

Recent Advances in Water Calorimetry at NPL

A J Williams, K E Rosser, N J Thomson and A R DuSautoy
Centre for Ionising Radiation Metrology, National Physical Laboratory
Teddington, Middlesex, UK

Abstract - At present, the primary standard at NPL for the measurement of absorbed dose in high energy electron and photon beams is a graphite calorimeter. However, the quantity of interest in radiation dosimetry is absorbed dose to water. Therefore, NPL is developing a new absorbed dose to water standard based on water calorimetry.

Key Words - Absorbed dose, calorimetry, dosimetry, water calorimeter

I. INTRODUCTION

Radiotherapy treatment requires the ability to accurately predict¹ the absorbed dose given to irradiated tissue. Water is radiologically, similar to tissue, and so is used as the reference material for determining absorbed dose. At present, NPL determines absorbed dose to water in high energy photon and electron beams not by using a water calorimeter, but by using a graphite calorimeter^{2,3}, and then converting from absorbed dose to graphite to absorbed dose to water. In order to avoid this conversion, NPL is now developing a water calorimeter. This paper describes the design and construction of the calorimeter, along with the some experimental results.

II. CALORIMETER DESIGN

One of the main requirements when building a calorimeter is to isolate the temperature sensing volume from any external influence. A number of different methods have been used previously to satisfy this requirement. For example, Palmans *et al*⁴ and Seuntjens *et al*⁵ successfully isolate their calorimeters by surrounding their phantom with temperature controlled air, while Shulz *et al*⁶ isolated his calorimeter by surrounding his phantom with temperature controlled water. In the latest version of the NPL calorimeter, temperature controlled water encloses all six sides of a cube. Using water as the controlling medium has the advantage of reducing the overall size of the calorimeter.

The main component in the calorimeter is the double

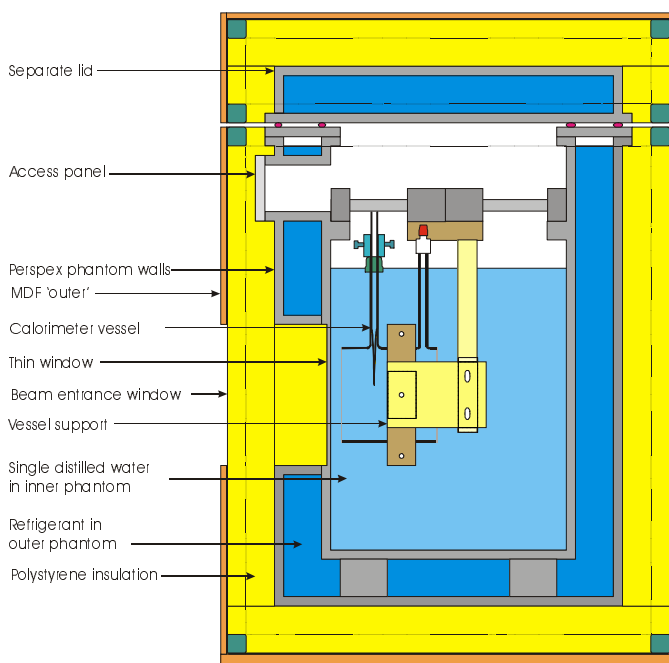


Figure 1 Schematic of calorimeter

skinned Perspex water phantom, as shown in Figure 1. The inner phantom is filled with standing single distilled water. A 4 mm thick window of diameter 15 cm is machined into its front to allow entry of the radiation beam. The inner phantom is surrounded by an outer phantom which allows a 4 cm wall of temperature controlled water to circulate around the inner phantom.

III. CALORIMETER VESSEL

The design of the calorimeter vessel is different from most other water calorimeters in use today: instead of the radiation beam entering the vessel through a curved side wall, it enters through a precision ground flat glass wall, as shown in Figures 2 and 3. The advantages of using a vessel orientated in this manner are:

- the cylinder walls of the vessel, which can be difficult to make thin and uniform, can be positioned well away from the measurement point where their influence on it is minimised.

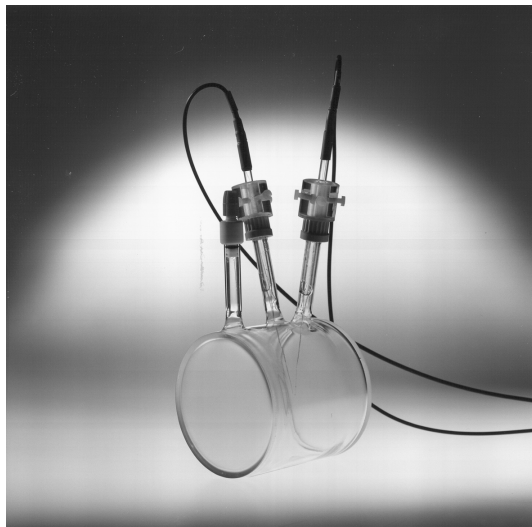


Figure 2 Photograph of calorimeter vessel

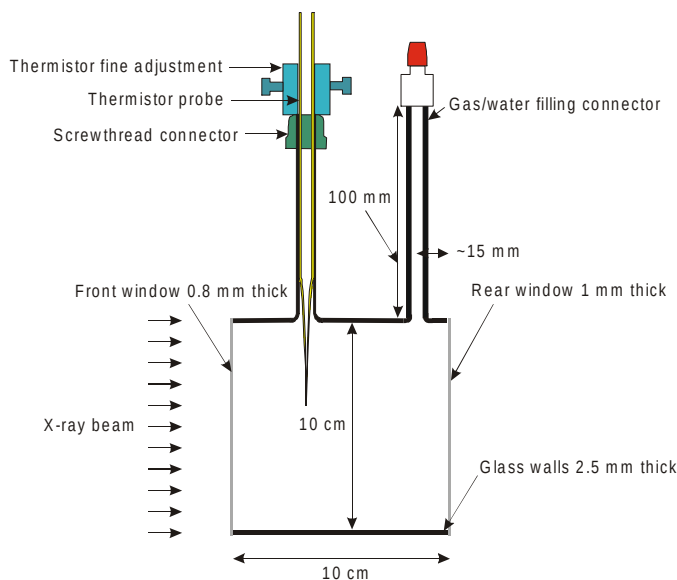


Figure 3 Schematic diagram of calorimeter vessel

- the front and rear walls of the vessel can be easily and uniformly ground down to a thickness of only 0.8 mm.

For high energy X-ray beams, two vessels have been built, one for use at a measurement depth of 5 cm for X-ray energies of 4 to 10 MV, the other for use at a measurement depth of 7 cm, for X-ray energies of above 10 to 19 MV. For high energy (16 MeV) electrons, a third vessel was built for use at a measurement depth of 3.3 cm.

As the glass walls of the vessels get hotter than the surrounding water during irradiation, correction

factors for this 'excess heat' were calculated for each of the vessels to take into account the flow of heat from the vessel walls to the measurement point. All of the correction factors are less than 0.1%.

IV. TEMPERATURE MEASUREMENT SYSTEM

An important part of the calorimeter is its temperature measurement system. It needs to be sensitive and have a high signal to noise ratio, while the sensing element itself must be small enough so that it does not (1) perturb the radiation field at the measurement point - using a probe that is too big would result in a measurement of 'absorbed dose to temperature probe', not absorbed dose to water, and (2) produce excess heat. Power dissipation must also be minimized to prevent incorrect temperature readings or convection occurring. For the sensors described below, the excess heat correction factor is 0.1 %.

The temperature sensors used in the calorimeter are glass bead thermistors, which have a resistance of 10 k Ω at 4 $^{\circ}\text{C}$. Each thermistor is fixed to the end of a pulled glass tube using solder glass, as shown in Figure 4. The thermistors, therefore, are exposed directly to the water, and only glass and solder glass comes into contact with the water.

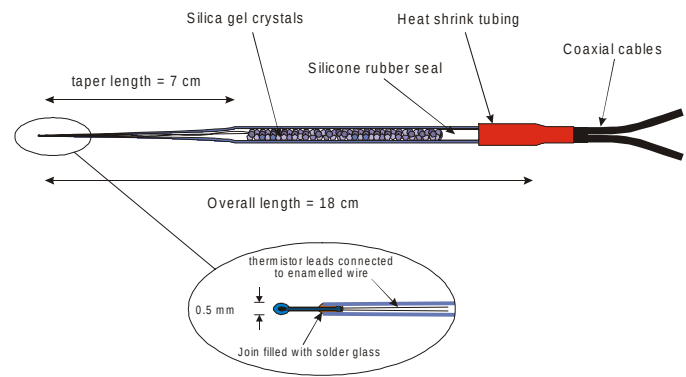


Figure 4 Thermistor probe

As the linear accelerator environment in which the calorimeter was to be used is known to be electrically noisy, considerable effort was put into minimising its effect on the temperature sensing electronics connected to the thermistor probes. The thermistor probes are either connected to a separate d.c. bridges, or more recently, a.c. bridges, or both to the same a.c. bridge. A new a.c. bridge is shown in Figures 5 and 6.

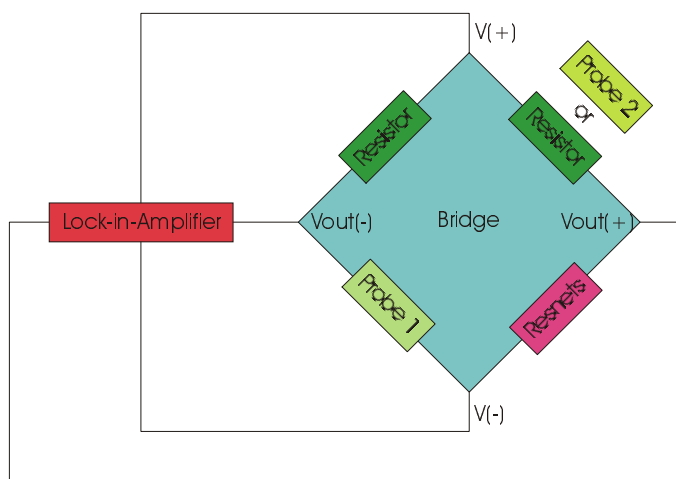


Figure 5 Diagram of a.c. bridge

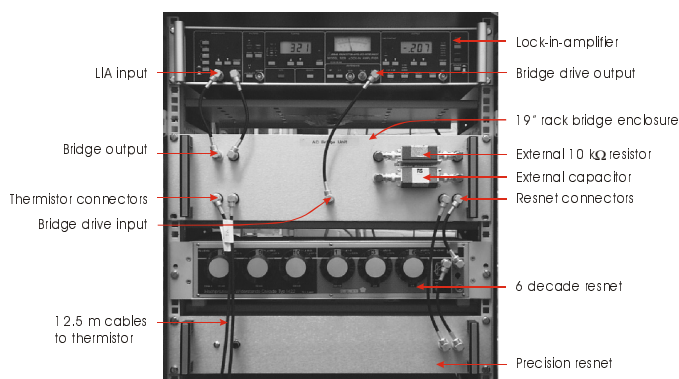


Figure 6 Photograph of a.c. bridge

The main components of the a.c. bridge system are:

1. a bridge made from Vishay⁷ precision resistors;
2. a Lock-in-Amplifier (LIA). This provides the bridge drive voltage, output amplification and phase sensitive detector;
3. one or two temperature sensing thermistor probes and;
4. two resistance networks (Resnets) to balance the resistive component of the bridge output.

The bridge drive voltage is 0.5 V, so the power dissipation in each of the thermistors is about 6 μ W. The end result is a system with a signal to noise of 300, and a typical standard uncertainty on the measured temperature rise of 0.2%.

V. HEAT DEFECT

Radiation induced chemical reactions are a main cause for concern in water calorimetry, as they effect

whether the measured temperature rise corresponds directly with the energy deposited by the incident radiation. This is known as the 'heat defect', and it can be positive or negative depending on whether the chemical reactions are endo- or exo-thermic. However, by carefully controlling the purity of the water in the calorimeter vessel, including what gases are dissolved in the water, a stable system can be produced with a known 'heat defect'.

At NPL, a simple system as shown in Figure 7 is used to allow the calorimeter vessel to be filled with ultra-pure water that is saturated with either the gas hydrogen or argon. In each case, the heat defect of the gas saturated water is zero. The whole experimental

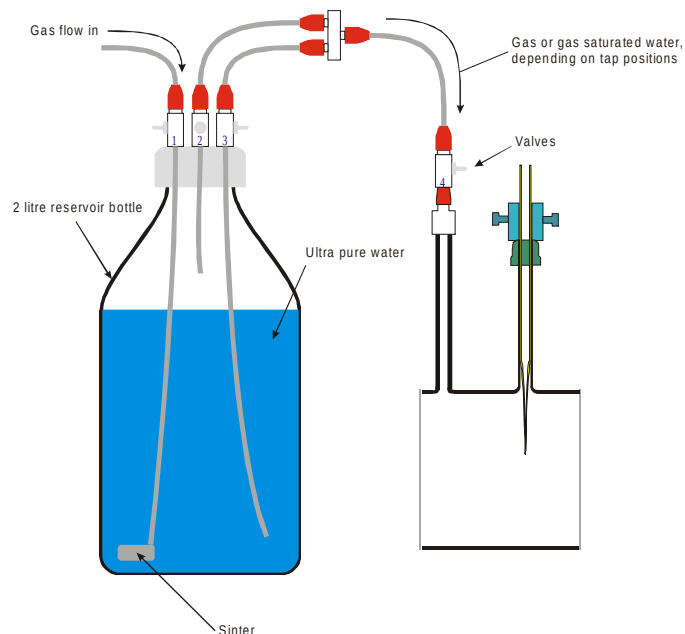


Figure 7 Water gas-saturation system

setup, including the valves, is cleaned with chromic acid prior to use. With the glass reservoir bottle filled with ultra pure water, valve 3 closed, valves 1, 2 and 4 open, and the screw cap holding the thermistors in place slightly loose, H₂ or Ar enters the reservoir bottle through valve 1. When the water is saturated with the gas, valve 2 is closed, and valve 3 opened. Gas pressure then forces water out of the reservoir into the calorimeter vessel. Valve 4 is then closed and the thermistor screw-thread connector is tightened, sealing the vessel.

VI. RESULTS

The experimental set-up that is typically used for irradiations is shown in Figure 8. Either the water calorimeter or an ionisation chamber can be placed in the radiation beam at any one time, along with a

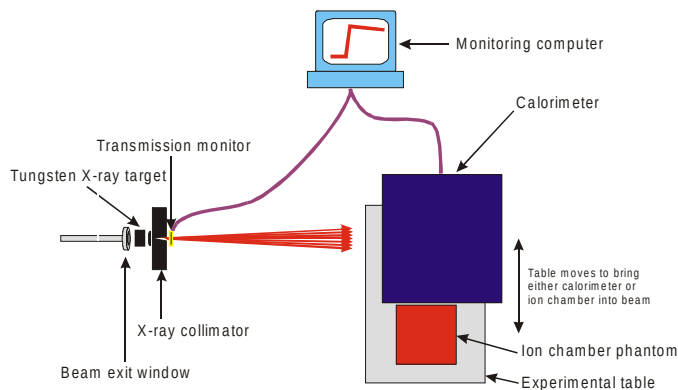


Figure 8 Experimental set up

transmission monitor (to correct for fluctuations in the intensity of the radiation beam). Absorbed dose to water measurements made with the calorimeter are bracketed by groups of measurements made using an ion chamber (the ion chamber also gives absorbed dose to water as it has been calibrated previously against the primary standard graphite calorimeter).

Measurements were made using 6, 10, 16, and 19 MV photons, and 16 MeV electrons with the calorimeter inner vessel filled with hydrogen saturated ultra-pure water, using the d.c. temperature measurement system. A typical calorimeter run from this set of measurements is shown in Figure 9.

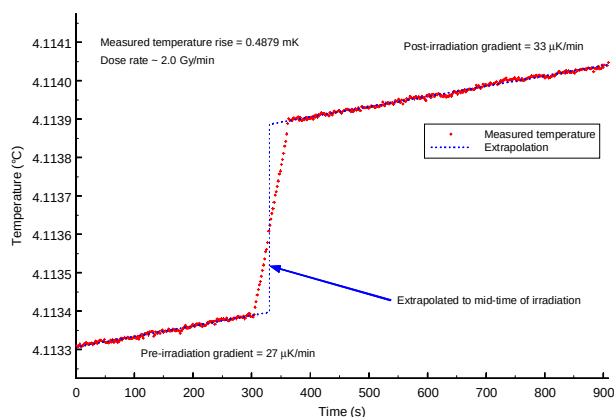


Figure 9 Typical calorimeter run

Initially, convection effects were seen due to temperature instabilities in the water phantom,

however, these problems have now been solved. These measurements showed an uncertainty of 2% (95% confidence limit) on the measurement of absorbed dose to water. Comparisons with the primary standard graphite calorimeter agreed within the measurement uncertainties. However, as 2% is too high an uncertainty, the calorimeter was subsequently redesigned to reduce the uncertainties.

Using the redesigned calorimeter and new a.c. temperature measurement system, measurements were performed in ^{60}Co radiation at a dose rate of $1 \text{ Gy} \cdot \text{min}^{-1}$. The standard deviation (type A) on the measured temperature rise using the new system was 0.7% for a typical set of 15 measurements, with a signal to noise ratio of 270. This compares with a standard deviation and signal to noise ratio of 1.6% and 95 respectively for the previous (d.c.) system.

The recent improvements to the calorimeter have reduced the estimated uncertainty on the measurement of absorbed dose to water to 1.3% (95% confidence limit).

VIII. CONCLUSION

The most recent tests have confirmed the feasibility of the calorimeter design although further work is required before the calorimeter can be used as a primary standard. Future work will focus on making measurements of the heat defect.

IX. ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the National Measurement System Policy Unit of the UK Department of Trade and Industry.

X. REFERENCES

1. ICRU, "Determination of absorbed dose in a patient irradiated by beams of X or gamma rays in radiotherapy" ICRU report 24 1976
2. DuSautoy A.R., "The UK primary standard calorimeter for photon beam absorbed dose measurement". Phys. Med. Biol. 41 p 137
3. McEwen M.R., DuSautoy A.R. and Williams A.J., "The calibration of therapy level electron beam ionisation chambers in terms of absorbed dose to water". Phys. Med. Biol. 43 p 2503-2519
4. Palmans H. and Seuntjens J. P., "Construction, Correction Factors and Relative Heat Defect of a High Purity, 4 °C Water Calorimeter for Absorbed Dose Determinations in High Energy Photon Beams", NPL Calorimetry Workshop, 1214 October 1994.
5. Seuntjens J. P., Ross C. K., Klassen N. V. and Shortt K. R., "A Status Report on the NRC Sealed Water Calorimeter", PIRS0584, NRC, April 1997.
6. Schulz R. J., Wu C.S. and Weinhaus M.S., "The Direct Determination of Dose to Water Using a Water Calorimeter", Med. Phys. 14(5), Sep/Oct 1987.
7. Vishay-Mann Ltd., Wymondham, Norfolk, Great Britain.

1. ICRU, "Determination of absorbed dose in a patient irradiated by beams of X or gamma rays in radiotherapy" ICRU report 24 1976
2. DuSautoy A.R., "The UK primary standard calorimeter for photon beam absorbed dose measurement". Phys. Med. Biol. 41 p 137
3. McEwen M.R., DuSautoy A.R. and Williams A.J., "The calibration of therapy level electron beam ionisation chambers in terms of absorbed dose to water". Phys. Med. Biol. 43 p 2503-2519
4. Palmans H. and Seuntjens J. P., "Construction, Correction Factors and Relative Heat Defect of a High Purity, 4 °C Water Calorimeter for Absorbed Dose Determinations in High Energy Photon Beams", NPL Calorimetry Workshop, 1214 October 1994.
5. Seuntjens J. P., Ross C. K., Klassen N. V. and Shortt K. R., "A Status Report on the NRC Sealed Water Calorimeter", PIRS0584, NRC, April 1997.
6. Shulz R. J., Wu C.S. and Weinhou M.S., "The Direct Determination of Dose to Water Using a Water Calorimeter", Med. Phys. 14(5), Sep/Oct 1987.
7. Vishay-Mann Ltd., Wymondham, Norfolk, Great Britain.