Absorbed Dose to Arbitrary Materials

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Abstract

Accurate absorbed doses of ^{60}Co γ radiation were delivered to samples of SiO_2. The work described here can be applied to arbitrary materials with a known elemental composition. The Australian primary standard of absorbed dose is a graphite calorimeter. The absorbed dose to other materials is found using the photon fluence scaling theorem. The Australian standard of absorbed dose to water at ^{60}Co is derived in this way - Agreement with the BIPM reference standard is excellent (0.1%). As aluminium is a reasonable analogue of SiO_2 for radiation interactions at ^{60}Co, a scaled Al phantom was constructed. A bulk sample holder for granular SiO_2 was made from grade 2011 Al (5.5% Cu). A second sample holder with only minor impurities was later made from grade 6060 Al, in which a 10 mm diameter cavity accommodates 51 Al disks, each 0.61 mm thick. Each disk has an indent at the centre, 0.35 mm deep by 1.2 mm diameter, to hold a single grain of SiO_2. The absorbed dose rate to graphite was determined at the scaled distance of 945.62 mm from the ^{60}Co source. The absorbed dose rate to SiO_2 at the reference distance of 650.00 mm was 8.5673 mGy/s, at 12:00 on 20/5/99. A series of nominated absorbed doses was delivered to 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.

1. Introduction

This investigation was prompted by a request from the LaTrobe University Department of Earth Sciences to deliver accurately known absorbed doses of ^{60}Co γ radiation to samples of Silica, SiO_2. Similar work has been done previously for other materials including a silicone rubber matrix with a pill capsule-sized sample cavity. In principle, the process can be applied to arbitrary materials with a known elemental composition.

2. Australian Standard of absorbed dose to graphite

The Australian Radiation Protection And Nuclear Safety Agency (ARPANSA) has been authorised by the Commonwealth Scientific and Industrial Research Organization (CSIRO) to maintain primary and secondary measurement standards for the ionizing radiation dosimetry quantities exposure and absorbed dose. This has been formalized in an Authority issued under the National Measurement Act 1960.

The Australian standard of absorbed dose for ^{60}Co γ radiation is a graphite microcalorimeter [1], which directly measures absorbed dose to graphite.

3. Conversion to absorbed dose to other materials

The absorbed dose to graphite from the microcalorimeter is converted to other materials using the photon fluence scaling theorem (pfst) [2]. This provides a simple conversion protocol to obtain the absorbed dose in one material from the absorbed dose in another. The radiation interactions in the two materials must be predominantly by Compton scattering. This condition is closely satisfied in the photon energy range 0.2 to 20 MV (typically used in external beam radiotherapy), and very closely at ^{60}Co. Only minor corrections are needed for non-Compton interactions, even above 10 MV.

All the phantom dimensions (L) are scaled by the inverse ratio of the electron densities in the two materials:

$$\mathbf{L_2/L_1 = \rho_1/\rho_2 \bullet Z_1/Z_2 \bullet A_2/A_1} \qquad \mathbf{(1)}$$

The scaled dimensions include:

- the distances from the radiation source,
- the depths of the reference points in the two materials,
- the radiation beam field sizes, and
- the physical sizes of the two phantoms.

Under these conditions, the absorbed dose to any material (m) from a point source of radiation is related to the absorbed dose to graphite (g) as measured by the calorimeter by:

$$\mathbf{D_m = D_g \bullet [\ (\mu_{en}/\rho) \bullet \beta \ /\ R^2\ ]_{m,g} \bullet \Pi k_i} \qquad \mathbf{(2)}$$

where μ_{en}/ρ is the mean mass energy absorption coefficient (averaged over the primary photon radiation energy spectrum), β is the absorbed dose to collision kerma ratio, R is the distance from the (point) radiation source to the reference point, $[...]_{m,g}$ denotes the ratio of the expression [...] taken for materials m and g, and Πk_i is the product of minor corrections.

The Australian primary standard of absorbed dose to water at ^{60}Co is derived using (2).

The scaled geometry of the graphite and water phantoms can be seen in Figure 1.

The reference point in graphite (in the calorimeter and in the graphite phantom) is 650 mm from the effective centre of the ^{60}Co source, while the reference point in the water phantom is 1050 mm from the source.

The Australian absorbed dose to water standard has been related to those of other countries by comparison with the reference standard held by the International Bureau of Weights and Measures (BIPM) in Paris [3]. The agreement (0.1%) is well within the uncertainty of the comparison (0.5%), most of which arises from the uncertainty of the BIPM ionometric standard.

4. Aluminium phantom

Ideally, to transfer the absorbed dose to graphite to a sample of material m, an appropriately scaled phantom of material m should be constructed and the sample inserted at the scaled depth as above, leaving only minimal air spaces.

As the construction of a phantom made of SiO_2 was expected to present certain technical difficulties, the suggestion was made [4] that aluminium would be a reasonable analogue.

This was confirmed by a comparison of the radiation interaction coefficients and other physical properties of SiO_2 and Al, as shown in Table 1.

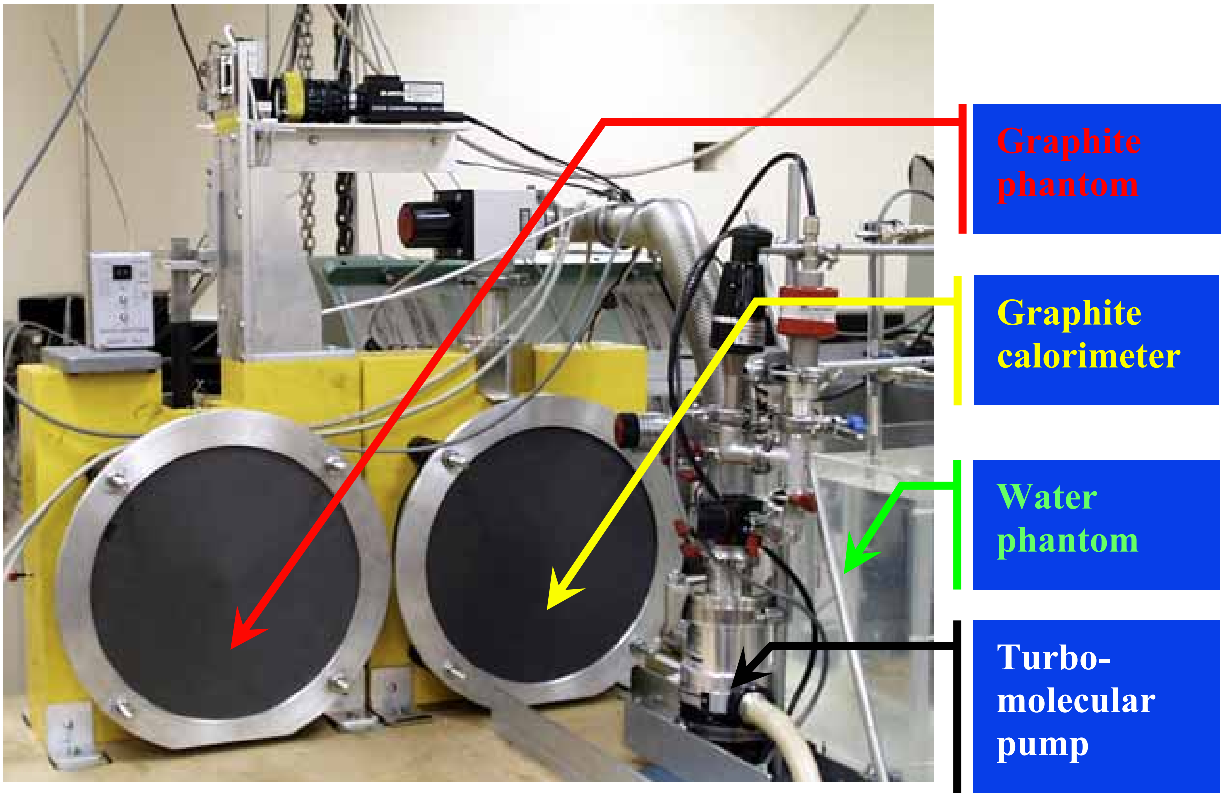

Figure 1. Graphite calorimeter with graphite and water phantoms

Table 1. Physical properties of C, Al, SiO_2 and air
for ^{60}Co, $E\gamma = 1.25$ MeV [5-9]

Property	**C**	**Al**	**SiO_2**	**Air 22°C**
mass density ρ, $g \cdot cm^{-3}$	1.79	2.698	2.65	0.001197
atomic number Z	6	13	30	
atomic weight A	12.01	26.98	60.09	
electron density scaling factor $[\rho Z/A]_{m,g}$	1.0000	1.4548	1.4795	
mass attenuation coefficient μ/ρ, $cm^2 \cdot g^{-1}$			0.0569	0.0598
mass energy absorption coefficient μ_{en}/ρ, $cm^2 \cdot g^{-1}$	0.0267	0.0256	0.0267	
mass electron stopping power s/ρ, $MeV \cdot cm^2 \cdot g^{-1}$	1.6120	1.4837	1.5978	
CSDA [1] electron range, $g \cdot cm^{-2}$	0.6501	0.7231	0.6727	

[1] Continuous Slowing Down Approximation

It is clear from Table 1 that the electron density scaling factors of Al and SiO_2 relative to graphite are similar. Furthermore, the mass density, the mass energy absorption coefficients, the mass electron stopping powers and the CSDA electron ranges in Al and SiO_2 are also similar. Therefore, a scaled Al phantom should produce a similar radiation spectrum in the SiO_2 sample to that which would be achieved in a solid SiO_2 phantom. Accordingly, a scaled aluminium phantom was constructed.

The Al phantom was scaled to the graphite phantom. Both are right circular cylinders irradiated axially, with a diametrical cylindrical sample holder parallel to the incident face. The dimensions are shown in Table 2.

Table 2. Graphite and Aluminium phantom dimensions

Dimensions in mm	graphite	aluminium
diameter	300.0	206.2
length	195.0	134.0
sample holder axis from front face	30.0	20.6
sample holder diameter	21.9	15.1

The Al 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 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. The copper impurity and the unavoidable air spaces between the grains of SiO_2 contribute significantly to the assessed uncertainty in the dose delivered to each grain.

Later, a second sample holder was 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%. The second sample holder has a cavity 10 mm diameter and 31 mm long, which 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 SiO_2. The disks are stacked in the cavity, leaving virtually no air spaces.

5. Experimental procedure

The absorbed dose rate to graphite was measured using a calibrated secondary standard ionisation chamber (type NE2611A #152), in the graphite phantom, at a distance of 945.30 mm from the effective centre of the ARPANSA ^{60}Co teletherapy source. The measurements were corrected to the scaled graphite reference distance of 945.62 mm by the inverse square law.

The Al phantom was set up close to the scaled reference distance of 650.00 mm. The front face was perpendicular to the gamma ray beam axis and was centred on a reference laser beam that defines a line within 3 mm of the beam axis. The actual distance of the Al phantom from the source was measured before each exposure. An inverse square law correction was made, in addition to radioactive source decay (half life 1925.5 days), to evaluate the required exposure time for the desired absorbed dose. The radial non-uniformity of the gamma ray beam will be measured so that corrections may be applied retrospectively.

The exposure time of the ARPANSA ^{60}Co source is controlled by an hp86 computer system with an uncertainty of 1 ms. The radiation source transit time correction of 11 ± 8 ms was negligible compared with the required exposure times.

An air attenuation correction (k_{air}) was applied when evaluating the absorbed dose rate to SiO_2 (at the Al reference distance) from the measured absorbed dose rate at the graphite reference distance. A correction (k_{pfst}) was applied to account for deficiencies in satisfying the conditions of the photon fluence scaling theorem.

The absorbed dose rate to SiO_2 at the reference conditions (d_{ref} = 650.00 mm, at 12:00 on 20/5/99) was 8.5673 mGy/s.

6. Uncertainties

The values and uncertainties u_j of the factors in equation (2) are shown in Table 3. These are expressed as percentage relative standard uncertainties of Type B, as described by the ISO [10].

Table 3. Percentage relative standard uncertainties

Factor	**Value**	**u_j for holder #**	
		1	**2**
Measurement of D_g			
secondary standard calibration N_c	91.99 mGy/nC	0.17	
current measurement I_m (typical)	43.883 pA	0.03	
decay correction k_t	various	0.01	
ambient correction $k_T.k_P.k_H$	various	0.03	
distance correction k_d	various	0.01	
saturation correction k_s	1.0014	0.03	
depth correction k_z	1.0000	0.01	
beam profile correction k_{rn} (at $_gd_{ref}$)	1.0000	0.01	
Conversion to D_m ($m=SiO_2$)			
$(\mu_{en}/\rho)_{m,g}$	1.0000	0.04	
$\beta_{m,g}$	1.0000	0.00	
$(R_{m,g})^{-2}$	2.1164	0.04	
k_{air}	1.00205	0.05	
k_{pfst}	1.0000	1.0	0.1
beam profile correction k_{rn} (at $_md_{ref}$) [1]	1.0000	0.05	0.02
beam axial gradient correction k_{an} (at $_md_{ref}$)	1.0000	0.05	0.00
exposure time for 20 Gy (typical)	2334.5 s	0.0003	
Combined percentage standard relative uncertainty in D_m		1.0	0.22

[1] Beam profile correction to be applied to each grain separately for sample holder #2. A mean value could be applied for sample holder #1.

7. Conclusions

A prescribed absorbed dose was delivered to SiO_2 grains, traceable to the Australian standard of absorbed dose, with a combined standard relative 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.

8. References

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Discussion

Heather Chen-Mayer – Do the thermal properties of these various materials do they come into play at all?

Robert Huntley – Thermal properties, no.

Malcolm McEwen – How accurate was the need for the dose?

Robert Huntley – As good as we could get. Initially one percent I think was mooted, but we did considerably better than that and they were quite pleased. They were looking for a small effect.

John Boas – A bit on the background. What the problem is, it was a question of being able to date very accurately, quartz grains, because there's this argument which has certainly raged in Australia about when did man arrive in Australia, and what the dates were which various parts of the continent were inhabited. And there’s the connection with what appears to have been a fairly significant climate change and the extinction of what’s called Australian megafauna, very large flightless birds and things like that at around, now, 46000 years ago. (They) suddenly disappeared and the question is whether that was due to the influence of man or just straight climate change. And the approach was made by the chap (who’s) really doing a combination of thermoluminescence and optically stimulated luminescence dating, and this difference led us to the question of the composition of the reference radiation, whether it’s mainly gammas, mainly betas, (or a) combination of both, complicated their analysis, that’s why they wanted very accurate dosimetry of the gamma rays.