FROM THE DEPARTMENT OF RADIATION PHYSICS, UNIVERSITY OF UMEÅ, S-901 85 UMEÅ, AND THE DEPARTMENT OF RADIATION PHYSICS, KAROLINSKA INSTITUTET, S-104 01 STOCKHOLM, SWEDEN.

FERROUS SULPHATE DOSIMETRY FOR ELECTRONS

A re-evaluation

H. SVENSSON and A. BRAHME

The ferrous sulphate dosimeter is often used as a reference dosimeter when careful absorbed dose measurements are to be carried out especially in electron beams. It is therefore very unsatisfactory that the uncertainty in the *G*-value recommended by the ICRU report No. 21 for electron radiation, is as large as 4 per cent. Recent investigations (EGGERMONT et coll. 1978) also indicate that the majority of the molar extinction coefficients used in experiments for *G*-value determination probably are 1 to 2 per cent too high. Furthermore, most *G*-values are determined without considering the perturbation effect introduced when the absorber of a calorimeter is replaced by the ferrous sulphate dosimeter. Finally, the reliability of the *G*-values determined by ionization chamber dosimetry must be doubted, as they in the past were based on insufficient knowledge of the cavity theory for electrons due to large uncertainties in stopping power ratios and perturbation corrections. Therefore, a re-evaluation of the ferrous sulphate dosimetry seems necessary. The present report is mainly concerned with electron dosimetry, but most of the discussions apply equally well to photons.

Absorbed dose to the ferrous sulphate dosimeter

The mean absorbed dose, $\bar{D}_1$, to the ferrous sulphate dosimeter is obtained from the change in absorbance in optical density units by the relation

---

Submitted for publication 15 February 1979.

$$\bar{D}_1 = \frac{A}{l\varrho\varepsilon_m G} \qquad (1)$$

where

A is the net absorbance in optical density units at 304 nm,
l is the length of light path in the photometer cell in cm,
ϱ is the density of the dosimeter solution in $g \cdot cm^{-3}$,
ε_m is the molar extinction coefficient in $l \cdot mol^{-1} \cdot cm^{-1}$, and
G is the ferric ion yield in $\mu mol\ kg^{-1}\ Gy^{-1}$ (G in ferric ions per 100 eV is obtained by multiplication with 9.649 $\mu mol^{-1}\ kg\ Gy$).

The molar extinction coefficient for a spectrophotometer cell of length l is determined from $\varepsilon_m = A/(C \cdot l)$, where C (in $mol \cdot l^{-1}$) is the concentration of Fe^{3+} in a reference solution of 0.4 $mol \cdot l^{-1}$ sulfuric acid and A is the net absorbance in optical density units determined as the difference with and without this ferric concentration.

Large differences in ε_m have been reported with values in the range 2 057 to 2 343 $l \cdot mol^{-1}\ cm^{-1}$ at 25.0°C (BRYANT & RIDLER 1968, BROSZKIEWICZ & BULHAK 1970) but those differences seem only to a minor part depend on the spectrophotometers as it has been shown that high performance spectrophotometers with cells agree within 1 per cent (PETTERSSON & HETTINGER 1967, BRYANT & RIDLER, SHARLEK & SMITH 1969, LAW & SVENSSON 1973, EGGERMONT et coll.). A recent careful intercomparison at three laboratories, all using modern high performance spectrophotometers, gave a still better agreement: ± 0.1 per cent when both the uncertainties in absorbance scale and cell length were included (MATTSSON, personal communication).

EGGERMONT et coll. have in detail analysed the reasons for the spread in published ε_m. They pointed out that using Fe^{3+} compounds in the reference solution an error of 2 to 3 per cent may arise due to water in the compounds and in a procedure with oxidation of metallic iron by H_2O_2 a systematic error may be introduced due to absorbance from residual H_2O_2. EGGERMONT et coll., who have considered these effects, obtained in a first series of measurements $\varepsilon_m = 2\,164 \pm 9$ $l\ mol^{-1}\ cm^{-1}$, a value which later was changed to $\varepsilon_m = 2\,174$ when using Fe^{3+} from a different manufacturer. These values are significantly lower than the mean value $\varepsilon_m = 2\,205$ $l\ mol^{-1}\ cm^{-1}$, suggested for use by the ICRU based on the review of 83 determinations by BROSZKIEWICZ & BULHAK. The spectrophotometer and cell used by EGGERMONT et coll. was included in the investigation by MATTSSON, and should therefore give a representative ε_m-value for a high performance instrument.

In most G-value investigations the ε_m-value has been measured with the same spectrophotometer and cell that later are used in the G-value determination. The ε_m-values used in these experiments may thus be systematically too high and the spread larger than what should be expected from instrument and cell differences. These uncertainties will directly influence the G-values. However, systematic errors in determining ε_m will cancel out if $\varepsilon_m \cdot G$ is reported (Table). It is thus accepted that the differences between the spectrophotometer facilities contribute less to the spread in ε_m-values than the individual ε_m-measurements.

Table

G-values determined from calorimetric measurements and reported in ICRU report No. 21 (1972) are given together with preliminary results by COTTENS *(1979). Corrections for different scattering properties in the calorimetric absorber and the dosimeter solution were carried out using eq. (6). Both uncorrected (u.-c.) G-values as reported by the authors and corrected values (c.) are given together with corresponding $\varepsilon_m G$*

Reference	Initial energy	Method	ε_m 1 mol^{-1} cm^{-1}	G μmol kg^{-1} Gy^{-1}		$\varepsilon_m G$ 1 cm^{-1} kg^{-1} Gy^{-1}	
	(MeV)		at 25°C	u.-c.	c.	u.-c.	c.
SCHULER & ALLEN (1956)	2	Charge input	2 194	1.601	same	3 512	same
COTTENS (1979)	9	Graphite	2 174	1.620	same	3 522	same
GIESSELSODER et coll. (1963)	10	Graphite cal.	2 200	1.588	1.599	3 492	3 517
ALMOND (1956)	13.3	Al cal.	2 177	1.601	1.620	3 485	3 527
ANDERSSON (1962)	15	Liquid absorber cal.	2 225	1.575	same	3 504	same
ALMOND (1967)	15.9	Al cal.	2 177	1.596	1.612	3 475	3 509
COTTENS (1979)	17	Graphite cal.	2 174	1.628	same	3 539	same
ALMOND (1967)	18	Al cal.	2 177	1.591	1.604	3 463	3 492
GIESSELSODER et coll. (1963)	20	Graphite cal.	2 200	1.572	1.577	3 458	3 469
PINKERTON (1969)	20	Graphite cal.	2 200	1.607	1.611	3 535	3 544
ALMOND (1967)	24	Al cal.	2 177	1.587	1.596	3 454	3 474
COTTENS (1979)	27	Graphite cal.	2 174	1.625	same	3 533	same
PETTERSSON (1967)	33	Water cal.	2 196	1.613	same	3 542	same
Mean value				1.601	1.607	3 502	3 515
Standard deviation, δ				0.018	0.017	31	24
Standard error of the mean, S_m						9	7

Calorimetric determination of *G*-values

In the calorimetric determination of *G*-values a common procedure is to replace the absorber by a ferrous sulphate dosimeter. The absorber is often of uniform graphite placed in the graphite body of the calorimeter. The mean absorbed dose in the calorimeter absorber in the uniform calorimeter medium, $\bar{D}_m$, is related to the mean absorber dose in the dosimeter, $\bar{D}_i$, by

$$\bar{D}_m = \bar{D}_i s_{m,i} p_{m,i} \qquad (2)$$

In published *G*-values the stopping power ratio $s_{m,i}$ is generally considered but perturbation correction, $p_{m,i}$, seems to be disregarded since a general expression for

$p_{m,i}$ is not available. Both $s_{m,i}$ and $p_{m,i}$ are discussed in detail in the following in order to make a critical analysis of published values of $\varepsilon_m \cdot G$ possible.

In the present context the interest is mainly focussed upon dosimeters which are much larger than the build-up and build-down depths of the secondary electron spectrum which usually are in the order of a few mg cm^{-2} (HARDER 1964a). This means that interface phenomena at the borders between materials (cf. BERTILSSON 1975) have been disregarded here.

The electron fluence in a non-medium equivalent dosimeter inserted in a medium will generally differ with regard to its energy, angular and spatial distribution from the fluence through an identical volume in a uniform unperturbed medium. This fact must be considered in the evaluation of $s_{m,i}$ and $p_{m,i}$.

The stopping power ratio, $s_{m,i}$ under assumption of secondary electron equilibrium and a linear variation of the stopping-power with energy (HARDER 1964b) should be calculated for different energy values if the mean energy in the dosimeter and in the medium do not coincide. The mean electron energy of the dosimeter ($\bar{E}_i$) is related to the mean energy in the medium ($\bar{E}_m$) at the effective point of measurement at a depth d below the front surface of the dosimeter by the relation:

$$\bar{E}_i = \bar{E}_m + (S_{tot,i} - S_{tot,m})d \tag{3}$$

It is assumed that the dosimeter is broad, so electrons scattered in from the medium have a small influence on the electron fluence in the dosimeter. An expression for the depth, d, of the effective point of measurement is derived in the appendix (eq. 22).

The stopping power ratio to be used to multiply the absorbed dose to the dosimeter in order to obtain the absorbed dose to the medium is therefore obtained from:

$$s_{m,i} = \frac{S_{col,m}(\bar{E}_m)}{S_{col,i}(\bar{E}_i)} \tag{4}$$

For high energies this stopping power ratio does not differ much from the stopping-power ratio at the mean electron energy in the medium, $\bar{E}_m$, since the collisional stopping power varies rather slowly with energy.

The most important fluence correction is therefore normally due to the changes in the spatial and angular electron fluence. These changes may be evaluated by calculating the mean tracklength of primary electrons in the dosimeter and compare it with that of a medium equivalent dosimeter. From the analysis in the appendix, eq. (18), the ratio of the mean tracklengths of primary electrons in the medium to that in the dosimeter for a cylindric detector volume of height H and radius R, with the front surface parallel to the surface of the medium, can, for fairly small depths and scattering angles, be written:

$$\frac{t_m}{t_i} = p_{m,i} = 1 - \frac{(T_i - T_m)\mathrm{H}}{4}\left(1 - \frac{\mathrm{H}^2}{3(\mathrm{e}-1)\mathrm{R}^2}\right) \tag{5}$$

where T is the linear scattering power (mass scattering power multiplied by density, BRAHME 1972, ICRU 1972). It is of interest to see how the two fundamentally different perturbation phenomena (HARDER 1973) appear in a practical situation. The figure 1 in the large parenthesis of eq. (5) represents the obliquity effect and the remainder the inscattering from the medium.

Eq. (5) can thus for flat dosimeters (H < R) be approximated further by

$$p_{m,1} = 1 - \frac{(T_1 - T_m)H}{4} \tag{6}$$

which is the perturbation correction factor used for correction of the G-values obtained with the graphite and aluminium calorimeters discussed in the Table.

Result and Discussion

Good agreement is obtained in the calorimetrically determined $\varepsilon_m \cdot G$-values (Table). The mean value is 3 515 l·cm^{-1}·kg^{-1}·Gy^{-1} with a standard deviation of $\sigma = 0.7$ per cent and a standard error of the mean of $S_m = 0.2$ per cent. The perturbation effect has a minor influence on the mean value. The individual $\varepsilon_m \cdot G$-values are here corrected for differences in scattering in the calometric absorber and the dosimetric solution used. The G-value would be 1.594 μmol·kg^{-1}·Gy^{-1} (15.38 ferric ions per 100 eV) if a standard extinction coefficient of 2 205 l·mol^{-1}·cm^{-1} is used as suggested in ICRU report No. 21. This G-value is very different from 1.63 μmol kg^{-1}·Gy (15.7 ions per 100 eV) as recommended in the ICRU report.

A group in Ghent (EGGERMONT et coll., COTTENS 1979) have just finished a series of G-value measurements with a graphite calorimeter at 9, 17 and 27 MeV (energy at phantom surface). They used a slightly different geometric position for the centre of the calorimetric absorber and the centre of the ferrous sulphate dosimeter, as they had the same amount of material in g·cm^{-2} to the centres of the absorber and of the liquid layer. By doing this geometric correction and by using different thicknesses of their dosimeters, they could prove that the scattering correction was no longer necessary. They determined a mean G-value of 1.627 μmol kg^{-1} Gy^{-1} (15.70 ions per 100 eV) with an insignificant difference between the three beam energies. The mean energy at the point of measurement varied between about 4 and 18 MeV. According to these results, and also to the experimental data in the Table, no significant energy dependence of the G-value exists. A further proof for the a very small energy dependence is that both PETTERSSON (1967) and PINKERTON (1969) obtained within 0.4 per cent the same G-value for a ^{60}Co γ beam and a high energy electron beam.

The uncertainties in determination of the G-values with the ionization chamber method is much larger than with careful calorimetric measurements. The reason is that a large uncertainty is introduced in the stopping power ratio water/air. However, the ICRU has in report No. 21 obviously also considered ionization chamber G-values in their recommendation of $G \doteq 1.63$ μmol kg^{-1} Gy^{-1}. Ionization chamber based G-values referred to in report No. 21 (i.e. MINDER 1961, LIESEM & POHLIT 1962) are between 1.63 and 1.69 μmol kg^{-1} Gy^{-1}, i.e. is several per cent higher than those measured with calorimeters (Table). However, more recent measurements do not indicate a discrepancy in calorimetric and ionization measurements. Thus, SVENSSON (1971) used the ferrous sulphate dosimeter with $\varepsilon_m \cdot G = 3\,542\ \mathrm{l \cdot cm^{-1} \cdot kg \cdot Gy^{-1}}$ (the same spectrophotometer facility as used by PETTERSSON in his determination of G-value, Table) to investigate C_E for phantom surface electron energies, $E_p(0)$, 10 to 30 MeV and for different phantom depths. His results agree, within 0.4 or 0.8 per cent dependenting on the choice of mean excitation energy, with theoretic C_E-values (BERGER et coll. 1975). This result is equivalent of stating that the ionization chamber measurements based on stopping power ratios from BERGER et coll. would give approximately $\varepsilon_m \cdot G = 3\,542\ \mathrm{l \cdot cm^{-1}\ kg^{-1}\ Gy^{-1}}$ ($G = 1.613\ \mu\mathrm{mol\ kg^{-1}\ Gy^{-1}}$). A similar investigation was carried out by ELLIS (1974), who also found a very good agreement between ionization chamber dosimetry based on C_E-values from ICRU report No. 21, and ferrous sulphate dosimeter measurements using $\varepsilon_m \cdot G = 3\,510\ \mathrm{l\ cm^{-1}\ kg^{-1}\ Gy^{-1}}$ ($G = 1.606\ \mu\mathrm{mol\ kg^{-1}\ Gy^{-1}}$). NAHUM & GREENING (1978) re-evaluated the ionization chamber determined G-values by LAW & NAYLOR (1972). They obtained G between 1.56 and 1.62 $\mu\mathrm{mol\ kg^{-1}\ Gy^{-1}}$ for $E_p(0)$ between 6 and 35 MeV, when they took into consideration the wall material composition of the ionization chamber. Finally, MARKUS (1978) made a series of measurements for $E_p(0)$ between 5 and 15 MeV, that indicated consistency between ionization chamber and ferrous sulphate dosimetry if $\varepsilon_m \cdot G = 3\,589\ \mathrm{l \cdot cm^{-1}\ kg^{-1}\ Gy^{-1}}$ ($G = 1.63\ \mu\mathrm{mol\ kg^{-1}\ Gy^{-1}}$).

Conclusions. (1) Some of the spread in published G-values most probably depends on systematic errors in ε_m determinations, (2) the spread in calorimetrically determined $\varepsilon_m \cdot G$ is small, especially if the scattering effect is considered ($S_m = 0.2\,\%$), (3) the best value of $\varepsilon_m \cdot G$ is $3.515 \cdot 10^3\ \mathrm{l \cdot cm^{-1}\ Gy^{-1}}$, which is obtained from calorimetric measurements but also agree well with most of the recent ionization chamber measurements. This value is 2.3 per cent lower than the value recommended by the ICRU in report No. 21, and the energy $E_p(0)$ dependence from a few MeV up to more than 30 MeV is insignificant.

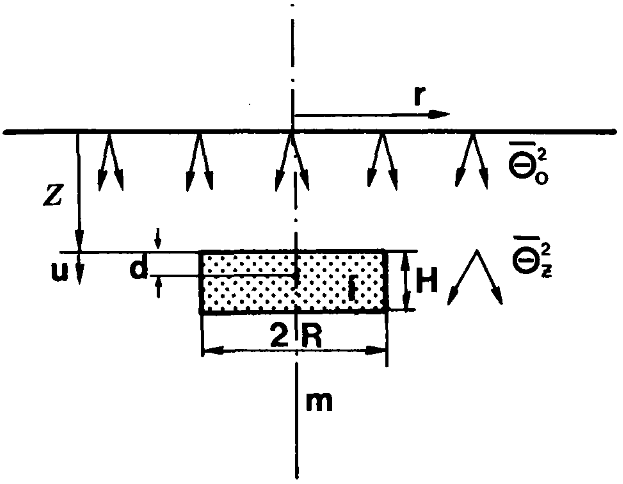
Appendix

The simple Fermi-Eyges theory of multiple scattering (FERMI 1941, EYGES 1948, BRAHME 1975) is used for calculating the mean tracklengths for a cylindric detector of radius R and height H placed with its front surface parallel to the surface of the medium at a depth z (cf. Figure).

The electron beam is asumed to be broad, uniform and of normal incidence with a gaussian angular distribution at each point in the beam specified by the mean square scattering angle $\overline{\theta_0^2}$. Furthermore, it is assumed that the detector is placed at a depth where the mean square scattering angle still increases linearly with depth. The detector should thus not be placed deeper than about one tenth of the electron range beyond dose maximum. When this condition is fulfilled the angular spread of the electrons at the front surface of the dosimeter is given by:

$$\overline{\theta_z^2} = \overline{\theta_0^2} + T_{m,0}\, z \tag{7}$$

where $T_{m,0}$ is the linear scattering power of the medium at the phantom surface. In or-



The irradiation geometry in the evaluation of the perturbation correction factor $p_{m,i}$ for a small cylindric dosimeter instrument (i) inside uniform medium (m). The effective point of measurement of the dosimeter is placed at a depth d (eq. 22) below the front surface of the dosimeter.

der to simplify calculations that part of the electron beam which hits the dosimeter can be assumed to have a gaussian radial fluence distribution with a root mean square radius equal to the radius of the dosimeter. The electron fluence differential in space and angle which hits the dosimeter may thus be written

$$\Phi(r,\theta,z) = \frac{\exp\left(\frac{-r^2}{R^2}\right)}{\pi R^2} \cdot \frac{\exp\left(\frac{-\theta^2}{\overline{\theta_z^2}}\right)}{\pi \overline{\theta_z^2}} \tag{8}$$

If it is now assumed that for this part of the electron beam the dosimeter is surrounded by the same material as in the dosimeter, the purely radial fluence at a depth $z+u$ in the dosimeter becomes:

$$\Phi(r, z+u) = \frac{\exp\left\{\frac{-r^2}{\overline{R_u^2}}\right\}}{\pi \overline{R_u^2}} \tag{9}$$

$$\text{where } \overline{R_u^2} = R^2 + \overline{\theta_z^2}\, u^2 + \frac{T_i u^3}{3} \tag{10}$$

and T_i is the linear scattering power of the dosimeter instrument at the energy $\bar{E}_i$ eq. (3).

The fraction, $f_i(u)$ of this beam which still is inside the dosimeter at a depth u below the front surface of the dosimeter can now easily be determined by integrating eq. (9) from the axis out to R:

$$f_i(u) = \frac{\int_0^R \Phi(r, z+u)\, 2\pi r\, dr}{\int_0^R \Phi(r, z)\, 2\pi r\, dr} = \frac{1 - \exp\left\{\frac{-R^2}{\overline{R_u^2}}\right\}}{1 - e^{-1}} \tag{11}$$

This is a simple analytic expression for the fraction of the electrons which enters the dosimeter, on its front surface and stays in it to deposit energy.

The second part of the incident electron beam is obtained by subtracting eq. (8) from the open beam giving a broad beam with a gaussian depression in the centre. The fraction of this hollow beam which will be scattered into the dosimeter at a depth u below its front surface, $g_m(u)$ can be determined if it is assumed that the dosimeter is made of the same material as the surrounding medium. In analogy to eq. (9) this fraction becomes simply

$$g_m(u) = 1 - f_m(u) \tag{12}$$

By adding eqs (11) and (12) a simple expression for total number of electrons in the dosimeter at a depth u behind its front surface is obtained. Even if this expression contains the essential properties of the fluence perturbation it should be pointed out that it is derived under several simplifying assumptions. The most important approximation is that the cylindric beam incident on the dosimeter is approximated by a bell-shaped gaussian beam. This results in an overestimation in eq. (12) both as a cylindric beam would lose electrons somewhat faster due to its higher fraction of electrons close to the boundary and as some electrons in the gaussian beam starting outside the dosimeter may be scattered into it. These errors compensate each other when the dosimeter and the medium are of similar composition. The error can be estimated by changing $\overline{R_0^2}$ from the used value R^2. The error in the resultant perturbation correction should on these grounds be less than 10 per cent.

The fraction of the electrons which enters the dosimeter within the depth interval du at the depth u is obtained from eq. (12)

$$\mathrm{d}g_m(u) = -f'_m(u)\,\mathrm{d}u \tag{13}$$

The mean path length, $\bar{t}_i$, in the detector due to electrons that enter the detector and are not lost to the medium and to electrons that are scattered into the detector from the medium thus becomes:

$$\bar{t}_i = \bar{t}_i(\mathrm{H}) + \int_0^{\mathrm{H}} \{\bar{t}_i(\mathrm{H}) - \bar{t}_i(u)\}\, f'_i(u)\,\mathrm{d}u \int_0^{\mathrm{H}} \bar{t}_i(\mathrm{H}-u)\, f'_m(u)\,\mathrm{d}u \tag{14}$$

where

$$\bar{t}_i(u) = u\left(1 + \frac{\overline{\theta_z^2}}{2} + \frac{T_i u}{4}\right) \tag{15}$$

is the mean path length in uniform dosimeter material of thickness u (Yang 1951, Brahme 1975) and

$$t_i(\mathrm{H}-u) = \left\{1 + \frac{\overline{\theta_z^2} + T_m u}{2} + \frac{T_i(\mathrm{H}-u)}{4}\right\} \tag{16}$$

is the mean path length of electrons entering uniform dosimeter material at a depth u and staying in it to the depth H. Eq. (14) can be evaluated by inserting eqs (15) and (16) and after partial integration also eqs (11) and (12). If it is assumed that the root mean square radial deflection in dosimeter and medium is small compared to the detector radius or more precisely if $\overline{\theta_z^2}\mathrm{H}^2 + T\mathrm{H}^3/3 < \mathrm{R}^2$, the mean path length can be expanded in a simple power series:

$$\bar{t}_i = \mathrm{H}\left\{1 + \frac{\overline{\theta_z^2}}{2} + \frac{T_i \mathrm{H}}{4} + \frac{(T_m - T_i)\,\mathrm{H}^3}{12(\mathrm{e}-1)\,\mathrm{R}^2}\left[1 + \frac{3}{2}\overline{\theta_z^2} + \frac{\mathrm{H}}{10}(3T_m + 4T_i) + \ldots\right]\right\} \tag{17}$$

The ratio of the mean electron path length or mean electron fluence in the dosimeter volume to that in a volume of identical shape and position in uniform medium can now be obtained from eqs (17) and (15) with $u = \mathrm{H}$ and $\mathrm{i} = \mathrm{m}$:

$$\frac{1}{p_{\mathrm{m,i}}} = \frac{\bar{t}_\mathrm{i}}{\bar{t}_\mathrm{m}} = 1 + (T_\mathrm{i} - T_\mathrm{m})\frac{\mathrm{H}}{4}\left\{1 - \frac{\mathrm{H}^2(1 + \overline{\theta_z^2} + (T_\mathrm{m} + 8T_\mathrm{i})\,\mathrm{H}/10)}{3\mathrm{R}^2(\mathrm{e}-1)} - \frac{\overline{\theta_z^2}}{2} - \frac{T_\mathrm{m}\mathrm{H}}{4}\ldots\right\} \tag{18}$$

When all angular deflections are small compared to unity it is possible to make the perturbation correction $p_{\mathrm{m,i}}$ unity in a non-trivial way by selecting the appropriate ratio of cylinder height and radius:

$$\frac{\mathrm{H}}{\mathrm{R}} = (3(\mathrm{e}-1))^{1/2} = 2.27 \tag{19}$$

The detector should thus be slightly higher than its diameter. The trivial way to obtain a small perturbation is either by using a very narrow dosimeter or a medium equivalent dosimeter with regard to the linear scattering power. It is interesting that the technique mentioned easily could be generalized to a more complicated cylindric geometry, for example that due to the many cylindric isolation cavities around the central absorber.

Eq. (18) can be evaluated in a completely different way if instead of asking how big the perturbation is, wording the question, at which point in the uniform medium is the fluence equal to the mean fluence in the dosimeter. The fluence at a depth d below the front surface of the dosimeter in uniform medium can in the first approximation (BRAHME 1975) be written:

$$\Phi_\mathrm{m}(z+d) = 1 + \frac{\overline{\theta_z^2}}{2} + \frac{T_\mathrm{m}d}{2} \tag{20}$$

The mean fluence in the dosimeter is obtained by dividing the total path length with the volume or by dividing the mean path length by the cylinder height, in the present geometry:

$$\bar{\Phi}_\mathrm{i} = 1 + \frac{\overline{\theta_z^2}}{2} + \frac{T_\mathrm{i}\mathrm{H}}{4} + \frac{T_\mathrm{m} - T_\mathrm{i}\mathrm{H}^3}{12(\mathrm{e}-1)\,\mathrm{R}^2}\left[1 + \frac{3}{2}\overline{\theta_z^2} + \frac{\mathrm{H}}{10}(3T_\mathrm{m} + 4T_\mathrm{i})\ldots\right] \tag{21}$$

The depth of the effective point of measurement below the front surface of the dosimeter is obtained by setting $\bar{\Phi}_\mathrm{i} \equiv \Phi_\mathrm{m}(z+d)$ in order to determine d. The result becomes

$$\frac{d}{\mathrm{H}} = \mathrm{a} - \left(\mathrm{a} - \frac{1}{2} + \frac{5}{6}\overline{\theta_z^2}\right)\frac{T_\mathrm{m}}{T_\mathrm{i}} \tag{22}$$

where

$$a = \frac{\mathrm{H}^2(1 - \overline{\theta_z^2}/6)}{6\mathrm{R}^2(\mathrm{e}-1)} \tag{23}$$

Again it is observed that for a beam of negligible angular spread ($\overline{\theta_z^2} \ll 1$) the factor in front of the linear scattering power ratio is zero when eq. (19) is fulfilled and thus $d = \mathrm{H}/2$. For a well designed cylindric dosimeter the effective point of measurement is thus at the centre of the cylinder independent of the depth, at least in the first approximation.

Of special interest is that for the present geometry and approximations the perturbation of the electron fluence can either be taken into account by using a perturbation correction factor or by using an effective point of measurement.

Acknowledgements

The authors would like to thank Mr E. Cottens for giving details of his work and for allowing them to quote unpublished data. This investigation was supported by grants from the Swedish Cancer Society.

SUMMARY

A theory was developed for the perturbation correction to be applied in the calorimetric determination of the ferrous sulphate dosimeter G-value. Recent determinations of the molar extinction coefficient, ε_m, have shown that systematic errors in ε_m may have influenced experimental G-values. With precision spectrophotometers this error is cancelled in the product $\varepsilon_m \cdot G$. It was shown that after applying the perturbation correction a very small spread was obtained in calorimetric $\varepsilon_m \cdot G$-values; the standard error of the mean being 0.2 per cent. The mean G-value is 2.3 per cent lower than that recommended in ICRU Report No. 21.

ZUSAMMENFASSUNG

Eine Theorie wurde entwickelt, um die Störung zu korrigieren, anwendbar bei der kalorimetrischen Bestimmung des Eisensulfatdosimeter G-Wertes. Neuere Bestimmungen des molaren Extinktions-Koeffizienten ε_m haben gezeigt, dass systematische Fehler im ε_m die experimentellen G-Werte beeinflussen können. Mit Präzisions-Spektrophotometern kann dieser Fehler im Produkt von $\varepsilon_m \cdot G$ verhindert werden. Es wurde gezeigt, dass nach Anwendung der Korrektiven für die Störung eine sehr kleine Streuung bei den kalorimetrischen $\varepsilon_m \cdot G$-Werten erhalten wurde; der Standard-Fehler des Mittelwertes betrug 0,2 Prozent. Der mittlere G-Wert ist 2,3 Prozent niedriger als der im ICRU Rapport Nr 21 rekommendierte.

RÉSUMÉ

Les auteurs ont mis au point une théorie pour la correction de perturbation à appliquer dans la mesure calorimétrique de la valeur G du dosimètre à sulfate ferreux. Des récentes mesures du coefficient d'extinction molaire ε_m, ont montré que les erreurs systématiques sur les ε_m peuvent avoir influencé les valeurs expérimentales G. Avec les spectrophotomètres de précision cette erreur disparaît dans le produit des $\varepsilon_m \cdot G$. Les auteurs montrent qu'après application de la correction pour la perturbation on obtient une très petite dispersion dans les mesures calorimétriques des $\varepsilon_m \cdot G$; l'erreur standard de la moyenne est de 0,2 pour-cent. La valeur moyenne de G est de 2,3 pour-cent inférieure à celle qui est recommandée dans le rapport N° 21 de l'ICRU.

REFERENCES

Almond P. R.: The physical measurement of electron beams from 6 to 8 MeV. Absorbed dose and energy calibration. Phys. in Med. Biol. 12 (1967), 13.

Andersson A. R.: A calorimetric determination of the oxidation yield of the Fricke dosimeter at high dose rates of electrons. J. Phys. Chem. 66 (1962), 180.

Berger M. J., Seltzer S. M., Domen S. R. and Lamperti P. J.: Stopping-power ratios for electron dosimetry with ionization chambers. *In*: Biological dosimetry, p. 594. IAEA-SM-193139 (1975).

Bertilsson G.: Electron scattering effects on absorbed dose measurements with LiF-dosimeters. Thesis. Institute of Radiation Physics, Lund, Sweden 1975.

Brahme A.: On the optimal choice of scattering foils for electron therapy. Royal Institute of Technology, Stockholm, TRITA-EPP-72-17 (1972).

— Simple expressions for the penetration of high energy electron beams in matter. Report SSI: 1975-011. National Institute of Radiation Protection, Stockholm 1975.

BROSZKIEWICZ R. K. and BULHAK Z.: Errors in ferrous sulphate dosimetry. Phys. in Med. Biol. 15 (1970), 549.

BRYANT T. H. E. and RIDLER T. P.: Factors affecting the measurement of the extinction coefficient of Fe^{3+} ions in a Fricke dosimeter solution. Hlth Phys. 15 (1968), 263.

COTTENS E.: Thesis. University of Ghent, 1979.

EGGERMONT G., BUYSSE J., JANSSENS A., THIELENS G. and JACOBS R.: Discrepancies in molar extinction coefficients of Fe^{3+} in Fricke dosimetry. *In*: National and international standardization of fadiation dosimetry. Vol. II, p. 317. IAEA-SM-222/42 (1978).

ELLIS S. C.: The dissemination of absorbed dose standards by chemical dosimetry. National Physical Laboratory, London. Rad. Sci. 30 (1974), 15.

EYGES L.: Multiple scattering with energy loss. Phys. Rev. 74 (1948), 1534.

FERMI B. B.: Lecture by Fermi at University of Chicago. Cited by B. B. ROSSI and K. GREISEN. Rev. mod. Phys. 13 (1941), 265.

GIESSELSODER J., KOEPKE K. and LAUGHIN J. S.: Calorimetric determination of absorbed dose and $G_{Fe^{3+}}$ of the Fricke dosimeter with 10 MeV and 20 MeV electrons. Radiat. Res. 20 (1963), 423.

HARDER D. (a): Berechnung der Energiedosis aus Ionisationsmessungen bei Sekundärelektronen-Gleichgewicht. *In*: Symposium on High-Energy Electrons, p. 40. Montreux 1964.

— (b): Energiespektronen schneller Elektronen in verschiedenen Tiefen. *In*: Symposium on High-Energy Electrons, p. 26. Montreux 1964.

— Fano's theorem and the multiple scattering correction. *In*: Proceedings on the Fourth Symposium on Microdosimetry, p. 677. Verbania-Pallanza 1973.

LAW J. and NAYLOR G. P.: A comparison of ionization and ferrous sulphate dosimetry for megavoltage electrons. Phys. in Med. Biol. 17 (1972), 400.

— Svensson H.: Comparisons of radiation dosimetry. Phys. in Med. Biol. 18 (1973), 464.

LIESEM H. und POHLIT W.: Dosismessung an schnellen Elektronen nach der Eisensulfatmethode. Z. Phys. Chem. 35 (1962), 352.

MARKUS B.: Eine einfache Formel zur Bestimmung der mittleren Elektronenenergie in einem mit schnellen Elektronen bestrahlten Körper. Strahlentherapie 154 (1978),388.

MATTSSON O.: Personal communication. Sahlgrenska Sjukhuset, Gothenburg.

NAHUM A. E. and GREENING J. R.: A detailed re-evaluation of C_λ and C_E with application to ferrous sulphate G-values. Phys. in Med. Biol. 23 (1978), 894.

PETTERSSON C.: Calorimetric determination of the G-value of the ferrous sulphate dosimeter with high-energy electrons and Co-60 gamma rays. Arkiv för Fysik 34 (1967), 385.

— HETTINGER G.: Dosimetry of high energy electron radiation based on the ferrous sulphate dosimeter. Acta radiol. Ther. Phys. Biol. 6 (1967), 160.

PINKERTON A. P.: Comparison of calorimetric and other methods for the determination of absorbed dose. Ann. N.Y. Acad. Sci. 161 (1969), 63.

SCHULER R. H. and ALLEN A. O.: Yield of the ferrous sulfate radiation dosimeter. An improved cathode-ray determination. J. Chem. Phys. 24 (1956), 56.

SHARLEK R. J. and SMITH G. E.: Chemical dosimetry for the measurement of high energy photons and electrons. Ann. N.Y. Acad. Sci. 161 (1969), 44.

SVENSSON H.: Dosimetric measurements at the Nordic medical accelerators. Acta radiol. Ther. Phys. Biol. 10 (1971), 631.

YANG C. N.: Actual path-length of electrons in foils. Phys. Rev. 84 (1951), 599.