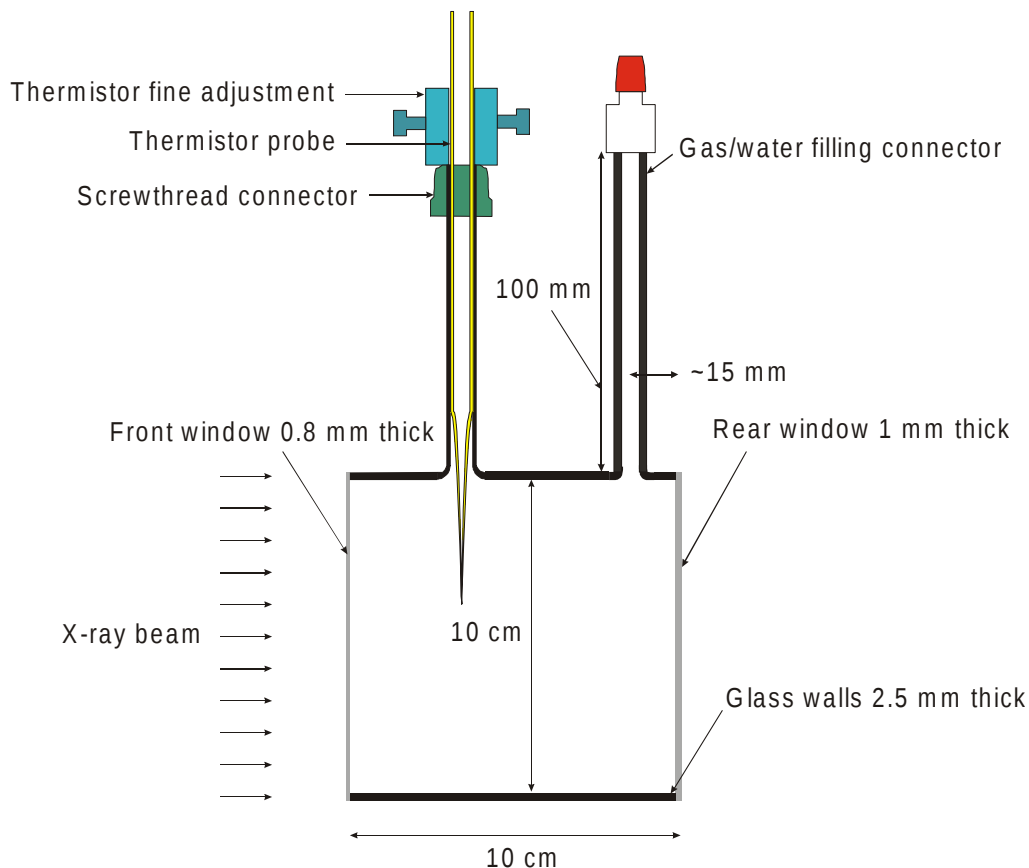


Figure 8 4 to 10 MV X-ray vessel - side view

Figure 8 and **Figure 9** show the 4 to 10 MV X-ray vessel. It was constructed in the following manner by the LGC glass blower and the NPL optical workshop:

- i. a section of glass tube with a diameter of 10 cm and a wall thickness of 2.5 mm was cut to produce a cylinder 10 cm long ,
- ii. a glass disk with a diameter of 10 cm and a thickness of 5.1 mm was fixed to each end of the cylinder (i),
- iii. the position of the glass connectors was identified, and short (1 cm) lugs were fixed to the side of the cylinder,
- iv. the front window was ground down to a thickness of 0.8 mm, and the back to a thickness of 1.0 mm and left unpolished,
- v. the glass connectors were fixed onto the lugs left at stage (iii)

The minimum thickness in stage (iv) to which the front window could be ground was determined by first grinding down a test piece (a glass cylinder with one end window).The window did not need to be polished, but just left with a ground finish (although opaque when

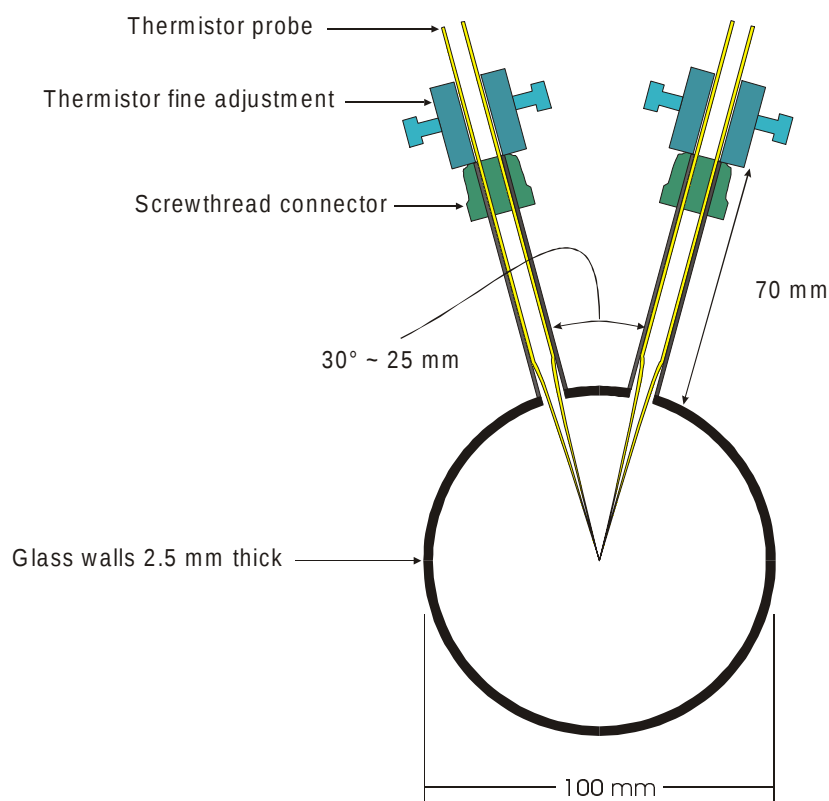


Figure 9 4 to 10 MV X-ray vessel - front view

dry, the window becomes clear when wet). The window was then ground down in stages to a thickness of 0.8 mm. At this point the window cracked when its thickness was being measured. It was decided that a safe thickness for the front window was 0.8 mm. For the vessel itself, the thickness of the front and rear windows was calculated by subtracting the amount of glass removed from the starting thickness of 5.1 mm.

The only materials that will be in contact with the water in the vessel are glass and a small amount of Teflon (seals) and PTFE (valves), all of which can be cleaned using chromic acid.

Two additional features on this vessel were the gas/water filling valve fitted towards the rear, and the thermistor fine adjustment - a simple device to allow more accurate positioning of the thermistors in the vessel, shown in detail in **Figure 10**.

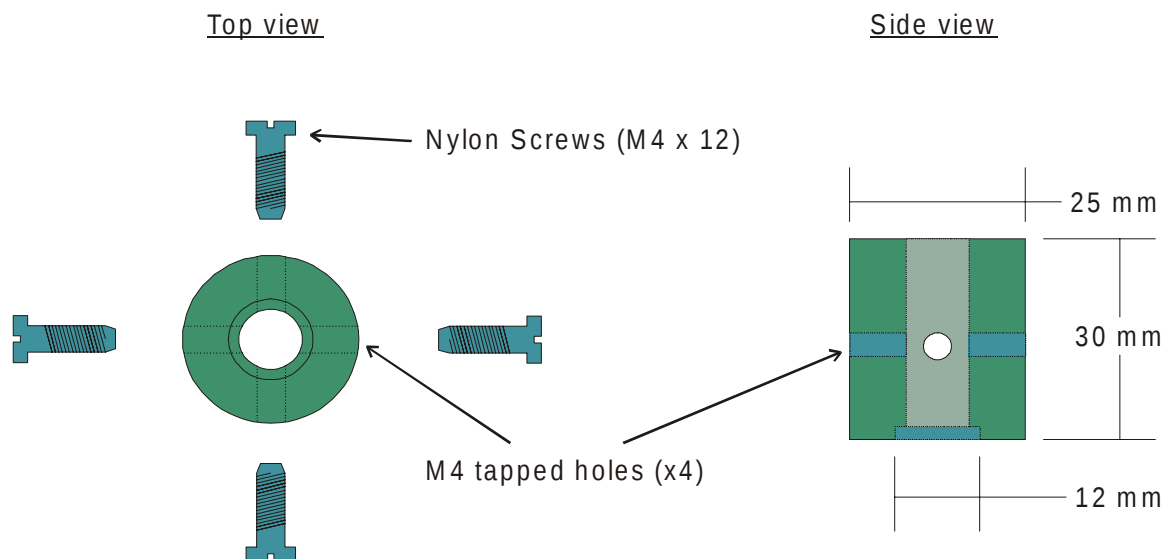


Figure 10 Thermistor fine adjustment

3.2 OTHER VESSELS

There are three other calorimeter vessels, all of which are similar to the low energy X-ray vessel, and were made using the same construction method. Their dimensions are shown in **Table 4**.

Beam quality	Length (cm)	Diameter (cm)	Measurement depth (cm)	Thermistor depth (cm)
16 MeV electrons	6	10	3.3	2.6
10 to 19 MV photons	12	10	7.0	5.2
4 to 10 MV photons	10	10	5.0	3.4
Medium energy x-rays	20	7.5	2.0	1.2

Table 4 Summary of vessel dimensions

4. TEMPERATURE MEASURING SYSTEM

A very important part of the calorimeter is its temperature measuring system. The system as a whole needs to be sensitive and low noise, while the sensing element must be small enough so that it does not perturb the radiation field at the measurement point, and not dissipate excessive amounts of heat that would cause incorrect temperature readings or convection to occur. Additionally, using a probe that was too big would result in a measurement of ‘absorbed dose to temperature probe’, not absorbed dose to water.

The three main types of temperature sensor available are the Platinum Resistance Thermometer (PRT), temperature sensitive resistor (thermistor), and the thermocouple. The thermocouple’s output voltage is related to its temperature; however, for calorimetry purposes it can be disregarded straight away, as it fails to meet the required noise and sensitivity criteria. This leaves the PRT and thermistor. Both of these sensors’ resistance changes with temperature. One way of using these sensors is to calibrate their functions of resistance against temperature directly, using a digital resistance meter and a number of triple point cells, for instance. An alternative method is to connect the sensors into one arm of a Wheatstone bridge and to calibrate the functions of bridge output against temperature.

For use as the main measurement sensor in calorimetry, PRTs can be disregarded because they also fail to meet the required sensitivity criteria, as well as being too large. This leaves us with the thermistor. Fortunately, thermistors can be made very small (less than 0.5 mm), and when used with suitable electronics such as a Wheatstone bridge, be part of a low noise, high sensitivity system.

The following two sections describe in detail the design and construction of the temperature sensing thermistor probes, and the associated electronics.

4.1 NPL DESIGNED THERMISTOR PROBES

There are two main types of thermistor bead that are suitable to be used as the temperature sensor in a water calorimeter. These are (see **Figure 11**) type (a), a Thermometric’s²⁷ type BR11

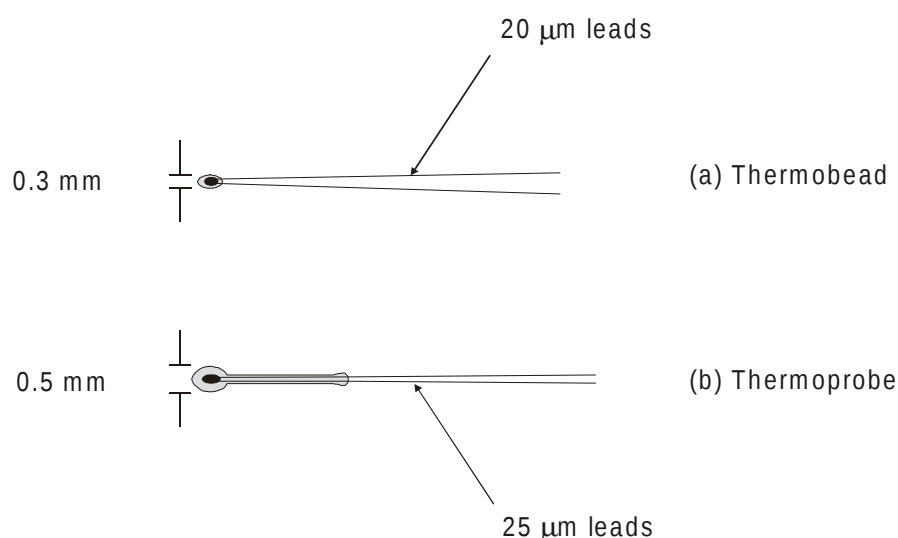


Figure 11 Two types of thermistor, (a) Thermobead, (b) Thermoprobe

thermobead (a ruggedized glass coated bead thermistor of nominal diameter 0.3 mm, with 20 μm platinum alloy leads), and type (b), a Thermometric's type P20 thermoprobe (a bead thermistor hermetically sealed in the tip of a shock resistant glass rod, of nominal diameter 0.5 mm, with 25 μm platinum alloy leads). They are typically used in two different ways. The first, as used by Domen, is to secure using epoxy a thermobead completely inside a pulled glass tube. The second, as used by Palmans and Seuntjens, is to secure using epoxy the shank end of a thermoprobe inside a pulled glass tube, thus leaving the sensor end of the probe exposed directly to water.

We have chosen to use the second method, but with a significant improvement: glass solder (a low melting point glass powder) is used to secure the thermobead in place, instead of epoxy. There are two advantages to using this method of construction: i) there is no epoxy to contaminate the water in the vessel and, ii) there is very little glass surrounding the sensing element of the thermistor (see **Figure 12**).

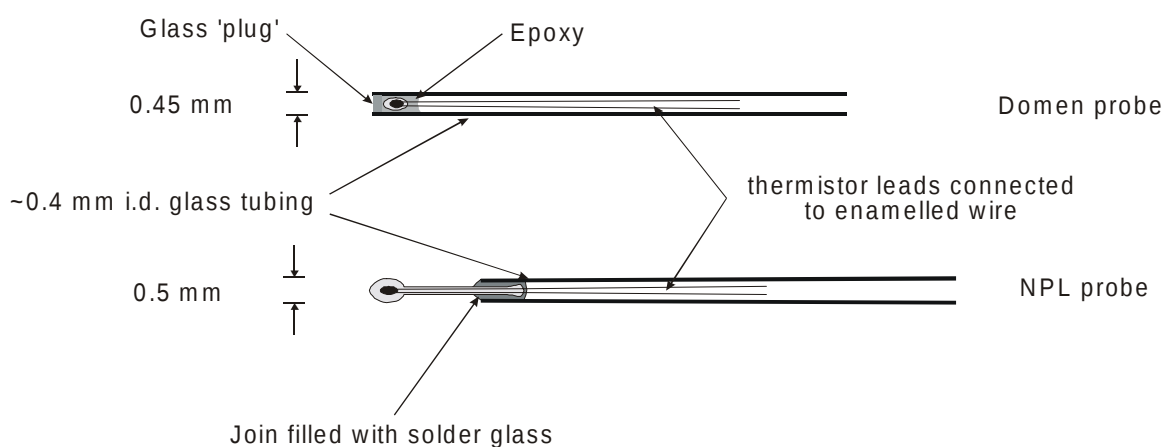


Figure 12 NPL and Domen probe design differences

The actual thermistor probe construction was performed by Alan Ainsworth²⁸, an external glass probe expert. His method of constructing the thermistor probes, is as follows:

- i. Glass tube pulled to required dimensions.

A 7 mm OD straight glass tube is fixed, with a weight on its base, into a rotating chuck. It is heated using an electric heating coil, which provides highly uniform heating over a well defined area of the tube. When the glass is hot enough, the weight fixed to the base of the tube causes it to stretch (in order to produce more consistent results, the tubing actually was pulled in two stages).

- ii. Thermoprobe fixed into end of pulled tubing

The shank end of a thermoprobe is secured using glass solder inside the glass tubing. The wires to the thermoprobe are soldered to enamelled copper wire and brought out to the end of the glass tubing where it is connected to low noise coaxial cable. In order to prevent an electrical short as they leave the thermoprobe, one of the leads is insulated from the other by a very fine glass capillary (OD ~ 0.2 mm).

The final dimensions are shown in **Figure 13**. The top part of the glass tube is filled with dry silica gel, then sealed with silicone rubber. This has two purposes, i) to absorb any condensation when the probes are placed in the cold 4 °C calorimeter and, ii) as a continuing indication that the solder glass join is not leaking.

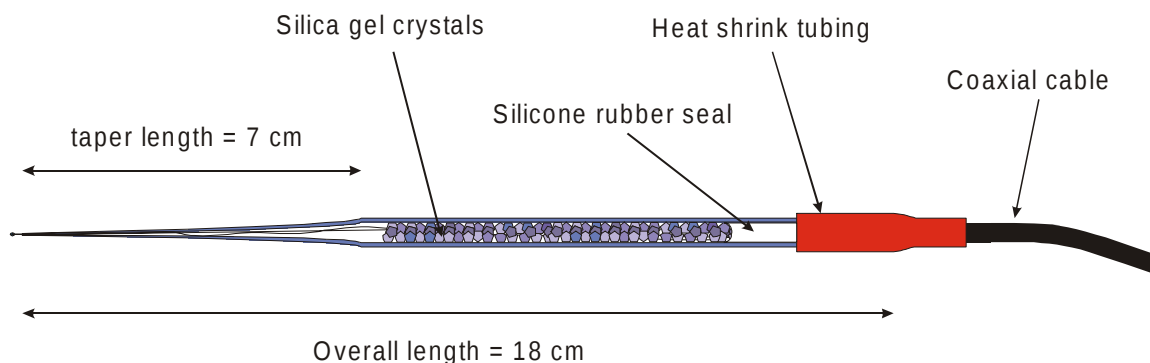


Figure 13 Final probe dimensions

4.2 ELECTRONICS

4.2.1 Double shielded DC Wheatstone bridge

As the linear accelerator environment is known to be electrically noisy (a combination of RF and mains born interference), considerable effort was put into minimising its effect on the bridge electronics. The whole of the new temperature sensing circuitry is double shielded, except for a short 3 m section of cable joining the two glass bead thermistor probes (10 k Ω at 4 °C) to their separate DC Wheatstone bridges. The braid on twisted pair cable makes up the inner shield,

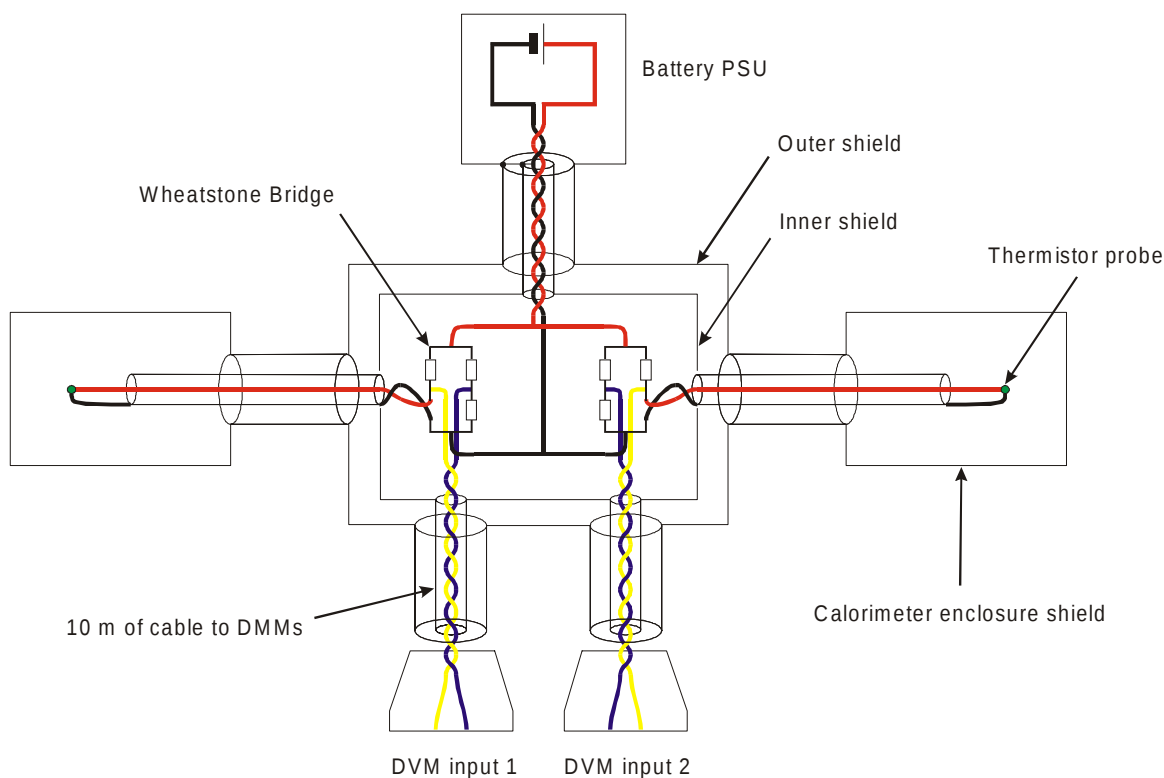


Figure 14 DC bridge arrangement

while the outer shield is made up of RF screened aluminium boxes and RF screened conduit as shown in **Figure 14**. The bridges are powered by a 2 V, NPL designed and built, battery powered precision voltage supply (having the 2 V supply powered by batteries instead of the mains reduces the output noise of the device). The 2 V from the supply can be stepped down to 1 V and 0.4 V by putting a precision resistor in series with the bridge. The power dissipation in each of the thermistors is therefore 100 μ W, 25 μ W, or 4 μ W, depending on the step-down resistor used. The bridge output voltages are read by two digital multi-meters (DMM), each with a resolution of 10 nV. The out-of-balance bridge voltages are calibrated against a platinum resistance thermometer (see section 4.2.2). The end result is a system with a maximum temperature resolution of 0.5 μ K, and a RMS noise of 3 μ K.

4.2.2 Thermistor calibration

The out-of-balance bridge voltages are calibrated against a calibrated platinum resistance thermometer using a method developed at NPL over a number of years²⁹:

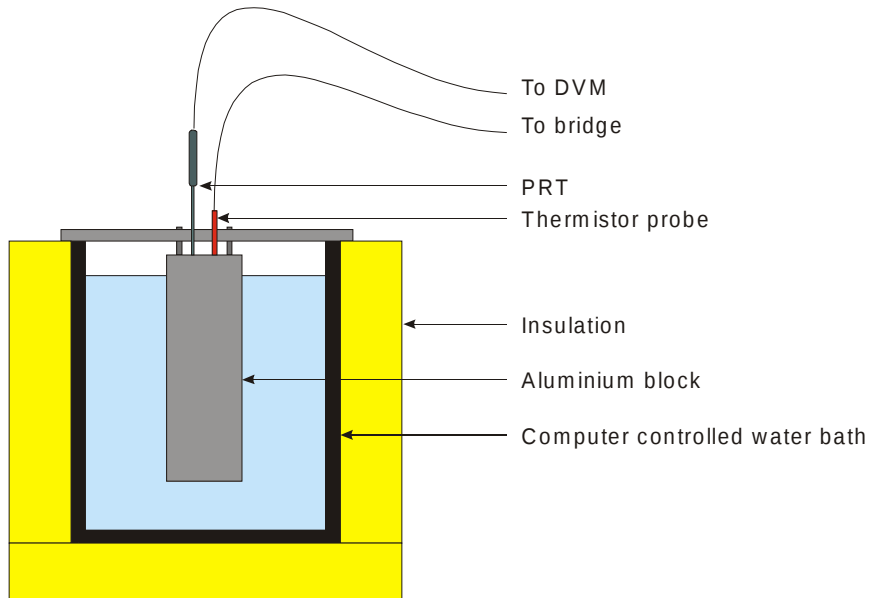


Figure 15 Thermistor calibration bath

The thermistor to be calibrated is placed inside an aluminium block along with the PRT as shown in **Figure 15**. The block is suspended in a computer controlled water bath. As the temperature of the water bath is varied over the required calibration range (usually in steps of 0.25 $^{\circ}$ C), the out of balance bridge voltage and PRT resistance are measured automatically by the computer (300 measurements per set temperature). A plot of the bridge voltage and PRT resistance at a temperature of 2.93 $^{\circ}$ C is shown in **Figure 16**. Once the PRT resistance is converted into degrees Celsius, a fit of bridge voltage against temperature can be made (usually a quadratic or cubic fit). For the plot shown in **Figure 17**, the fit is:

$$T = 3.643584 + 0.0758764 \times V_{bridge} + 1.731 \times 10^{-5} \times V_{bridge}^2 \quad (6)$$

where T is the measured temperature in $^{\circ}$ C, and V_{bridge} is the bridge voltage in mV.

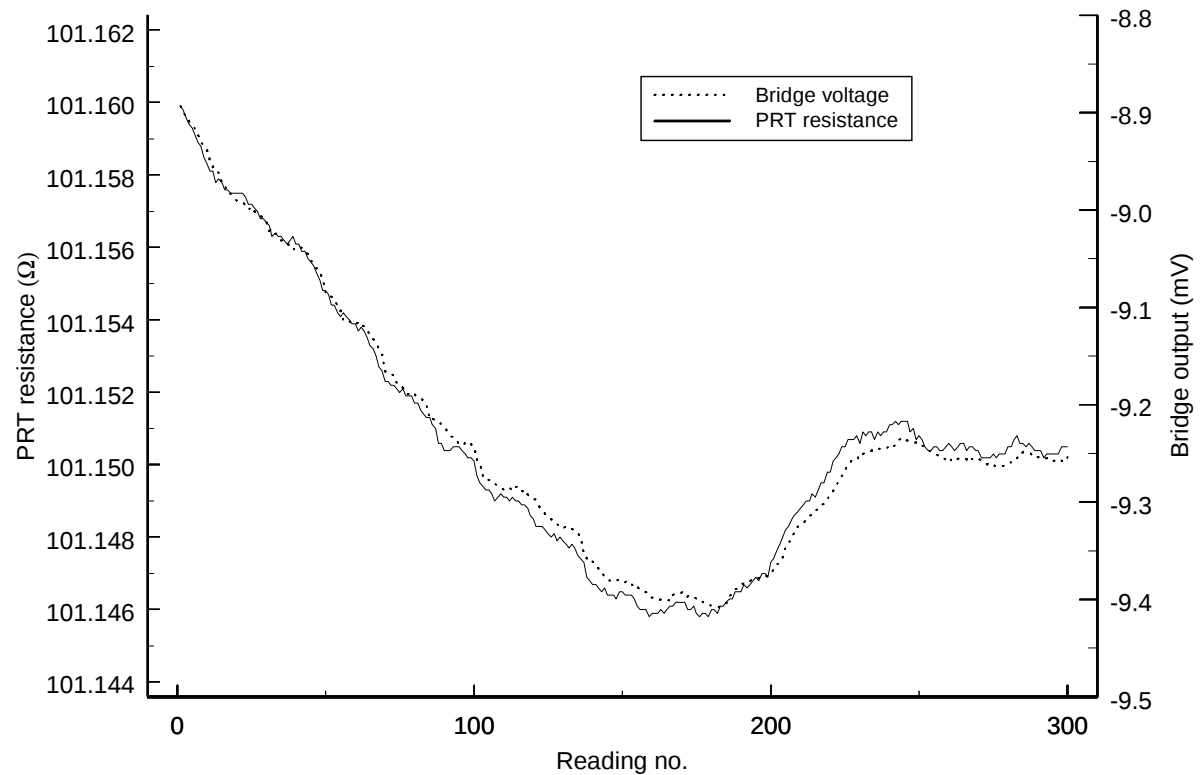


Figure 16 Plot of PRT resistance and bridge voltage during calibration

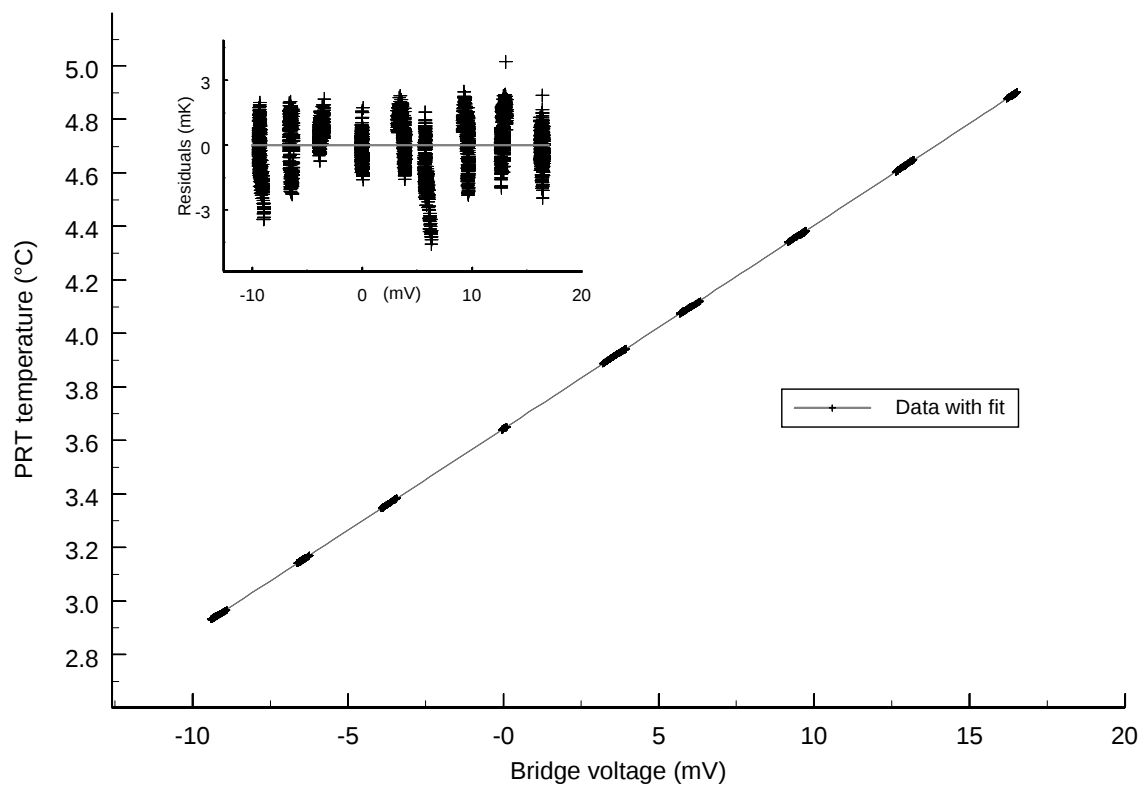


Figure 17 Plot of PRT temperature against bridge voltage

Typically, the RMS deviation from the fit is less than 0.5 mK. The estimated uncertainty on a thermistor calibration is 0.11%, being made up largely of the uncertainty on the PRT calibration estimated to be 0.1% at the 95% confidence level.

4.2.3 Stability of thermistor calibrations

Crucial to the accuracy of the calorimeter, is the stability of the thermistor calibrations. Therefore, a calibration history has been built up for each thermistor probe used. The thermistor calibrations were compared by looking at the change in the thermistor's sensitivity at 4 °C. Although the absolute calibration function such as that in equation (6) may change from calibration to calibration, the sensitivity should remain constant. **Figure 18** shows a plot of the sensitivity for three different thermistors. The first calibration was made using a simple DC bridge, with the rest of the calibrations being made using double shielded DC bridge. The calculated thermistor sensitivities fluctuate, a typical standard deviation being ~ 0.15 %. A plot of all the calibration readings for one of the thermistor probes is shown in **Figure 19**, the data being normalised to a supply voltage of 1 V. The data from different calibrations is very similar - it is actually quite difficult to distinguish one calibration from another.

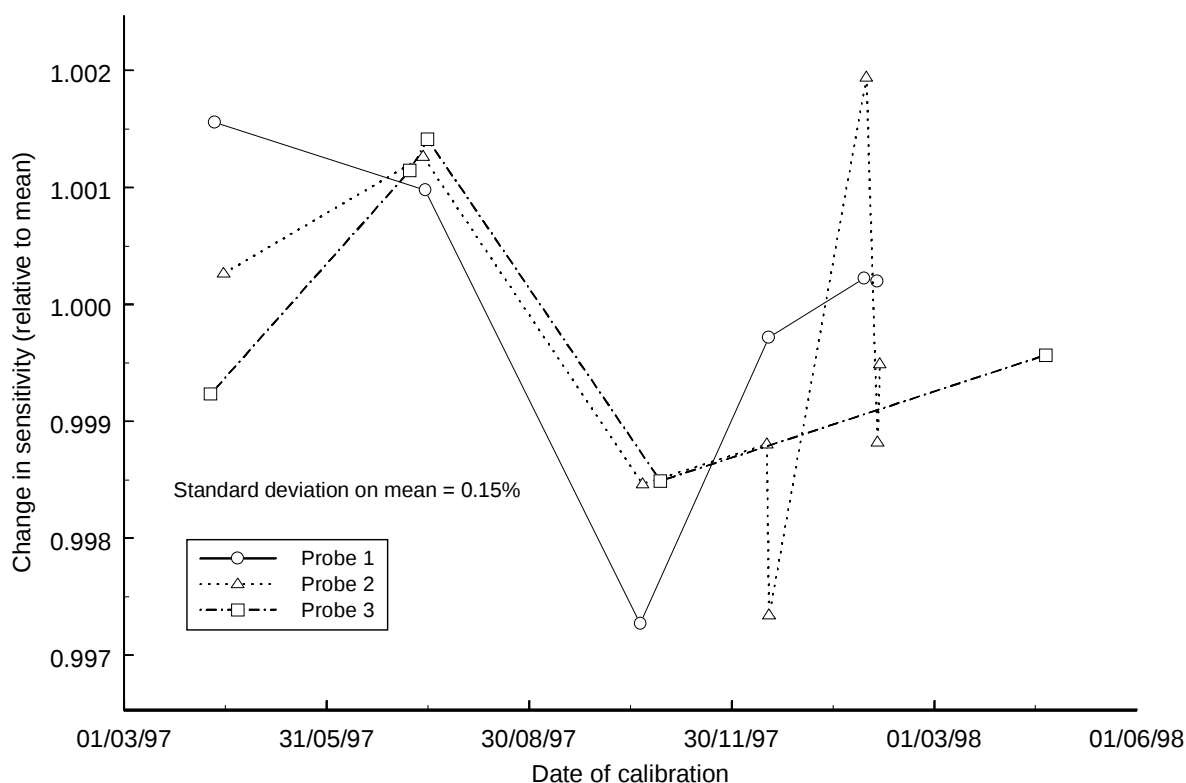


Figure 18 Calibration stability

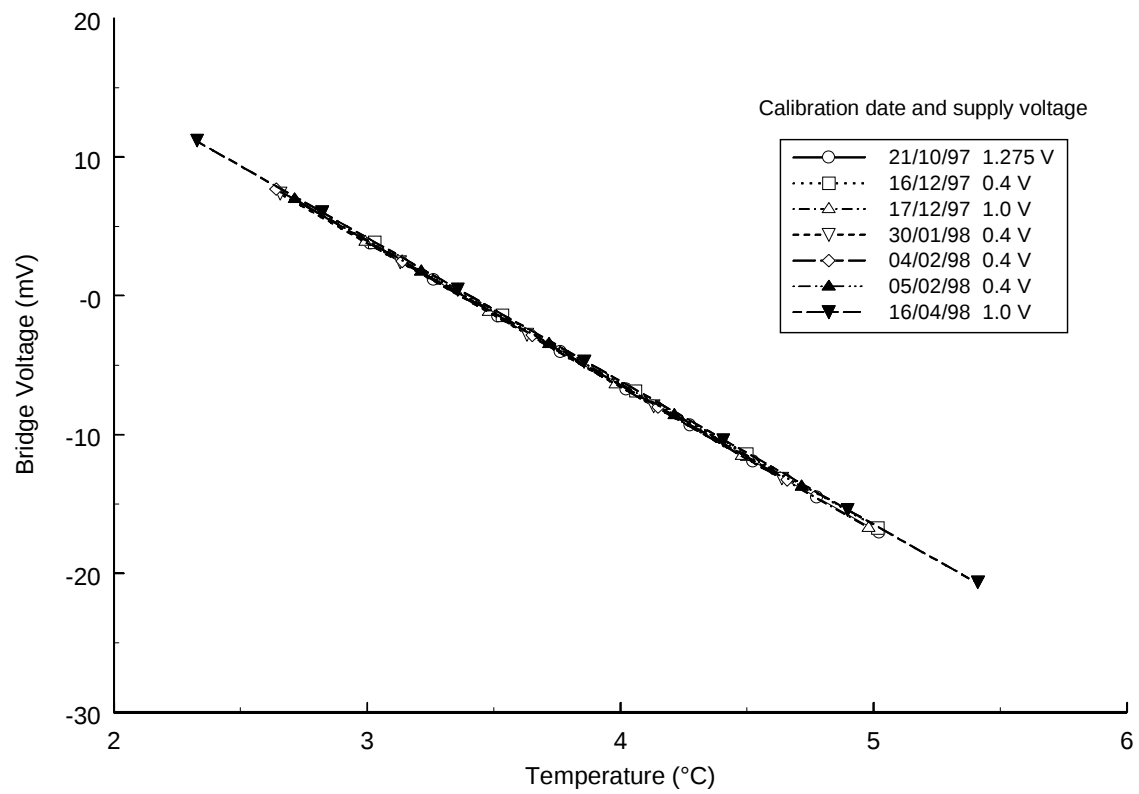


Figure 19 Plot calibration readings for a single thermistor probe

5. GAS FLOW SYSTEM

5.1 HEAT DEFECT

One of the problems with water calorimetry is that the measured temperature rise may not correspond directly with the energy deposited by the incident radiation. This difference between the measured (as heat) and actual energy deposition is known as the heat defect, and is defined in equation (7) below,

$$k_{HD} = \frac{E_{\checkmark} - E_a}{E_{\checkmark}} \quad (7)$$

where k_{HD} is the heat defect, E_a is the energy absorbed and E_h is the energy appearing as heat.

In general, there are several mechanisms that can give rise to a heat defect, such as radiation-induced optical emission, and radiation-induced chemical reactions. Ross and Klassen³⁰ estimated that only the radiation-induced chemical reactions were a significant source of a heat defect in water. If these chemical reactions are endothermic, the heat defect is positive; if they are exothermic, it is negative. It is possible to calculate the heat defect for various aqueous solutions using an established model for the radiolysis of water³¹. From comparisons between model calculations and experiment, several aqueous systems that are suitable for water calorimetry have been identified³¹. These include pure water, water saturated with hydrogen gas, and water saturated with a 50:50 mixture of hydrogen and oxygen gases. Pure water is usually saturated with an inert gas such as argon or nitrogen, the purpose of which is to remove all other gases from the water. However, pure water is susceptible to impurities, and although the calculated heat defect is zero, these impurities can cause spurious results. Simulations by Klassen *et al*³² predicted a heat defect of 0.5% endothermicity, but measurements gave a heat defect of 0.3 % exothermicity. In the case of the hydrogen only system, simulations by Klassen *et al*³² predicted that its heat defect should reach a steady state of zero (0.0%) after the system is irradiated to a dose of 20 Gy. This was in excellent agreement with measurements they made (0.0%). However any contamination of the system by oxygen may give spurious results. In the case of 50:50 H₂:O₂ saturated water, Klassen *et al*³² measured an exothermicity of 2.4%, again in excellent agreement with their model prediction of 2.4 %.

5.2 THE NPL GAS FLOW SYSTEM

Initially, hydrogen, argon, and oxygen aqueous systems are to be used at NPL. The use of a 50:50 hydrogen and oxygen saturated water has the advantage of being rather insensitive to impurities³³, but requires a complicated gas flow/mixing system to ensure accurate mixing of the two gases, and is explosive. Conversely, hydrogen saturated water is more sensitive to impurities and oxygen contamination, but provided sufficient care is taken during the preparation of the water, this should not be a problem.

A relatively simple system, as shown in **Figure 20**, is used to allow the calorimeter vessel to be filled with water that is saturated with a single gas, such as hydrogen. The whole system, including the valves, is cleaned with chromic acid prior to use. The 2 litre glass reservoir bottle and calorimeter vessel are then filled with ultra pure water (either triple distilled or water purified using a commercial ion exchange system). Gas enters the reservoir bottle via a sinter (the sinter reduces the time it takes for the water to become saturated with the gas by producing fine gas bubbles). While this process is going on, valve 3 is kept closed, valves 2 and 4 open,

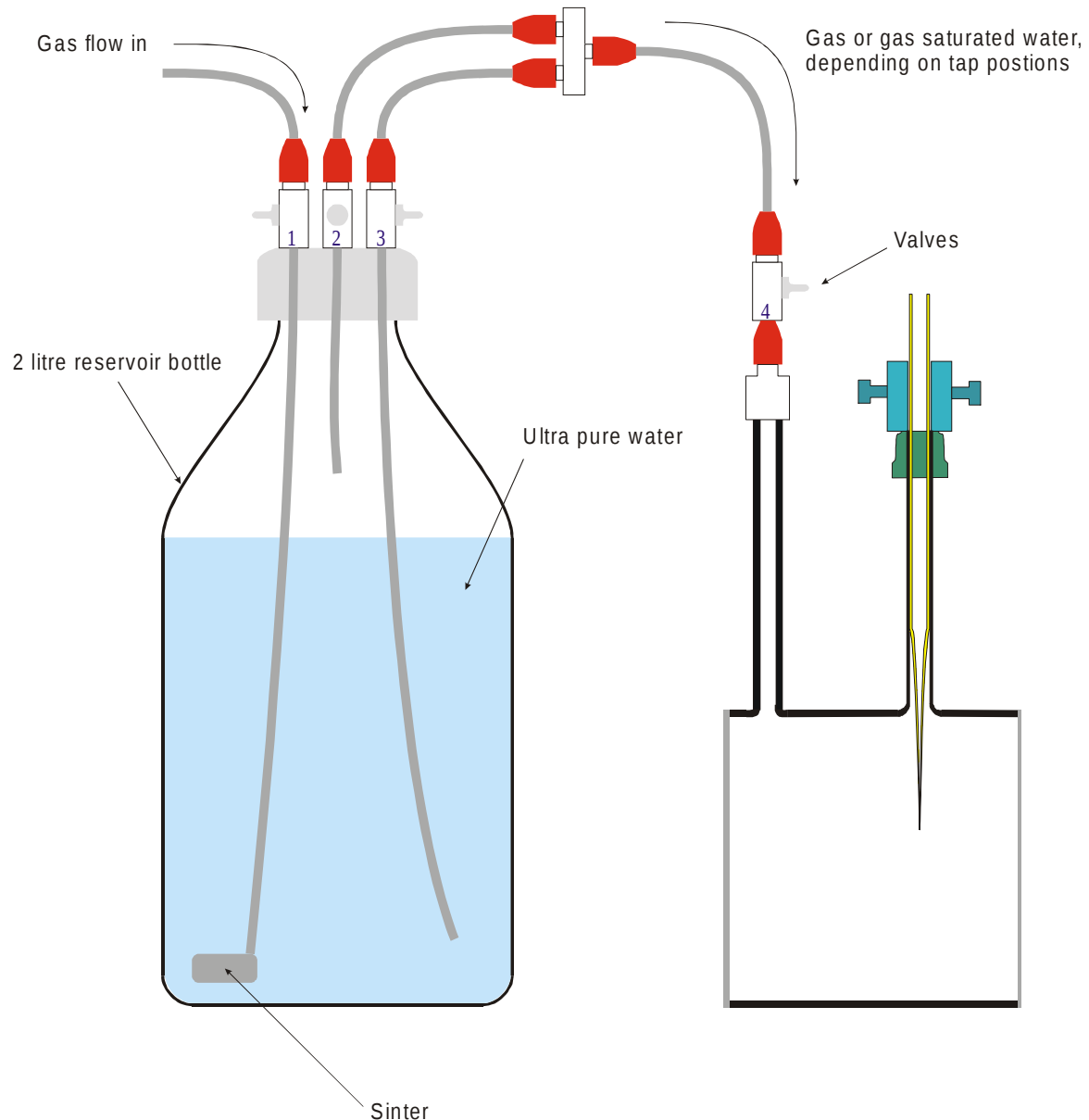


Figure 20 The NPL gas flow system

and the screw cap holding the thermistors in place slightly loose. The calorimeter vessel is orientated so that the hydrogen gas entering the vessel flushes the water and any oxygen etc. from the calorimeter vessel prior to it being filled with the gas saturated water. When the water in the reservoir bottle is saturated with the gas, valve 2 is closed, and valve 3 opened. The gas pressure then forces the water out of the reservoir bottle into the calorimeter vessel. Once the calorimeter vessel has been flushed through with the gas saturated water a couple of times, the gas pressure is reduced by shutting valve 1, and the thermistor screw-thread connector is tightened. With valve 2 open, and the 2 litre reservoir bottle still attached, the calorimeter vessel is cooled down to approximately 4 °C. Valve 4 is then closed, the connecting tubing removed, and the vessel installed in the main water phantom ready for use.

6. HEAT-FLOW MODELLING

6.1 THE HEAT-FLOW CODE

To help determine the optimum vessel dimension, and the effect of the vessel walls and thermistor probe on the temperature at the measurement point, the heat-flow within the calorimeter phantom and inner glass vessel was modelled.

The modelling system used was specially developed for this application, and took advantage of the fact that, if we treat the calorimeter vessel and probes separately, RZ cylindrical geometry can be used. The code was based on the simple one dimensional equation³⁴

$$\frac{dQ}{dt} = \kappa A \frac{d\theta}{dz} \quad (8)$$

where Q is heat (J), t is time (s), κ is the thermal conductivity of the medium ($\text{W m}^{-1} \text{K}^{-1}$), A is the cross sectional area across which heat is flowing (m^2), θ is temperature (K), and z is distance (m).

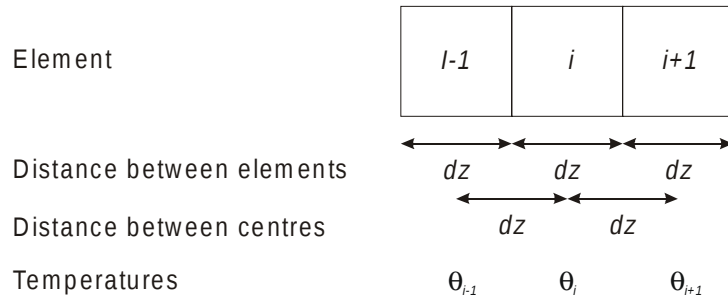


Figure 21 1D heat-flow

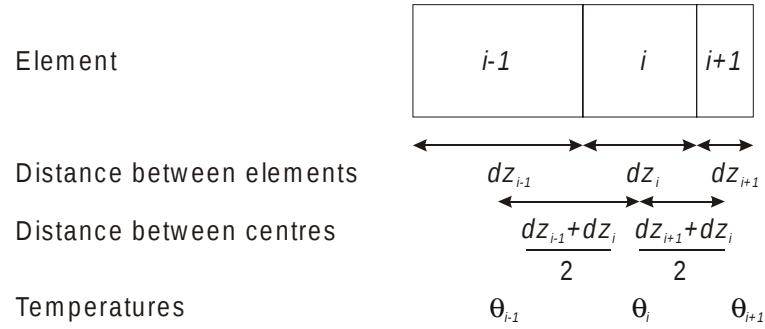
If we consider the problem in one dimension for a single medium using finite sized elements (see **Figure 21**), then the heat-flow dQ into the i^{th} element from the $i-1^{\text{th}}$ and $i+1^{\text{th}}$ in time dt for all dz equal is

$$dQ_i = \kappa A \times \left[\frac{\theta_{i-1} - \theta_i}{dz} + \frac{\theta_{i+1} - \theta_i}{dz} \right] \times dt \quad (9)$$

The temperature rise in the i^{th} element can then be evaluated using the following equation

$$d\theta_i = \frac{dQ_i}{A dz_i \rho c_p} \quad (10)$$

where $d\theta_i$ is the temperature rise, ρ the density and c_p the specific heat capacity of the i^{th} element.

**Figure 22** 1D heat-flow - unequal dz

Extending equation (9) to account for unequal dz (see **Figure 22**), we get

$$dQ_i = 2 \kappa A \times \left[\frac{\theta_{i-1} - \theta_i}{\frac{dz_{i-1} + dz_i}{2}} + \frac{\theta_i - \theta_{i+1}}{\frac{dz_{i+1} + dz_i}{2}} \right] \times dt \quad (11)$$

Extending equation (11) to include RZ cylindrical geometry, we get

$$dQ_{ij} = 2 \kappa \pi \times \left((r_{j+1}^2 - r_j^2) \times \left(\frac{\theta_{i,j-1} - \theta_{i,j}}{dz_{i,j-1} + dz_i} + \frac{\theta_{i,j+1} - \theta_{i,j}}{dz_{i,j+1} + dz_i} \right) + \right. \\ \left. \left(\frac{\theta_{i,j-1} - \theta_{i,j}}{dr_{j-1} + dr_j} \times r_j + \frac{\theta_{i,j+1} - \theta_{i,j}}{dr_{j+1} + dr_j} \times r_{j+1} \right) \times 2 dz_i \right) \times dt \quad (12)$$

where r_j is the radius of the j^{th} cylinder, and dr_j is the distance between the r_{j-1} and r_j^{th} cylinders. As before, the temperature rise of element i,j can be easily calculated using equation (13) below.

$$d\theta_{ij} = \frac{dQ_{ij}}{\pi (r_{j+1}^2 - r_j^2) dz_i \rho c_p} \quad (13)$$

In order to simulate the heating effect of the incident radiation, a single heating term dE_{ij} has to be added to equation (13)

$$d\theta_{ij} = \frac{dQ_{ij} + dE_{ij}}{\pi (r_{j+1}^2 - r_j^2) dz_i \rho c_p} \quad (14)$$

where dE_{ij} is the energy deposited in the i,j^{th} element due to radiative heating.

Equations (12) and (14) only apply to a single medium. They therefore had to be extended to apply to at least two media, glass and water. The main problem occurs when trying to calculate the heat-flow dQ_{ij} across the boundary between two different media, with different thermal conductivities. This problem was solved by calculating the arithmetic mean thermal conductivity

of the media on either side of the boundary as shown in equation (15). Although this is an approximate method, the accuracy of the calculation increases as dz and dr at the boundary approach zero.

$$dQ_{ij} = \left((r_{j+1}^2 - r_j^2) \times \left(\frac{\theta_{i-1,j} - \theta_{i,j}}{dz_{i-1} + dz_i} \times (\kappa_{i-1,j} + \kappa_{i,j}) + \frac{\theta_{i+1,j} - \theta_{i,j}}{dz_{i+1} + dz_i} \times (\kappa_{i+1,j} + \kappa_{i,j}) \right) + \right. \\ \left. \left(\frac{\theta_{i,j-1} - \theta_{i,j}}{dr_{j-1} + dr_j} \times r_j(\kappa_{i,j-1} + \kappa_{i,j}) + \frac{\theta_{i,j+1} - \theta_{i,j}}{dr_{j+1} + dr_j} \times r_{j+1}(\kappa_{i,j+1} + \kappa_{i,j}) \right) \times 2 dz_i \right) \times \pi dt \quad (15)$$

Equations (12) and (14) formed the basis of a FORTRAN program which could calculate the heat-flow in RZ geometry. **Table 5** shows the data that needs to be input into the program in order to carry out a calculation, and sample data for a 10 cm by 9.5 cm glass vessel in a water phantom. The sizes of dz and dr were mainly determined by the thickness of the vessel's glass walls. The 0.8 mm thick front wall was split into 0.2 mm slabs, and the 2.5 mm side wall was split into 0.5 mm cylinders. No slabs or cylinders were more than 2.5 times the thickness of their

Input required	Example value
total length of geometry (cm)	14.62
number of slabs m	58
dz_i for each slab ($i = 1$ to m)	0.72, 1.0, 0.4,, 0.4, 0.4, 0.26
total radius of geometry (cm)	7.5
number of cylinders n	24
dr_j for each cylinder ($j = 1$ to n)	1.55, 1.5, 0.5,, 0.5, 0.5, 0.8
dt the size of the time slice (s)	0.025
total number of time slices to be calculated	37000
'beam on' time (s)	0.0
'beam off' time (s)	60.0
number of media used $nmed$	2
thermal conductivities κ ($\text{W cm}^{-1} \text{K}^{-1}$)	0.00566, 0.011
heat capacities of the media c_p ($\text{J g}^{-1} \text{K}^{-1}$)	4.2, 0.78
densities of the media ρ (g cm^{-3})	1.0, 2.23
type of media for each element	m by n grid of numbers 1 to $nmed$
energy deposited per unit mass in each element during 'beam on'	m by n grid of numbers

Table 5 Inputs required for heat-flow code

neighbours. The size of the time step dt was chosen such that the output of the simulation did not oscillate. In practise, this meant keeping dt small with many iterations being performed.

6.2 CALCULATION OF THE RADIATIVE ENERGY DEPOSITION

A simple heat-flow simulation could be carried out if we assumed that the energy deposition throughout the whole phantom and calorimeter vessel was uniform. This would give some idea of the heat build-up in the glass walls of the calorimeter vessel. However, it would be much more useful if we could simulate the energy deposition of a real electron or photon beam. As the heat-flow code uses RZ cylindrical geometry, this is, in fact, a straight forward procedure, as the energy deposited in each element can be calculated using Monte Carlo techniques. The Monte Carlo code used was Electron Gamma Shower 4 (EGS4)³⁵, a general purpose package for the simulation of the coupled transport of electrons and photons in an arbitrary geometry. The dose deposited in the calorimeter was calculated using the EGS4 user code DOSRZ, which makes use of the PRESTA³⁶ algorithm (DOSRZ calculates dose in regions with RZ geometry). The DOSRZ input file used to create the energy deposition data for a heat-flow calculation specified the positions of all the cylinders, planes, and media used in a similar manner as for the heat-flow input files. In addition, it also specified the EGS4 parameters ECUT=0.536 MeV and PCUT=0.01 MeV (the energy below which electrons and photons respectively are discarded from the simulation), and ESTEPE=0.05 (the fraction of an electron's energy that can be lost in a single step).

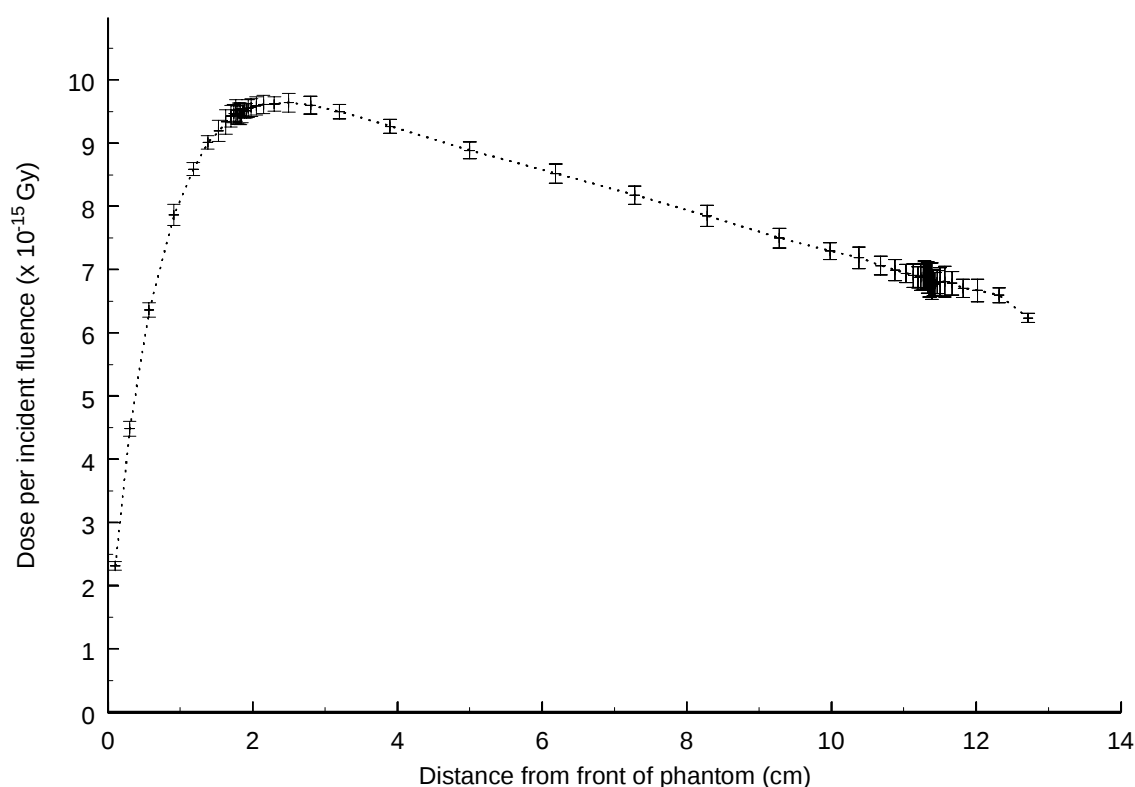


Figure 23 Depth dose curve for 10 MV photons in water

Figure 23 and **Figure 24** show plots of the calculated absorbed dose per incident fluence (indistinguishable from experimental measured data) against depth and radial distance from the

central axis respectively for 10 MV photons incident on a 13 x 15 cm water phantom. For these particular simulations, the SSD was 120 cm, and the beam diameter at a depth of 5 cm in water was approximately 11 cm. The incident photon spectra used to calculate the dose distributions at 6, 10 and 16 MV had been generated previously at NPL using Monte Carlo techniques³⁷. The resultant dose data is imported directly into the heat-flow program.

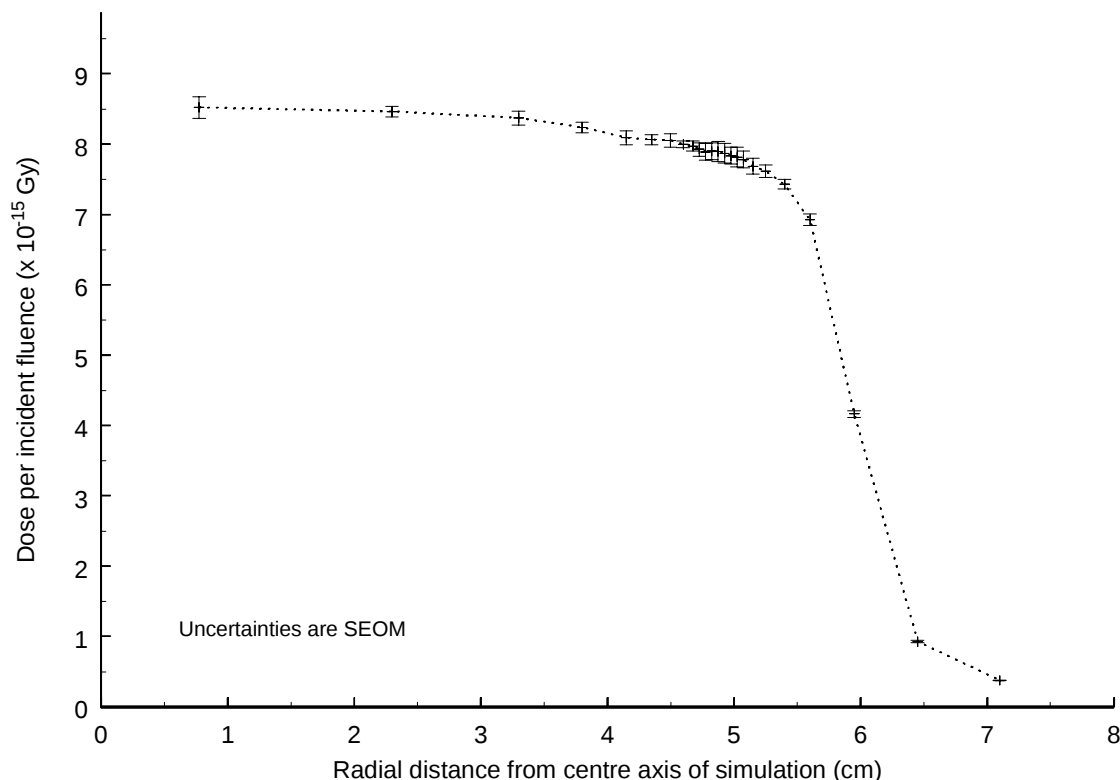


Figure 24 Radial dose curve for 10 MV photons at 5 cm depth in water

6.3 CALORIMETER VESSEL SIMULATIONS

6.3.1 Vessel temperature profiles

Temperature profiles were calculated for the various calorimeter vessels at the appropriate beam qualities. Two temperature simulations were performed at each beam quality: one with a homogenous water phantom (later referred to as ‘water vessel’), and one with a glass calorimeter vessel in a water phantom (referred to as ‘glass vessel’). Combining the results of the two simulations enable the effect of the glass vessel on the temperature at the measurement point to be calculated. **Figure 25** to **Figure 28** show the temperature profiles for 16 MV photons, and medium energy X-rays. The effect that the glass walls of the vessels have on the temperature profiles of the phantom can be seen quite clearly: at the end of the irradiation period, the glass walls of the vessels reach a temperature that is considerably higher than that of the surrounding water. The figures also reveal how heat from the glass walls of a vessel spreads out with time, raising the temperature of the water near to the walls of a vessel. As time increases, a combination of heat flowing from the cylindrical walls and from the front face of the vessel to the measurement point slightly raises its temperature.

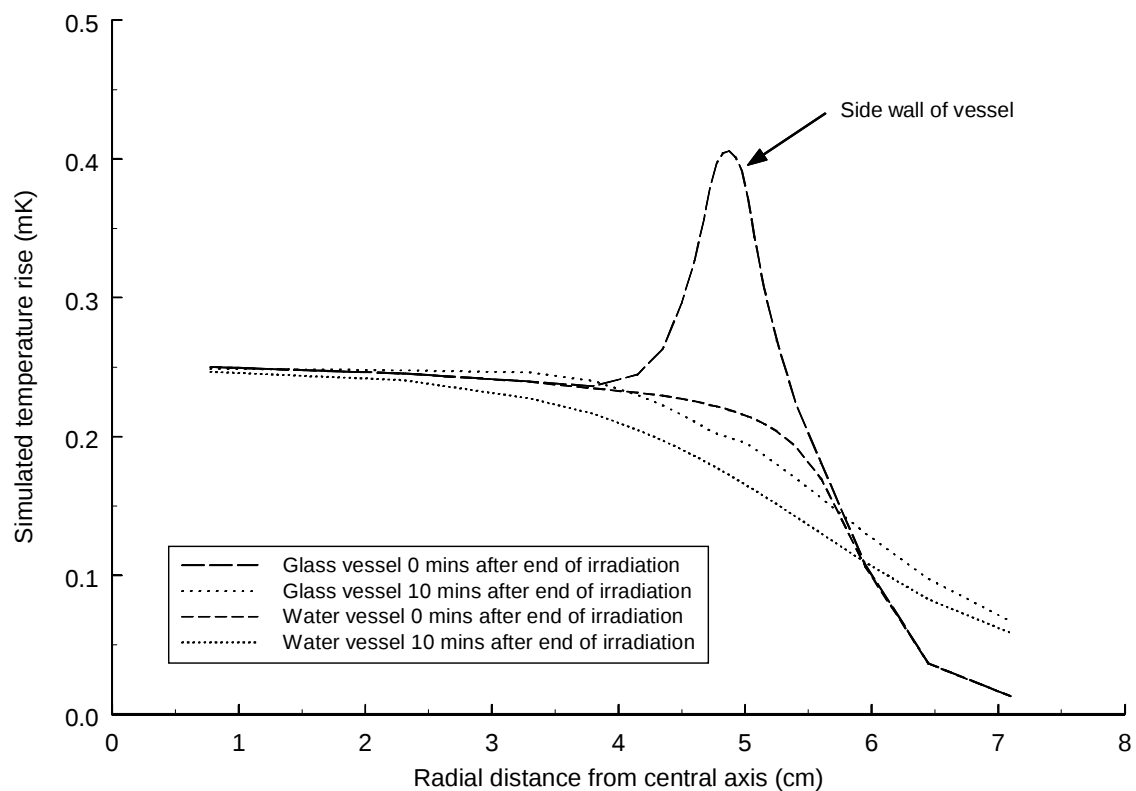


Figure 25 16 MV photon radial temperature profile

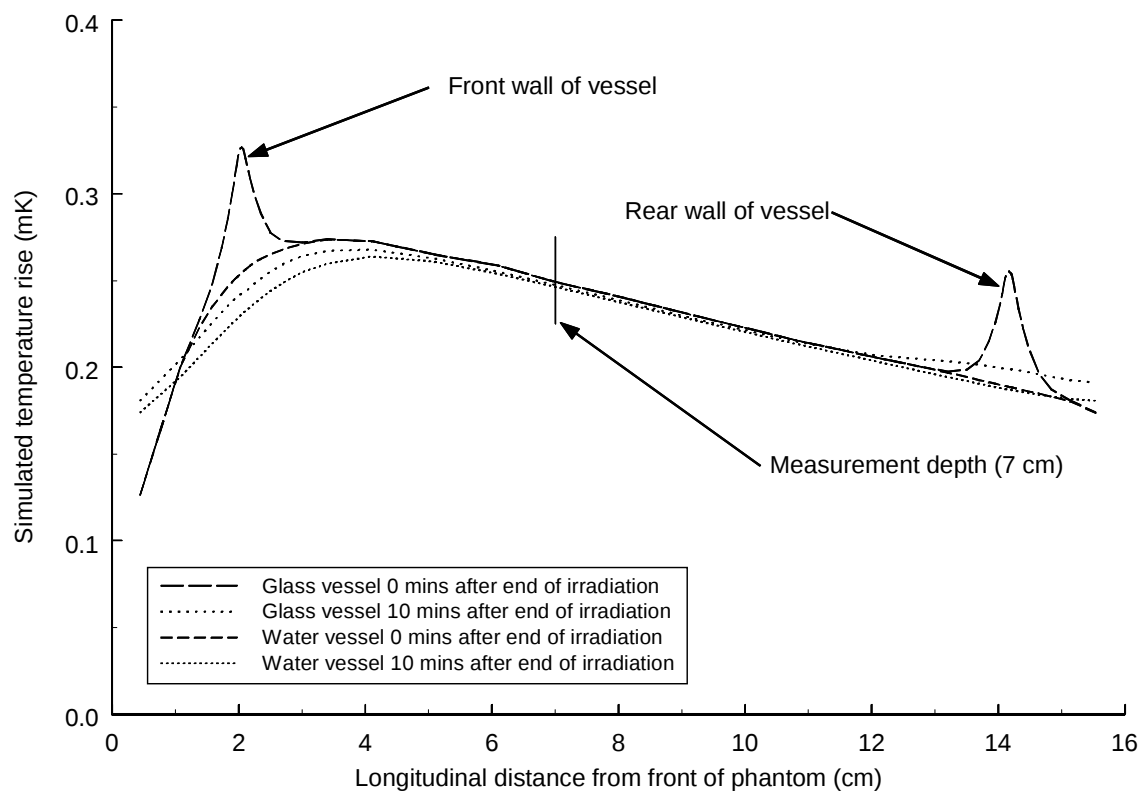


Figure 26 16 MV photon longitudinal temperature profiles

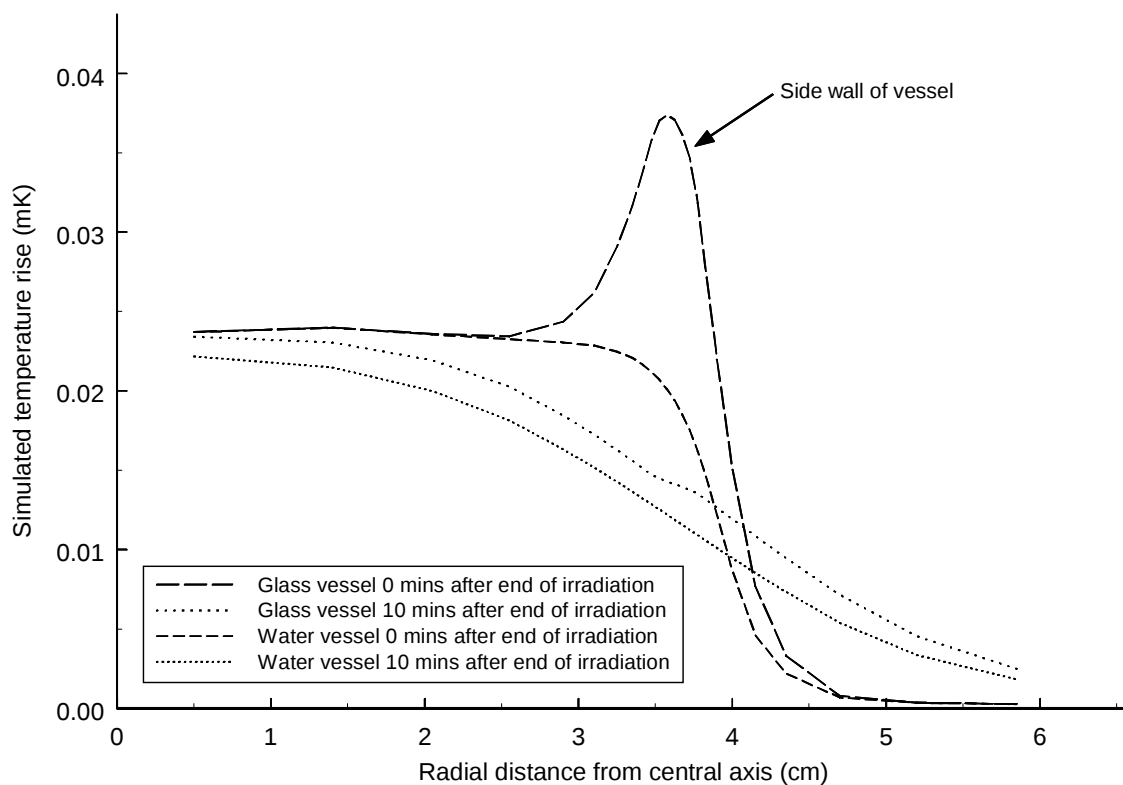


Figure 27 Medium energy X-ray radial temperature profile

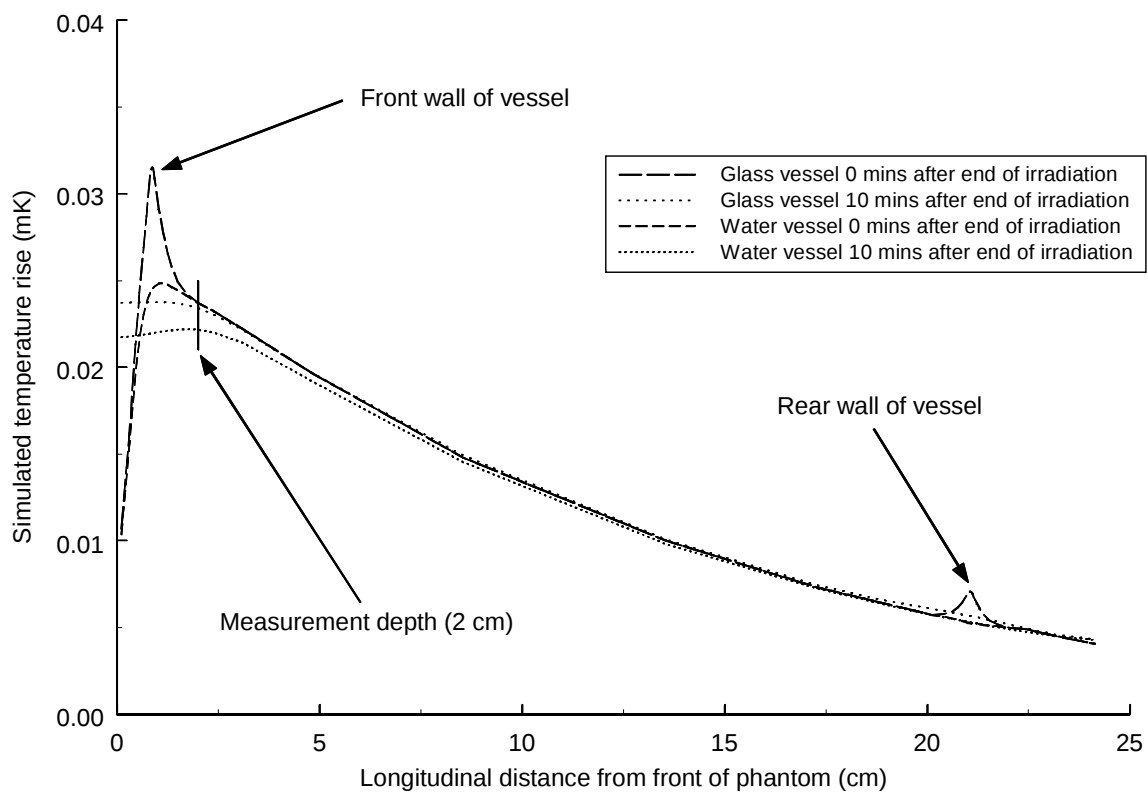


Figure 28 Medium energy X-ray longitudinal temperature profiles

6.3.2 Vessel temperature corrections

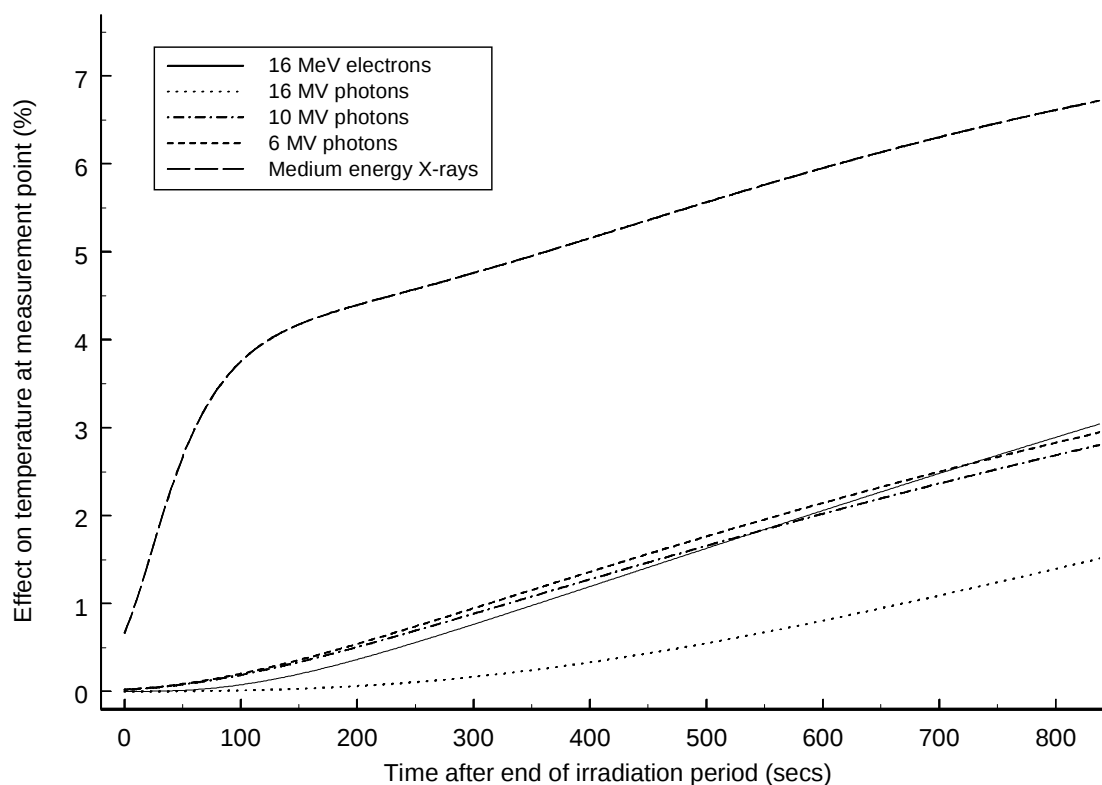


Figure 29 Effect of calorimeter vessels on temperature at measurement point

Figure 29 shows the effect that the various calorimeter vessels have on the temperature at the measurement point. However, extrapolating the temperature to the mid point of irradiation (see section 7.2 for more details) almost completely corrects for this effect. **Table 6** shows the correction factors that need to be applied after the temperature rises have been calculated using the extrapolation technique (quadratic fit to post-irradiation data).

Beam quality	Correction factor (%)
16 MeV electrons	+0.09
16 MV photons	+0.05
10 MV photons	+0.21
6 MV photons	+0.20
Medium energy photons	-2.58

Table 6 Temperature rise correction factors

6.4 THERMISTOR PROBE SIMULATIONS

6.4.1 Thermistor probe temperature profiles

Taken separately from the vessel, the heat-flow in the thermistor probes can also be modelled using the heat-flow code. However, unlike for the vessel, the Monte Carlo code DOSRZ could not be used to calculate the energy deposition due to the incident radiation as it cannot produce the required radial dose profile. Instead a uniform energy deposition had to be assumed.

As the different beam qualities do not have much of an effect on the thermistor probe, only two temperature simulations needed to be performed: one with a homogenous water phantom, i.e., a probe made out of water, and one with a glass probe in a water phantom. **Figure 30** shows the radial temperature profile for a thermistor probe in a water phantom.

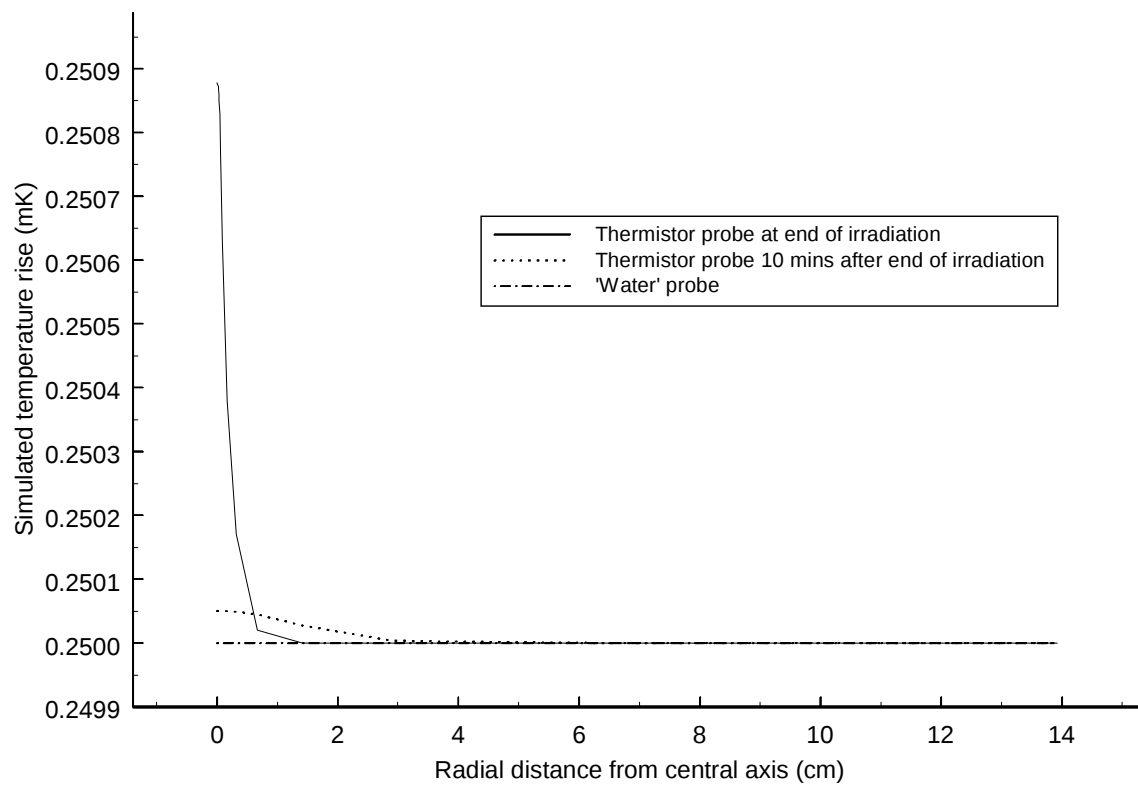


Figure 30 Thermistor probe radial temperature profile

6.4.2 Thermistor probe temperature corrections

Combining the results of the two simulations enables the effect of the glass probe on the temperature at the measurement point to be calculated. However, there is a relatively large uncertainty in this correction factor due to the uncertainty in the type of glass out of which the thermistor is made (C_p varies from 0.50 for flint, to $0.78 \text{ J kg}^{-1} \text{ K}^{-1}$ for Pyrex glass, and ρ from 2.4 to 6.1 g cm^{-3} for various optical glasses). **Figure 31** shows the percentage increase in temperature reading due to the presence of the thermistor probe. Unlike for the vessel corrections, when the temperature deviations from the ideal all water system, caused by excess heat produced in the glass walls, increases with time, the opposite is true in this case: the temperature deviations decrease with time.

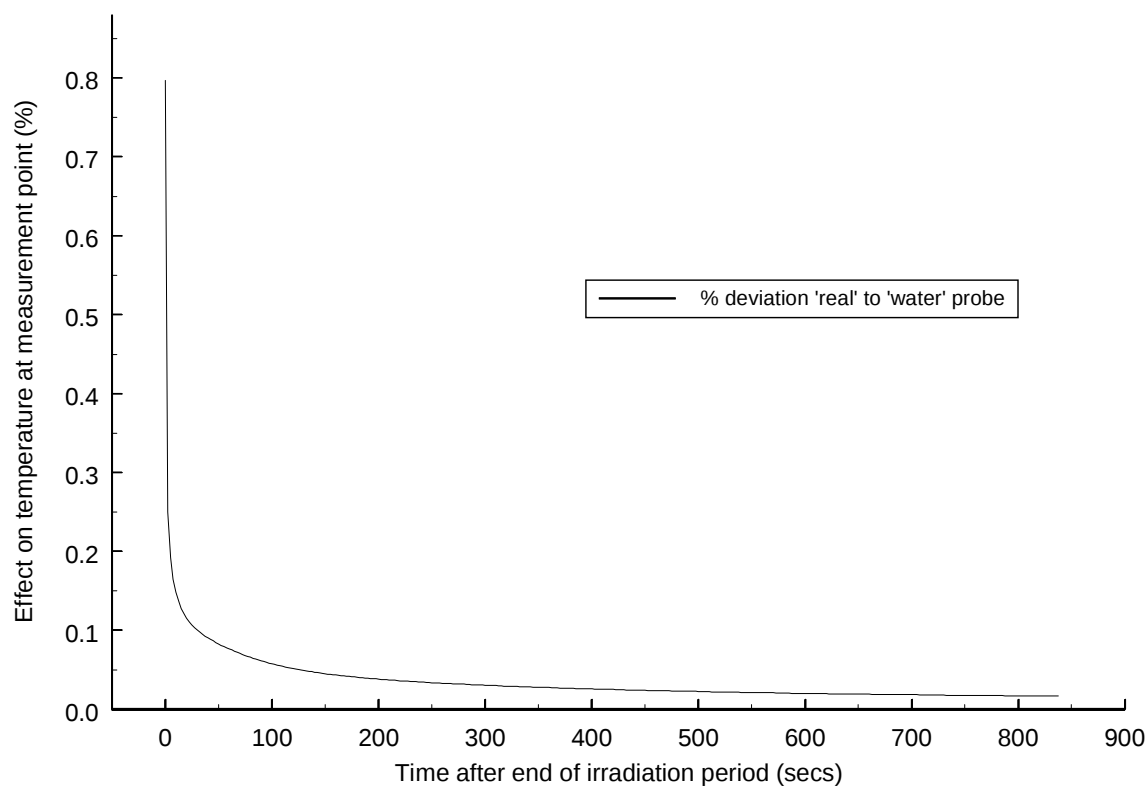


Figure 31 Thermistor probe temperature deviations

6.5 TOTAL CORRECTION FACTORS

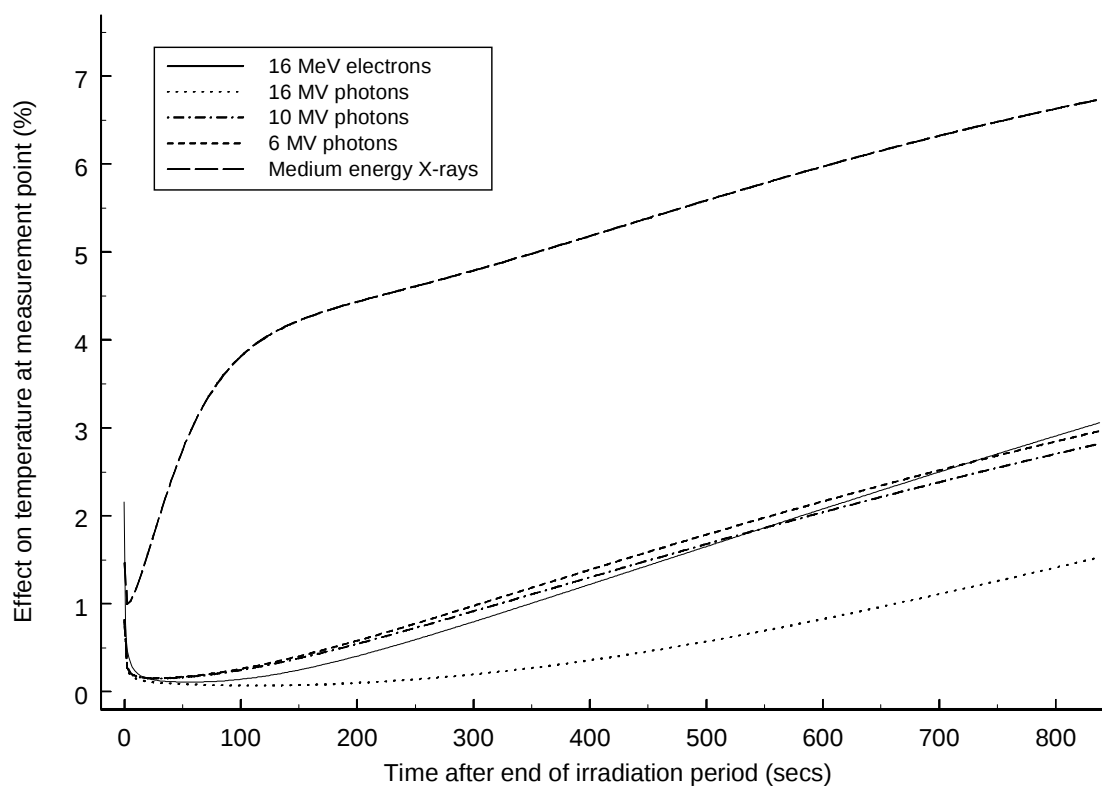


Figure 32 Total temperature deviations

Combining the vessel and thermistor probe results enables the total heat-flow correction factors and temperature deviations to be calculated. **Figure 32** shows the combined temperature deviations and **Table 7** shows the combined vessel and thermistor probe heat-flow correction factors calculated using the temperature extrapolation technique.

Beam quality	Correction factor (%)
16 MeV electrons	-0.08
16 MV photons	-0.08
10 MV photons	+0.08
6 MV photons	+0.08
Medium energy photons	-2.71

Table 7 Combined temperature rise correction factors

6.6 SELF-HEATING OF THERMISTOR PROBES

Heat-flow calculations were carried out in order to estimate the increase in temperature of the thermistor bead compared to its surroundings caused by the electrical power dissipated in the bead (known as thermistor self-heating). It was assumed that all the thermistor power was deposited in a small cylinder of length 0.1 mm by 0.1 mm diameter at the centre of the glass thermistor bead.

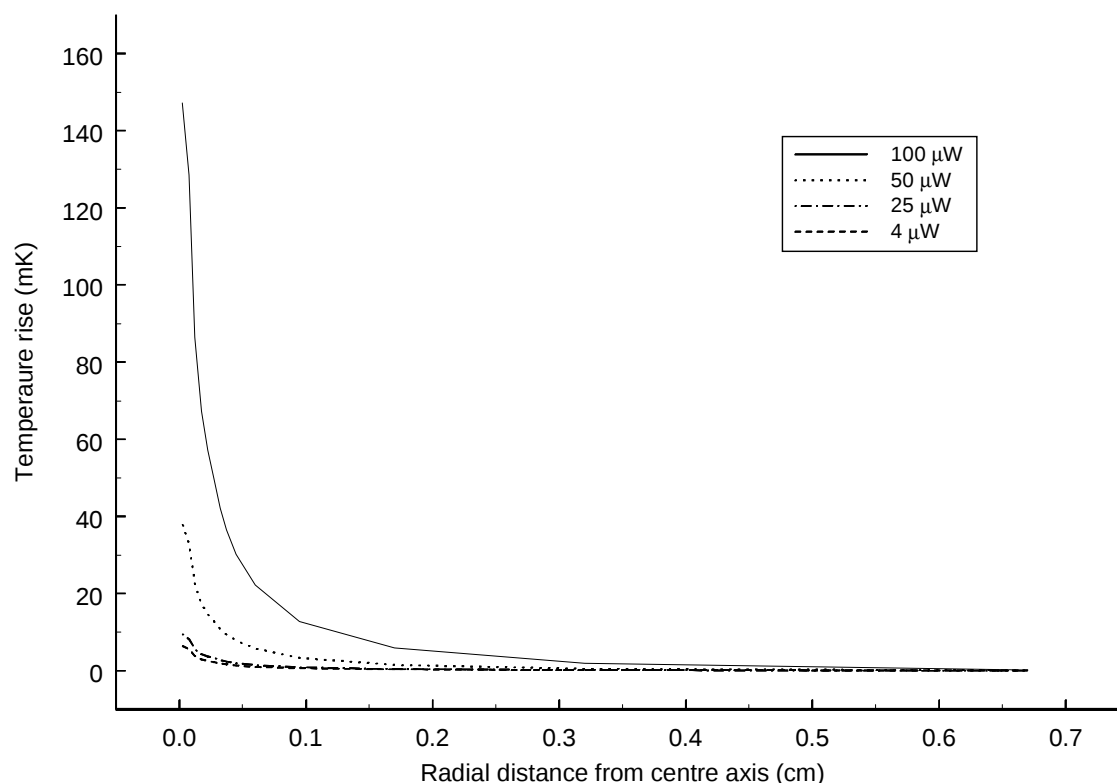


Figure 33 Thermistor self-heating

The results of these calculations (see **Figure 33**) indicated that the thermistor bead was about 150 mK hotter than the surrounding water for a power dissipation of 100 μ W, with the temperature rise dropping to about 6 mK when the thermistor power dissipation was reduced to 4 μ W. This is in good agreement with measurements made by Domen²³ that gave a temperature rise of 1.5 mK per μ W. Domen also estimated that, at room temperature, convection would be present for thermistor powers above about 50 μ W. More recently, Seuntjens³⁰ concluded that, at room temperature, convection may be present for thermistor powers as low as 5 μ W. However, he also suggested that the effect of this source of convection would not significantly affect the temperature measurements. Therefore in order to minimise any possible effect that convection, caused by the self-heating of the thermistor, has on the measured temperature rise, all later calorimetry was performed using thermistor power levels of 25 μ W or 4 μ W, corresponding to a 1 V or 0.4 V bridge supply.

7. EXPERIMENTAL MEASUREMENTS

7.1 EXPERIMENTAL SET-UP

The calorimeter and ionisation chambers (where used) were set up as shown in **Figure 34**. The computer records the transmission monitor output and either the ionisation chamber output or the calorimeter vessel temperature, depending on which one is in the radiation beam. This data is then stored to computer disc for later analysis. Measurements sets are usually made using ion chambers (typically about 10 measurements), then the calorimeter (up to about 15 measurements), then ion chambers again (another 10 measurements). The electron-beam experimental set-up is similar to the X-ray experimental set-up: the X-ray tungsten target, beam flattening filter, collimator and monitor chamber are replaced with a single 2 mm aluminium scattering foil, and an electron monitor chamber and collimator (fixed at the front of the experimental table).

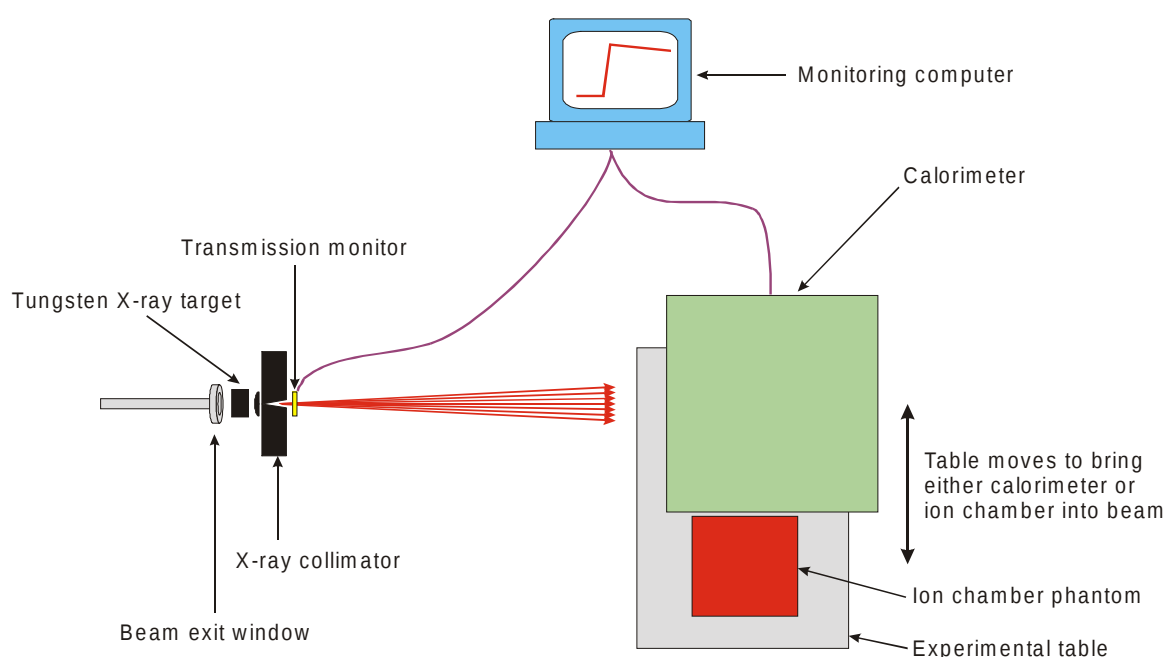


Figure 34 Schematic diagram of X-ray beam experimental set-up

For all of the calorimetry, the calorimeter vessels were filled with hydrogen saturated ultra-pure water after being cleaned with chromic acid.

7.2 DATA ANALYSIS

Ion chamber measurements data analysis was relatively straight forward: each ion chamber reading was divided by the simultaneous transmission monitor reading (to correct for variations in dose rate throughout the irradiations) to give the chamber-to-monitor ratio.

Calorimeter data analysis was slightly more complicated. The first stage was to calculate the measured temperature rise in the calorimeter by extrapolating the temperature data for before and after the irradiation period, to the mid-time of the irradiation period, as shown for a typical calorimeter run in **Figure 35**. This temperature rise was converted to absorbed dose to water using equation (1) and a value for c_p of 4.2 kJ kg^{-1} , then corrected for variations in dose rate throughout the irradiations by dividing the calculated absorbed dose by the simultaneous

transmission monitor chamber reading. This gave a calorimeter-to-monitor ratio for each calorimeter irradiation which could be compared to the chamber-to-monitor ratios measured before and after the calorimetry.

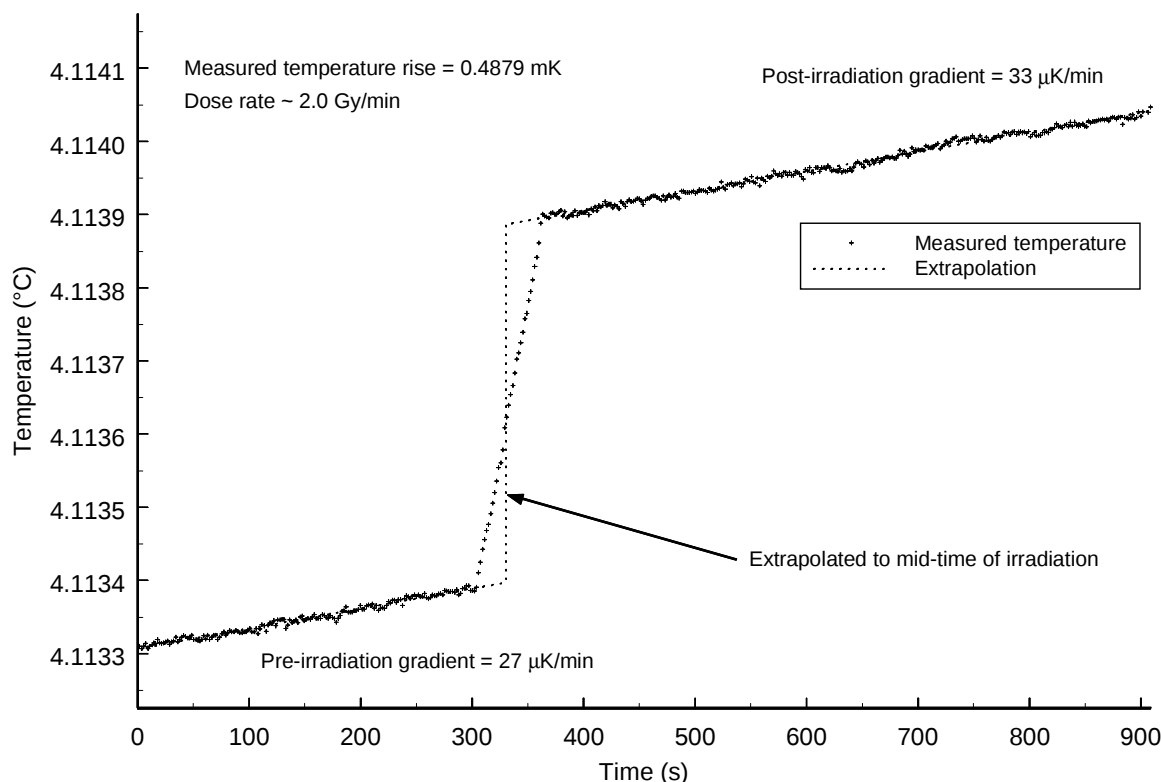


Figure 35 Temperature extrapolation method for a typical 16 MV calorimeter run

7.3 RESULTS

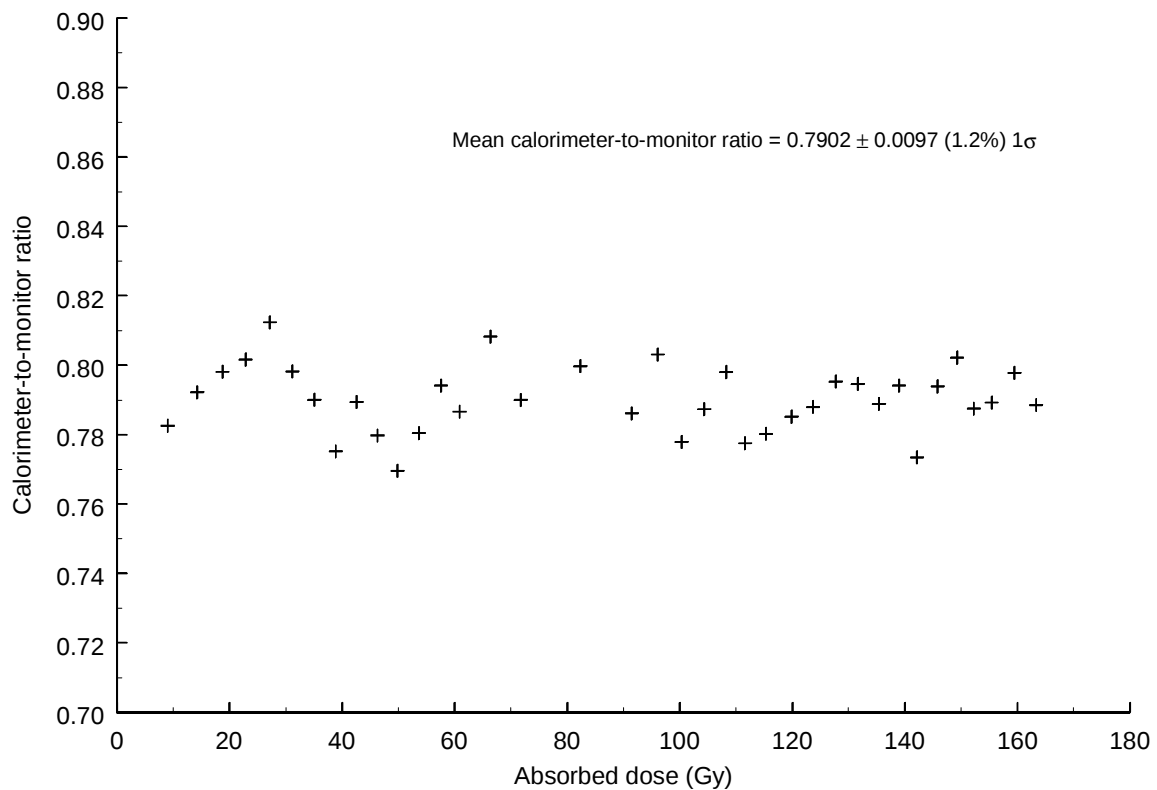
7.3.1 Uncertainties

The uncertainties (quoted as standard uncertainties according to UKAS (1997)³⁸) in the determination of absorbed dose are given in **Table 8**. The reported expanded uncertainties are based on the standard uncertainties multiplied by a coverage factor $k = 2$, providing a level of confidence of approximately 95%.

7.3.2 Absorbed dose measurements

Measurements were made at 6, 10 and 16 MV using the calorimeter and three secondary standard ionisation chambers, at 16 MeV using the calorimeter and a single electron ionisation chamber, and in medium energy X-rays using the calorimeter alone. A major test of the performance of the system is to compare the response of the calorimeter (the calorimeter-to-monitor ratio) against time. As absorbed dose increases with time, this also tests if there is any variation in the heat defect of the system with increasing absorbed dose. **Figure 36** shows a typical plot of calorimeter response against absorbed dose. Within the uncertainties, there is no dependence on accumulated absorbed dose, the response being stable to $\pm 1.2\%$ (1σ). **Table 9** shows the complete calorimeter-to-monitor ratios for 16 MeV electrons, 16, 10 and 6 MV photons and Medium energy X-rays with the errors quoted being the random standard uncertainty. A more detailed discussion on the calorimeter results and the measurements made using the ion chambers is made elsewhere by Rosser and Williams³⁹.

Source		Standard uncertainties ($\pm$)				
NON-RANDOM	Beam quality	16 MeV	16 MV	10 MV	6 MV	280 kV
	PRT calibration	0.05	0.05			0.05
	Thermistor calibration	0.06	0.06			0.06
	Specific heat capacity of water	0.6	0.6			0.6
	Depth in water	0.5	0.5			1.4
	Heat-flow correction	0.1	0.1			0.7
	Combined uncertainty	0.8	0.8			1.7
RANDOM	Calorimeter reading	0.2	0.4	0.6	0.5	2.6
	Heat defect	0.5				
	Combined uncertainty	0.5	0.6	0.8	0.7	2.6
Combined total uncertainty		1.0	1.0	1.1	1.1	3.1
Expanded uncertainty		1.9	2.0	2.2	2.1	6.3

Table 8 Uncertainties in photon and electron beams**Figure 36** 16 MeV calorimeter-to-monitor ratios for increasing time (accumulated dose)

Beam Quality	TPR	Calorimeter-to-monitor ratio	Experimental conditions	
			Bridge supply (V)	Dose-rate (Gy/min)
16 MeV electrons		0.7902 ± 0.0016 (0.20%)		16.3
16 MV photons	0.779	0.3291 ± 0.0015 (0.47%)	0.4	2.7
		0.3214 ± 0.0007 (0.21%)	1.0	2.3
		0.3184 ± 0.0011 (0.36%)	1.0	1.3
10 MV photons	0.742 0.746	0.2854 ± 0.0017 (0.60%)	0.4	2.7
		0.2586 ± 0.0016 (0.63%)	0.4	2.4
6 MV photons	0.670	0.3017 ± 0.0015 (0.5%)	0.4	1.2
Medium energy X-rays		0.06526 ± 0.00172 (2.6%)	1.0	0.1

Table 9 Results of calorimeter measurements

7.4 CONCLUSION

The testing of the calorimeter that has been carried out has confirmed the feasibility of the calorimeter design. Random uncertainties are comparable to those achieved at other standards laboratories (for example, the National Research Council, Ottawa, Canada, quote a standard uncertainty of 0.5% for comparable measurements), however, further work is required to reduce the non-random uncertainties, at present dominated by the uncertainty on the heat defect and the specific heat capacity of water.

8. ACKNOWLEDGEMENTS

The authors would like to thank the following people for their help with this project: David Crossley and Kamalini Rajendran their hard work cleaning the glassware and probes, Sam Gnaniah for help building the calorimeter and Alan Ainsworth our thermistor probe expert. The authors would also to acknowledge the financial support of the National Measurement Policy Unit of the UK Department of Trade and Industry.

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