

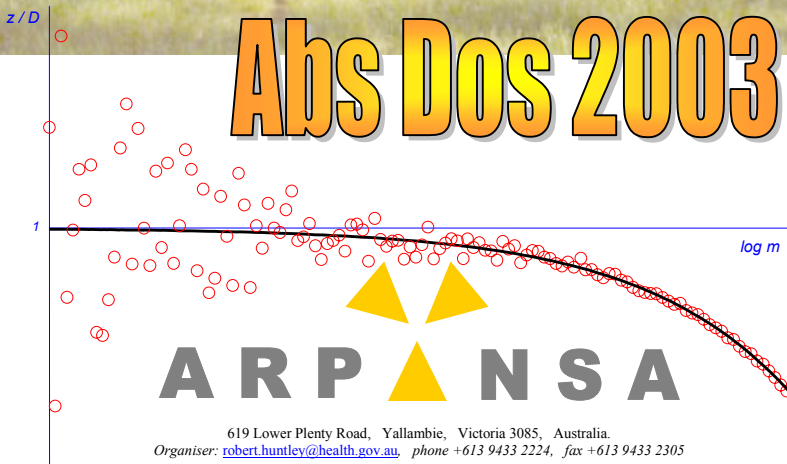


Australian Radiation Protection  
and Nuclear Safety Agency

**WORKSHOP ON RECENT ADVANCES IN  
ABSORBED DOSE STANDARDS**

**SYNOPSIS AND SCIENTIFIC  
PROGRAM**

**19-21 August, 2003**



*Partly sponsored by:*



The Australasian College of  
Physical Scientists and  
Engineers in Medicine  
(Victorian-Tasmanian Branch)



# **AbsDos 2003**

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## **WORKSHOP ON RECENT ADVANCES IN ABSORBED DOSE STANDARDS**

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Held at the Melbourne office of  
the Australian Radiation Protection and Nuclear Safety Agency  
619 Lower Plenty Road  
Yallambie, VIC, 3085  
AUSTRALIA

August 19-21, 2003

## **SYNOPSIS AND SCIENTIFIC PROGRAM**

### **AbsDos Steering Committee**

Chair: Robert Huntley

David Webb

Milly Cox

Duncan Butler

Lew Kotler

Roland Sargent

### **Acknowledgments**

John Boas

Karren Rosser

## SUMMARY OF SCIENTIFIC PROGRAM

Time	Details	mins	Presenter	ORG
<b>DAY ONE: TUESDAY 19<sup>th</sup> August 2003</b>				
<b>SESSION 1. Chair David Webb (ARPANSA)</b>				
1000	Opening by ARPANSA CEO	15	J Loy	ARP
1015	Introduction by Workshop Organiser	10	R Huntley	ARP
<b>calorimetry</b>				
1025	"Evaluation of a second generation Dosem-type water calorimeter for absorbed dose in a <sup>60</sup> Co beam at NIST"	25	H Chen-Mayer	NIST
1115	"The METAS photon-beam primary standard sealed water calorimeter"	25	G Stucki	METAS
1140	"Development of the NPL portable graphite calorimeter and its operation in hospital radiotherapy departments"	25	S Duane	NPL
1205	"Development of a primary standard calorimeter for low energy electron beams"	25	M McEwen	NRC
<b>SESSION 2. Chair Malcolm McEwen (NRC)</b>				
1330	"The heat defect in the PTB water calorimeter: A discussion on uncertainty"	30	H-M Kramer	PTB
1400	"Thermal modelling of graphite calorimeters"	30	S Duane	NPL
1430	"Dosimetry of high-energy photon beams with the NMi water calorimeter"	30	A Aalbers	NMi
1530	"BNM-LNHB graphite calorimeter: a new constant-temperature operating mode for absorbed dose rate measurements"	30	J Dures	LNHB
1600	"Scatter and heat conduction correction factors for two glass vessel geometries in sealed water calorimeters"	30	H Palmans	NPL
1630	"Feasibility of graphite and water calorimetry in low-energy clinical proton beams"	30	H Palmans	NPL
<b>DAY TWO: WEDNESDAY 20<sup>th</sup> August 2003</b>				
<b>SESSION 3. Chair Frank Pernicka (IAEA)</b>				
<b>ionometry</b>				
0915	"The determination of absorbed dose to water in x-ray fields with a graphite extrapolation chamber"	25	H-M Kramer	PTB
0940	"Low energy proton beam dosimetry with plane parallel chambers using NPL electron and <sup>60</sup> Co calibrations"	25	R Thomas	NPL
<b>chemical and solid state dosimetry</b>				
1005	"The METAS electron-beam primary standard chemical dosimeter"	25	G Stucki	METAS
1100	"EPR dosimetry - Applications, problems and prospects"	30	J Boas	Mon U
<b>Uncertainty</b>				
1130	"International symposium on standards and codes of practice in medical radiation dosimetry - Recommendations"	30	F Pernicka	IAEA
1200	"The measurement uncertainty at Australian Secondary Standard Dosimetry Laboratory (ASSDL)"	30	J Davies	ANSTO
<b>SESSION 4. Chair Lew Kotler (ARPANSA)</b>				
1330	"Uncertainty Workshop: Everything you always wanted to know about the ISO GUM but were afraid to ask"		R Bentley	NML
<b>DAY THREE: THURSDAY 21<sup>st</sup> August 2003</b>				
<b>SESSION 5. Chair Simon Duane (NPL)</b>				
<b>general interest</b>				
0845	"Performance of an 'off-the-shelf' clinical linac for radiation standards dosimetry"	25	M McEwen	NRC
0910	"Continuity of Australian standards of absorbed dose for <sup>60</sup> Co: Comparison of beam quality correction factors for 18 MV beams from clinical and research linacs"	25	J Boas	Mon U
0935	"Absorbed dose to arbitrary materials"	15	R Huntley	ARP
0950	"Problems with the adoption of TRS 398 as a kilovoltage CoP in hospitals for HVL's less than 3 mm Al"	25	RM Millar	WBRC
1040	"Australian secondary standards of dosimetry"	25	J Davies	ANSTO
1105	"The role of trilateral comparisons in the assessment of uncertainty"	25	D Webb	ARP
<b>posters</b>				
1130	"The measurement of the absorbed dose to water in <sup>60</sup> Co using the pancake ionization chamber"	60	S-H Su	INER
	"Air kerma standard for medium X-rays"		T Kurosawa	AIST
	"A new dosimetry protocol for external beam radiotherapy in Japan"		A Fukumura	NIRS
	"A novel signal processing method for the NMi water calorimeter"		L de Prez	NMi
<b>SESSION 6. Chair H-Michael Kramer (PTB)</b>				
<b>panel discussion</b>				
1330	Conclusions and Recommendations. Next meeting.	90		

## WORKSHOP PROGRAM

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<b>SATURDAY 16<sup>th</sup> August 2003</b>				
0700	<i>Snow trip departs – see separate itinerary</i>		D Webb	
<b>SUNDAY 17<sup>th</sup> August 2003</b>				
2200	<i>Snow trip returns</i>		D Webb	
<b>MONDAY 18<sup>th</sup> August 2003</b>				
0940	<i>Shuttle bus departs Downtowner on Lygon</i>	15	R Huntley	
0955	<i>Shuttle bus departs Quest Apartments</i>	35	R Huntley	
1030	<i>Shuttle bus departs Greensborough Motor Inn</i>	30	R Huntley	
1100	<i>Penguin Parade Trip departs ARPANSA – see separate itinerary</i>		R Huntley	
1800	<b>Welcome reception Eltham</b>		D Webb	
2230	<i>Penguin Parade Trip returns via Eltham</i>		R Huntley	
<b>DAY ONE: TUESDAY 19<sup>th</sup> August 2003</b>				
0740	<i>Shuttle bus departs Downtowner on Lygon</i>	15	R Huntley	
0755	<i>Shuttle bus departs Quest Apartments</i>	35	R Huntley	
0830	<i>Shuttle bus departs Greensborough Motor Inn</i>	15	R Huntley	
0845	Registration desk opens	75	Cox/Butler/ Mason	
<b>SESSION 1. Chair David Webb (ARPANSA)</b>				
1000	Opening by ARPANSA CEO	15	J Loy	ARP
1015	Introduction by Workshop Organiser	10	R Huntley	ARP
<b>calorimetry</b>				
1025	<a href="#">AbsDos2003-12</a> “Evaluation of a second generation Domen-type water calorimeter for absorbed dose in a <sup>60</sup> Co beam at NIST”	25	H Chen- Mayer	NIST
1500	<i>coffee break</i>	30		
1115	<a href="#">AbsDos2003-10</a> “The METAS photon-beam primary standard sealed water calorimeter”	25	G Stucki	METAS
1140	<a href="#">AbsDos2003-25</a> “Development of the NPL portable graphite calorimeter and its operation in hospital radiotherapy departments”	25	S Duane	NPL
1205	<a href="#">AbsDos2003-07</a> “Development of a primary standard calorimeter for low energy electron beams”	25	M McEwen	NRC
1230	<i>lunch</i>	60		
<b>SESSION 2. Chair Malcolm McEwen (NRCC)</b>				
1330	<a href="#">AbsDos2003-05</a> “The heat defect in the PTB water calorimeter: A discussion on uncertainty”	30	H-M Kramer	PTB
1400	<a href="#">AbsDos2003-23</a> “Thermal modelling of graphite calorimeters”	30	S Duane	NPL
1430	<a href="#">AbsDos2003-08</a> “Dosimetry of high-energy photon beams with the NMI water calorimeter”	30	A Aalbers	NMi
1500	<i>coffee break</i>	30		
1530	<a href="#">AbsDos2003-15</a> “BNM-LNHB graphite calorimeter: a new constant-temperature operating mode for absorbed dose rate measurements”	30	J Daures	LNHB
1600	<a href="#">AbsDos2003-14</a> “Scatter and heat conduction correction factors for two glass vessel geometries in sealed water calorimeters”	30	H Palmans	NPL
1630	<a href="#">AbsDos2003-13</a> “Feasibility of graphite and water calorimetry in low-energy clinical proton beams”	30	H Palmans	NPL
1700	<i>happy hour</i>	60		
1800	<i>Shuttle bus departs ARPANSA</i>		R Huntley	

<b>DAY TWO: WEDNESDAY 20<sup>th</sup> August 2003</b>				
0740	<i>Shuttle bus departs Downtowner on Lygon</i>	15	R Huntley	
0755	<i>Shuttle bus departs Quest Apartments</i>	35	R Huntley	
0830	<i>Shuttle bus departs Greensborough Motor Inn</i>	15	R Huntley	
0845	Registration desk opens	30	M Cox or D Butler	
<b>SESSION 3. Chair Frank Pernicka (IAEA)</b>				
<b>ionometry</b>				
0915	<a href="#">AbsDos2003-04</a> "The determination of absorbed dose to water in x-ray fields with a graphite extrapolation chamber"	25	H-M Kramer	PTB
0940	<a href="#">AbsDos2003-16</a> "Low energy proton beam dosimetry with plane parallel chambers using NPL electron and <sup>60</sup> Co calibrations"	25	R Thomas	NPL
<b>chemical and solid state dosimetry</b>				
1005	<a href="#">AbsDos2003-11</a> "The METAS electron-beam primary standard chemical dosimeter"	25	G Stucki	METAS
1030	<i>coffee break</i>	30		
1100	<a href="#">AbsDos2003-20</a> "EPR dosimetry - Applications, problems and prospects"	30	J Boas	Mon U
<b>Uncertainty</b>				
1130	<a href="#">AbsDos2003-21</a> "International symposium on standards and codes of practice in medical radiation dosimetry - Recommendations"	30	F Pernicka	IAEA
1200	<a href="#">AbsDos2003-03</a> "The measurement uncertainty at Australian Secondary Standard Dosimetry Laboratory (ASSDL)"	30	J Davies	ANSTO
1230	<i>lunch</i>			
<b>SESSION 4. Chair Lew Kotler (ARPANSA)</b>				
1330	<a href="#">AbsDos2003-02 part 1</a> "Uncertainty Workshop: Everything you always wanted to know about the ISO GUM but were afraid to ask"	30	R Bentley	NML
1410	<a href="#">AbsDos2003-02 part 2</a> "Uncertainty Workshop: Everything you always wanted to know about the ISO GUM but were afraid to ask"	30	R Bentley	NML
1450	<a href="#">AbsDos2003-02 part 3</a> "Uncertainty Workshop: Everything you always wanted to know about the ISO GUM but were afraid to ask"	30	R Bentley	NML
1520	<i>coffee break</i>	30		
1550	<a href="#">AbsDos2003-02 part 4</a> "Uncertainty Workshop: Everything you always wanted to know about the ISO GUM but were afraid to ask"	30	R Bentley	NML
1620	ARPANSA tour or discussions with ARPANSA staff by prior arrangement	145		
1845	<i>Shuttle bus departs ARPANSA</i>	5	R Huntley	
1850	<b>Workshop Dinner</b>	160	Da Roberta	
2130	<i>Shuttle bus departs Restaurant</i>		R Huntley	

<b>DAY THREE: THURSDAY 21<sup>st</sup> August 2003</b>				
0740	<i>Shuttle bus departs Downtowner on Lygon</i>	15	R Huntley	
0755	<i>Shuttle bus departs Quest Apartments</i>	35	R Huntley	
0830	<i>Shuttle bus departs Greensborough Motor Inn</i>	15	R Huntley	
<b>SESSION 5, Chair Simon Duane (NPL)</b>				
<b>general interest</b>				
0845	AbsDos2003-09 "Performance of an 'off-the-shelf' clinical linac for radiation standards dosimetry"	25	M McEwen	NRC
0910	AbsDos2003-17 "Continuity of Australian standards of absorbed dose for <sup>60</sup> Co: Comparison of beam quality correction factors for 18 MV beams from clinical and research linacs"	25	J Boas	Mon U
0935	AbsDos2003-24 "Absorbed dose to arbitrary materials"	15	R Huntley	ARP
0950	AbsDos2003-26 "Problems with the adoption of TRS 398 as a kilovoltage CoP in hospitals for HVL's less than 3 mm Al"	25	RM Millar	WBRC
1015	<i>coffee break</i>	25		
1040	AbsDos2003-01 "Australian secondary standards of dosimetry"	25	J Davies	ANSTO
1105	AbsDos2003-27 "The role of trilateral comparisons in the assessment of uncertainty"	25	D Webb	ARP
<b>posters</b>				
1130	AbsDos2003-19P "The measurement of the absorbed dose to water in <sup>60</sup> Co using the pancake ionization chamber"	60	S-H Su	INER
	AbsDos2003-06P "Air kerma standard for medium X-rays"		T Kurosawa	AIST
	AbsDos2003-18P "A new dosimetry protocol for external beam radiotherapy in Japan"		A Fukumura	NIRS
	AbsDos2003-22P "A novel signal processing method for the NMI water calorimeter"		L de Prez	NMI
1230	<i>lunch</i>	60		
<b>SESSION 6, Chair II-Michael Kramer (PTB)</b>				
<b>panel discussion</b>				
1330	Conclusions and Recommendations. Next meeting.	90		
1500	<i>coffee break</i>	30		
<b>ARPANSA tour or discussions</b>				
1530	ARPANSA tour or discussions with ARPANSA staff by prior arrangement	120		
1730	<i>Shuttle bus departs ARPANSA stopping for take away meal</i>	70		
1840	<i>Shuttle bus arrives Peter MacCallum</i>	20		
1900	<b>F Pernicka addresses ACPSEM Branch meeting</b>	90		
2030	<i>Shuttle bus departs Peter MacCallum</i>			
<b>FRIDAY 22<sup>nd</sup> August 2003</b>				
0830	<i>Shuttle bus departs Downtowner on Lygon</i>	15		
0845	<i>Shuttle bus departs Quest Apartments</i>	35		
0920	<i>Shuttle bus departs Greensborough Motor Inn</i>	25		
0945	<i>Healesville trip departs ARPANSA</i>	75		
1000	Discussions with ARPANSA staff by prior arrangement			
1100	<b>Healesville Sanctuary guided tour</b>	120		
1300	<b>BYO lunch at Healesville</b>	30		
1330	<b>Free time at Healesville</b>	75		
1445	<i>Shuttle bus departs Healesville</i>	75		
1600	<i>Shuttle bus departs ARPANSA</i>			

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## Evaluation of a second generation Domen-type water calorimeter for absorbed dose in a $^{60}\text{Co}$ beam at NIST

H. Heather Chen-Mayer, Kathryn W. O'Connor<sup>\*</sup>, Ronaldo Minniti,<sup>a</sup> Kenneth P. Gall  
The National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA  
<sup>a</sup>The University of Texas Southwestern Medical Center, Dallas, Texas 75235, USA

### Synopsis

#### Introduction and aims

A second generation Domen-type sealed water calorimeter constructed at University of Texas Southwestern Medical Center for NIST has been reported in the last Absorbed Dose Workshop at the National Physical Laboratory (UK). This calorimeter design, conceived after reviewing other designs from PTB Germany, INEA Italy, NPL UK, and NRC Canada, features several improvements over the original Domen design in the areas of thermistor probe fabrication, glass core design, magnetic stirring mechanism, AC lock-in-amplifier in the electrical circuitry, and computer interfaced data acquisition. The calorimeter is now at NIST for testing. We have rebuilt the thermistor probes, refilled the core with  $\text{H}_2$  saturated high purity water, and evaluated the assembly in a  $^{60}\text{Co}$  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  $^{60}\text{Co}$  source obtained using the original Domen water calorimeter with  $\text{H}_2$  saturated core water. Ultimately we seek to establish the new water calorimeter as the primary standard for absorbed dose in water at NIST.

#### Apparatus and methods

The components and operational characteristics of the water calorimeter are briefly summarized as follows. A sealed glass core blown from Pyrex tubing, with an ID less than 35 mm and wall thickness less than 0.3 mm at the center, is fitted with two threaded Teflon (PTFE) plugs with through holes allowing glass capillaries of 0.4 mm OD to be inserted. It also has a valve 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 ridge. Through each plug, a thermistor with a nominal resistance of 10 k $\Omega$  is inserted through the capillary into the center of the core. The two thermistors and a pair of fixed resistors of 10 k $\Omega$  nominal resistance form the arms of the bridge, along with additional compensating fixed resistances and coarse or fine adjustable resistances. 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  $\mu\text{W}$ . The sensitivity of the device is as follows: 1 Gy of radiation dose causes a temperature rise in water of about 1/4 mK, which corresponds to a 0.2  $\Omega$  change in the total resistance of the two thermistors, or a 3.5  $\mu\text{V}$  change in the bridge output voltage.

Measurements have been carried out in a  $^{60}\text{Co}$  teletherapy unit, with the center of the core at 1 m from the source and 5 cm below the water surface in a water phantom enclosed in a tank of 30 x 30 x 30  $\text{cm}^3$  made with PMMA. The entrance window is thinned to 1 mm for an area of

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<sup>\*</sup> Summer intern from Department of Physics, Miami University, Oxford, Ohio 45056, USA

12 cm x 12 cm, sufficient to accept a 10 cm x 10 cm radiation field. The nominal absorbed dose rate, as determined with a transfer ionization chamber in reference to the original Domen water calorimeter measurement in 1994, 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. Radiation exposure has been made at 30 s intervals (corresponding to about 0.5 Gy) to evaluate the response to the input sine wave frequency, and then at increasing time intervals 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  $\mu$ V 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 bridge in the same operational circuitry has been calibrated by being submerged in a separate temperature controlled bath monitored with a calibrated mercury thermometer with a precision of 0.01  $^{\circ}$ C at the operational excitation voltage (1 V) and frequency (100 Hz).

### Results

Sample raw data from a repeated exposure is shown in Fig. 1, representing 16 irradiation runs between 30 and 90 s each. The drift for approximately one hour after the end of the last irradiation run is also shown in the graph. Three adjustments of the bridge balance are clearly shown 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, thereby yielding a temperature rise attributed to the radiation.

Figure 2 is a summary of the evaluation of the linear dependence of the total dose as a function of the irradiation time. A total of four sets of measurements taken about a week apart are shown, each with a varied irradiation time from 30 to 90 s, with three replicate runs per setting. A weighted linear fit with a forced zero intercept ( $y = kx$ ) to each set of data is also shown, along with the fitted slope  $k$ . The slope thus determined represents the determined dose rate in Gy/s, and the maximum deviation from the nominal value of 19.2 mGy/s is 1.6%.

These are preliminary results, as no assessments of the sources of errors and none of the necessary corrections have been made. The initial aim is to simply evaluate the characteristics and the reproducibility of the device. We obtain 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.

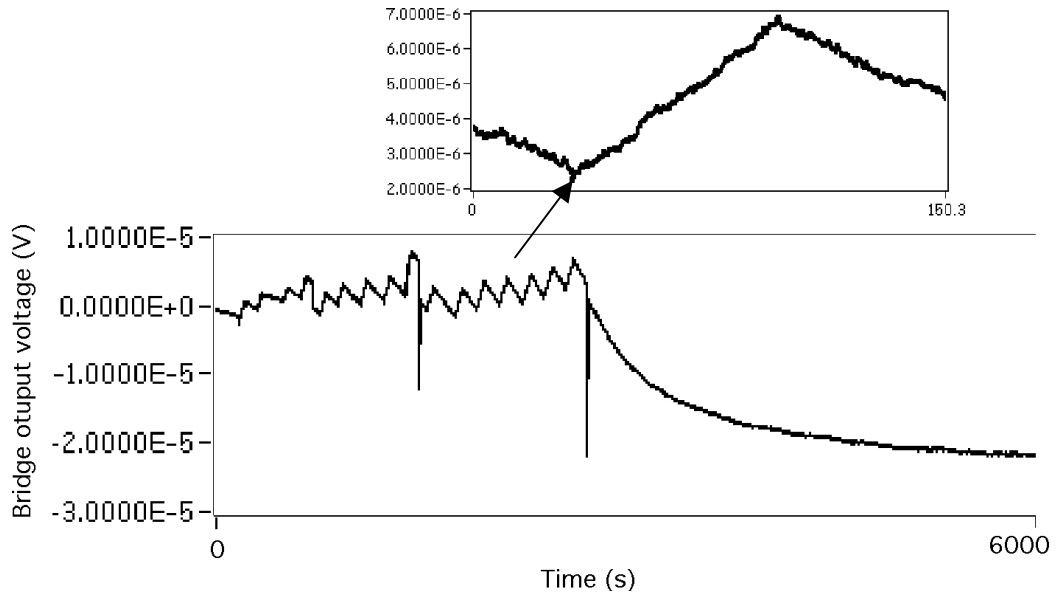


Fig. 1. Sample raw data from a repeated exposure representing 16 irradiation runs between 30 and 90 s each, and the drift after the irradiation ends. The drastic dips are the result of a bridge balance readjustment. The upper right graph is a magnification of the last run.

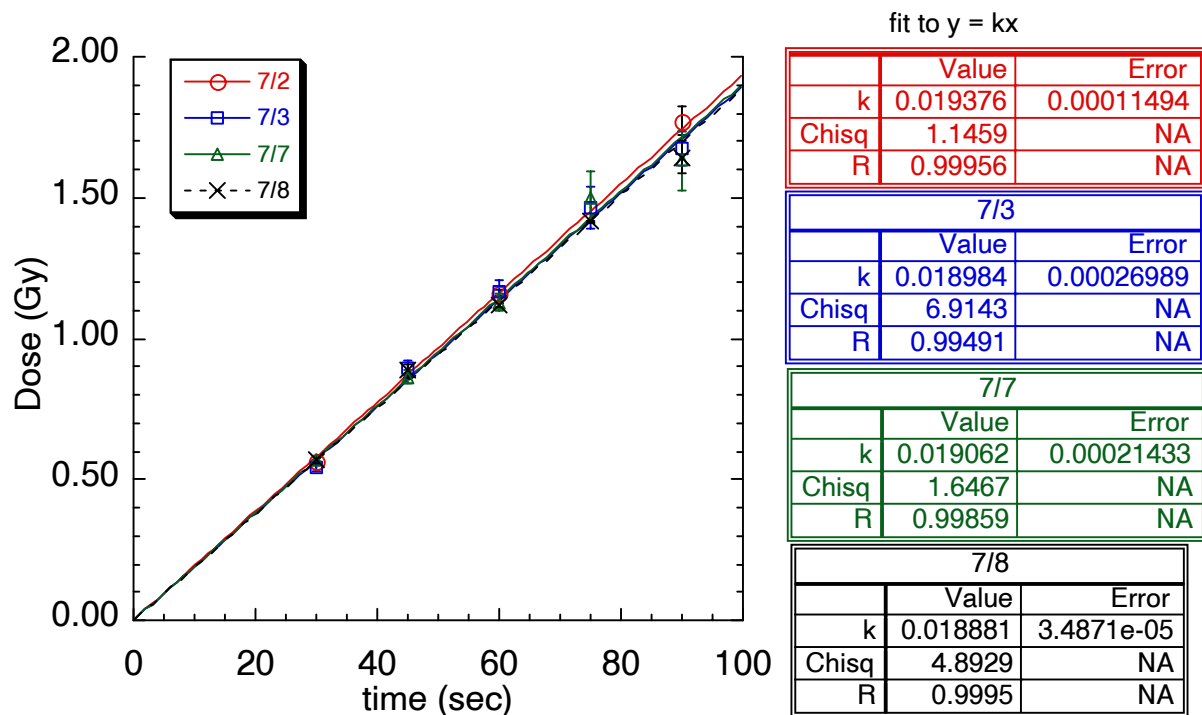


Fig. 2. Dose accumulation as a function of time. Four sets of measurements have been taken about a week apart, each with a varied irradiation time from 30 to 90 s. A linear fit to each set of data is also shown, with the slope being the determined dose rate in Gy/s.

## The METAS photon-beam primary standard sealed water calorimeter

G. Stucki, R. Schafer R., H. Quintel  
Swiss Federal Office of Metrology and Accreditation (METAS)  
Bern-Wabern, Switzerland

### Synopsis

In 2001 the METAS sealed water calorimeter became the Swiss primary standard for therapy-level photon-beam calibrations of the reference dosimeters of the hospitals. The calorimeter was originally constructed by the NRC as part of a collaborative agreement between the NRC and the METAS. The calorimeter is of the Domen type and described in references [1,2]. Recently several modifications to the original design were made by the METAS and the use of the calorimeter was extended from  $^{60}\text{Co}$   $\gamma$  radiation to high-energy x-ray beams with energies in the range from 4 MV to 21 MV.

This paper describes the currently used calorimeter and gives a short overview on the experimental results obtained since the last workshop in 1999.

The modifications made by the METAS in 2001 were: The sensitivity of the AC bridge was doubled by moving one of the two thermistors into the opposite arm of the bridge. An electrical heater remotely controlled by a PID controller was installed to improve the long-term stability of the water temperature. The water tank as well as the wooden box were each provided with an electrical shield, consisting of an aluminized mylar foil. For the measurements in the x-ray beams, two ionization chambers, used as monitors, were installed in the water tank behind the vessel. They are operated at 4°C.

About two thousand  $^{60}\text{Co}$  irradiations have been carried out at the METAS so far, the uncertainty of the dose determination being 0.41% ( $k=1$ ). The calorimeter was bilaterally compared with the primary standards of the BIPM [3] as well as of the NRC [1]. In either case the standards were in agreement within the uncertainty of the comparison. The calorimeter was also used to determine the calibration coefficients of NE2611 and NE2571 type ionization chamber working standards for high-energy x-ray beams. Thirteen radiation qualities in the range from TPR=0.626 to TPR=0.802 were measured so far. The uncertainty of the calibration coefficients is typically 0.65% ( $k=1$ ).

A possible future project is to measure the heat defect of different aqueous systems directly. The method would be based on the total absorption experiment developed at the METAS [4]: An electron beam of known particle energy and known beam charge is fully absorbed in a calorimeter. The measured dose is compared to the dose derived from the known particle energy and the known number of absorbed electrons. The heat defect can be obtained directly from this comparison. It is anticipated that the uncertainty of the heat defect determination will be less than 0.3% ( $k=1$ ).

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## **Development of the NPL portable graphite calorimeter and its operation in hospital radiotherapy departments**

S. Duane<sup>1</sup>, R.A.S. Thomas<sup>1</sup>, M.R. McEwen<sup>2</sup>, H. Palmans<sup>1</sup>, M.H. Simon<sup>1</sup>

<sup>1</sup>National Physical Laboratory, Teddington, Middlesex, UK

<sup>2</sup>National Research Council of Canada, Ottawa, Ontario, Canada

### **Synopsis**

The transfer of absorbed dose standards between the primary laboratory and the radiotherapy clinic is subject to an uncertainty associated with radiation beam quality-dependence of the transfer instrument's calibration coefficient. Calorimetry provides a means to make absolute measurements of absorbed dose in which this uncertainty may be reduced. A graphite calorimeter has been developed at the National Physical Laboratory which is sufficiently robust that it is feasible to make measurements in the radiotherapy clinic, with a sensitivity which is comparable to that of the primary standard at NPL. Its modular design enables the calorimeter configuration to be optimized for measurements in beams of high-energy photons, electrons or protons. The aim of this development is to enable independent checks on the dissemination of our absorbed dose standards by ionisation chambers, including an investigation of beam quality-related issues.

This calorimeter includes a level of thermal isolation and active internal temperature control which enables operation in a typical radiotherapy department, where the ambient temperature may vary by a few degrees per hour. The sensitivity of the measurement system has been improved to the point where the reproducibility is comparable to that of the NPL primary standard photon calorimeter.

Field testing of the calorimeter has been carried out at four UK hospitals, with measurements in four different high-energy photon beams from clinical linear accelerators and also in one proton beam. It has also been taken to and operated at the BIPM in <sup>60</sup>Co  $\gamma$ -radiation.

Measurements in hospital radiotherapy departments are affected by electrical noise which is up to twice the level seen at NPL. Particular care must be taken to determine and correct for the effect of any interference which is correlated with the beam being switched on and off, which otherwise may introduce systematic errors of up to 1% in the measured dose. After correction, measurements with the portable calorimeter are consistent with the primary standard to better than 0.5%.

The design adopted for the portable calorimeter differs from the primary standard in two important respects: the gap around the calorimeter core is air-filled, instead of being evacuated; and the measurement system employs DC Wheatstone bridges instead of AC. Heat is transferred much more rapidly across air filled gaps, and this leads to a greater reliance on models of heat flow within the calorimeter surround to determine the effects of beam non-uniformity upon measurements of the absorbed dose at a point.

## Development of a primary standard calorimeter for low energy electron beams

Jakob Helt-Hansen<sup>\*</sup>, Arne Miller<sup>\*</sup>, Malcolm McEwen<sup>‡</sup>, Peter Sharpe<sup>¶</sup> and Simon Duane<sup>¶</sup>

<sup>\*</sup>Riso National Laboratory, Roskilde, Denmark

<sup>‡</sup>National Research Council of Canada, Ottawa, Canada

<sup>¶</sup>National Physical Laboratory, Teddington, UK

### Synopsis

#### Introduction

Low energy electron beams (< 250 keV) are finding increasing application in the field of radiation processing. There are obvious advantages of using such beams for surface treatments - sterilization of packaging materials or curing of inks - over conventional high-energy accelerators. A low energy accelerator can deliver very high doses (typically 10 - 80 kGy) in a few seconds using simple components, and radiation shielding is much easier to achieve than for a 10 MeV accelerator or <sup>60</sup>Co irradiator. However, at present there are no dose standards for such low electron energies and the current practice is to calibrate the dosimeters used – thin films – at 10 MeV and assume that the calibration is energy independent. The aim of this project, which builds on the initial work of Mod Ali *et al* (2000), is to develop a primary standard calorimeter system to calibrate film dosimeters at energies around 100 keV.

#### Apparatus and Methods

The calorimeter consists of a graphite disk 50 mm in diameter and 2 mm thick. Two thermistors embedded in the disk measure the radiation-induced temperature rise. The calorimeter is incorporated in an assembly that includes a DC bridge and data-logger so that no external leads are required for data acquisition. The graphite disk totally stops the electron beam from an AEB accelerator installed at Riso for the purposes of this investigation. The accelerator provides beams in the range 80-100 keV and Monte-Carlo calculations, confirmed by measurements using Riso B3 film, give the range of the electrons to be around 50  $\mu\text{m}$ . The calibration procedure developed uses the calorimeter to determine the total energy in the beam together with a stack of film dosimeters (which also totally stop the beam) to relate this energy measurement to dose.

#### Results

Initial measurements using the accelerator and calorimeter were encouraging in terms of dose linearity and day-to-day consistency, but the acquired calorimeter temperature-time distributions showed that there were significant thermal effects that needed to be taken into account. Much of the work has focused on determining the source and magnitude of these thermal effects. The high doses involved – typically around 40 kGy – lead to significant heating effects within the accelerator and a series of investigations showed that the dominant effect was heating of the air between the accelerator exit window and the calorimeter. A finite-element model indicated that the air temperature could exceed 100 °C and it has been estimated that the calorimeter over-reads by around 25% ( $\pm$  5%) due to thermal conduction from the heated air.

This value for the calorimeter temperature excess is in good agreement with initial film calibration measurements, which showed a difference in the film calibration of around 30% from 10 MeV to 100 keV. The indication is therefore that there is little change in the energy

response of Riso B3 film over this energy range. However, further work is required to confirm this result and reduce the uncertainty on the measurement from the present value of around 10% to the target of 5%.

As a result of the investigations to date, the calorimeter is currently being re-designed to include a vacuum system to isolate the calorimeter from the hot air. Although this will introduce other corrections (e.g. radiative heat transfer from the vacuum vessel window) it should be simpler to obtain such corrections than determine the conduction effect. Initial measurements showed that a vacuum could be achieved with a very thin ( $< 10 \mu\text{m}$  Kapton) vacuum window and that there was a difference of around 15% between the vessel at atmospheric pressure and at  $10^{-4}$  mbar, which is in good agreement with the estimate of the thermal excess. Work is currently focusing on improving the design of the vacuum vessel to maintain the necessary high vacuum without a pump attached.

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Mod Ali N, Smith F and McEwen M R 2000 *A Real-time graphite calorimeter, Proceedings of the NPL Workshop on Recent Advances in Calorimetric Absorbed Dose Standards* (Teddington: National Physical Laboratory)

## The heat defect in the PTB water calorimeter: A discussion on uncertainty

A. Krauss, H.-M. Kramer

Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

### Synopsis

Inside the plane-parallel detector vessel of the PTB water calorimeter, the so-called H<sub>2</sub>-system, i.e. high-purity water saturated with H<sub>2</sub> gas is used. Model calculations for the radiolysis of this system predict a stationary state with a zero heat defect, independent on dose rate or accumulated absorbed dose.

The results of different calorimetric experiments (Fig.1) using the H<sub>2</sub> system, with each experiment involving several hundred single measurements, show a stable response within about 0.1 % over a dose range of more than 1.5 kGy. These results as well as comparisons between experiment and model calculations for the H<sub>2</sub>/O<sub>2</sub>-system lead to the conclusion that the response of the calorimeter can be adequately understood on the basis of such model predictions. However, the question arises within what reasonable uncertainty the heat defect can be assumed to be zero (for the H<sub>2</sub>-system) or, in other words, whether an uncertainty for the heat defect can be determined from the experimental data.

As the statistical uncertainty of each calorimetric experiment shown in Fig.1 is in the same order as the variation between the experiments, it could be concluded that a separate uncertainty, due to changes in the heat defect, should be lower than 0.1 %. And, naturally, this effect would already have been considered by the statistical uncertainty stated for each experiment.

On the other hand, it cannot be excluded with certainty, that the single measurements underlying the results in Fig.1 may show a small linear dependence on the accumulated dose, although the mean values remain nearly unchanged. As the distributions of the single measurements are rather broad, which is mainly due to the low dose rate of the <sup>60</sup>Co- $\gamma$ -source used for the experiments, the slope of a linear fit over a certain dose range could then be used as a measure of a possible change of the heat defect.

A further point for discussion is the question, as to whether the measured stable response of the calorimeter might also be explained by a non-zero heat defect caused for example by a small amount of unknown impurities in the water. As the water calorimeter is not suitable to determine the heat defect in absolute terms, there is no direct proof by this method that such a possibility can be ruled out. Furthermore, model calculations for the H<sub>2</sub>-system on the assumption of a small radiation-induced source of O<sub>2</sub> contamination can predict a stable non-zero heat defect.

In this paper, the different points of view regarding the uncertainty of the heat defect in the PTB water calorimeter will be discussed in depth.

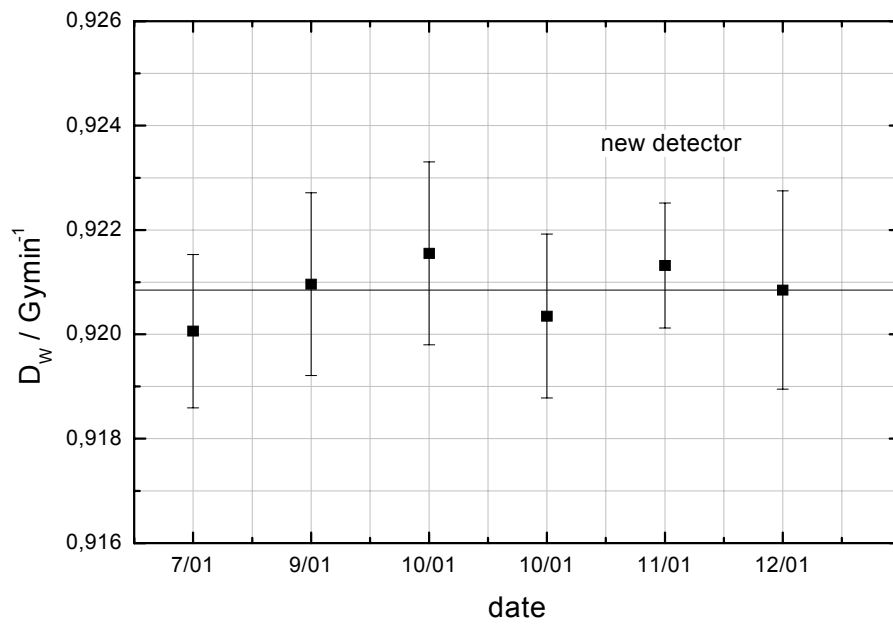


Fig. 1 Results of six experiments from the year 2001 obtained with the PTB water calorimeter using the  $\text{H}_2$ -system and two different detectors. Shown are the mean values of the measured dose rate (corrected for  $^{60}\text{Co}$  decay to 1993-01-01) including their standard deviations. The solid line indicates the mean value of all experiments.

## Thermal modelling of graphite calorimeters

S. Duane

National Physical Laboratory, Teddington, UK

### Synopsis

#### Introduction and aims

Graphite calorimetry remains the basis of many primary standards of absorbed dose, even though dose to water is usually of more interest than dose to graphite. The thermal diffusivity of graphite is such that local measurement of the energy absorbed from radiation is possible only if the processes responsible for heat transport are understood, controlled and their uncertainty minimised.

#### Apparatus

Calorimeters of various designs are considered: the NPL primary standard for high-energy photon absorbed dose is a Domen-type calorimeter, in which the rate of heat transfer between the core and other components is minimised by the use of evacuated gaps; the portable graphite calorimeter, which has been designed for use at radiotherapy dose rates and where environmental temperature control is poor; and a thin calorimeter, developed in collaboration with Riso National Laboratory, for the measurement of absorbed dose in 100 keV electron beams.

#### Methods

Various approximations to the heat equation are presented and solved, sometimes analytically, usually numerically and, where necessary, using finite element models. A systematic approach is developed by considering eigensolutions (normal modes) of the heat equation. A detailed picture emerges, in which a distinction is made between the sensed temperature (inside the thermistor, embedded in the calorimeter core), the temperature that relates to absorbed dose (which involves an average over the core volume), and the temperature that relates to heat transport (involving an average over the surfaces of the core and other components). Models are tested against experimental data, which are available in most detail for the Domen-type calorimeter operated in "thermostatic mode", in which the temperature of every component is actively controlled, and energy measurements are obtained as time-integrals of electrical heating powers. The correction for heat transferred between the core and its environment is based on measured temperature differences and is demonstrably small.

#### Results

In the past, the NPL primary standard was operated almost exclusively in quasi-adiabatic mode, and it emerged that transient heat transfers during electrical calibration were responsible for a systematic error of the order 0.5%, leading to an underestimate of radiation dose. Thermostatic mode eliminates this error, and also makes practical operation of the calorimeter much easier. Not only are the AC bridges always close to balance, but the networks of switched stable resistors formerly required to adjust the bridge balance points are redundant, since the thermistors are maintained at fixed temperatures. Those networks were responsible for a variable capacitance that limited the accuracy with which the resistive component could be selected in measuring the bridge out of balance voltage. Not the least advantage is that the characteristic time associated with calorimeter response is now determined by heat flow within each graphite component, rather than heat transfer across the evacuated gaps. This represents an improvement by one or two orders of magnitude.

Measurements in  $^{60}\text{Co}$  and high-energy X-ray beams are reported here: results using the portable and thin calorimeters are presented in other contributions to this workshop.

## Dosimetry of high-energy photon beams with the NMI water calorimeter

M.W.H. Pieksma, L.A. de Prez, A.H.L. Aalbers  
NMI Van Swinden Laboratorium, Delft, The Netherlands

### Synopsis

The NMI has developed a water calorimeter as the new primary standard for absorbed dose to water. This calorimeter is of the sealed-water type [1,2], and has as a unique feature that it is transportable, and can therefore be used to determine absorbed dose rates on location in accelerator beams. The electronic detection circuit of the calorimeter is based on a method that involves a high-accuracy digital multimeter (DMM), rather than on a more traditional technique that employs Wheatstone bridges.

As a first test of the NMI water calorimeter in high-energy photon beams, measurements of absorbed-dose-to-water rates were performed at the BNM-LNHB with a Saturne 43 accelerator for 6, 12, and 20 MV photon beams. By calibrating a set of 5 NE2611A chambers against the water calorimeter, beam quality correction factors  $k_Q$  were derived that agreed very well with the literature [3].

Next, the NMI water calorimeter was compared directly with the absorbed-dose-to-water standard based on the NMI graphite calorimeter for  $^{60}\text{Co}$  gamma radiation. A preliminary evaluation of this comparison yields a value of  $1.0014 \pm 0.44\%$  for the ratio of the dose rate determined with the water calorimeter compared to that derived from the graphite calorimeter.

Presently, a NCS subcommittee 'Uniformity Dosimetry Protocols' is working on implementing absorbed-dose-based Codes of Practice (CoP) for external beam radiotherapy in The Netherlands and Belgium. These CoP's will be consistent with international recommendations [4,5], will be aimed at the specific conditions in the Dutch and Belgian radiotherapy institutes, and will replace the current CoP's based on air kerma calibration factors [6,7].

In agreement with the recommendation given in IAEA TRS-398 [4], that preferably experimental  $k_Q$  values should be used, the subcommittee is presently performing  $k_Q$  measurements in nine representative clinical photon beams with the portable NMI water calorimeter for four different graphite-walled ionization chamber types. With respect to this clinical measurement program, a big advantage of using a DMM turns out to be that measurements with the calorimeter can be performed in a much shorter time than when using Wheatstone bridges. The first results of the  $k_Q$  measurements will be presented.

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## **BNM-LNHB graphite calorimeter : a new constant-temperature operating mode for absorbed dose rate measurements.**

J. Daures, A. Ostrowsky

Bureau National de Métrologie – Laboratoire National Henri Becquerel (BNM-LNHB),  
CEA-Saclay, France

### **Synopsis**

The present graphite calorimeter is the reference for the absorbed dose to graphite in Cobalt 60 and high-energy photon beams at BNM-LNHB. The core is surrounded by a jacket and a shield whose temperature is kept constant by means of a commercially available PID regulator. Heat exchanges between the various bodies are carefully minimized (1 mm vacuum gaps, aluminised Mylar, very thin threads for suspension and connections). Although reproducibility and accuracy are excellent [1], some improvements can be implemented concerning the flexibility in use and, to some extent, accuracy.

The usual operating mode of this calorimeter is based on a thermal feedback between the core and the jacket. When a core-jacket temperature difference is detected, a PID regulator (same type of the shield one's), sends to the jacket an electrical power to reduce the deviation. Thus, with this thermal feedback applied to the jacket, the calorimeter is currently working according to a quasi-adiabatic mode. As the temperature of the core and the jacket increase continuously with irradiation runs and electrical calibrations and as the power available from the PID regulator system is defined, the number of measurements per day is limited. Moreover, the thermal balance is more and more difficult to realize.

Before building a new graphite calorimeter, a different operating mode has been tested to check the possibility of reducing the number of vacuum gaps. Smaller depths of measurement and higher dose rates will then be allowed in addition to a smaller corrective factor.

This method consists in maintaining the core and the jacket at fixed temperatures (above the room temperature). First, the power in the core without irradiation is measured. It has to be significantly higher than the rate of heat generated by the beam to be measured. Second, under irradiation, the power necessary to maintain the assigned temperature in the core is reduced proportionally to the heat generated by ionizing radiation. This residual electrical power is carefully measured too. The core temperature is maintained at the set-point value using a PID regulator (Proportional, Integral, Derivative) developed at the laboratory on PC LabView. This regulator is versatile and perfectly adapted to calorimetry purposes. The quality of this type of measurements is strongly dependant upon the quality of the core thermal regulation. The value of the dose rate of the beam is quite simply proportional to the difference of the powers without and with irradiation. An alternance of irradiation and rest periods makes repeated measurements possible. Core and jacket temperatures are kept constant throughout the period of measurement, so that thermal transfers are constant (as well as the sensitivity of the thermistor used for the core temperature control). Moreover the Wheatstone bridge used for this thermistor resistance measurement is continuously balanced. This constant-temperature operating mode also makes possible to carry out more measurements per day since the core temperature does not increase. Furthermore it would allow measurements in much stronger beams.

Nevertheless, it is to be noted that this constant-temperature operating mode measures the absorbed dose rate instead of the absorbed dose as given by quasi-adiabatic mode.

Figures 1 and 2 show the plot of the measured quantity for the different operating mode.

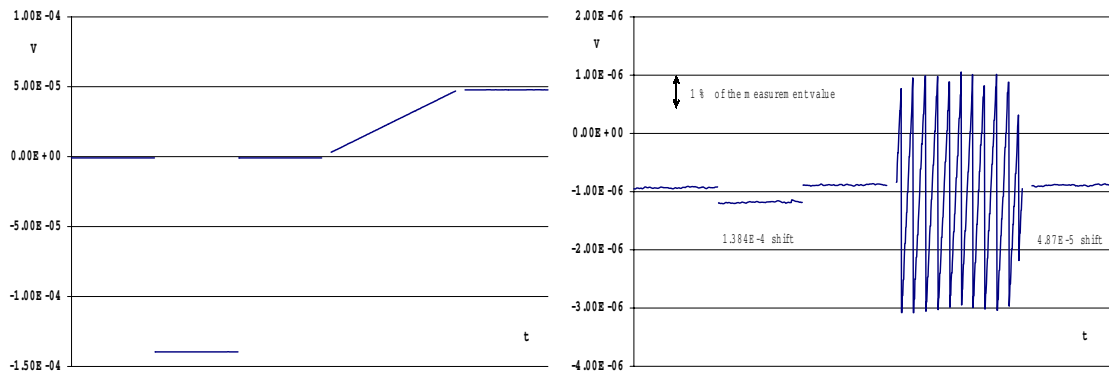


Figure 1 : Quasi-adiabatic mode with thermal feedback of the jacket for absorbed dose measurement ; Wheatstone Bridge voltage versus time; a typical run in  $^{60}\text{Co}$  beam; different scale with graphical shifts on the right

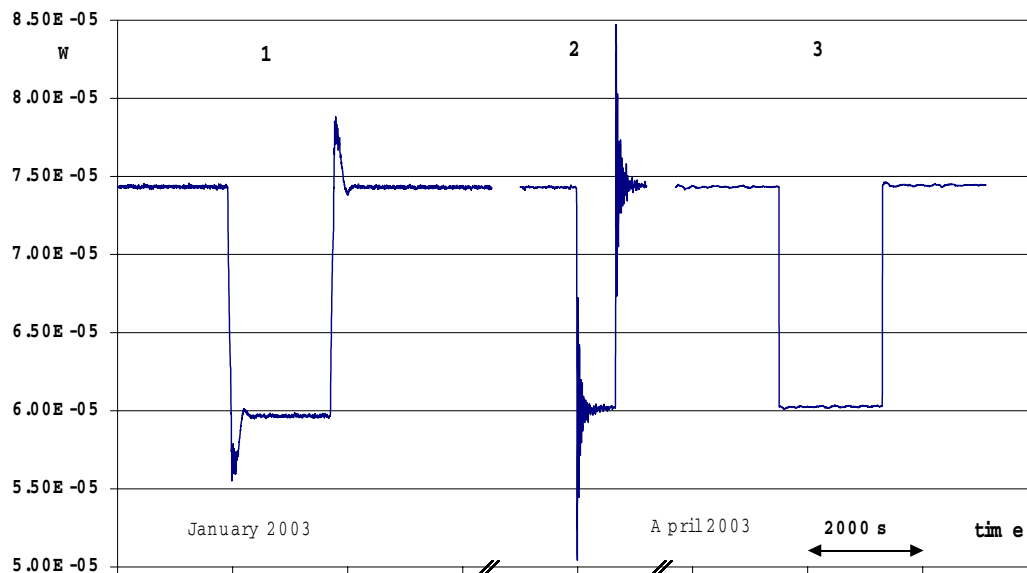


Figure 2 : Constant-temperature with temperature control of the core for absorbed dose rate measurement ; Power in the core with and without irradiation versus time; typical runs in  $^{60}\text{Co}$

The first plot in the figure 2 is relative to a standard adjustment of the PID parameters. The second part is a more sensitive and fast combination involving too high overshoot. In the third part the overshoot is avoided by a synchronised decrease and reset of the core power when the beam is turned on and off respectively.

Preliminary measurements in a cobalt 60 beam have shown no significant difference between the two operating modes with an equivalent reproducibility. These encouraging results are still to be followed by complementary measurements.

#### Reference:

J. Daures, A. Ostrowsky, B. Chauvenet ; Graphite Calorimeter, the primary standard of absorbed dose at BNM-LNHB ; IAEA-CN-96-6

## Scatter and heat conduction correction factors for two glass vessel geometries in sealed water calorimeters

H. Palmans<sup>1</sup>, M. Defloor<sup>2</sup>, S. Benmokhtar<sup>1</sup>, K. Rosser<sup>1</sup>

<sup>1</sup>Centre for Acoustics and Ionising Radiation, National Physical Laboratory, Middlesex, UK

<sup>2</sup>Medical Physics Department, Ghent University, Gent, Belgium

### Synopsis

If properly designed, sealed water calorimeter (SWC) glass vessels containing high purity water induce only small perturbation effects and thus require small corrections which can be determined with acceptably small uncertainties. Nevertheless, it is worth performing a systematic investigation yielding generic formulae as a function of vessel dimensions and/or energy for those correction factors.

Two perturbations are due to the presence of a glass vessel: firstly, the perturbation of the radiation field at the point of measurement due to the change in scatter conditions and due to attenuation of the primary beam and secondly, the perturbation due to an excess temperature rise in the glass vessel which produces excess heat to flow towards the point of measurement.

In this work, two SWC vessel geometries are investigated for <sup>60</sup>Co photon beams: the cigar type and the pancake type. In the cigar type, which is used in many laboratories and is also called the Domen type, a cylindrical vessel is positioned perpendicular to the beam direction and the thermistors are normally positioned on the cylinder axis. In the pancake type, which is used at NPL and PTB, a cylindrical vessel with two parallel flat faces at the top and bottom is positioned with its cylinder axis coincident with the beam axis. For the cigar type, a set of glass vessels with various diameters and wall thicknesses is used to systematically measure the relative effects of both perturbations. Presently, for the pancake type, the work is restricted to numerical work at present.

The experimental determinations of the scatter perturbation factors was performed using a diamond detector positioned at the point of measurement by comparing its response and the presence of the vessel with that in the absence of the vessel. The experimental results were compared with numerical results from Monte Carlo simulations using the egsnrc code system and from a simplified analytical model. The results for the cigar type vessels obtained by these three methods are found to be in good agreement and are represented by a simple formula as a function of the vessel wall thickness and the vessel diameter. The same set of vessels was used to measure their relative responses in the calorimeter operation. These were compared with results from heat conduction simulations with programs from Ghent and from a commercial package (FEMLab).

## Feasibility of graphite and water calorimetry in low-energy clinical proton beams

H. Palmans<sup>1</sup>, R. Thomas<sup>1</sup>, S. Duane<sup>1</sup>, A. Kacperek<sup>2</sup>, R. Nutbrown<sup>1</sup>, A. DuSautoy<sup>1</sup>, F. Verhaegen<sup>3</sup>

<sup>1</sup>Centre for Acoustics and Ionising Radiation, National Physical Laboratory, Middlesex, UK

<sup>2</sup>Douglas Cyclotron, Clatterbridge Centre of Oncology, Wirral, UK

<sup>3</sup>Medical Physics Unit, McGill University, Montreal, Canada

### Synopsis

Proton therapy offers an attractive alternative to conventional high-energy photon and electron therapy due to the characteristic dose distributions for a proton beam, exhibiting a typical Bragg peak (BP). Calorimetry is generally recommended as primary dosimetry method for clinical proton beams and given the growing number of proton therapy centres worldwide, the development of a set of standard calorimeters for protons would be very valuable. Another reason for developing calorimeters for proton beams is that in a recent code of practice, IAEA TRS-398, preference is given to using absorbed dose calibration factors for ionisation chambers obtained in proton beams or, equivalently, to using measured beam quality correction factors  $k_Q$ . Despite all this, no long-term primary calorimetry based standards for protons exist at present.

The feasibility of calorimetry for dosimetry of clinical high-energy proton beams as well as for relatively low-energy beams has been demonstrated and a few number of experimental comparisons between calorimetry and ionization chamber dosimetry has yielded indispensable information on the average energy required to produce an ion pair in dry air by protons. For low-energy proton beams used for the treatment of ocular melanoma, on the other hand, the feasibility of calorimetry has not been explored mainly because of the short range of these beams (lower than 3.5 cm) and their limited lateral extension (a few cm in diameter).

At NPL, graphite and water calorimeters have been developed for photon and electron beam dosimetry. Among the graphite calorimeters, a portable device was developed which is used in clinical photon and electron beams. In this work, the feasibility of adapting the NPL calorimeters for dosimetry of low-energy proton beams is investigated. The focus is on low-energy protons, but where the results have interesting consequences for high-energy proton dosimetry they will be discussed as well. The major aim of this work is to propose designs for graphite and water calorimeters dedicated to low-energy proton beam dosimetry.

For graphite calorimetry, the equivalence of graphite and water for proton beam dosimetry is investigated. The basic interaction data of protons with graphite and water are compared. It is shown that the contribution to absorbed dose from electromagnetic interactions can be accurately scaled to water. Differences in non-elastic nuclear interaction cross sections, however, result in fluence perturbation corrections. Monte Carlo calculations for a 60 MeV beam indicate that they are smaller than 1% at the reference depth. By comparing experimental depth dose curves in water and graphite using plane-parallel ionization chambers this result is confirmed. Gap effects and volume averaging effects are calculated using Monte Carlo simulations. For non-modulated beams, the gap corrections amount to 2-5% in the entrance region (at depths lower than half the csda range), whereas compensated gap corrections are smaller than 0.1% except in the BP region. Volume averaging corrections

for a core with a thickness of 2mm amount to 3-10% in the entrance region and impose restrictions to the applicability of graphite calorimetry in non-modulated proton beams. In modulated proton beams, both gap and volume averaging corrections can be kept smaller than a few tenths of a percent at the reference depth, demonstrating that accurate dosimetry is possible for those beams. Preliminary measurements with the portable calorimeter in a 60 MeV proton beam will be presented and discussed. Heat transport phenomena associated with this experiment will be discussed in another talk at this meeting.

For water calorimetry, dose distributions, scatter perturbations and dose perturbations are calculated using Monte Carlo simulations. Calculated dose distributions are used as input for heat flow simulations of profile heat losses using FEMLab. The same is used for evaluating excess heat arriving from vial walls. Knowledge of the magnitude of these effects will allow a proposal for a water calorimeter design for dosimetry in a 60MeV proton beam.

## The determination of absorbed dose to water in x-ray fields with a graphite extrapolation chamber

H.-M. Kramer

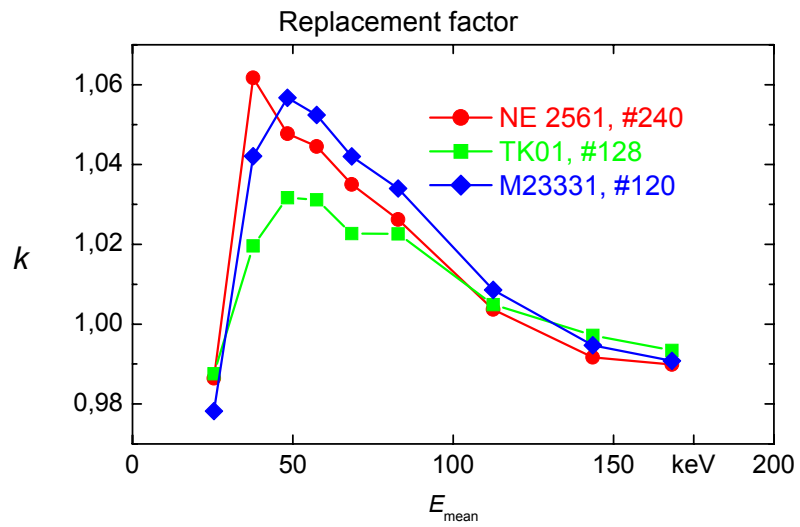
Physikalisch-Technische Bundesanstalt, Braunschweig, Germany

### Synopsis

In PTB a graphite extrapolation chamber is employed for the determination of absorbed dose to water in x-ray fields. By measuring the charge per unit volume in the limit of zero plate separation the absorbed dose to the air cavity is determined. The conversion to absorbed dose to graphite is done by means of an extension of the two-component model. In the two component model the spectrum of secondary electrons is divided into a component originating from a Compton and another one from a photo-electric interactions. At a graphite to air interface there exists electronic equilibrium of the first component, which allows the determination of absorbed dose to graphite resulting from this component. The other component may be evaluated in terms of absorbed dose to graphite by means of the Bragg-Gray theory. The extension of the model consists of taking into account the energy transferred to Auger electrons. At a graphite to air interface the Auger electrons cause a significant deviation from secondary electron equilibrium in the energy range between 0.2 keV and 3.0 keV.

In the plane of measurement inside the graphite phantom and in absence of the air cavity there exists secondary electron equilibrium. Therefore is the absorbed dose to graphite equal to the graphite collision kerma which in turn can be converted to water kerma by means of the ratio, water to graphite, of the mass-energy absorption coefficients averaged over the energy fluence spectrum of the photons in the plane of measurement. Detectors with a wall thickness larger than the practical range of the most energetic electrons can be calibrated in terms of water kerma. If used inside a water phantom such a detector measures water kerma and hence absorbed dose to water. This allows a direct calibration of secondary standards in terms of absorbed dose to water.

As a starting point the physics of the model will be presented with special emphasis on the plausibility of the two component model and its extension. The results obtained with the graphite extrapolation chamber will be compared with results obtained by means of Monte Carlo calculations. Further potential methods for verifying the extrapolation measurements will be discussed. The extrapolation chamber was used for determining the so-called replacement or perturbation correction factor of several ionization chambers. Results are shown in the figure for a depth of 2 g/cm<sup>2</sup> displaying considerable chamber type dependent variations. On outlook will be given on the possibilities for determining absorbed dose to water in the near field of radionuclide sources like <sup>103</sup>Pd and <sup>125</sup>I used for the treatment of prostate cancer.



The replacement factor of three ionisation chambers for medium energy x-rays as function of the mean energy. X-ray tube voltages range from 50 kV to 289 kV.

## Low energy proton beam dosimetry with plane parallel chambers using NPL electron and $^{60}\text{Co}$ calibrations.

R. Thomas<sup>a</sup>, H. Palmans<sup>a</sup>, A. Kacperek<sup>b</sup>, S. Duane<sup>a</sup>.

<sup>a</sup> Centre for Acoustics and Ionising Radiation, National Physical Laboratory, Middlesex, UK

<sup>b</sup> Douglas Cyclotron, Clatterbridge Centre of Oncology, Wirral, UK

### Synopsis

#### Introduction and aims

IAEA TRS 398 [1] recommends that proton dosimetry using ionisation chambers be based on absorbed dose calibrations. In the absence of a primary standard against which to calibrate chambers directly in terms of proton beam absorbed dose, TRS 398 provides factors to convert a chamber calibration in terms of photon or electron beam absorbed dose to one in terms of proton beam absorbed dose. The aim of this work was to compare the measured absorbed dose in the proton beam derived from an electron and photon calibration of the same chamber.

#### Apparatus

Measurements were carried out on the 60 MeV proton beam at the Clatterbridge Centre for Oncology, a clinical beam used in the treatment of eye tumours. Ionisation chambers used were the NE2561/2611 cylindrical chamber and the Scanditronix NACP-02, the PTW Roos and PTW Markus parallel plate chambers. All chambers had been calibrated at NPL in terms of absorbed dose, the parallel plate chambers were calibrated in both  $^{60}\text{Co}$  and electron beams whilst the cylindrical chambers were calibrated only in  $^{60}\text{Co}$ . A transmission monitor was used for all measurements and the chambers were placed in a Perspex thin window water filled phantom. Readings were taken using Keithley 617 electrometers.

#### Methods

Measurements were made in both modulated and unmodulated beams for two of each of the four types of chamber. For each chamber starting with the same proton beam measurement the absorbed dose was then derived, using TRS 398, from the photon and/or electron beam calibration of the chamber. The transmission monitor was used to try and limit the influence of beam variation in the measurements. The ion recombination and polarity effects in the proton beam for each type of chamber were investigated and measurements corrected accordingly. Corrections were also applied for temperature and pressure.

#### Results

In a modulated beam the dose ratio, parallel/thimble, varied between 0.995 and 1.018 depending on the type of parallel plate chamber and on the choice of starting calibration, photon beam or electron beam absorbed dose. For the same beam and starting calibrations, the dose ratio parallel/NACP obtained using Markus and Roos chambers varied between 0.987 and 1.008. In an unmodulated beam (in which only the parallel plate chambers were used) the ratio parallel/NACP varied from 0.986 to 1.019 for Markus and Roos chambers with photon beam and electron beam calibrations. The unmodulated beam has much larger dose gradients and so these measurements are more sensitive to chamber position.

[1] Absorbed dose determination in external beam radiotherapy, International Atomic Energy Agency, Vienna 2000.

## The METAS Electron-Beam Primary Standard Chemical Dosimeter

G. Stucki, R. Schafer, O. Brunschwig, H. Quintel  
Swiss Federal Office of Metrology and Accreditation (METAS)  
Bern-Wabern, Switzerland

### Synopsis

In 2002 the METAS chemical dosimeter became the Swiss primary standard for therapy-level electron-beam calibrations of the reference dosimeters of the hospitals. This standard was developed at the METAS in the years 1995 to 2002 [1].

This paper describes the primary standard and gives a short overview on the experimental results obtained so far.

Fricke solution (ferrous ammonium sulphate) is used as a chemical dosimeter, the response of which is determined by a total absorption experiment: A monoenergetic electron beam of known particle energy,  $E_e$ , and known total number of electrons,  $N$ , is fully absorbed in a vessel containing Fricke solution of a given mass,  $m$ .

The electron energy is measured using a magnetic spectrometer and the total number of absorbed electrons is determined by means of an inductive beam charge monitor. This experiment is similar to the one described by Feist [2], but extended to an energy range from 5.3 MeV to 22.4 MeV (which allows the determination of the response of the Fricke solution in that energy range). The absorbed dose to the Fricke solution,  $D_F$ , is given by:

$$D_F = \frac{E_e N}{m} f_T \quad (1)$$

where  $f_T$  is a product of several correction factors. The main correction factors are for losses due to bremsstrahlung, reabsorption of bremsstrahlung, backscattering of electrons and energy losses in the exit and entrance foils. These factors were determined by Monte Carlo calculations.

The Fricke dosimeter is an aqueous solution of ferrous ions in 0.4M H<sub>2</sub>SO<sub>4</sub>. Ionizing radiation converts ferrous ions, Fe<sup>2+</sup>, into ferric ions, Fe<sup>3+</sup>, with a radiation yield that is proportional to the absorbed dose. The increase in the concentration of Fe<sup>3+</sup>, compared with the concentration in the unirradiated solution, is determined by measuring the change in the optical density,  $\Delta A_T$ , at 304 nm using an ultraviolet spectrometer. The absorbed dose to the Fricke solution is then given by:

$$D_F = \frac{\Delta A_T}{\varepsilon G \rho l_T} \quad (2)$$

where

- $\varepsilon$  is the extinction coefficient of Fe<sup>3+</sup> at 304 nm;
- $G$  is the radiation yield of Fe<sup>3+</sup>;
- $\rho$  is the density of the Fricke solution;
- $l_T$  is the optical path length of the readout cell.

Combining Eqs (1) and (2) the calibration factor  $\Delta A_T/(\varepsilon G)$  of the Fricke solution can be determined:

$$\frac{\Delta A_T}{\varepsilon G} = \rho l_T \frac{E_e N}{m} f_T \quad (3)$$

This calibration factor is measured for different beam energies in the range from 5.3 to 22.4 MeV.

The thus calibrated Fricke solution is filled into small vessels made of polyethylene with a volume of 30 mm × 40 mm × 2 mm, which are placed in turn in a water phantom at the reference depth and compared with the plane-parallel chamber working standards at each radiation quality. As working standards NACP02 type ionization chambers are used. The calibration coefficient,  $N_{D,w,Q}$ , of a working standard under reference conditions is then given by:

$$N_{D,w,Q} = \frac{\Delta A_B}{\Delta A_T} \frac{l_T}{l_B} \frac{1}{M_Q} \frac{E_e N}{m} f_T f_e \quad (4)$$

where

$\Delta A_B$  is the change of the optical density due to the irradiation in the water phantom;

$M_Q$  is the dosimeter reading, corrected to reference conditions and for recombination losses;

$l_B$  is the optical path length of the readout cell;

$f_e$  is the general Fricke to water dose conversion factor.

So far 10 radiation qualities have been measured. The uncertainty of the calibration coefficients of a NACP02 working standard is typically 0.9% ( $k=1$ ). The METAS calibration coefficients agree within 1.2% with the factors derived from TRS 398 [3].

## References

[1] Stucki, G., Muench; W., Quintel, H., “The METAS Absorbed Dose to Water Calibration Service for High Energy Photon and Electron Beam Dosimetry”, Standards and Codes of Practice in Medical Radiation Dosimetry (Proc. International Symposium IAEA, Vienna 2002), in preparation.

[2] Feist, H., “Determination of absorbed dose to water for high energy photons and electrons by total absorption of electrons in ferrous sulphate solution”, Phys. Med. Biol. **37** (1982) 1937–1947.

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Absorbed Dose Determination in External Beam Radiotherapy, Technical Reports Series No. 398, IAEA, Vienna (2000).

## **EPR dosimetry - Applications, problems and prospects**

John F Boas<sup>a</sup>, Robert B Huntley<sup>b</sup> and John R Pilbrow<sup>a</sup>

<sup>a</sup>School of Physics and Materials Engineering, Building 27, Monash University, Clayton, Victoria 3800, Australia

<sup>b</sup>Australian Radiation Protection and Nuclear Safety Agency, 619 Lower Plenty Road Yallambie, Victoria 3085, Australia

### **Synopsis**

Electron Paramagnetic Resonance (EPR) dosimetry, using alanine, is a well established technique and has advantages over thermoluminescent dosimetry (TLD) for industrial and medical applications where the doses delivered are in the range from 10 Gy to 10 kGy. It has the advantages of small fading rates, approximate tissue equivalence and non-destructive readouts. Its disadvantages include the potentially longer time per readout compared to TLD, a lower limit of sensitivity of approximately 0.1 Gy and the rather higher capital cost of an EPR spectrometer compared to that of a simple TLD reader.

There are also some hidden disadvantages or potential difficulties with EPR dosimetry using alanine as a dosimetry material. These mainly arise from the complexity of the spectrum, which consists of 5 main lines of varying intensity. The spectrum also includes contributions from forbidden transitions and radical species other than that due to the 3 methyl and 1 amino protons.

This paper will discuss some of these issues and the constraints these place on accurate dosimetry with alanine. We will also discuss some preliminary experiments using other amino acids or small peptides, glycylglycine and glycylglycylglycine. These have the advantage of much simpler EPR spectra, although they suffer from the disadvantage of being less sensitive to radiation. The application of EPR dosimetry to geological and archaeological dating will be briefly mentioned.

## **International symposium on standards and codes of practice in medical radiation dosimetry - Recommendations**

F. Pernicka, K. R. Shortt, J. Izewska, A. Meghifene, S. Vatnitsky, B. Zimmermann  
International Atomic Energy Agency, Vienna, Austria

### **Synopsis**

The Symposium took place at the IAEA headquarters in Vienna from 25 to 28 November 2002. More than 250 scientists representing 62 countries attended the four-day meeting at which 140 presentations were delivered covering a broad range of topics in medical radiation dosimetry. Recommendations following the papers and discussions were prepared at the end of the meeting. Although many of these recommendations concern the scientific community, some are directed to governments and industry as these affect the practical application in developing countries.

There are several themes that appear consistently throughout the various recommendations. Education and training for health care workers required to diagnose and treat patients safely and effectively is of utmost importance. Appropriate and affordable equipment is required to meet the needs, particularly of developing countries, and manufacturers are partners in this process of technology transfer. It is essential that treatment methodologies be supported by services in medical physics. This is particularly true for more advanced countries in the process of developing new techniques to enhance cancer cure rates. Programmes in quality control and assurance should provide the necessary auditing tools to demonstrate the safe and effective application of nuclear technology in medicine.

Within the field of medical radiation dosimetry explicitly, there are recommendations to develop physical standards, perform comparisons, and participate in audits within the sub-fields of radiation medicine. Primary and secondary standards dosimetry laboratories should develop further their standards for absorbed dose to water and air kerma, to examine their corresponding uncertainties and to participate in comparison exercises in order to build confidence in their measurement capabilities. The symposium recommended that uncertainties assigned to absorbed dose to water primary standards should be examined in detail, preferably in a working group of the international Consultative Committee (CCRI) in order to rationalize any apparent discrepancies." The principal elements of the different approaches to uncertainty assessments for calorimeters also need to be discussed. The primary standard laboratories and the ICRU should address the unresolved issues pertaining to air kerma dosimetry standards, including the re-evaluation of the correction factors  $k_{\text{wall}}$  and  $k_{\text{an}}$  (including the BIPM standard),  $W_{\text{air}}$  values and uncertainties, stopping power ratios, and type B uncertainties related to Monte Carlo methods, taking account of the underlying interaction coefficients.

Several recommendations regarding the practice of radiotherapy dosimetry were also proposed. Above all, there is a need for consistency, both within a country and between countries. There is a need to enhance the application of the Agency's dosimetry code of practice (TRS-398) for external beam therapy and to complete the development of the new code for diagnostic radiology. The number of laboratories that can provide calibrations for dosimetry in diagnostic radiology is not sufficient. A set of recommendations that will provide an interim approach to traceability for countries with no access to an SSDL is needed.

A series of recommendations concerning internal dosimetry for radionuclide therapy and diagnostics was forwarded. There is a need for clinical measurements of radioactivity to be traceable to national and international standards. In addition, a standardized code of practice for dosimetry calculations involving internal emitters should be developed.

Quality assurance (QA) and quality audit for dosimetry in radiotherapy were also covered in the symposium and this has resulted in a large number of recommendations. The Symposium expressed the view that quality assurance and quality audits are a very effective way to ensure the correct delivery of the radiation dose to the patient and to enable the therapeutic outcome to be assessed in a consistent manner. QA programmes for radiotherapy equipment, dosimetry and processes should be promoted, implemented and strengthened to ensure accurate reproducible dose delivery to each radiotherapy patient. Quality audit should cover the medical aspects of radiotherapy as well as the physics and technical aspects and should be available to all radiotherapy centres for all clinically used external beam treatment units, as recommended internationally (e.g. International Basic Safety Standards, the EC Medical Exposure Directive 97/43/Euratom). As a minimum external audit for radiotherapy beam dosimetry, each beam dose output should be measured independently of the institution procedures, e.g., using a mailed TLD from an external laboratory, at least once every two years. At the same time there is a need to develop and promote audit programmes for complex treatment situations (e.g. total body irradiation, stereotactic radiosurgery, intensity modulated radiotherapy).

At the clinical level, two areas of concern were discussed, these being dose measurements and dose calculations. There is a need for industry to develop affordable systems for practical use in QA and dosimetry (e.g. tissue equivalent materials, phantoms) that are easy to use, robust and reliable. With regard to dose calculations, guidelines should be developed as to which QA tests of treatment planning systems should be performed by manufacturers, user groups and individual users. Recognizing that errors in treatment monitor units and treatment time calculations have caused accidents, it was recommended that all radiotherapy institutions should implement an independent monitor unit or time calculation protocol for each patient.

The recommendations proposed at the Symposium will be presented in this talk along with a description of actions that will be taken by the IAEA to meet the identified needs.

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## **The measurement uncertainty at Australian Secondary Standard Dosimetry Laboratory (ASSDL)**

Haider Meriaty, Justin Davies  
Australian Nuclear Science & Technology Organization (ANSTO)  
PMB 1, Menai, NSW 2234, Australia

### **Synopsis**

ANSTO runs and maintains an Australian secondary standard dosimetry laboratory (SSDL). The laboratory is part of the IAEA network of SSDLs that facilitates uniformity of the dose measurement at the radiotherapy level. We apply the IAEA Technical Report 277 to conduct measurements at cobalt-60 and adopt the ISO 'Guide to the Expression of Uncertainty in Measurement' for the application of the associated uncertainty in the measurement.

This paper explains implementation the guide's methodology in evaluating the standard uncertainty (type A and B) at ASSDL as well as the format of reporting result to the client. Also, the paper demonstrates the comprehensive use of Microsoft Excel, which was developed to automate uncertainty calculations.

## **Uncertainty Workshop: Everything you always wanted to know about the ISO GUM but were afraid to ask**

Robin Bentley  
National Measurement Laboratory  
Commonwealth Scientific and Industrial Research Organisation

**Wednesday 20 August 2003  
2:00 pm to 4:30 pm**

The aim of this session will be to encourage a healthy understanding of the ISO 'Guide to the Expression of Uncertainty in Measurement' (GEUM or GUM) – it is too easy to get lost in the detail of the GUM. To this end, the GUM will be stripped down to its two main ingredients:

- (1) basic statistical notions and concepts that underpin its recommendations and
- (2) the recommended procedure for error analysis.

As a result, the purpose of the GUM may be more easily understood, various difficulties will appear simpler, when put into perspective, and the calculations required to get a value of uncertainty will appear more straightforward. The approach taken will be a pragmatic one and a strong emphasis will be placed on developing a healthy 'feel' for what is required and why.

The topic is fully discussed in Monograph 1 from NML, "Uncertainty in Measurement: the ISO Guide", which includes much practical advice. All participants will receive a copy.

**Presented by Mr Robin Bentley**  
**National Measurement Laboratory**  
**Commonwealth Scientific and Industrial Research Organisation**

Robin has been employed at the NML as a research physicist since graduating with an M.Sc. from Sydney University. He has worked in high-temperature electrical conduction in ceramics, thermoelectric thermometry and plasma physics. Throughout his career he has maintained a strong interest in error analysis. He is the author of NML Monograph 1 (above).

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## Performance of an “off-the-shelf” clinical linac for radiation standards dosimetry

Malcolm McEwen, Carl Ross  
Ionizing Radiation Standards, National Research Council, Ottawa, Canada

### Synopsis

#### Introduction

This paper describes the experience gained in Ionizing Radiation Standards Group at the NRC, Canada using an “off-the-shelf” Elekta clinical linear accelerator for radiation dosimetry measurements. It was felt that this information would be of interest to the standards community for a number of reasons:

- i) The present generation of research linacs in use worldwide are nearing the end of their operational lifetimes and standards labs are looking for the best route to take with replacements
- ii) A number of standards labs have used older, modified clinical linacs with varying degrees of success, the assumption being that a “standard” linac will not provide the necessary levels of performance.
- iii) A modern clinical linac offers the obvious advantages of ease of use and low down time as well as ensuring that the calibration and user’s beam are the same.

#### Method

An Elekta Precise linac was installed at NRC in July 2002. It offers three photon energies - 6, 10, & 25 MV - and five electron energies – 4, 8, 12, 18, 22 MeV. The maximum dose rate available is 5 Gy/min for photons and 8 Gy/min electrons (although there is an option to extend this latter figure by a factor of ~ 10). A range of PRFs are available from 400 Hz (6 MV only) down to ~ 6 Hz.

The precision required by the standards laboratory is generally better than the manufacturers testing specification and therefore it was not clear at the outset that the unmodified linac would meet our needs. The investigation of performance focused on four main areas – geometrical precision, doserate stability, energy constancy, and the calibration of the ion monitor.

#### Results and Discussion

##### *Geometry*

The ability to rotate the gantry offers a range of experimental setups but also introduces a possible error if the gantry moves or does not return to the same position. It was found that with the gantry positioned to give a horizontal beam there was no measurable rotational movement at the 0.05° level over several weeks and that short term repeatability was better than 0.03°. The other main issue was the precision of the SSD and measurements with the standard mechanical pointer gave a value of  $\pm 0.25$  mm.

##### *Energy*

Depth-dose measurements have shown day-to-day variations in beam-quality at the  $\pm 1\%$  level, which is larger than for research linacs (e.g those at NRC or NPL) but is not a major

problem. A 1% change in beam quality is equivalent to a 0.3% change in the  $k_Q$  factor for an ion chamber. There has been no significant drift in energy over the last year and no measurable effect is seen at startup – the energy is stable within one second of beam-on.

#### *Doserate*

A clinical linac uses feedback from the monitor chamber to control the output from the accelerator and therefore it was anticipated that beam stability would be good. This was found to be the case with an equilibrium doserate stability of 0.25% for both photons and electrons, with no dependence on energy. All beams show some run-up effect, but generally the doserate is within 2% of the equilibrium value doserate within 4 seconds for photons (within 10 seconds for electrons), although equilibration at the 0.25% level can take up to 60 seconds.

#### *Monitor calibration*

It was expected that that an external monitor chamber would be necessary to achieve the precision required for calorimetry. However, the internal monitor chamber has performed very impressively to date. The precision on delivering a dose of 1 Gy is typically  $\pm 0.05\%$ , which means that an external monitor is unnecessary. The drift in the monitor calibration over the period of a day depends on the energy and modality but is typically 0.1% and there is no significant effect when repeatedly changing energy. However, there are significant day-to-day variations at the  $\pm 0.5\%$  level, which are probably due to the monitor chamber being of the unsealed type. These variations appear to be random as there is no apparent long-term drift of the 6 months of available data.

#### **Conclusion**

The measurements to date indicate that a “standard” clinical linac can be used for reference dosimetry with a precision of better than 0.1%. One of the main concerns at the outset was that start-up effects would significantly affect calorimetry measurements, which use relatively short irradiations, but this does not appear to be the case.

The ease of use, particularly in terms of selecting energy and doserate, together with this level of performance makes a clinical accelerator a real choice for the standards laboratory. However, the absolute calibration of the accelerator is only stable at the  $\pm 0.5\%$  level, which means for the highest accuracy measurements one must develop a suitable measurement protocol to monitor such drifts.

## Continuity of Australian standards of absorbed dose for $^{60}\text{Co}$ : Comparison of beam quality correction factors for 18 MV beams from clinical and research linacs

John F Boas<sup>1,3</sup>, Robert B Huntley<sup>1</sup>, Stuart L Sherlock<sup>2</sup>, Haitse A Van der Gaast<sup>2</sup> and David V Webb<sup>1</sup>

<sup>1</sup>Australian Radiation Protection and Nuclear Safety Agency, 619 Lower Plenty Road, Yallambie, Victoria 3085.

<sup>2</sup>Australian Nuclear Science and Technology Organisation

<sup>3</sup>Present address: School of Physics and Materials Engineering, Building 27, Monash University, Victoria 3800.

### Synopsis

**Introduction.** A series of comparisons of Australian absorbed dose standards held by the Australian Nuclear Science and Technology Organisation and the Australian Radiation Protection and nuclear Safety Agency between 1987 and 1998 show that with the consistent application of the appropriate correction factors, the standards have remained constant to better than 0.5% for  $^{60}\text{Co}$  radiation. The consistency of the performance of the ionization chambers allows us to compare calibration and beam quality correction factors for 18 MV beams from a research linac and a clinical linac.

**Apparatus and Methods.** The primary standards were graphite calorimeters. The ANSTO calorimeter (the Australian primary standard until 1996) was constructed by Urquhart et al. and modified by Sherlock. The ARPANSA calorimeter (the Australian primary standard since 1996) was constructed at the OFZS. The comparisons used, as transfer standards, NE 2561 ionization chambers. Radiation beams were provided by  $^{60}\text{Co}$  sources at ANSTO and ARPANSA. Measurements in linac beams were made with beams in the range 16-19 MV with the ARPANSA linac and at 18 MV with a Varian CLINAC 1800 linear accelerator at the Royal North Shore Hospital, Sydney. Beam qualities were expressed as Tissue-Phantom Ratios (TPR). Measurements were made in graphite and water phantoms, with the results being expressed in terms of dose to graphite prior to conversion to dose to water where required.

**Results.** The differences in ion chamber calibration and beam quality correction factors as determined at ARPANSA and ANSTO are expressed as ratios  $R = \text{ARPANSA}/\text{ANSTO}$ . For the absorbed dose to graphite calibration factors,  $R = 1.0044$  ( $\sigma = 0.0033$ ) at  $^{60}\text{Co}$ . In 18 MV beams with a nominal TPR of 0.781 and after corrections for differences in graphite depth, the ratios are  $R = 1.012$  ( $\sigma = 0.005$ ) for the calibration factors and 1.010 ( $\sigma = 0.005$ ) for beam quality correction factors in water. The value of  $k_Q$  for the ARPANSA beam is closely similar to that given by the IAEA absorbed dose protocol (TRS 398), whereas that determined by ANSTO in the CLINAC 1800 beam of 0.962 is the same as that determined for the NRC soft beams.

### References

Huntley, R B, Boas, J F and Van der Gaast, H A. The 1997 determination of the Australian standards of Exposure and absorbed dose at  $^{60}\text{Co}$ . ARL/TR126 (ARPANSA, Yallambie, 1998, ISSN 0157-1400).

## Absorbed dose to arbitrary materials

Robert B Huntley  
ARPANSA, Lower Plenty Road, Yallambie, Vic, 3085

### Synopsis

#### Introduction and Aims

The Australian standard of absorbed dose for  $^{60}\text{Co}$   $\gamma$  radiation is a graphite microcalorimeter at ARPANSA. This standard has been used to deliver accurately known absorbed doses of  $^{60}\text{Co}$   $\gamma$  radiation to samples of Silica,  $\text{SiO}_2$ . Earlier work has been done for other materials and in principle could be applied to arbitrary materials with a known composition.

#### Apparatus and Methods

The absorbed dose to graphite is converted to absorbed dose to other materials using the photon fluence scaling theorem, which requires that all the linear dimensions, including the depths of the reference points and the distances of the phantoms from the radiation source, are scaled by the inverse ratio of the electron densities in the two materials. The absorbed dose to any material (m) from a point source of radiation is related to the absorbed dose to graphite (g) by:

$$D_m = D_g (\mu_{\text{en}}/\rho)_{\text{m,g}} \beta_{\text{m,g}} (R_{\text{m,g}})^{-2} \prod k_i$$

where  $(\mu_{\text{en}}/\rho)_{\text{m,g}}$  and  $\beta_{\text{m,g}}$  are the quotients of the values in the two materials of the mean mass energy absorption coefficients and of the absorbed dose to collision kerma ratios respectively,  $R_{\text{m,g}}$  is the ratio of the distances from the  $^{60}\text{Co}$  source to the reference points in the two materials and  $\prod k_i$  is the product of minor corrections.

The Australian standard of absorbed dose to water at  $^{60}\text{Co}$  is derived in this way. Agreement with the BIPM reference standard is excellent (0.1%).

Aluminium is a reasonable analogue of  $\text{SiO}_2$  for radiation interactions at  $^{60}\text{Co}$ . The electron density scaling factors of Al and  $\text{SiO}_2$  relative to graphite are similar. Furthermore, the mass energy absorption coefficients, the mass electron stopping powers and the CSDA electron ranges in Al and  $\text{SiO}_2$  are also similar. Therefore, a scaled Al phantom should produce a similar radiation spectrum in the  $\text{SiO}_2$  sample to that which would be achieved in a solid  $\text{SiO}_2$  phantom. A scaled aluminium phantom was constructed from grade 6351 Al, which contains impurities of 1.0% Si, 0.6% Mn and 0.6% Mg.

Initially, a sample holder was made with a simple 9.7 mm diameter cavity of variable length, to accommodate a sample of granular  $\text{SiO}_2$ . This first sample holder was made from grade 2011 Al, which contains 5.5% Cu. This is a "standard" machining grade of Al.

A second sample holder was later made from grade 6060 Al, which contains 0.3-0.6% Si, 0.1-0.3% Fe, 0.1% Cu, 0.1% Mn, 0.35-0.6% Mg, 0.05% Cr, 0.15% Zn and others (unspecified) 0.2%. A cavity 10 mm diameter and 31 mm long, accommodates 51 Al disks, each 0.61 mm thick. Each disk has a small conical recess at the centre, approximately 0.35 mm deep by 1.2 mm diameter, to accommodate a single grain of  $\text{SiO}_2$ .

The absorbed dose rate was determined at the scaled graphite reference distance of 945.62 mm from the  $^{60}\text{Co}$  source.

The exposure times in the Al phantom were adjusted for small deviations from the scaled reference distance of 650.00 mm and for minor deficiencies in satisfying the conditions of the scaling theorem.

### **Results and Conclusions**

A series of nominated absorbed doses was delivered to  $\text{SiO}_2$  grains, traceable to the Australian standard of absorbed dose, with a combined relative standard uncertainty of 0.22% (for single grains). For a bulk sample, an uncertainty of 1.0% allows for the combined effects of the Cu impurity in the sample holder, and any boundary and bulk density effects due to the air spaces between the grains.

This work has provided a key input to a University research project.

## Problems with the adoption of TRS 398 as a kilovoltage CoP in hospitals for HVL's less than 3 mm Al.

R. M. Millar<sup>1</sup> and F. Gagliardi<sup>2</sup>

<sup>1</sup>William Buckland Radiotherapy Centre

<sup>2</sup>The Alfred, Melbourne, Australia

### Synopsis

#### Introduction

The Radiotherapy Interest Group (RIG) of the Australasian College of Physical Sciences and Engineering in Medicine (ACPSEM) has recommended that physicists in Australia and New Zealand adopt the IPEM (1996) Kilovoltage CoP for the calibration of Kilovoltage units and has also recommended that radiotherapy centres change over to the IAEA TRS 398 CoP by the end of 2004.

The IPEM CoP is an Air Kerma protocol and breaks the kilovoltage range into three categories, Medium energy X-rays (0.5-4 mm Cu HVL), Low energy X-rays (1.0-8 mm Al HVL), and Very Low energy X-rays (0.035-1.0 mm Al HVL). Medium energy X-rays are calibrated in water at a depth of 2 cm. Low energy X-rays are calibrated in air. Very Low energy X-rays are calibrated with a parallel plate ionisation chamber in a full scattering phantom.

The TRS 398 CoP is an absorbed dose to water protocol and uses two categories, Medium energy X-rays with an HVL > 3 mm Al, 100 kV, and Low energy X-rays with an HVL < 3 mm Al, 100 kV. An overlap region between 2 and 3 mm Al HVL is allowed when either method may be used. Medium energy X-rays are calibrated in water at a depth of 2 cm, and Low energy X-rays are calibrated with a parallel plate ionisation chamber in a full scattering phantom. The calibration procedure for the low and medium energy categories for the IPEM CoP and for the medium energy category for TRS 398 are straightforward.

The very low energy category for the IPEM CoP and for the low energy category for TRS 398 are not straight forward and require information from the standards laboratories which they do not appear to be able to provide. This leaves the hospital physicist in the position of attempting to measure some parameters, a procedure which both CoP's explicitly suggest should not be done.

For TRS 398, the standards laboratory is required to provide  $N_{D,wQ0}$  for a suitable range of HVL's and likewise for  $k_{Q,Q0}$ . For the IPEM CoP,  $N_k$  and  $k_{ch}$  are required. Most standards laboratories can provide  $N_k$  for a suitable range of HVL's but not in a full scatter phantom. In the original IPEM CoP,  $k_{ch}$  was considered to be unity due to a lack of experimental or monte-carlo data. I understand that Dr Rosser from NPL has measured a suitable set of  $k_{ch}$  data (personnel communication) but this has not been published yet.

#### Conclusion

The only way that a hospital physicist can obtain the above parameters at the moment is to do measurements in or close to the overlap regions of 2-3 mm Al HVL using an in-air technique and in a full scatter phantom as required by the above CoP's and deduce the relevant

parameters. Some results of attempting this sort of intercomparison will be presented. Alternatively one could abandon the above CoP's and use the AAPM TG 61 CoP.

One of the attractions of TRS 398 is that it is an integrated CoP covering all energies and modalities used in radiation oncology and that it is based on an absorbed dose to water method. In the kilovoltage region, the adoption of TRS 398 can only happen with the support of the local standards laboratories. This is also likely to require a research commitment from the local standards laboratory.

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## **Australian secondary standards of dosimetry**

Justin Davies, Haider Meriaty and Dimitri Alexiev  
Australian Nuclear Science and Technology Organisation (ANSTO)  
PMB 1 Menai 2234 NSW Australia

The Secondary Standard Dosimetry Laboratory (SSDL) is part of an international network of dosimetry laboratories established by the IAEA and WHO. The Network provides a framework of international comparisons of the absorbed dose measurements that help to maintain consistency and accuracy particularly amongst the radiotherapy community. The SSDL's are designated by national laboratories (such as Primary Standard Dosimetry Laboratories, PSDL's) to provide national and international radiation dosimetry traceability for users in that country.

In Australia, the traceability of ionising radiation measurements is required under the National Measurement Act, 1960. ANSTO is authorised to maintain the secondary standard of exposure in air (kerma) and absorbed dose in water, by delegation from the CSIRO, under the Act. Australia's national primary standard is the responsibility of the PSDL at ARPANSA. The ANSTO SSDL has measurement traceability to the PSDL; thus an Australian SSDL facility provides an interface between the primary standard and Australian hospitals, significantly reducing waiting time for instrument calibration.

The ANSTO SSDL provides a calibration service, at cobalt-60, primarily to Australian hospital departments for radiotherapy level dosimeters and thimble chamber types NE2561, NE2611A, NE2571 and NE2581. Other services include charge sensitivity and linearity tests of dosimeters and strontium-90 stability check source calibrations. The paper describes the facility and the available services to clients.

## The role of trilateral comparisons in the assessment of uncertainty

David V Webb, Robert B Huntley and John F Boas<sup>‡</sup>

Ionizing Radiation Standards Section, Medical Radiation Branch

Australian Radiation Protection and Nuclear Safety Agency (Melbourne)

<sup>‡</sup>Present address: School of Physics and Materials Engineering, Building 27, Monash University, Victoria 3800, Australia

Most international standards comparisons are made directly or indirectly with the International Bureau of Weights and Measures (BIPM) in Paris. The results of these Key Comparisons are tabulated in the newly established Mutual Recognition Arrangement (MRA) [1] and the uncertainties are used to determine the degree of equivalence between two national standards. Bilateral comparisons can be made directly between two National Measurement Institutes. When two laboratories have also made recent comparisons with a third laboratory such as the BIPM, it is possible to compare the bilateral comparison result with a prediction based on the recent results of each laboratory with the third laboratory.

This “trilateral” comparison can be represented as a triangular structure. If the primary standards are equivalent and invariant, all three ratios should be close to unity and the “triangle” of comparisons is closed. We have developed a linear model using the deviation of each ratio from unity to define a “gap” as a measure of the inconsistency of the three bilateral comparisons. The random uncertainties of the transfer chamber measurements at each laboratory contribute to the precision that should determine the size of the “gap” which is a measure of the failure of the “triangle” to close.

The recent comparison between ARPANSA, Australia (A) and NRC, Canada (C) [2], both laboratories having made recent comparisons with the BIPM (B) [3-6], has been analysed in this way and shows a gap consistent with the random uncertainties, for both air kerma and absorbed dose. Analysis of another recent comparison between NRC and LNHB (France) [7], from which a trilateral result can be constructed with the BIPM [4,6,8], leads to similar results. The observed gaps are commensurate with their uncertainties.

Consistent participation in several “trilaterals” will provide confidence in the primary standards involved and may also help to resolve difficulties in the interpretation of the degrees of equivalence assigned to these standards.

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## The measurement of the absorbed dose to water in $^{60}\text{Co}$ using the pancake ionization chamber

\*Shi-Hwa Su \*\*Chiung-Yu Lin \*Chun-Liang Chen \*Wen-Song Hwang  
 \*National Radiation Standard Laboratory  
 Health Physics Division, Institute of Nuclear Energy Research  
 \*\*Radiation Protection Association R.O.C.  
 P.O. Box 3-10 Lung-tan 325, Taiwan

### Synopsis

In Taiwan, the measurement of the output dose rates of medical accelerators goes by using the ionization chamber that has been calibrated by the  $^{60}\text{Co}$  air kerma standard and the various conversion factors quoted from the AAPM TG-21 protocol (1983) to determine the absorbed dose to water of the accelerator. The AAPM published the TG-51 protocol in 1999 which recommended medical ionization chambers to be calibrated in water with the absorbed dose to water standard in  $^{60}\text{Co}$ . This makes it more convenient to measure the absorbed dose to water of the accelerator.

To meet the domestic demands of calibrating the ionization chamber with the absorbed dose to water, the Institute of Nuclear Energy Research (INER) undertook the establishment of the primary standard of the absorbed dose to water in  $^{60}\text{Co}$  according to the requirements of TG-51 in 2000.

The establishment method referred to the approach used in 1992 by  $\acute{A}$ M Boutillon and A-M Perroche who employed the pancake ionization chamber as the standard of the  $\acute{A}$ Bureau International Des Poids Et Mesures (BIPM) for the measurement of the absorbed dose to water in  $^{60}\text{Co}$ . Their design and measurement technology were referred to and a pancake ionization chamber was constructed (shown as Fig.1.) Besides the measurement of the ionization chamber volume, through experiment or quoted data, the measurement parameters were evaluated included the charge collected in the mass of air in the cavity, the average energy required to produce an ion pair in air ( $W$ ), the electronic charge ( $e$ ), the ratio of the mean stopping powers of graphite and air averaged over the electron spectrum ( $(S/\rho)_{c,a}$ ), the corresponding ratio of the photon energy fluence ( $\psi_{w,c}$ ), the ratio of the absorbed dose to water with kerma ( $(1+\varepsilon)_{w,c}$ ), the ratio of the mean mass-energy absorption coefficient averaged over the photon energy spectra in water to that in graphite ( $(\bar{\mu}_{en}/\rho)_w/(\bar{\mu}_{en}/\rho)_c$ ), correction factor for the inadequacy of the chamber with the ideal Bragg-Gray cavity ( $K_{cav}$ ), correction factor for recombination losses ( $K_s$ ), the correction factor for the influence of the perspex support on the chamber ( $K_{ps}$ ), correction factor for the front face of the water phantom which is not water-equivalent ( $K_{pf}$ ), correction factor for the non-uniformity of the beam ( $K_m$ ), correction factor for humidity ( $K_h$ ), etc. The evaluation results are given in Table 1. The measurement uncertainty of the absorbed dose to water in  $^{60}\text{Co}$  is 0.3 % ( $k=1$ )

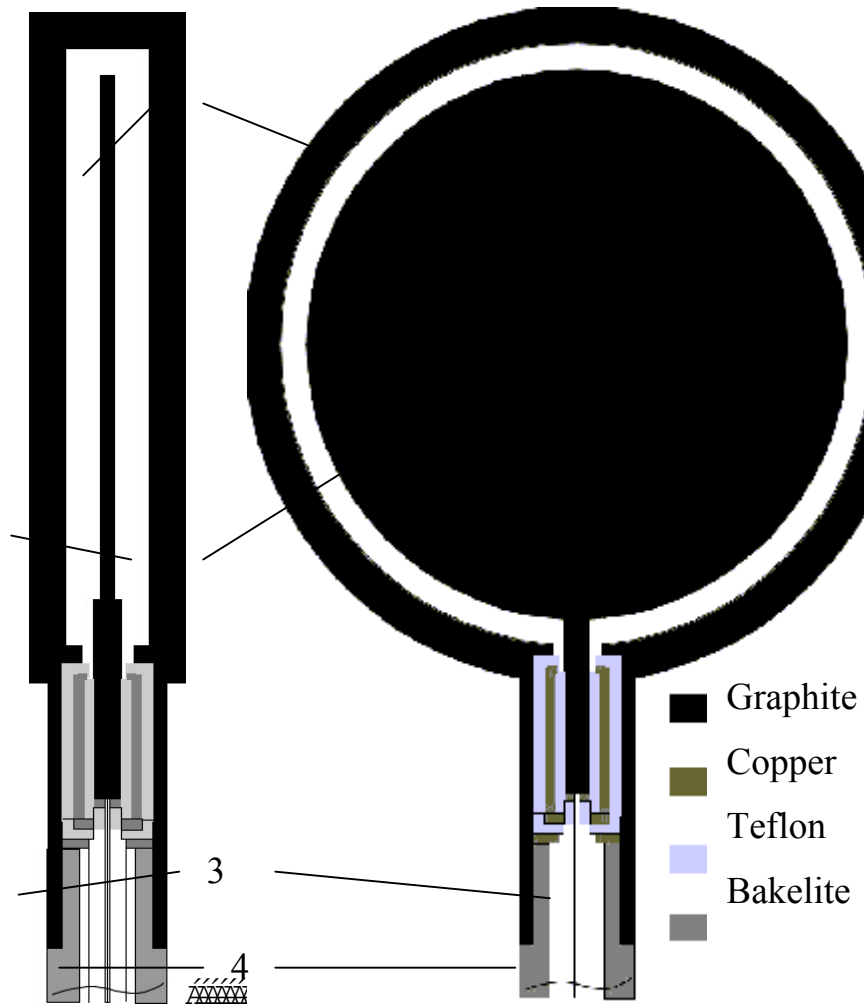


Figure 1. A profile of the standard ionization chamber. 1. Body of the chamber cavity. 2. Central electrode board. 3. Central conducting wire. 4. Handle of the chamber.

Table 1. Measurement of the absorbed dose to water, various correction factors to the ionization chamber and physical constants.

Ionization chamber parameter	PC3	PC4	Uncertainty	
			Type A	Type B
<b>Mass of Cavity (<math>m = v \times \rho_{\text{air}} \times 1013.25 / P \times T / 273.15</math>)</b>				
V (cm <sup>3</sup> )	*8.4083	*8.5679	0.0080	
$\rho_{\text{air}}(\text{STP})$ kg/m <sup>3</sup>	1.293	1.293		0.010
P	*	*		
T	*	*		
<b>Charge (<math>Q = C_f \times \Delta V_{\text{out}}</math>)</b>				
$\Delta V_{\text{out}}$	*	*	0.040	0.0031
$C_f$	$9.9175 \times 10^{-7}$	$9.9175 \times 10^{-7}$		0.0070
<b>Physical constant</b>				
W/e (J/C)	33.97	3.97		0.11
(S/ $\rho$ ) <sub>c,a</sub>	1.0025	1.0025		
<b>Perturbation correction factor <math>k_p</math></b>				
$K_{\text{cav}}$	0.9857	0.9857	0.030	0.040
$(\mu_{\text{en}}/\rho)_{\text{w}}/(\mu_{\text{en}}/\rho)_{\text{c}}$	1.1125	1.1125	0.010	0.14
$\Psi_{\text{w,c}}$	1.0065	1.0065	0.040	0.060
$(1+\epsilon)_{\text{w,c}}$	1.0015	1.0015		0.060
<b>Other correction factor</b>				
$k_{\text{pf}}$	0.9996	0.9996		0.010
$k_{\text{ps}}$	1.000	1.000		0.15
$k_{\text{s}}$	1.00027	1.00027		0.0021
$k_{\text{rn}}$	1.0051	1.0051	0.010	0.030
$k_{\text{h}}$	0.997	0.997		0.030
Quadratic sum			0.258	0.0630
Combined uncertainty			0.27	

Note: 1. “ \* “ means the value depends on the figures at the time when the measurement is being done.

## Air kerma standard for medium X-rays

T. Kurosawa, N.Takata, Y. Koyama, T.Matsumoto  
National Metrology Institute of Japan, AIST

### Synopsis

As a results of new filter system, we reestablished air kerma standard for medium X-rays. As a parameter the so-called “quality index” (effective energy in keV / tube voltage in kV) is introduced instead of the homogeneous coefficient to express the characteristic of the X-ray spectrum. Air kerma standards have been established for series of quality indexes of 0.4, 0.5, 0.6, 0.7, 0.8 in a tube voltage ranging from 50kV to 250kV respectively.

The free-air ionization chamber is used for absolute measurements. We applied Monte Carlo calculation to estimate correction factor for electron loss,  $K_e$ , and for scattered photons,  $K_{sc}$ . The calculations were performed using the EGS4-LSCAT(low-energy photon-scattering expansion for the EGS4 code) code with the PRESTA electron transport algorithm. LSCAT is a group of file used to calculate keV-photon transport by EGS4 with an expanded physical model. For a given incident photon energy  $E$ , let  $P_{tot}(E)$  be the total primary deposited in the scoring regions and  $P_{col}(E)$  be the primary energy deposited in the collecting region. Then  $K_e(E)$  is calculated as

$$K_e(E) = \frac{P_{tot}(E)}{P_{col}(E)} \quad (1)$$

Similarly, let  $S_{col}(E)$  be the scattered energy deposited in the collecting region. Then

$$K_{sc} = \frac{P_{col}(E)}{P_{col}(E) + S_{col}(E)} \quad (2)$$

Calculations were made in 10keV steps from 10keV to 250keV. From monoenergetic results, there is a peak around 130keV that due to photoelectrons. As the photon energy is increased, a larger fraction of the photoelectron energy escapes the collecting volume. However, in this energy range the cross-section for photoelectron production is rapidly decreasing and it is the competition of the two effects which produces the peak. Above 200keV, Compton electrons start to reach the chamber walls and their effect increases very rapidly with energy.

Spatial distributions of medium X-ray fields are measured for secondary standard chamber calibrations. The shape of horizontal distribution depends on a tube voltage, and it becomes sharp for high energy X-ray field.

## A new dosimetry protocol for external beam radiotherapy in Japan

Fukumura, T. Hiraoka, T. Kanai  
National Institute of Radiological Sciences, Chiba, Japan

### Synopsis

Japan Society of Medical Physics (JSMP) published a new code of practice for dosimetry, titled "Standard Dosimetry of Absorbed Dose in External Beam Radiotherapy" [1] in 2002. The principal purposes of the publication were to adopt the absorbed-dose-to-water based formalism, to update physical data, to recommend to use water phantom, to harmonize with international protocols, to note narrow beam dosimetry and to deal with proton and carbon beams.

The new Japanese dosimetry protocol mostly follows IAEA Technical reports series No. 398 [2], which is based on  $N_{D,w,Q_0}$ , i.e., the calibration factor in terms of absorbed dose to water for a dosimeter at a reference beam quality  $Q_0$ . According to the protocols, absorbed dose is given by

$$D_{w,Q} = M_Q N_{D,w,Q_0} k_{Q,Q_0} \quad (1)$$

where  $D_{w,Q}$  is the absorbed dose to water at the reference depth in a water phantom irradiated by a beam of quality  $Q$ ,  $M_Q$  is the reading of a dosimeter at quality  $Q$ , corrected for influence quantities other than beam quality, and  $k_{Q,Q_0}$  is the factor to correct for the difference between the response of an ionization chamber in the reference beam quality  $Q_0$  used for calibrating the chamber and in the actual user beam quality  $Q$ .

The Japanese primary standard dosimetry laboratory, however, has supplied the calibration factors in terms of exposure,  $N_{X,Q_0}$ , instead of in terms of absorbed dose to water. The peculiar feature of the new Japanese protocol is to provide the data table of the calculated ratio of  $N_{D,w,Q_0}$  to  $N_{X,Q_0}$  for many types of ionization chambers used in radiation therapy. Using the data table, the Japanese secondary standard dosimetry laboratory for radiation therapy facilities has supplied the calculated  $N_{D,w,Q_0}$  to end-users since 2002, in addition to the measured  $N_{X,Q_0}$ .

It seems to take a couple of years to implement the new protocol with  $N_{D,w,Q_0}$  calibration factor over the whole country. It is expected that the use of the new Japanese dosimetry protocol strengthen inter-institutional uniformity in dosimetry for external beam radiotherapy including proton and carbon beam therapy.

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## A novel signal processing method for the NMI water calorimeter

L.A. de Prez, M.W.H. Pieksma, E. van Dijk, A.H.L. Aalbers  
NMI Van Swinden Laboratorium, Delft, The Netherlands

### Synopsis

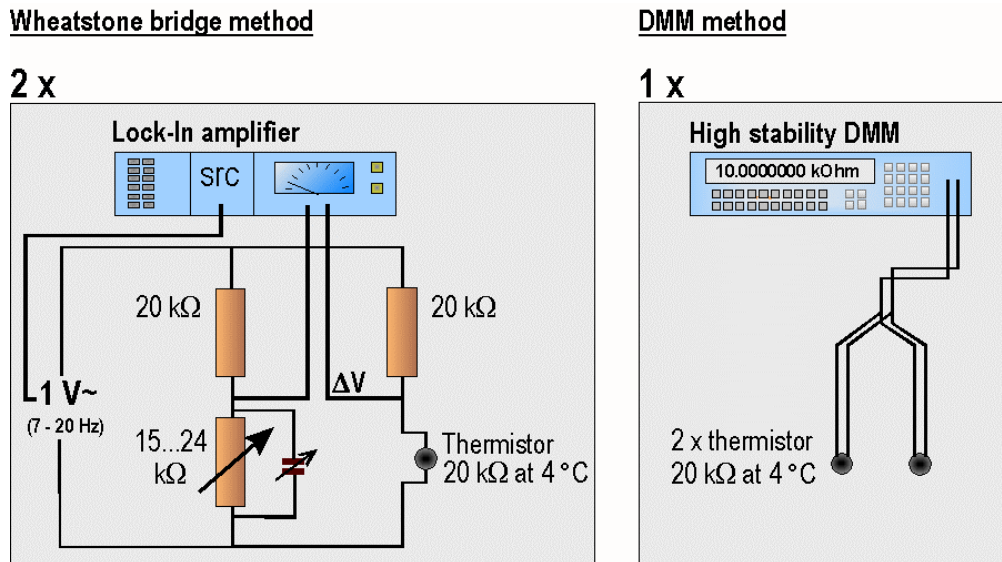
#### Introduction

The NMI has developed a water calorimeter as a new primary standard for absorbed dose to water in photon beams. This calorimeter is of the sealed-water type [1, 2], it is portable and is used in radiotherapy clinics to measure generic  $k_Q$  values [3].

The signal processing method for the water calorimeter employs a high precision digital multimeter (DMM). This method has been chosen instead of a Wheatstone bridge technique with lock-in amplifiers as used with our graphite calorimeter because detection of the small measurement signals<sup>1</sup> generated in a water calorimeter are difficult to measure using lock-in amplifiers.

#### Wheatstone bridge method

Figure 1 shows the AC-Wheatstone bridge as used with our graphite calorimeter and initially used with the water calorimeter. Two thermistor probes are connected each to their own bridge circuit. In the circuit, a variable resistance and thermistor are placed in opposite arms. The bridge is balanced each time before irradiation. Additionally, a variable capacitor compensates for parasitic capacity in the signal cables.



**Figure 1:** Simplified electrical scheme of the Wheatstone bridge method and the DMM method.

Employing the graphite calorimetry, the bridge is re-balanced during irradiation and the lock-in amplifier is used as a zero-detector. The total resistance change of a thermistor probe is determined using the difference of the balancing resistor and the change in offset voltage of the lock-in amplifier. A deviation of the bridge calibration factor has only a small influence in the measured resistance change.

<sup>1</sup> The temperature rise in water is approximately 5 times smaller than that in graphite for  $^{60}\text{Co}$  radiation due to differences in energy absorption coefficient and specific heat.

Accurate determination of the bridge calibration factor is not possible, because the calibration factor is dependent on the bridge frequency. Its value is only valid when impedances in opposite arms are closely matched and when the unbalance of the bridge is small.

Due to the small signal generated in a water calorimetry the bridge cannot be re-balanced during irradiation. This means that a deviation in the bridge calibration factor directly enters into the measured resistance and the lock-in amplifier is then used as a voltmeter. Increasing the signal by applying longer drift times is not a solution due to excess heat and temperature drifts in the calorimeter phantom.

In addition, the Wheatstone bridges and lock-in amplifiers are very sensitive to electrical noise, especially in non-standard environments like radiotherapy clinics.

### **DMM method**

The above problems led to a new approach for processing the signal for our water calorimeter. This measurement method had to be frequency independent, insensitive to electrical noise, accurate, stable and sensitive enough to perform traceable measurements of small resistance changes in different experimental environments. The solution was found in the use of a high precision, highly stable DMM.

With the new system, two parallel connected 20 kOhm thermistors are used. Their resistance change is measured with an Agilent 3458A high stability DMM. This DMM has a display resolution of 0,001 Ohm and is capable of producing more digits when readout by a remote computer.

The 10 kOhm scale has been calibrated at the Electrical Standards laboratory of NMI. In order to assure that the measured small resistance changes<sup>2</sup> between the calibration points are in fact traceable, the linearity of the 10 kOhm scale has been verified. However, direct calibration against resistance standards with such resolution is not possible. Therefore the linearity of the 10 kOhm scale test voltage has been measured, which is the 1 V scale. The maximum deviation of the linearity is a measure for the non-statistical (type B) uncertainty in the resistance change and turns out to be better than 300  $\mu$ Ohm. For a 2 Gy irradiation in <sup>60</sup>Co gamma radiation this results in an uncertainty contribution of 0,15 %.

Other advantages using a high precision DMM are:

- Excellent electrical characteristics with respect to noise in radiotherapy clinics (see Figure 2).
- Less time consuming compared to the Wheatstone bridge approach because no bridge calibrations are needed.
- The DMM method is easy and straightforward.
- No correction for self-heating of the thermistors is needed because they are calibrated in combination with the DMM as one system.
- The system is compact, easy to transport and easy to install on location.

### **Conclusions**

In order to measure small resistance changes in the NMI water calorimeter the Wheatstone bridge method, as used with our graphite calorimeter is not suited. The main cause for arising

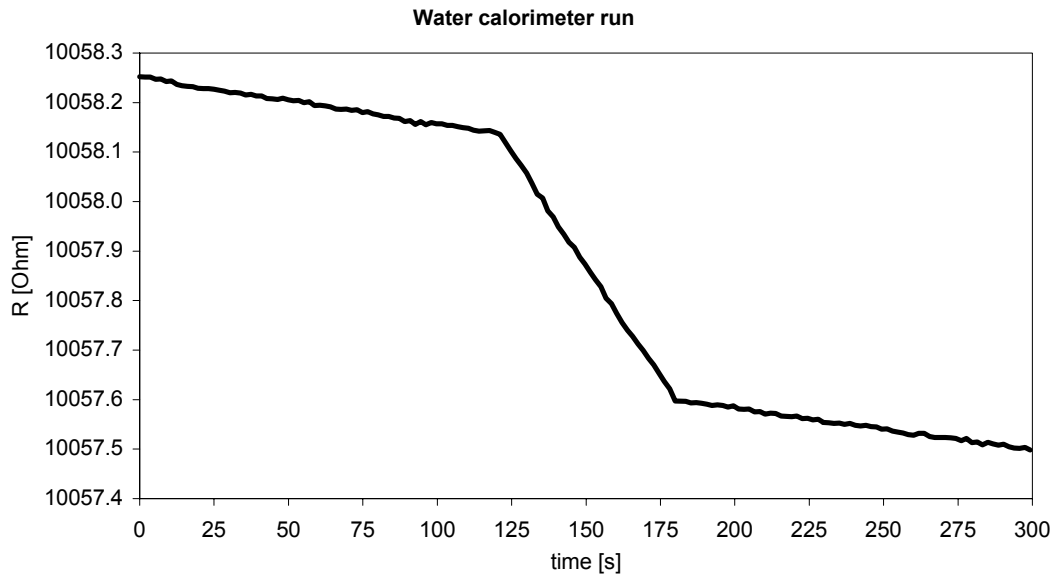
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<sup>2</sup> The resistance change is approximately 0,1 Ohm·Gy<sup>-1</sup>.

problems is a deviation in the bridge calibration factor, which enters directly the measured resistance change. Another problem that arose was the sensitivity of the system to electrical noise in non-standard environments.

The DMM method provides accurate and traceable measurements for small resistance changes. The total non-statistical uncertainty contribution is 0,15 % for a 2 Gy irradiation.

The new method is straight forward, insensitive for electrical noise, compact and easy to operate at different locations.



**Figure 2:** A water calorimeter run in the Elekta SL15 10 MV clinical accelerator beam at the Academic Medical Center, Amsterdam.

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## LIST OF PARTICIPANTS

**Tony Aalbers**

NMi  
Van Swinden Laboratorium  
PO Box 654  
Delft  
2600AR  
The Netherlands  
Tel +311 5269 1500  
Fax +311 5261 2971  
aalbers@nmi.nl

**Robin Bentley**

National Measurement  
Laboratory  
PO Box 218  
Lindfield NSW 2070  
Australia  
Tel +612 9413 7764  
Fax +612 9413 7383  
robin.bentley@csiro.au

**John Boas**

School of Physics and Materials  
Engineering  
Monash University  
Clayton VIC 3800  
Australia  
Tel +613 9853 8269  
Fax +613 9855 1665  
johnb001@bigpond.com

**David Burns**

BIPM  
Pavillion de Breteull  
F-92312 Sevres Cedex  
France  
Tel +331 4507 7080  
Fax +331 4534 2021  
dburns@bipm.org

**Duncan Butler**

ARPANSA  
619 Lower Plenty Road  
Yallambie VIC 3085  
Australia  
Tel +61 9433 2274  
Fax +61 9432 1835  
duncan.butler@health.gov.au

**Huaiyu Heather Chen-Mayer**

NIST  
100 Bureau Drive, Mail Stop  
8460  
Radiation Interactions and  
Dosimetry Group  
Gaithersburg MD 20899-8460  
USA  
Tel +1 301 975 5595  
Fax +1 301 869 7682  
chen-mayer@nist.gov

**Milly Cox**

ARPANSA  
619 Lower Plenty Road  
Yallambie VIC 3085  
Australia  
Tel +613 9433 2268  
Fax +613 9432 1835  
milly.cox@health.gov.au

**Josiane Daures**

CEA Saclay,  
DIMRI-LNHB, Batiment 534  
Gif-sur-Yvette Cedex 91191  
France  
Tel +331 6908 6670  
Fax +331 6908 4773  
josiane.daures@cea.fr

**Justin Davies**

ANSTO  
PMB 1  
Menai NSW 2234  
Australia  
Tel +612 9717 9002  
Fax +612 9717 9265  
jbd@ansto.gov.au

**Leon de Prez**

NMi  
PO Box 80.000  
Utrecht  
3508 TA  
The Netherlands  
Tel +3130 253 9097  
Fax +3130 253 9095  
ldeprez@nmi.nl

**Simon Duane**

NPL  
Queens Road  
Teddington  
Middlesex TW11 0LW  
UK  
Tel +4420 8943 6568  
Fax +4420 8943 6070  
simon.duane@npl.co.uk

**Wasantha Fernando**

Austin Health Radiation  
Oncology Centre  
Banksia Street  
West Heidelberg VIC 3081  
Australia  
Tel +613 9496 2315  
Fax +613 9496 2826  
wasantha.fernando@austin.com.au

**Akifumi Fukumura**

National Institute of Radiological  
Sciences  
Division of Medical Physics,  
Research  
4-9-1 Anagawa  
Inage-ku  
Chiba-shi  
263-8555  
Japan  
Tel +8143 251 2111  
Fax +8143 251 1840  
fukumura@nirs.go.jp

**Frank Gagliardi**

William Buckland Radiotherapy  
Centre  
Commercial Road  
Melbourne VIC 3004  
Australia  
Tel +613 9276 3512  
Fax +613 9276 2669  
frank.gagliardi@wbrc.org.au

**Kent Gregory**

EPA (SA)  
Radiation Protection Division,  
Environment  
PO Box 721  
Kent Town SA 5071  
Australia  
Tel +618 8130 0713  
Fax +618 8130 0777  
kent.gregory@state.sa.gov.au

**Rashmi Gupta**

St George Cancer Care Centre  
Gray Street  
Kogarah NSW 2217  
Australia  
Tel +612 9350 3919  
guptar@sesahs.nsw.gov.au

**Robert Huntley**

ARPANSA  
619 Lower Plenty Road  
Yallambie VIC 3085  
Australia  
Tel +613 9433 2224  
Fax +613 9432 2305  
robert.huntley@health.gov.au

**Lew Kotler**

ARPANSA  
619 Lower Plenty Road  
Yallambie VIC 3085  
Australia  
Tel +613 9433 2333  
Fax +613 9432 1835  
lew.kotler@health.gov.au

**Hans-Michael Kramer**

PTB  
Bundesalle 100  
Braunschweig D-38116  
Germany  
Tel +49 531 592 6200  
Fax +49 531 592 6405  
Hans-Michael.Kramer@ptb.de

**Tadahiro Kurosawa**

AIST Quantum Radiation  
Division  
1-1-1 Umezono  
Tsukuba  
Ibaraki 305-8568  
Japan  
Tel +8129 861 5927  
Fax +8129 861 5673  
tadahiro-kurosawa@aist.go.jp

**Jenny Lydon**

Radiation Oncology Victoria  
132 Grey Street  
East Melbourne VIC 3002  
Australia  
Tel +613 9418 2210  
Fax +613 9418 2288  
jenny@mira.net

**Malcolm McEwen**

NRCC  
Montreal Road, Building M35  
Ottawa  
ON  
K1A 0R6  
Canada  
Tel +1 613 993 2197  
Fax +1 613 952 9865  
malcolm.mcewen@nrc.ca

**Malcolm Millar**

William Buckland Radiotherapy  
Centre  
Commercial Road  
Melbourne VIC 3004  
Australia  
Tel 03 9276 3512  
Fax 03 9276 2669  
malcolm.millar@wbrc.org.au

**Aimé Ostrowsky**

CEA-Saclay  
DIMRI-LNHB-LMDO Bat 534  
Gif sur Yvette  
State Cedex 91191  
France  
Tel +331 6908 4276  
Fax +331 6908 4773  
aime.ostrowsky@cea.fr

**Hugo Palmans**

National Physical Laboratory  
Queens Road  
Teddington  
Middlesex TW11 0LW  
UK  
Tel +44 20 8943 6568  
Fax +44 20 8943 6070  
hugo.palmans@npl.co.uk

**Virendra Patel**

Royal Prince Alfred Hospital  
Missenden Road  
Camperdown NSW 2050  
Australia  
Tel +612 9515 8807  
Fax +612 9515 8070  
vpatel@email.cs.nsw.gov.au

**Frantisek Pernicka**

IAEA  
PO Box 100  
Vienna  
Austria  
Tel +431 2600 21663  
f.pernicka@iaea.org

**Gerhard Stucki**

METAS  
Lindenweg 50  
Bern-Wabern  
CH-3003  
Switzerland  
Tel +41 31 323 3331  
Fax +41 31 323 3210  
gerhard.stucki@metas.admin.ch

**Shi-Hwa Su**

Institute of Nuclear Energy  
Research  
1000 Wenhua Road, Chia-an  
Village  
Lungtan Hsiang  
Taoyuan Hsien Taiwan 325  
Republic of China  
Tel +886-3-471 4088  
Fax +886-3-471 4132  
shwasu@iner.gov.tw

**Russell Thomas**

National Physical Laboratory  
Kaye Building, room 102, Queens  
Road  
Teddington  
Middlesex  
TW11 0LW  
Tel +4420 8943 6052  
Fax +4420 8943 6070  
russell.thomas@npl.co.uk

**David Webb**

ARPANSA  
619 Lower Plenty Road  
Yallambie VIC 3085  
Australia  
Tel +613 9433 2227  
Fax +613 9432 1835  
david.webb@health.gov.au

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