

# Calorimetry for Absorbed-dose Measurements at BNM-LNHB

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## *Abstract*

At BNM-LNHB, the references in terms of absorbed dose to water are based on graphite calorimeter measurements. In the cobalt-60 beam, measurements were performed directly with the graphite calorimeter in a graphite phantom. Absorbed dose to water in a water phantom was then determined using a transfer method by means of relative measurements made with ionisation chambers and Fricke dosimeters. Our medical linac (Saturne 43 from GE-Medical Systems) is being characterised in the same way for three photon beam qualities 6 MV, 12 MV and 20 MV.

Special attention was given to the vacuum-gaps correction, one of the most important source of uncertainty. We carried out measurements in a graphite device similar to the calorimeter, using a very small diode embedded in a body corresponding to the calorimeter core. Measurements were made alternatively with and without vacuum gaps in the graphite phantom. The ratio of the results leads directly to the vacuum-gap correction factor. Monte-Carlo calculations were also carried out using both EGS4 and PENELOPE codes. The results are in good agreement, regarding the uncertainties.

At present, a water calorimeter is being realised. The aim is to get an absorbed dose standard independent of and complementing those based on graphite calorimetry. Particular attention will be devoted to the possibilities in terms of uncertainty compared with those attainable using graphite calorimetry.

## I. INTRODUCTION

The BNM-LNHB is the French national laboratory for absorbed dose metrology.

The first of July 1999, the former LPRI changed its name to LNHB, which means National Laboratory Henri Becquerel.

The graphite calorimeter is the standard of absorbed dose to graphite. At present the references of absorbed dose to water are derived from this standard. Considering the importance of the graphite calorimetric technique, the laboratory has to maintain and improve it carefully. As the vacuum-gaps correction is the main source of uncertainty, it was decided to measure it by means of very small diode and to calculate it again for our cobalt-60 beam and for high-energy photon beams (6 MV, 12 MV, and 20 MV) from our GE-Saturne 43 medical type linear accelerator. Experimental and theoretical results are in good agreement and confirm the previous estimation in the cobalt-60 beam.

The tissue-equivalent calorimeter developed by the laboratory in the early 80's for the calibration of neutron-therapy and proton-therapy beams is maintained operational.

Water calorimetry is now in progress with high-level priority.

## II. EVOLUTION OF THE CALORIMETRIC TECHNIQUE AT BNM-LNHB

Since the early seventies, the laboratory did constant efforts in the calorimetry field and built several instrument versions.

The graphite calorimeter n° 4 was compared to Domen's one in our cobalt-60 beam in 1975. The French reference was 0.3 % lower than the US one [1]

In 1977 and 1993, measurements were performed in the BIPM cobalt-60 beam for comparison using different calorimeters with good results. In 1977, the graphite calorimeter n° 5 was used. The result was 0.01 % lower than the BIPM reference at 5 g.cm<sup>-2</sup> depth [2]. In 1993, the graphite calorimeter n° 8 showed with a difference of -0.05 % compared to BIPM [3]. For this last calorimeter, the improvement consisted in the electrical calibration by Joule effect through specific thermistors instead of conducting resin. In the meantime, measurements were carried out in a linear accelerator in Saclay for the determination of  $W_{\text{air}}$  and G for Fricke solutions with 35 MeV photon and electron beams using the graphite calorimeter n° 6. The feed-back control of the jacket was introduced at that time. Aimé Ostrowsky thus built a total of eight graphite calorimeters and two T. E. calorimeters

The present references of absorbed dose to water in cobalt-60 and high-energy photon beams at BNM-LNHB are based on measurements with the graphite calorimeter n° 8.

The tissue-equivalent calorimeter was developed around 1980. It is made of A150 Shonka plastic whose hydrogen and nitrogen compositions are similar to those of tissue. At this time, neutron therapy seemed very promising (high LET secondary particles). Later on, proton treatment was developed for its ballistic qualities. In hospitals, the dosimetry is mainly performed by means of tissue-equivalent ionisation chambers calibrated in terms of air kerma. The protocols give guidance on methodology and recommend values for the needed parameters. The overall uncertainty, for one standard deviation, is more than 4 %, mainly due to the poor knowledge of the mean energy expended to create an ion pair in the gas of the cavity and gas-to-wall stopping power ratios for neutrons or protons.

For radiotherapy purpose, it has been proven by clinical studies that the total uncertainty must be lower than 5 % in the tumour volume [4]. Then it is important to reduce the uncertainty on the reference dose to give some safety margin for treatment planning.

In neutron or proton beams, the uncertainty obtained with the tissue-equivalent calorimeter is about 0.7 % for one standard deviation. It is higher than for the graphite calorimeter because of the heat defect correction, but the determination of absorbed dose to tissue is easier, especially for neutrons. Direct calibration

of ionisation chambers in the user's beam by means of the calorimeter, although long and delicate, reduces considerably the uncertainties [5]. Moreover the ratio of the corresponding calibration factor in terms of absorbed dose to that in terms of air kerma in a cobalt-60 beam gives a measured value of  $C_n$  or  $C_p$  coefficients.

Measurements were performed with our first tissue equivalent-calorimeter in the cyclotron neutron-therapy beam of Orléans (1982) and Louvain la Neuve (1983) [6,7]. The results were in agreement with the  $C_n$  values calculated with the protocol.

The second tissue-equivalent calorimeter was used in the Orsay proton-therapy beam in 1991. Measurements were performed at three energies (32, 52, 169 MeV). Several European centres came to perform ionisation measurements. At that time there was a significant difference between calorimetric and ionometric measurement results. Applying the new values of stopping powers published later, the ionometric results felt in agreement with the calorimetric determination [8].

A comparison with the PTB standards took place in 1984 in its cyclotron neutron beam ( $d(13.35 \text{ MeV}) + \text{Be}$ ) [9]. The calorimetric absorbed dose was in good agreement with the Monte Carlo calculation and the ionometric measurement of PTB.

No comparison with any other tissue equivalent calorimeter could be done yet.

### III. GRAPHITE CALORIMETER

#### A. Design

The diagram of the graphite calorimeter n° 8 is given in figure 1. The core is a flat cylinder (3 mm thick and 16 mm in diameter). The jacket surrounding the core is 2 mm thick. The shield surrounding these two first bodies is 2 mm thick. These three bodies are kept in position and glued in the block by three silk threads. The gaps between each bodies and the block are evacuated to reduce thermal transfers. The dimensions of these gaps are close to 1 mm along the axis and about 2 mm perpendicular to the axis.

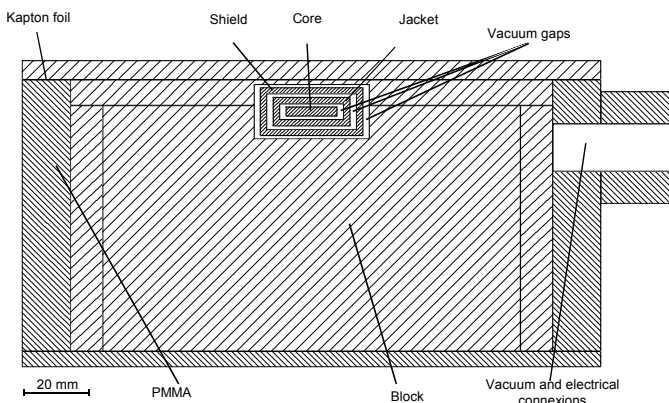


Figure 1: Diagram of the graphite calorimeter n° 8.

#### B. Temperature Control

Since the sensitivity of the graphite calorimeter is only a millikelvin per gray, the stability of the core temperature before and after irradiation must be better than 10 microkelvins.

The shield is the first thermal control step. Its temperature is kept constant at about 2 degrees above the room temperature, which is the cold source of the system. A thermistor embedded in the shield and associated to a DC Wheatstone bridge measures the temperature. If the temperature decreases, a PID thermal regulator sends an adjusted electrical power to the shield heating supply (8 thermistors). The shield control system is shown on the right of figure 2.

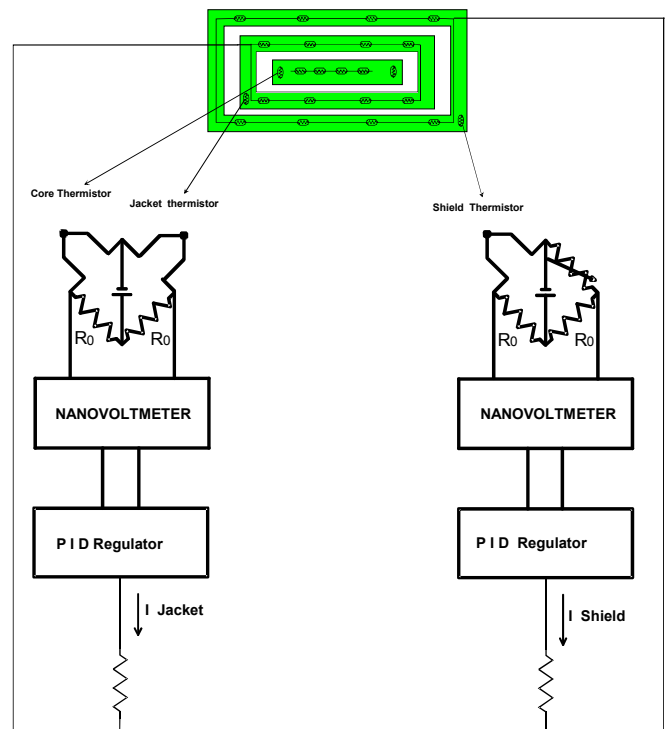


Figure 2: Thermal control of graphite and tissue-equivalent calorimeters.

The jacket temperature is controlled to follow, as closely as possible, the core temperature, minimising thus the thermal transfers between the core and the jacket. One thermistor embedded in the core and another in the jacket make two opposite arms of a DC Wheatstone bridge. The two thermistors are carefully selected to have the same characteristics. An electrical power is sent to the jacket heating supply (8 thermistors) by means of a PID regulator on the base of the Wheatstone bridge voltage. This jacket thermal feed-back is shown on the left of figure 2. This is the essential difference with Domen-type graphite calorimeters [10]. This jacket thermal feed-back has improved the stability and the flexibility of this calorimeter.

#### C. Measuring System and Electrical Calibration

During irradiation or electrical calibration heating, the temperature rise is measured with a thermistor embedded in the core. The thermistor used for the measurement is identical to the

one used for thermal control. These thermistors are of the “pearl type covered” from Fenwall; type GB38j14. Their mass is about 0.5 mg. Their diameter is close to 0.35 mm. Their relative sensitivity is about  $3.8 \cdot 10^{-2} \text{ K}^{-1}$ . Their resistance values are close to  $8 \text{ k}\Omega$  at  $20^\circ \text{C}$ .

The relative variation of the thermistor resistance,  $L$ , is measured by means of a very precise DC Wheatstone bridge shown on figure 3. High-accuracy and high-precision Vishay resistors; type VHP 103; are used. They were chosen for their very low temperature coefficient ( $<10^{-6} \text{ K}^{-1}$ ) as they are usually outside the regulated irradiation room. A mercury battery provides a 1.35 V potential. A Keithley 181 nanovoltmeter is used to measure the bridge voltage. As it is impossible to balance the bridge during the measurement, it works out off equilibrium. Just before irradiation or electrical calibration, the sensitivity of the bridge is measured, in similar conditions, by introducing in the other arm a resistor of known value.

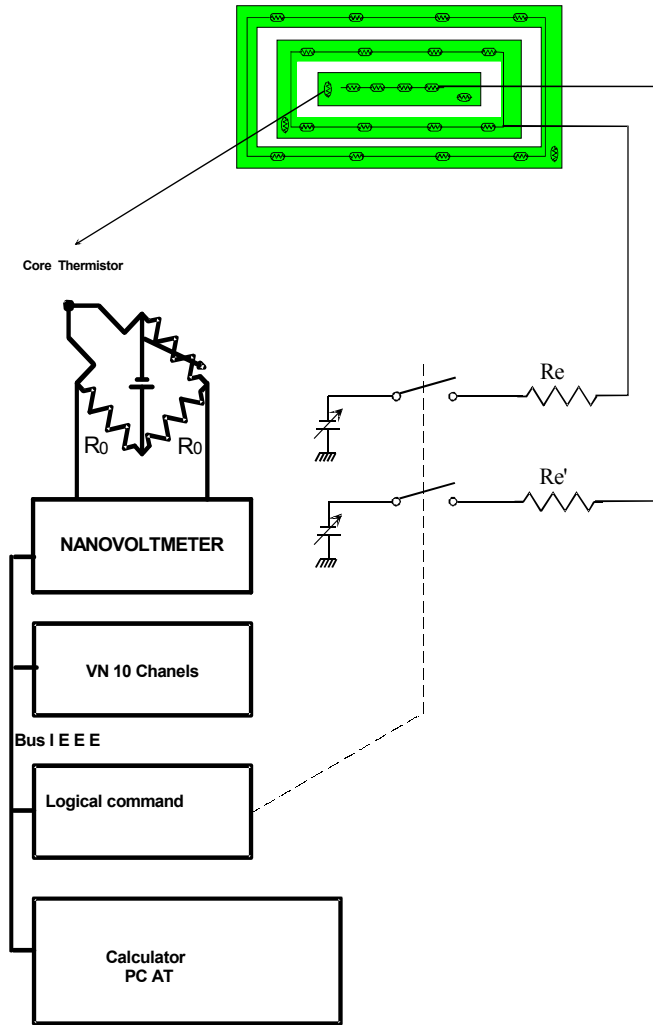


Figure 3: Calorimetric measurement.

The electrical calibration of the calorimeter consists in measuring  $L_{el}$ , when dissipating in the core,  $Q_{el}$ , a well measured electrical power through four specific embedded thermistors. The electrical calibration factor,  $F$ , is the ratio of those two quantities. Then, the heat capacity of the core, the temperature calibration

of the thermistor and the residual heat transfers between the core and the surrounding have not to be precisely known.

#### D. Performances and Analysis of Uncertainties

As an example, the uncertainty components relative to the reference absorbed dose to graphite in the BNM-LNHB cobalt-60 beam are given in table 1

Table 1

Values and uncertainties for graphite calorimetric determination of the reference absorbed dose rate at  $5 \text{ g.cm}^{-2}$  depth in graphite phantom in BNM-LNHB cobalt-60 beam.

Term	Value	Uncertainties (1s, %)	
		s	u
$F$	}1.42488 36655 J.s <sup>-1</sup>	0.015	0.016
$L$		0.026	
$M$	1.1177 g		0.02
$r_{cal}$	1.0000		0.1
$k_f$	1.0000		0.05
$k_v$	0.9909		0.15
$k_i$	0.9989		0.1
$k_{gr}$	1.0002		0.01
$k_{ff}$	0.9988		0.01
$k_k$	0.9999		<0.01
$k_{et}$	1.0000		0.05
$k_{fant}$	1.0045		0.1
$k_z$	1.0017		0.01
$k_d$	1.0003		0.01
$k_{air}$	1.0000		<0.01
		0.03	0.24
$\dot{D}_g \text{ (Gy h}^{-1}\text{)}$	45.66		0.24

$$\dot{D}_g = \frac{L \cdot F}{m} \cdot r_{cal}^{-1} \cdot k_f \cdot k_v \cdot k_i \cdot k_{gr} \cdot k_{ff} \cdot k_k \cdot k_{et} \cdot k_{fant} \cdot k_z \cdot k_d \cdot k_{air} \quad (1)$$

With :

$F$  : electrical calibration factor

$L$  : relative variation of the thermistor resistance

$m$  : mass of the core

$r_{cal}$  : calorific yield, equivalent to heat defect correction

$k_f$  : correction for difference of thermal transfers between electrical calibration and irradiation

$k_v$  : correction for vacuum gaps

$k_i$  : correction for impurities

$k_{gr}$  : correction for absorbed dose gradient in the core

$k_{ff}$  : correction for the calorimeter front slab

$k_k$  : correction for the front kapton foil

$k_{et}$  : correction for the PMMA back and radial thickness

$k_{fant}$  : correction for density difference between the phantom and the calorimeter

$k_z$  : correction for depth measurement

$k_d$  : correction for source-reference point distance

$k_{air}$  : correction for air attenuation

A typical set of fifteen runs was involved in this experiment. The uncertainties are given for one standard deviation.

A statistical uncertainty better than 0.03 % has been achieved in a cobalt-60 beam of  $0.7 \text{ Gy} \cdot \text{min}^{-1}$  dose rate. In the high-energy photon beams of the Saturne 43, this uncertainty is higher as beam monitoring introduces an irreducible fluctuation. The overall uncertainty of the reference absorbed dose to graphite is 0.24 % in the cobalt-60 beam.

The main component of the uncertainty stems from the vacuum-gaps correction. Its value is estimated at 0.15 % .

The improvement of the absorbed dose to graphite measured by calorimetry depends on the knowledge of the vacuum gaps correction.

#### IV. VACUUM-GAP CORRECTION FACTOR DETERMINATION

The definition for the vacuum gaps correction at BNM-LNHB is quite different from the definition published by BIPM [11]. The distance between the reference point and the entrance surface phantom is kept constant. The vacuum gaps correction factor is defined as the ratio  $R$  of the mean absorbed dose in the core with “vacuum gaps” filled with graphite, to the value with “vacuum gaps” empty.

Measurements or simulations are performed in the same conditions.

##### A. Experimental Determination Based on Diode Measurements

A new experimental determination of that correction has been performed by means of a very small detector inserted in a reproduction of our graphite calorimeter at the centre of the body simulating the core.

The detector is a p-type silicon diode EDE from Scanditronix. Epoxy and build-up cap for medical application were removed. The resulting outside dimensions are 0.4 mm for thickness and 4 mm for diameter.

Two different measurements are done, according to figures 4 and 5, at the reference depth in the graphite phantom. The value of the vacuum gaps correction factor is determined from the ratio of these two measurements. During the experiment gaps were filled with air.

Compared to the ionisation chamber [12, 13], the diode presents a density closer to graphite than air. In addition the perturbation introduced by insulating material is minimised. The symmetry allows the determination of the whole gaps effect (front, back and annular) at the same time. Moreover the small size of the diodes leaves a large amount of graphite in the body simulating the core.

The ionisation current of the diode is measured by a classical ionometric system based on a Keithley 642. No bias voltage is applied to the diode.

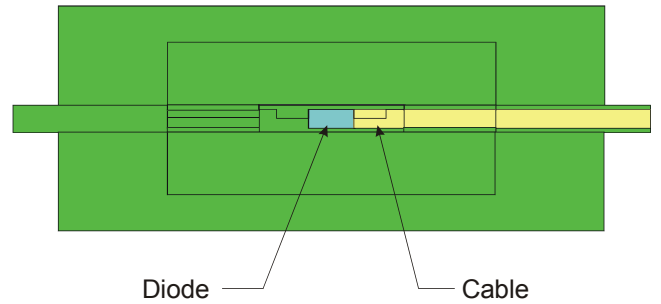


Figure 4: «Vacuum gaps» filled with graphite.

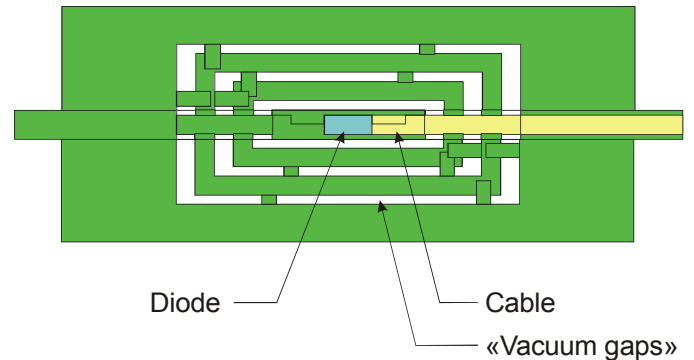


Figure 5: «Vacuum gaps» filled with air.

The copy of the calorimeter is quasi symmetric, and it was irradiated on each side for each configuration.

Measurements were performed in a cobalt-60 beam and high-energy photon beams (6 MV, 12 MV and 25 MV) from the G. E. Saturne 43. The values of the effective attenuation coefficient measured with the diode is different from the one measured with ionisation chambers, especially in the cobalt beam. This is an effect of the diodes hyper-sensitivity to low-energy photons (compared to ionisation chambers) due to the presence of silicium of higher atomic number. The ratio of ionisation currents,  $R$ , is corrected for this difference of effective attenuation coefficient applied to a graphite thickness equal to that of vacuum gaps.

The results are summarised in table 2.

##### B. Monte-Carlo Determination using EGS4-Dosimeter and PENELOPE Codes

For cobalt-60, the photon spectrum in air at the front face of the phantom was measured by gamma spectrometry, replacing the source with an identical one of much lower activity. Both sources had the same geometry and were positioned the same way [14].

For the high-energy photon beams, the spectra were calculated by Monte-Carlo simulation with EGS4 [15] and PENELOPE [16] codes.

The vacuum gaps correction factors were then calculated using EGS4-DOSIMETER [15] and PENELOPE [17].

The results are reported in table 2.

Hundred millions histories were necessary to obtain 0.1 % standard deviation.

Table 2

Vacuum-gaps corrections for graphite calorimeter.

	Co60	6 MV	12 MV	20 MV
$k_v$ (f1)	0.99	0.9917	0.9929	0.9948
$k_v$ (f2)	0.9907	0.9916	0.9924	0.9942
mean experimental $k_v$	0.9903	0.9917	0.9926	0.9945
EGS4 et ITS3 JD 1994	0.9909			
EGS4-dosimeter JG 1999	0.9909	0.9920	0.9929	0.9951
PENELOPE JM 1999		0.9910	0.9923	0.9931
Mean MC $k_v$	0.9909	0.9915	0.9926	0.9941

(f1) face 1 toward the source

(f2) face 2 toward the source

In the cobalt-60 beam, the agreement between the former values and the new simulations is excellent. For high-energy photons, the values obtained with both codes agree within the uncertainties.

### C. Results in a Cobalt-60 Beam and High Energy Photon Beams (6 MV, 12 MV and 25 MV)

The experimental results and Monte-Carlo determinations of the vacuum gaps correction factor are given in table 2. They are consistent for all beam qualities.

## V. REFERENCE ABSORBED DOSE TO WATER

### A. Based on Absorbed Dose to Graphite Standard

The primary standard of absorbed dose to water at BNM-LNHB in cobalt-60 beam and high energies photons from Saturne 43 is based on graphite calorimetry measurements in a graphite phantom. The absorbed dose to water in a water phantom is derived by a transfer procedure using ionisation chambers and Fricke chemical dosimeter [18].

The overall uncertainty is 0.35 % for cobalt-60 and is under evaluation for the other qualities.

### B. Water Calorimeter

In complement to these references, it was decided to develop a water calorimeter.

The principle of the water calorimeter is attractive because the measurement is directly performed in water, the reference material, avoiding the transfer from graphite to water. Moreover the low diffusivity of water allows temperature variation measurement without thermal insulation of the sensitive volume. The delicate determination of the perturbation of the thermal insulating material does not exist (like vacuum gaps for graphite calorimeter).

In practice, there are unfortunately many problems which basically do not exist for graphite calorimeters. The heat defect of water is difficult to control and to determine. At present a realistic evaluation of its uncertainty leads to a value of the same order than the overall uncertainty estimated for the absorbed dose to water derived from the graphite absorbed dose (cf section V.A.). To reduce the convections present in water measurements can be done at 4 °C (and with a vessel). Thermal transfers and heat excesses coming from the vessel containing the purity controlled water have to be thoroughly investigated.

A first probe was built in the laboratory. It is a thermistor bead (0.18 mm in diameter) embedded in a quartz capillary 0.5 mm tube thickness filled by epoxy. The thermistor resistance change is measured with a DC Wheatstone bridge and a nano-voltmeter. We plan to use a lock-in amplifier for measurements.

After some tests at ambient temperature, a thermostatic enclosure was built in order to regulate the water phantom at 4°C. The drift rate obtained with this system is lower 0.5  $\mu$ K/s compared to an irradiation drift of 700  $\mu$ K/s in cobalt-60 beam.

## VI. CONCLUSION

At the present time, graphite calorimetry is for us a well-established technique. The very good reproducibility of the measurements is most likely due to our specific thermal control. Moreover regular experiments with graphite calorimeters as well as TE calorimeters in our laboratory, or even in other laboratories or radiotherapy units, helped us to maintain and improve the technique. In the cobalt-60 beam whose dose rate is about 0.7 Gy/min the typical overall uncertainty on the reference absorbed dose to graphite is 0.24 % for one standard deviation. The precision of the absorbed dose to graphite is confirmed by the new experimental and Monte-Carlo determinations of the correction factor for vacuum gaps which is the main source of uncertainty.

After a period of interest in neutron-therapy (seventies, eighties) and then in proton-therapy (early nineties) where experiments with TE calorimeters have allowed to corroborate protocols (neutron) or to confirm new stopping powers values (proton), these kind of measurements are now rare. But this TE calorimeter is kept operational.

A water calorimeter is being built. It will be operated at 4 °C. This calorimeter will be considered as a metrological complement to measurements based on graphite calorimetry

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## QUESTIONS AND ANSWERS

**Carl Ross:** The BIPM devoted considerable effort to measuring the vacuum gaps. As I remember, they gave a way of getting the correction for different sizes of gaps. How do your numbers compare to theirs?

**Josiane Daures:** Our correction factor is less than 1. Is that your question? The  $k_v$  factor calculated by the BIPM for our calorimeter and for the  $^{60}\text{Co}$  beam of BIPM is 0.5%. When they performed the measurement they put an additional thickness of graphite in front of the calorimeter whose thickness is equal to the vacuum gaps, but in our case we do not add this. The thickness of the three vacuum gaps is about 3.31 mm and we do not add 3mm in front of the phantom so our correction factor is 0.99 and not 1.005. It is not a mistake.

**Alan DuSautoy:** There is a difference of material at the front. Can you say whether or not you get agreement because it is easy to remove this attenuation. Whether or not you have material at the front, you can correct for it. So are you in agreement with the BIPM calculations?

**Josiane Daures:** We are in agreement with the BIPM because if we compare strictly the attenuation and the  $k_v$ ,  $k_v$  is higher than expected if we only take into account the attenuation because when the vacuum gaps are present they induce a leak of scattered photons. We can't simply do with a transmission correction. We agree with the calculation of BIPM. Our calculation, the calculation of BIPM and measurements with the diode are very consistent.

**Alan DuSautoy:** How do you compare with the NPL measurement?

**Josiane Daures:** With the ionisation chamber?

**Alan DuSautoy:** Yes.

**Josiane Daures:** At the time when you published the paper I noticed quite slight differences and I know you tried to calculate it with EGS4. Have you got some results?

**Alan DuSautoy:** The results for then, which was a while ago, were for a compensated mode where you have added the graphite from the gaps at the front. We got 0.5% from ionisation chamber measurements and about 0.7% from the EGS4 calculations - I don't know if that agrees with your results.

**Josiane Daures:** I am not a specialist on Monte Carlo code but J Jeannot in our lab is very able. In 1994 I made some calculations, as a common user of EGS4, and I was very

surprised - the values of J Jeannot are exactly the same as what we have found now. It is quite miraculous!

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**Jan Seuntjens:** The uncertainty on the temperature rise measurement, is this the sample standard deviation on the mean?

**Josiane Daures:** This is the uncertainty for the electrical calibration factor. It is one standard deviation on the mean.

**Jan Seuntjens:** How many measurements are involved?

**Josiane Daures:** About 15. The graphite calorimeter is very precise. This result was for the measurements made in a  $^{60}\text{Co}$  beam. In the linear accelerator the uncertainty is a bit higher but we paid a lot of attention to monitoring because our LINAC is very stable so we can have very a low uncertainty.

**Alan DuSautoy:** This is in dose to graphite?

**Josiane Daures:** Yes.

**Jan Seuntjens:** What is the reason that the standard deviation is low. Is it because of the specific heat capacity of graphite? The temperature rise is much more easily measured?

**Josiane Daures:** We do not have to know the heat capacity of graphite because of the electrical calibration factor.

**Jan Seuntjens:** Yes, but why can you get this uncertainty on 15 measurements when in a water calorimeter we have to make 500 measurements to get this uncertainty. Is it because of the specific heat capacity of graphite?

**Josiane Daures:** The heat capacity? No, because it is only 5 times higher. I think that thermal control for the graphite calorimeter is easier than with water calorimetry. It is because of the thermal control.

**Jan Seuntjens:** It must be the signal because the thermal control of the drift rates in the water calorimeter are very low. It is just the signal which is small in the water calorimeter.

**Tony Aalbers:** Yes, you have stronger signals in the graphite calorimeter.

**Alan DuSautoy:** For the graphite calorimeter at the NPL the absorbed dose to graphite has exactly the same total uncertainty but random uncertainty I believe is slightly higher. So your temperature measurements are very good.

**Josiane Daures:** The feedback on the adjacent body to the core is a very good system.

**Alan DuSautoy:** If you repeat the same measurement exactly the same way you might get a very low random uncertainty but you have got to decide whether that is the right temperature.

**Josiane Daures:** I don't understand.

**Alan DuSautoy:** I'll have to think about that.