Evaluation of a Second Generation Domen-Type Water Calorimeter for Absorbed Dose in a ^{60}Co Beam at NIST

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Abstract

A second generation Domen-type sealed water calorimeter constructed at University of Texas Southwestern Medical Center for the National Institute of Standards and Technology (NIST) has been reported in the last Absorbed Dose Workshop at the National Physical Laboratory (NPL) United Kingdom. This calorimeter design, conceived after reviewing other designs from Physikalisch-Technische Bundesanstalt Germany, Istituto Nazionale di Economia Agraria Italy, NPL, and National Research Council Canada, features several improvements over the original Domen design in a number of areas. These include thermistor probe fabrication, glass core design, magnetic stirring mechanism, alternating current (AC) lock-in-amplifier in the electrical circuitry, and personal computer (PC) interfaced data acquisition. The calorimeter is now at NIST for testing. We have rebuilt the thermistor probes, refilled the core with H_2 saturated high purity water, and evaluated the assembly in a ^{60}Co beam at a dose rate of about 19 mGy/s for thermal and electrical stability. In this work-in-progress report, we show preliminary results of dose-rate determination and compare these with the transferred value from a different ^{60}Co source obtained using the original Domen water calorimeter with H_2 saturated core water. Ultimately we seek to establish the new water calorimeter as the primary standard for absorbed dose in water at NIST.

1. Introduction

The Domen-type sealed water calorimeter [1,2], the basis for all the currently existing water calorimeters for the absolute measurement of absorbed dose in water from ionizing radiation, has been undergoing improvements in other metrology laboratories in the world. We report the results of the recent testing of a second generation calorimeter designed and constructed previously for NIST at the University of Texas Southwestern Medical Center [3,4]. This new design, aiming at simplifying the construction and use of the calorimeter, features several improvements over the original Domen design in the following areas:

- Thermistor probes constructed from commercially available glass capillary tubes rather than home-drawn capillaries for efficiency;
- Glass bead thermistors sealed within the capillary with a ultra-violet light curing plastic directly, eliminating the original glass end cap for easy positioning and good thermal conductivity;
- Seal between the capillary and the glass core made with Teflon for better compressibility than the original polyethylene;
- Bridge excitation and readout using an AC lock-in amplifier, an improvement over the original DC (direct current) excitation in terms of noise filtration and suppression;
- Amplifier readout controlled with a PC computer interface, enabling automation;

- Data analysis performed on the PC computer for rapid processing of a large amount of repeat results;
- Sealed water tank surrounding the sealed glass core, no longer requiring daily refilling to compensate for evaporation;
- Ability to make depth adjustment of the core to measure at different absorbed dose rates; and
- Magnetic mechanical stirring of the surrounding water to reduce the effect of excess heat.

The recent effort at NIST includes rebuilding and calibrating the thermistor probes, refilling the core with H_2 saturated high purity water to eliminate heat defects, and evaluating the assembly in a ^{60}Co beam at a dose rate of about 19 mGy/s for thermal and electrical stability. Various aspects regarding the operation are partially assessed. The preliminary results of dose-rate determination are compared with the transferred value from a different ^{60}Co source obtained using the original Domen water calorimeter with H_2 saturated core water [5,6]. These testings are important first steps toward establishing a new primary standard for absorbed dose in water at NIST.

2. Apparatus and Methods

The components (schematically shown in Fig. 1) and operational characteristics of the water calorimeter are briefly summarized as follows. The radiation sensing part is a sealed glass core (Fig. 1a) blown from Pyrex tubing, with an inner diameter less than 35 mm and wall thickness less than 0.3 mm at the center. The core is fitted with two threaded Teflon [†] plugs with through holes allowing glass capillaries of 0.4 mm outer diameter to be inserted. It also has a valve (not shown) on each end serving as water inlet and outlet. The core is filled with hydrogen saturated high purity water with a small air bubble (contained by a narrower “bottle neck”) to allow for volume expansion during radiation heating. Through each plug, a thermistor is inserted through the capillary into the center of the core. The two thermistors, designated as RT1 and RT2, form one opposite pair of arms of a Wheatstone bridge (Fig. 1b). The thermistors (Thermometrics) are the negative temperature coefficient type glass coated bead with a nominal diameter of 0.18 mm and nominal resistance of 10 kΩ and with Pt alloy leads. The response time constant is 7 ms in water, and the power dissipation constant is 0.3 mW/°C.

A pair of fixed resistors, designated as F1 and F2, where F1= 12.2 kΩ and F2 = 10 kΩ, form the other pair of opposite arms of the Wheatstone bridge. RT1 is in series with an adjustable resistance bank, R_{adj}, ranging between 0 and 12.1 kΩ at 1.1 kΩ steps, whereas F1 is in series with another fine adjustable resistance bank, R_{box}, ranging between 0 and 1111 Ω in steps of 0.1 Ω. The bridge is excited and measured by a lock-in amplifier that produces a sine wave modulated input signal and separates the output by amplitude and phase. Operated at room temperature, the input voltage of 1 V is used to limit the power dissipation in the thermistors to a maximum of 25 µW. The sensitivity of the device is as follows: 1 Gy of radiation dose causes a temperature rise in water of 0.24 mK, which corresponds to a 0.2 Ω change in the total resistance of the two thermistors, or a 3.5 µV change in the bridge output voltage.

Measurements have been carried out in a ^{60}Co teletherapy unit, with the center of the glass core at 1 m from the source and 5 cm below the water surface in a water phantom (Fig. 1c) enclosed in

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[†] Certain commercial equipment, instruments, or materials are identified in this paper to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

an acrylic tank of 30 x 30 x 30 cm^3. The entrance window is thinned to 1 mm for an area of 12 cm x 12 cm, sufficient to accept a vertical radiation field with a cross section of 10 cm x 10 cm. The nominal absorbed dose rate, as determined with a transfer ionization chamber in reference to the original Domen water calorimeter measurement in 1994 (with a combined uncertainty of 0.4%), is 19.2 mGy/s for these new measurements. A magnetic stirrer in the bottom of the tank provides circulation to achieve a more uniform temperature throughout measurements. Since the wall of the glass core generates certain amount of excess heat due to radiation that can affect the thermistor's sensing region in time, the moving water due to stirring helps carrying away this excess heat from the core and into the larger water body. Therefore, this feature can significantly reduce the impact of the exothermic effect in the external once-distilled water and within the region of the collimated beam [7].

The principle of operation is a standard one using the Wheatstone bridge balancing technique to measure a very small signal in a somewhat noisy environment, aided by an AC lock-in amplifier with phase-sensitive detection to filter out the random noise from the modulated signal. Radiation exposure is made by opening the source shutter for 30 s (corresponding to about 0.5 Gy) at first to evaluate the response to the input sine wave frequency. The duration of the exposure is then increased to assess the linearity as a function of total dose. Custom-developed software using National Instrument Labview is used to record the bridge output voltage change at a data rate of 10 per second. The bridge is balanced to within 1 µV before the first exposure; a pre- and post-irradiation base line is established by continuous data collection for about 25 s before and after the shutter opens/closes. The average net change of the bridge output voltage, ΔV, is used to calculate the change of resistance, ΔR, in the thermistors. The temperature change, ΔT, is then determined by the thermistors' resistance-temperature calibration. The dose Q is obtained by $Q = c\,\Delta T$, where c is the specific heat of water at room temperature.

The calibration is carried out by submerging the glass core/thermistors assembly with the same operational circuitry in a separate temperature controlled bath monitored with a calibrated mercury thermometer with a precision of 0.01 °C. The bridge output voltage is recorded as a function of the control temperature with the lock-in amplifier at the same operational excitation voltage (1 V) and frequency (100 Hz).

3. Results and Discussions

Raw data from a repeated exposure is shown in Fig. 2, representing 16 irradiation runs between 30 and 90 s each. The drift for approximately an hour after the end of the last irradiation run is also shown in the graph. Three adjustments of the bridge balance can be seen in the graph as jumps in the output voltage. Each of these runs, shaped like the last run as depicted in the magnified graph, is individually recorded and analyzed. A base line is fitted to the pre- and post-irradiation portion of the curve, and the average difference within the region of irradiation is taken as the voltage rise, ΔV, thereby yielding a temperature rise, ΔT, attributed to the radiation. The absorbed dose is then calculated as described above.

A study of the effect of varying the amplifier operation frequency, *f*, has been performed by measuring the absorbed dose at 30 s intervals, varying *f* from 50 Hz to 175 Hz (Fig. 3), and at two different sensitivity settings that corresponds to the level of noise attenuation. The vertical bars are standard deviations from the mean of three replicate measurements for each setting. This shows that at the higher level of noise attenuation, within the measurement uncertainty the response is relatively independent of the operation frequency. More data are needed to establish a statistically meaningful conclusion.

Figure 4 is a summary of the evaluation of the linear dependence of the total dose as a function of the shutter opening time. Results from 4 sets of measurements taken within a week are shown; each set of measurement is performed at various irradiation duration from 30 to 90 s with three replicate runs per setting. A weighted linear fit with a forced zero intercept ($y = kx + b$, where k is the slope, and b the intercept, set to 0) to each set of data is also shown, along with the fitted slope k. (Setting $b = 0$ is a simplified assumption that at zero dose the temperature rise is indeed zero. The effect of this assumption is to be investigated further.) The slope thus determined represents the determined dose rate in Gy/s, and is to be compared with the dose rate obtained from the transfer chamber. This is shown in Fig. 5, in which the nominal decay corrected dose rate is plotted as a dotted line. In addition, the dose rate obtained from an earlier run (day –5) of five 30 s exposures is also reported for comparison. The seemingly faster-than-expected downward trend of the measured dose rate is not yet understood and needs further investigation.

These are preliminary results, as no assessments of the sources of errors and none of the necessary corrections including possible changes in the thermistors' calibration coefficient that might cause the seemingly downward trend in Fig. 5. The initial aim is to simply evaluate the characteristics and the reproducibility of the device. We have obtained a reasonable agreement between the data and the expected value within experimental uncertainties. This is a starting point for more rigorous and systematic study in the future. Many more irradiation cycles are necessary to improve the statistics of the measurements suitable for standards use in a vertical ^{60}Co field with improved noise reduction schemes. Measurements in electron beams and high energy photon beams will also be considered. Thermal modeling is intended for studying heat transfers in the system at room temperature as well as the eventual migration to a 4°C operation.

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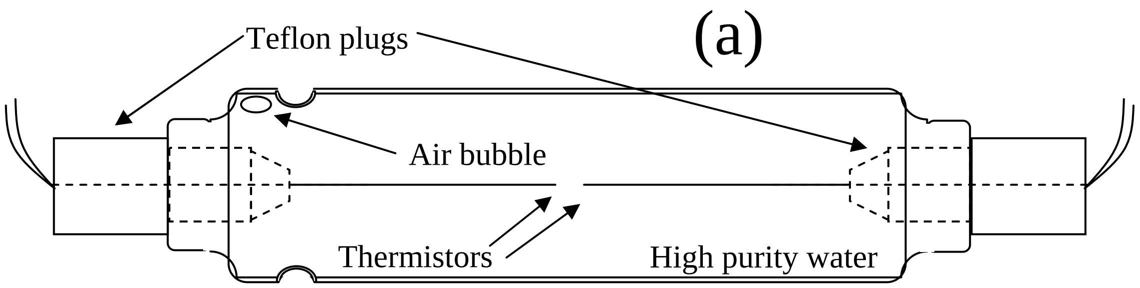
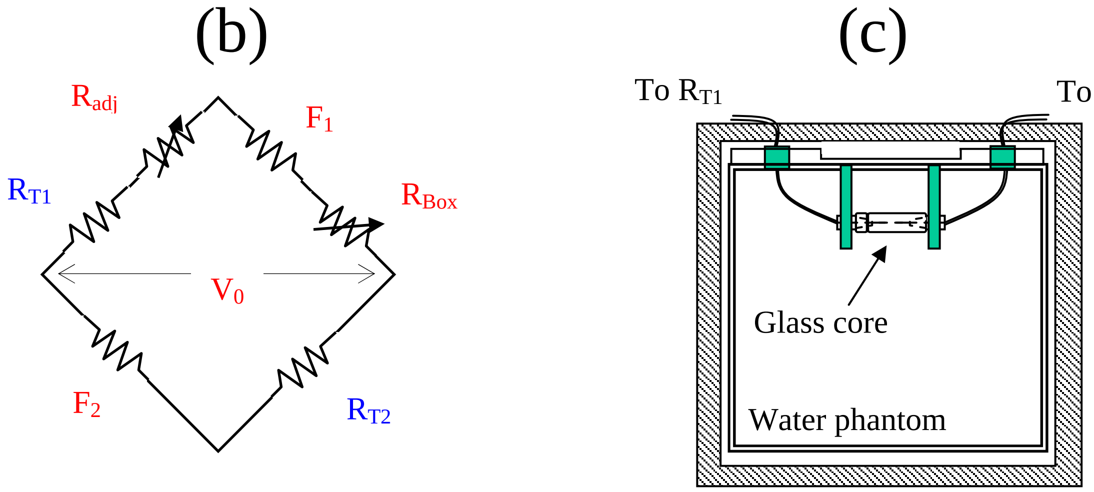


Glass core details



Wheatstone bridge

Calorimeter metal housing and foam insulation

Fig. 1a. Glass core details showing the thermistors threaded through Teflon plugs into the center of the core. 1b. Wheatstone bridge circuit used in the water calorimeter. R_{T1} and R_{T2} are the thermistors for temperature measurements. 1c. The entire calorimeter containing the core submerged in the water phantom 5 cm below the surface, and the foam insulated aluminum outer housing.

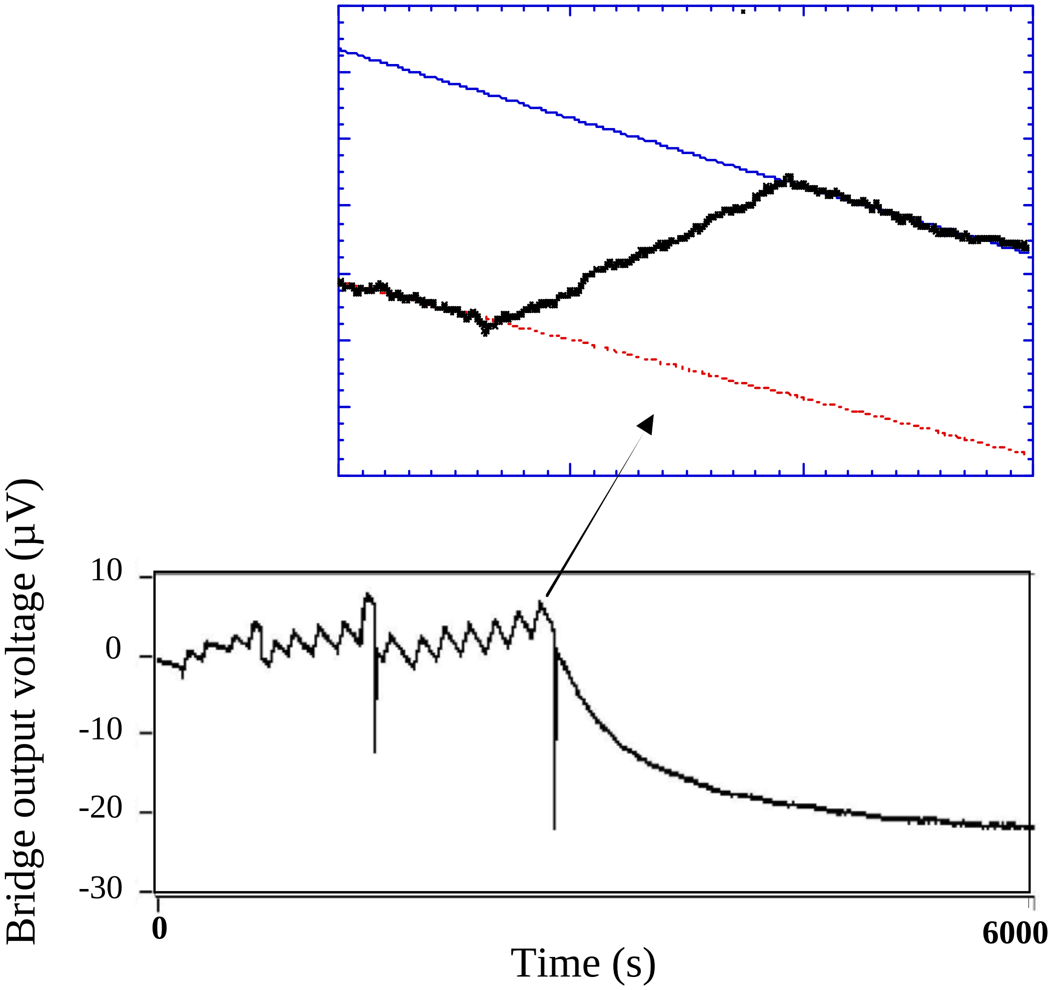


Fig. 2. Raw data from a repeated exposure representing 16 irradiation runs between 30 and 90 s each, and the drift after the irradiation ends. The drastic dips are the result of a bridge balance readjustment. The upper right graph is a magnification of the last run. Each run is individually recorded and analyzed.

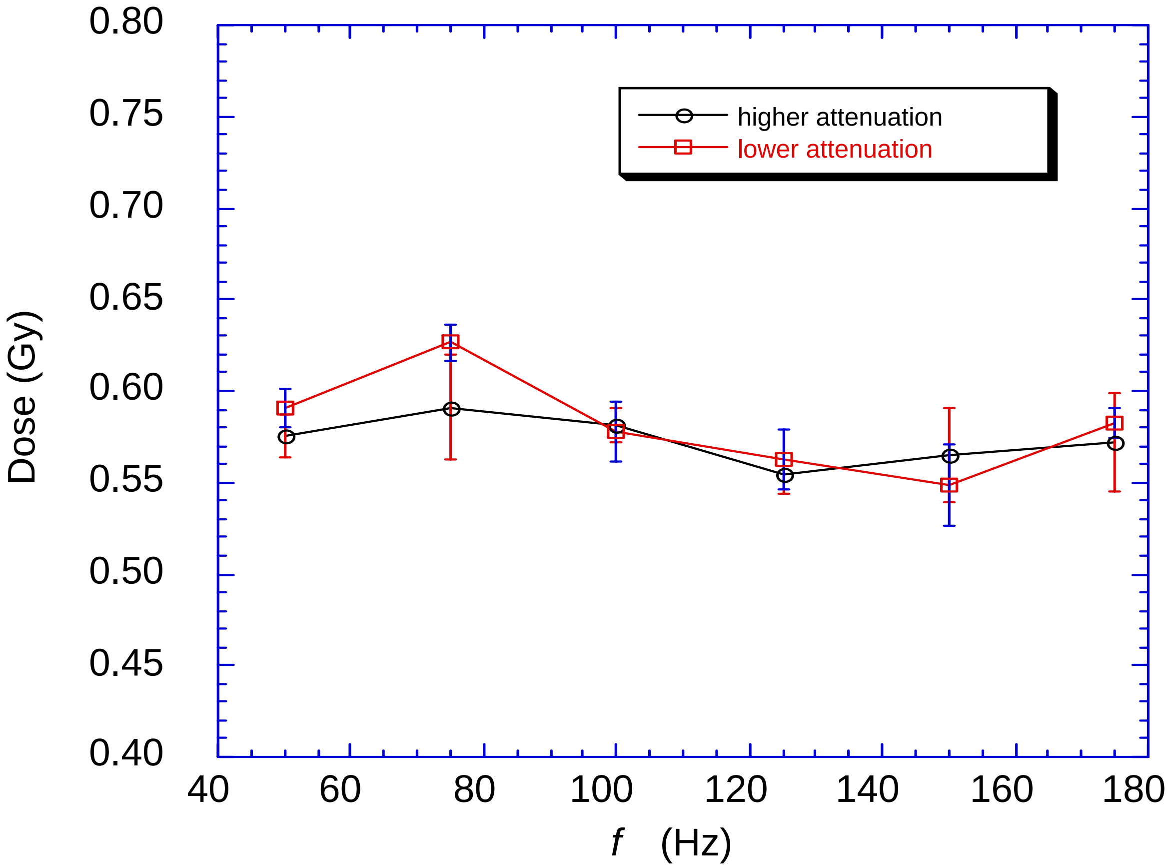
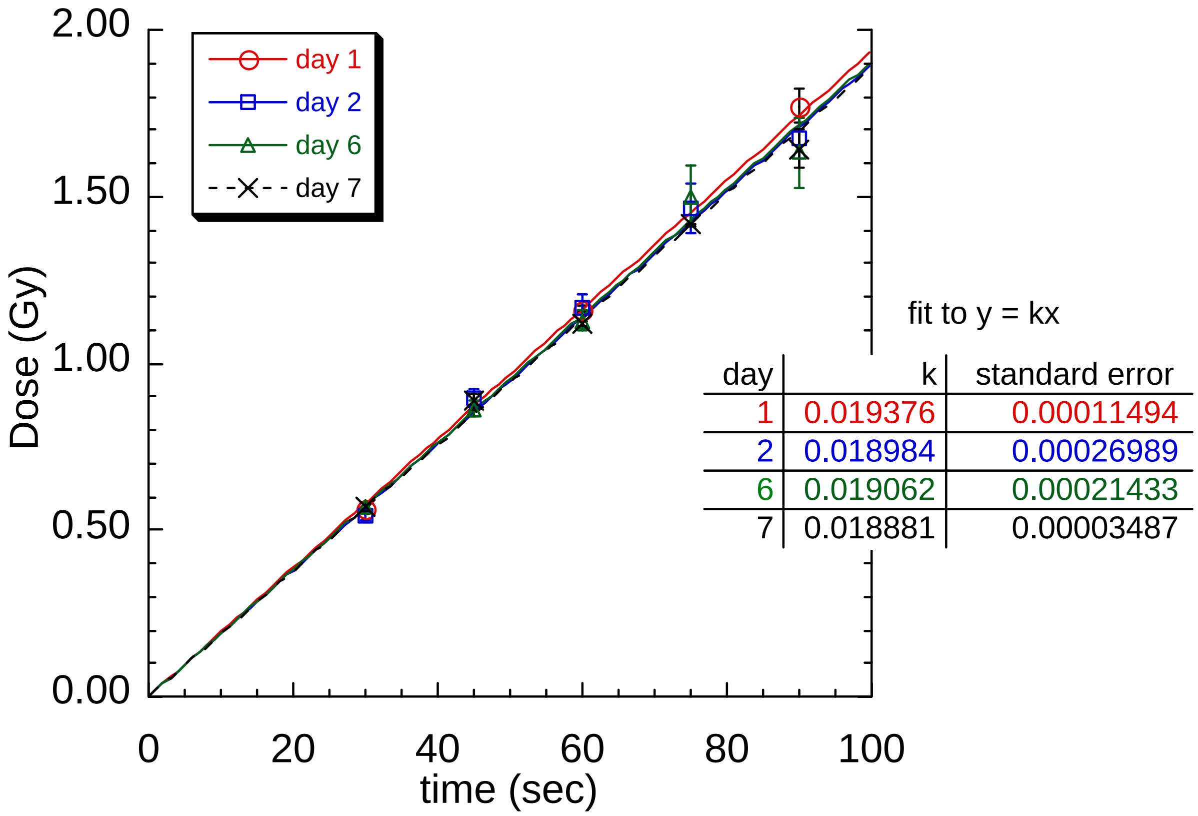


Fig. 3. The absorbed dose at 30 s intervals determined at operation frequencies between 50 and 175 Hz and for two different settings for noise attenuation, higher (circle) and lower (square), respectively.



fit to y = kx

day	k	standard error
1	0.019376	0.00011494
2	0.018984	0.00026989
6	0.019062	0.00021433
7	0.018881	0.00003487

Fig. 4. Dose accumulation as a function of time. Four sets of measurements have been taken within a week, each with a varied irradiation time from 30 to 90 s. A linear fit to each set of data is also shown, with the slope being the determined dose rate in Gy/s.

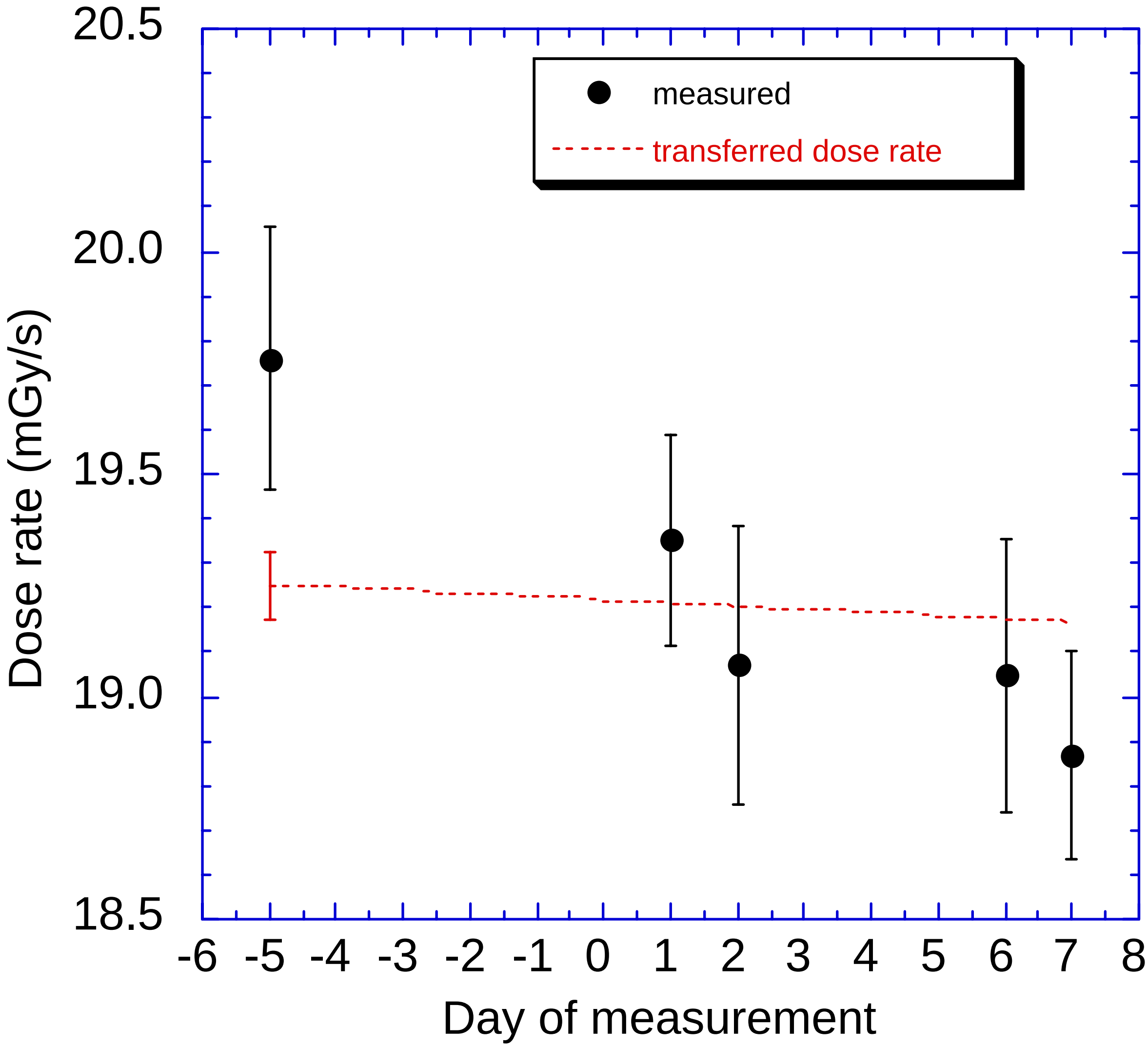


Fig. 5. The slope determined using the data shown in Fig. 3 as compared to the decay corrected dose rate obtained by using the transfer chamber (dotted line, with an uncertainty of 0.4% indicated). The horizontal scale is relative to a reference date of July 1, 2003 (Day 0). The first measurement carried out on day –5 has been obtained by averaging the dose rate from 5 repetitions of 30 s exposures, unlike the other four data points which are determined by the slope of a linear fit to the time dependent total dose measurement.

Discussion

Malcolm McEwen – Could you just confirm it's primarily designed for the vertical beam at the moment, or is it designed to operate in a horizontal beam as well? I can't remember from Ken's presentation in 1999. Can it be rotated?

Heather Chen-Mayer – Yes, that was a question, I looked at the transcript from the last workshop, and I meant to have it tilted but I didn't have time. It looks like it's do-able but the question is whether the window will be bulging -

Malcolm McEwen – It's one mm ...

Heather Chen-Mayer – It could be, yes, it could be. But we can account for it.

Malcolm McEwen – Well, that's what you will have to do for the accelerator.

Heather Chen-Mayer – Yes, we'll have to turn it on its side. But the fact it's sealed I think it's do-able.

David Webb – Yes, that prompts me to ask a question about the window, that's a very thin window for such a large area (HCM - Yes) and with water on one side it may deform over time, perhaps.

Heather Chen-Mayer – It could be, but you see the water is really filled (DW - Yes), there are no air bubbles, but it could be there is some bulging. Well you see, I wish I had done it before I came, so I could answer the question from last time, but there wasn't time.

Michael Kramer – You did the measurements with your new cobalt source, and you compared this with the results of Domen, who didn't have that source (HCM – Right). How did you make the transfer from Domen's source to your new source (HCM – Right).

Heather Chen-Mayer – We had this ... We just used an A12 ionization chamber, a small cylindrical chamber, we did some measurements in Domen's original setting, 10 x 10, at 1m, 5 cm under the water, and then just used a water phantom to see if it would transfer to another source under the same condition, and just repeat measurements ...

Hugo Palmans – I was wondering if you were stirring the phantom, while you were doing measurements (HCM – Yes), because I have a concern about that because it means that shortly after the irradiation you will have a steep temperature gradient quite close to the thermistor, and that could cause large conduction, heat conduction across ... (HCM – Yes)

Heather Chen-Mayer – Yes, that certainly is a concern, when we did these irradiations, we did it basically within 100s, to finish the whole run, (HP – Yes) Off – On – Off within 100s, and we didn't really wait that long as according to Domen, you are supposed to wait maybe 20 minutes in between. We didn't do that because we think that we can account for this drift by looking at the data. Certainly if it decays in a linear fashion, then we can fit it up to that point. At some point it does go up, it changes, the drift changes apparently. The data we cannot use in that case. But in order to get more accurate results, I think we should wait. But this is the testing. It certainly is a concern. Now Ken Gall actually said that he's run it with and without the stirring and he didn't see a big difference, but it is certainly something we'll need to look into.

David Burns – If I understood correctly, what you call a run was a series of irradiations at different times. And then one way to analyse that data would be to extrapolate to zero time (HCM – Right). But I'm wondering if what you then measure as the calculated value is the temperature rise to the probe rather than to the water. Because at zero time you're measuring the temperature rise in the probe before any heat has dissipated.

Heather Chen-Mayer – I think it's a relative change rather than an absolute change – did I understand the question correctly, or ... ?

David Burns – Well, at zero time you've got the temperature rise in the probe itself because the specific heat of the probe is different from that of water, before heat is transferred to ... water, so you would need to supply corrections in that case ...

Heather Chen-Mayer – No, we have not done any corrections, as I mentioned, any heat corrections at all. This is just taken at face value. Look at a temperature change, before and after, extrapolate it to a bending region of the irradiation and take the average. Even that is not a constant, as I've shown. But the change is very small. So right now, for this type of measurement, for the uncertainty, certainly that correction is small (I think).

Malcolm McEwen – This is the only calorimeter that is still operating at room temperature, that I am aware of. Are you planning to ever do a four degrees C version, or going to keep it as you what you've got at the moment?

Heather Chen-Mayer – Well at the moment, room temperature, but certainly, I can see a lot of advantage at four degrees C, we probably will try it.

Robert Huntley – Whereabouts do you get the thermistors, do you know what brand they are, who supplies them?

Heather Chen-Mayer – Yes, Thermometrics.

David Burns – This is just an evaluation study but have you looked approximately at the absorbed dose rate that you're getting? Is it close to what you expect?

Heather Chen-Mayer – Yes, probably I didn't explain well there. The transfer dose from Domen's values are in red so that over here nominally 19.2 mGy/s. That blue value is what we measured. So within uncertainty, it's agreed. It is good agreement within here, but this is little bit off. But what I mentioned is that there seems to be a downward trend of the measured value. I think it may have to do with the fact that the calibration beta value has changed over time. As Domen observed, beta actually increases as time goes by. He thinks it's some kind of stability factor in the thermistors. So when you look into it, if the beta increases, that would account for this downward trend. And that's a problem with ...

David Burns – I see, it's the calibration?

Heather Chen-Mayer – The calibration changes.

Malcolm McEwen – It seems a very sharp change in very short time scales. I mean your other thing that can give a decay like that is impurities giving a heat defect isn't it? If you tried irradiating it for a couple of hundred gray, and see if the sensitivity changes ...

Heather Chen-Mayer – Right, we have not gotten that far. So I certainly would take suggestions from you what to do next, and this is the place to ask.

Virendra Patel – Yes, I must remember that, I am actually from a hospital. What sort of advantages do you see if you do it at four centigrade?

Heather Chen-Mayer – Oh, well the expert is behind you, I think Malcolm is going to say something.

Malcolm McEwen – You’ve got problems with convection. At four degrees C, you maximise the density, and the corrections for convection are minimised. A number of people have shown that the corrections at room temperature are seriously ... so the majority of standards labs have moved to four degrees C. It’s more complicated to build, but it’s more accurate, potentially.