Dosimetry for Electron Beam Applications

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DOSIMETRY FOR ELECTRON BEAM APPLICATIONS

Arne Miller

Abstract. This report describes two aspects of electron beam dosimetry, on one hand development of thin film dosimeters and measurements of their properties, and on the other hand development of calorimeters for calibration of routine dosimeters, e.g. thin films. Two types of radiochromic thin film dosimeters have been developed in this department, and the properties of these and commercially available dosimeters have been measured and found to be comparable. Calorimeters, which are in use for routine measurements, are being investigated with reference to their application as standardizing instruments, and new calorimeters are being developed.

INIS-descriptors: ACCURACY; CALIBRATION; CALORIMETERS; CALORIMETRIC DOSEMETERS; DOSE-RESPONSE RELATIONSHIPS; DOSE RATES; DYES; ELECTRON BEAMS; HUMIDITY; IONIZING RADIATIONS; LINEAR ACCELERATORS; RADIATION DOSES; THIN FILMS.

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1. INTRODUCTION

Thin film dosimeters that can be used for absolute as well as relative dose measurement at industrial electron accelerators are developed. The wide range of energy of such accelerators (~ 150 keV - 10 MeV) and their high dose rates suggest the application of dosimeters which are thin and display little dependence of dose rates. Radiochromic dye films (McLaughlin et al., 1977) seem to possess these properties (McLaughlin et al., 1979). During this work measurements have been performed on commercially available thin film dosimeters as well as on dosimeters made in this department, in part to confirm previous findings (Miller and McLaughlin, 1980) and in part to extend these measurements, which include studies of the influence of relative humidity and storage effects.

When determining various properties of dosimeters it is important to employ calibration procedures, which provide a fixpoint beyond dispute. In the course of this work it has become apparent that the procedures employed for calibration of electron accelerators - not only in this department, but also more worldwide - might in fact be disputed. It still remains to be seen if such a dispute is justified or not, but an effort has been initiated to show the merits of electron beam calibration procedures, and if needed to improve them.

This report describes measurements made on various types of radiochromic dye films, as well as status for calorimetric work for calibration purposes. The calibration procedures are not restricted to be used with thin films only, but can of course be employed for any dosimeter system.

2. PROPERTIES OF RADIOCHROMIC FILM DOSIMETERS

2.1 Types of radiochromic films

Three types of film dosimeters have been investigated:

a. Nylon films containing hexa(hydroxyethyl)pararosaniline cyanide as dye precursor. Commercially available (Kantz and Humpherys, 1979). Type designation: FWT-60.

b. Polyvinylbutyral (PVB) films containing hexa(hydroxyethyl)pararosaniline cyanide. Made in this departm· t on a small scale (Miller and McLaughlin 1980).
Type designation: P-15.

c. Polyvinylbutyral (PVB) films containing pararosaniline cyanide. Made in this department on a small scale.
Type designation: P-15 R.

2.2 Preparation of films

FWT-60. No information has been published on the preparation of Nylon films. They are normally supplied in 1×1cm² pieces, and each batch is supplied with a calibration factor, referring to a common calibration curve. This factor is usually between 0.8 and 1.2. The thickness of tne films is around 50 μm and within a batch varies less than ± 3-5 μm.

P-15. Radiochromic dye films made from PVB are cast on flat glass as described by Miller and McLaughlin (1980). The recipe is as follows:

285 cm³ 2-ethoxy-ethanol
0.4 cm³ diocthyl phthalate
25 g PVB
1.5 g hexa(hydroxyethyl)pararosaniline cyanide, MW = 578
0.6 g citric acid.

This amount is enough for 6 films of ~ 30 cm diameter. The thickness is ~ 65 μm. After stripping from the glass plane, the films are dried for one week in

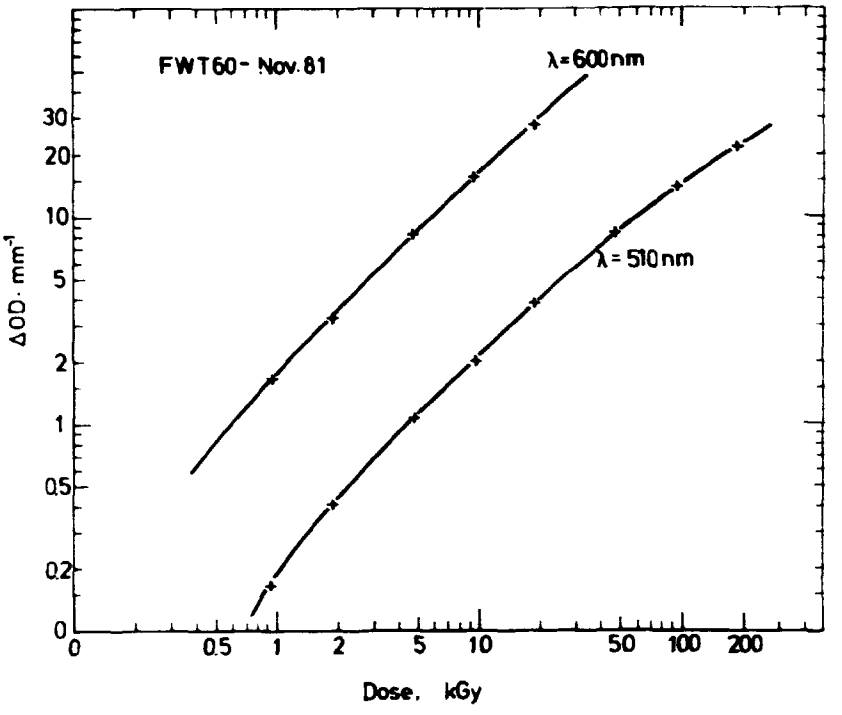

Fig. 1. Response curves for Nylon radiochromic dosimeters (FWT-60). Irradiations were made at Cobalt-60.

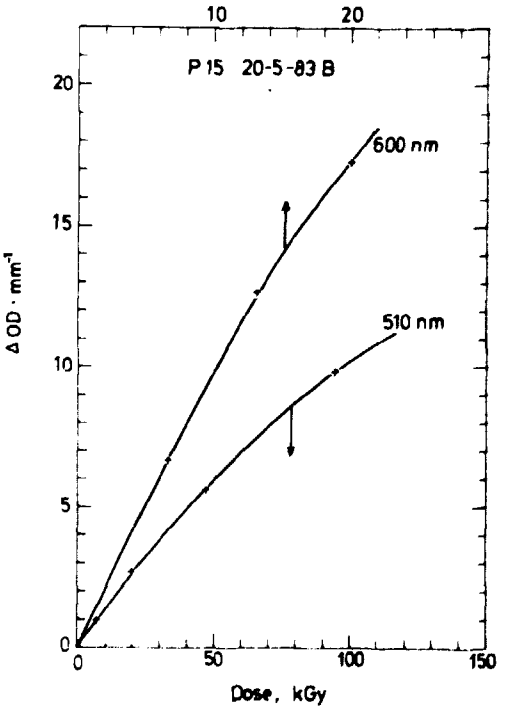

Fig. 2. Response curves for PVB radiochromic dosimeters (P-15). Cobalt-60 irradiations.

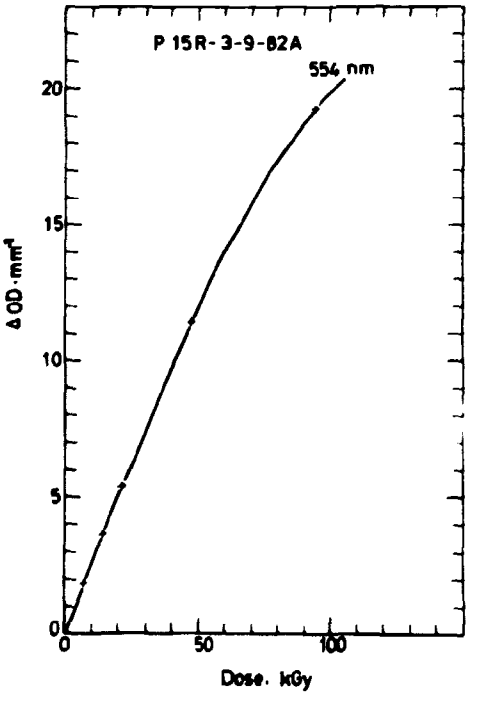

Fig. 3. Response curve for PVB radiochromic dosimeters (P-15 R). Cobalt-60 irradiations.

vacuum at ~ 50°C for removal of residual amounts of solvents. The films are then allowed to stabilize in air for a week or more before measurements are made.

P-15 R. Films containing pararosaniline cyanide, MW = 314, are made from the same recipe as above, but with a reduced amount of dye (0.8 g) according to the molecular weight. Further details about the casting of P-15 and P-15 R films have been described earlier (Miller and McLaughlin, 1980), and are based on earlier work at Risø (McLaughlin et al., 1977).

2.3 Response curves

Response curves of the three film types are shown in Figs. 1-3, and absorption spectra are shown in Fig. 4. Wavelengths of 600 nm and 510 nm are used for dose measurements with FWT-60 and P-15 dosimeters, while 554 μm is used for P-15 R. When comparing irradiations with Cobalt-60 γ-rays and at 10 MeV electrons, some dose rate dependence is found above 50 kGy for the FWT-60 dosimeter (McLaughlin et al., 1983). Measurements for the PVB dosimeters show less dose rate dependence than the FWT-60 dosimeters (ibid.). Gehringer (1979) has demonstrated dose rate dependence at very low gamma dose rates for FWT-60 dosimeters, particularly at low relative humidities.

The trend toward saturation, which is observed at high doses on the curves, is instrumental saturation rather than film saturation, which is demonstrated by measuring the response curve of a 5 μm film. In this case the film saturates at an ΔOD/mm value of ~ 450. This corresponds to an optical density of 2.25 for the 5 μm film. Saturation would have been OD = 22.5 for the 50 μm, which cannot be measured directly.

2.4 Relative humidity

The influence of relative humidity on these radiochromic dosimeter films must be taken into account. The influence on PVB (P-15) dosimeters has been studied (Miller and McLaughlin, 1980), and the influence on Nylon (FWT-60) has been studied by Gehringer et al. (1979,1982) and Levine et al. (1979). All studies used cobalt γ-ray irradiation. In the newer work by Gehringer a link between oxygen content, relative humidity and dose rate seems to be established.

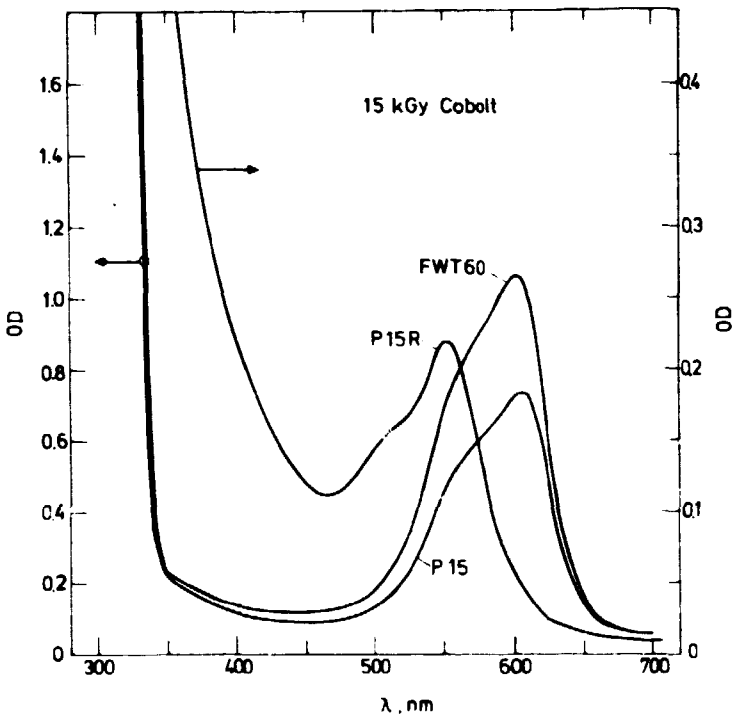

Fig. 4. Absorption spectra for the three different types of dosimeters whose response curves are shown in Figs. 1-3.

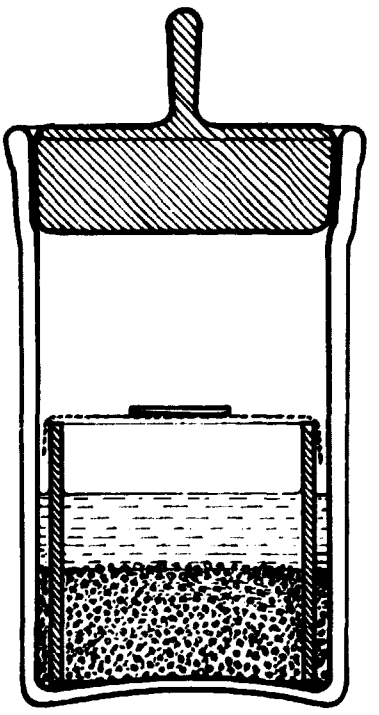

Fig. 5. Glass vial used for humidity studies at cobalt irradiations. The diameter of the vial is approx. 25 mm.

In the present study some of Gehringer's measurements have been confirmed, and the humidity response at 10 MeV electron irradiations have been measured.

2.5 Cobalt irradiations

In each set of measurements, dosimeters were stored over saturated salt solutions for at least 5 days. The salts used were:

12.4% r.h.: LiCl
33.6% r.h.: $MgCl_2$
54.9% r.h.: $Mg(NO_3)_2$
75.5% r.h.: NaCl

The stated r.h. values are for 20°C, but they are found to change less than 1% in the range of 20° - 30°C (Wexler and Hasegawa, 1954). Normally the films were stored at ~ 20°C and 40-60% r.h. before conditioning. We also tried to dry the dosimeters over P_2C_5 first, but we saw no influence on the subsequent measurements.

In a first set of cobalt-irradiations, dosimeters were irradiated in small glass vials. The dosimeters were resting on a stainless steel mesh above saturated salt solutions (Fig. 5). The dose was calibrated by exposing Fricke solution in similar glass vials. It is realized that transfer of dose in the Fricke dosimeter to dose in the thin film dosimeter is not readily made under these conditions, but relative measurements are significant in this case.

Cobalt γ-ray irradiations were made in a gamma-source with dose rate of 1.1 $Gy \cdot s^{-1}$, and also within a lead cylinder, which lowers the dose rate to 0.2 $Gy \cdot s^{-1}$. The temperatures during irradiations were measured to be between 20° and 30°C.

FWT-60. Figure 6 shows the measurements at only 3 different relative humidities together with Gehringer's measurements (Gehringer, 1979). There is a good relative agreement, although the absolute value may be inaccurate as mentioned previously.

FWT-60 dosimeters have all been given a heat treatment after irradiation as suggested by Chappas (1981). We used 60°C and 5 minutes, although for cobalt-irradiations this is scarcely needed, and the treatment was used only for reasons of standardization.

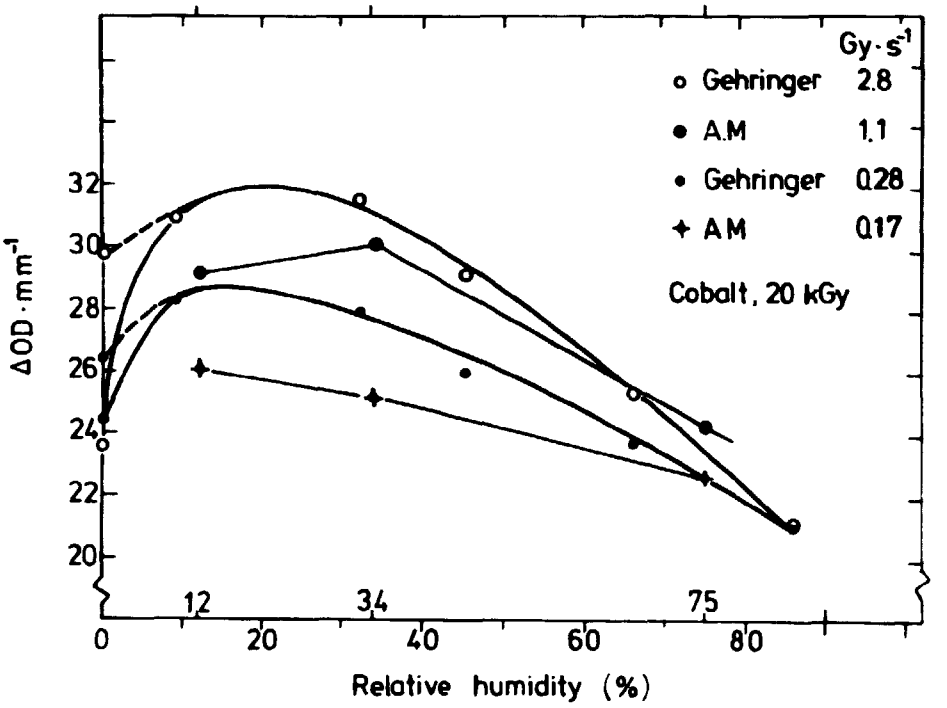

Fig. 6. The influence of relative humidity on Nylon radiochromic dosimeters. The results of this study are shown superimposed on the results by Gehringer et al. (1979).

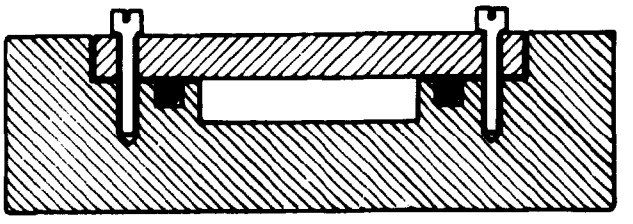

Fig. 7. Nylon block used for humidity studies at the 10 MeV linear accelerator. The thickness of the lid is 5 mm and the diameter is 75 mm.

The apparent dependence of dose rate at low rates is not found in all studies (McLaughlin et al., 1981) and may depend on long-term pretreatment of the dosimeters as well as on irradiation conditions.

P 15. Dosimeters made as described earlier were irradiated under conditions equal to FWT-60 dosimeters. Generally the PVB-based dosimeters show increased sensitivity by +(0.4-0.5)% per percent increase in relative humidity, and a 10% lower response as the dose rate is lowered from 1.1 to 0.2 Gy·sec^{-1} (Miller and McLaughlin, 1982), which is similar to earlier findings of Levine

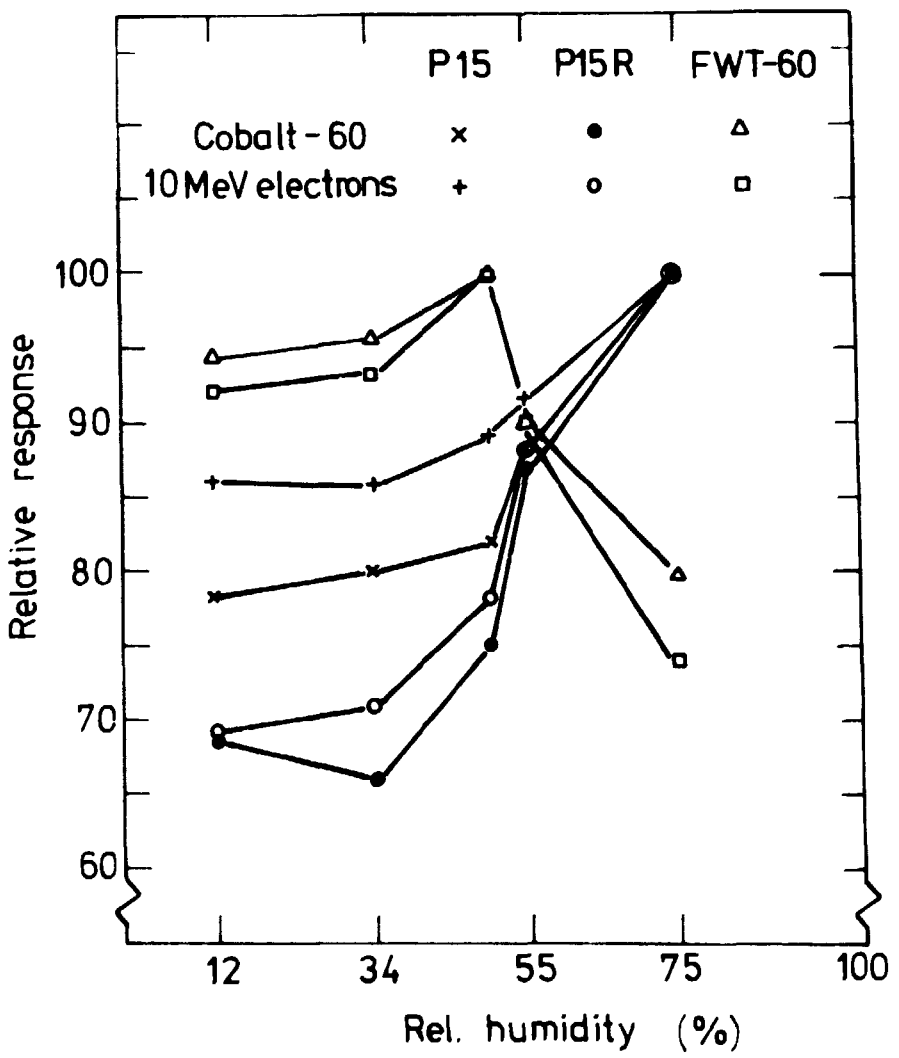

Fig. 8. Dependence of relative humidity for the 3 different radiochromic dye dosimeters, irradiated at 10 MeV electrons and Cobalt-60. The dose was 20 kGy in all cases.

et al. (1979). Also in this case dosimeters were dried over P_2O_5 without finding any differences in response, as compared to storage at room temperature and humidity.

2.6 Accelerator irradiations

An approach similar to the one by Gehringer et al. (1979) was used in order to irradiate at different humidities at the 10 MeV linear accelerator. Small cylindrical nylon blocks, as shown in Fig. 7, were stored for one month at the different relative humidities. Dosimeters, which have been stored for one week at the same humidities, were then placed in the cavity in the nylon block, the lid tightly secured, and the blocks were irradiated, first on cobalt in order to see if the same response would be obtained as in the experiment above. That was in fact the case, and thereby it seemed safe to assume that the humidity conditions were not seriously disturbed during the 5-6 hours of irradiation in the nylon blocks, and it might thus be safe to proceed with irradiations with 10 MeV electrons.

The results are shown in Fig. 8, where cobalt and 10 MeV electron irradiations are compared for 3 types of dosimeters, normalized to the most sensitive measuring point. At that point the difference, before normalization between cobalt and electron irradiations, is less than 5%, which is within the precision of the dosimeters, and thus no dose rate dependence is demonstrated over this range of dose rates, which is in accordance with earlier findings (McLaughlin et al., 1979).

The parameters for the accelerator irradiations were as follows:

Energy 10 MeV
Pulse current 1.2 A
Pulse length 4 μsec
Pulse frequency 200 pps
Irradiations on scanned beam on conveyor
Scan frequency 5 Hz
Scan width 40 cm
Conveyor speed at 20 kGy: 0.8 m/min.

The dependence on relative humidity seems to be comparable for electron and cobalt irradiations. Only in case of P-15 R there seems to be a significant

difference so that electron irradiation in that case shows less dependence of relative humidity.

As previously mentioned all dosimeters were given a short heat treatment (60°C, 5 min.) after irradiation, which is found to accelerate a colour developing process after irradiation. This heat treatment was also found to decrease the humidity dependence for all investigated dosimeters.

2.7 Stability after irradiation

All investigated dosimeters are found to develop their final colour in the first hours after irradiation. This is particularly observed after electron irradiation, while cobalt γ-ray irradiation does not give rise to any such effect, because of the long irradiation time. A brief heat treatment of 5 minutes at 60°C in an oven accelerates this development of colour and leaves the films ready for reading. The long-time stability for the different dosimeter types is as follows:

FWT-60. The optical density of these films reaches the same "saturation level" after heat treatment as is reached after 24 hours of storage without heat treatment. There does not seem to be any need for great accuracy in administering the treatment; the same result is achieved by time variation from 3 to 10 minutes and for temperatures from 50° to 70°C.

Storing the dosimeters for a long time after heat treatment may give rise to some fading of the colour. For the batch used in this study it was found that 3 months storage reduced the optical density by 15%, but other batches may be more stable (Levine et al., 1979).

The dose response of FWT-60 dosimeters seems largely to be independent of pre-irradiation time. Repeated cobalt-60 irradiations usually give responses within ± 5% of each other.

P-15. Heat treatment (60°C, 5 min.) of these dosimeters gives rise to an optical density, which is higher than the value reached after 24 hours, or even several days of storage after irradiation. Variation of the temperature and time seems also in this case to be allowed without influencing the response of the dosimeter as above. The stability after irradiation is very good. The change in optical density after storage at normal laboratory condi-

tions for up to half a year does not change the optical density by more than ± 2%.

The dose response over long-term pre-irradiation storage is less stable than for FWT-60 dosimeters. Variation of more than 20% has been observed for repeated irradiation at Cobalt-60. The relative high humidity dependence of these dosimeters is suspected to be one of the causes of this apparent instability, but investigations are being made in an attempt to improve this.

P-15 R. This dosimeter reacts to the heat treatment in the same manner as the P-15 dosimeter. The long-time stability after irradiation is also very good with changes being less than ± 2% for half a year storage.

The dose response for repeated irradiations seems to be more stable than P-15 with changes of less than ± 5% for pre-irradiation storage times of 9 months, but further measurements are needed to confirm this.

2.8 Light sensitivity

The sensitivity to light was previously measured for FWT-60 and P-15 dosimeters (Miller and McLaughlin, 1980). These measurements have been repeated, P-15 R included (Fig. 9). All 3 dosimeters are most sensitive around 330 nm, but the relative sensitivity of the 3 types is: FWT-60: 100%; P-15: 25%, and P-15 R: 2%.

3. CALORIMETRIC MEASUREMENTS

The measurement at different types of irradiation with relative dosimeters requires that the absorbed dose on the different irradiation facilities can be measured with accuracy by some common standard.

Ferrous-sulphate (Fricke) dosimetry is used as the standard on gamma irradiation facilities, but that dosimeter cannot be used without corrections at the 10 MeV linear accelerator because of dose-rate problems (Sehested et al., 1973), or at the 400 keV DC accelerator because of very low penetration at this energy.

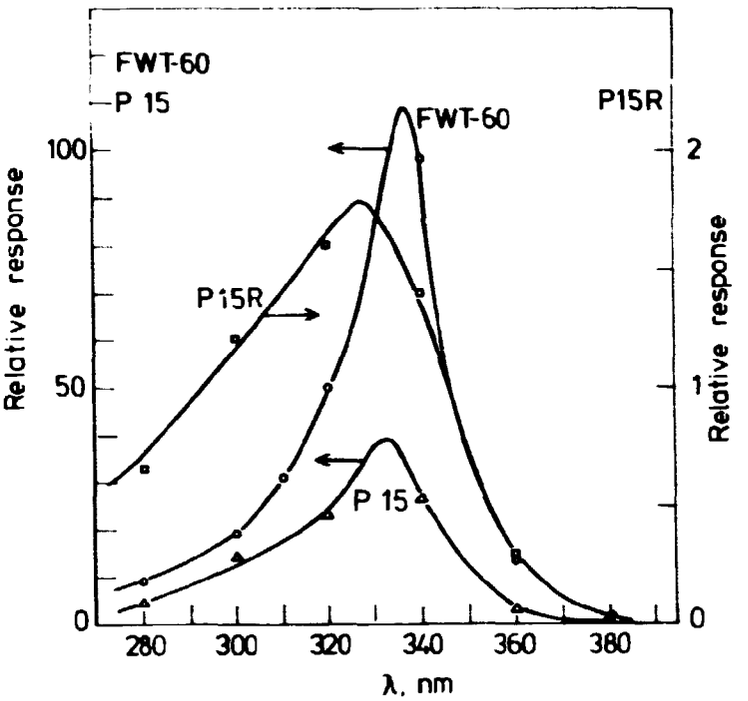

Fig. 9. Response to light for the three different radiochromic dye dosimeters. The same arbitrary units are used for all three curves.

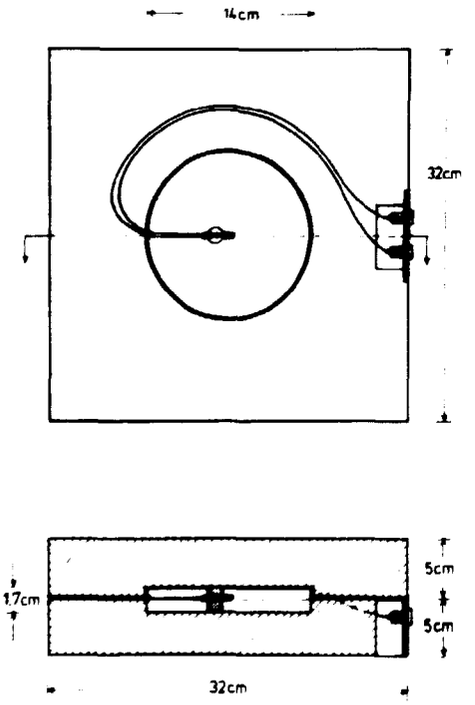

Fig. 10. The water calorimeter that is used for dose measurement at Risø 10 MeV linear accelerator.

A water calorimeter is used as reference at the Risø 10 MeV linear accelerator (Fielden and Holm, 1970) and a calorimeter has also been designed for calibration of the 400 keV accelerator (Radak et al., 1973). These calorimeters have been investigated and a new simple calorimeter made of graphite with potential of being used both on the 10 MeV and the 400 keV accelerators has been constructed (Miller, 1982a, 1982b). This is similar to one designed by Humphreys & McLaughlin (1983) at NBS for use in 10 MeV electron beams.

3.1 10 MeV electrons

The water calorimeter described here is not designed to be a reference instrument, but rather as a process calorimeter. Nevertheless it is reasonably accurate and precise, as will be discussed, and it seems possible to apply the water calorimeter in standardized measurements.

The calorimeter consists of a polystyrene Petri dish filled with water (for dimensions see Fig. 10). The dish is isolated by polystyrene foam, and temperature can be measured by means of a glass-encapsulated calibrated thermistor. The calorimeter will normally be irradiated on a product conveyor making on-line measurement of temperature difficult. The measurements are therefore restricted to before and after irradiation, and the observed temperature difference is a measure of the absorbed dose. The usual extrapolation technique is not used, but temperatures are assumed to be constant before and after irradiation. The former can be obtained if the calorimeter is in equilibrium with its surroundings, and it was determined that the temperature after irradiation increases at 10 kGy by 0.5% per minute over a 10-minute period. The temperature will increase because the plastic is heated more than the water during irradiation because of its lower specific heat. Measurement is usually made between 1 and 2 minutes after irradiation.

The calculation of absorbed dose is based on material properties only, as no calibration heater is employed. The absorbed dose D is:

$$(1) \quad D = \frac{\Delta E}{m} = \frac{\Delta T \cdot c \cdot m}{m}$$

where c is the specific heat, m the involved mass and ΔT the temperature difference. When several components are heated by the absorbed dose the equation becomes:

$$(2) \quad D = \frac{\Delta T \cdot \Sigma(c_i \cdot m_i)}{\Sigma m_i}$$

It is assumed that the components contributing to the total calorimeter body are the following:

Water, specific heat 0.998 $Cal \cdot g^{-1} \cdot °C^{-1}$
Polystyrene dish, specific heat 0.335 $Cal \cdot g^{-1} \cdot °C^{-1}$
Thermistor and wires, heat capacity 0.12 $Cal \cdot °C^{-1}$
mass 1.0 g

For each calorimeter the masses of the Petri dish and of the water are determined individually, while the thermistors are assumed to have equal mass and heat capacity.

Typical, the mass of the water is 240 g and of the Petri dish 60 g, so that the dose can be calculated as:

$$D = \frac{240 \cdot 0.998 + 60 \cdot 0.335 + 0.12}{240 + 60 \quad 1} \cdot 4.18 \cdot 10^3$$

$$= \underline{\Delta T \cdot 3610} \text{ Gy}$$

It is recommended not to measure doses below 3 kGy corresponding to a temperature rise of ~ 1.0°C, since the time between the two temperature measurements can vary somewhat, which may give rise to unwanted temperature changes due to influence from the environment.

It is uncertain whether the mass and specific heat of the Petri dish should be included fully in the calculations, or if some of the mass and specific heat of the insulation should be included. The very slow temperature rise after irradiation seems to indicate that the Petri dish is in thermal equilibrium, and that the continued contribution to the temperature rise is due to the insulation, which again suggests that shortly after irradiation this has a negligible effect.

3.2 Precision

For routine dose measurements on the linear accelerator 20-30 calorimeters are in use so that an unirradiated calorimeter in thermal equilibrium can always be used. 25 calorimeters were irradiated to 2 Mrad on the conveyor in rapid succession of each other, and the scatter of individual measurements were within ±2% of the average.

3.3 Accuracy

The International Atomic Energy Agency is currently initiating a "Dose Assurance Program" (Chadwick 1982; Miller et al., 1983) for gamma irradiation plants and work is in progress to expand this service also to include electron irradiation facilities. As part of this work the water calorimeter was tested in intercomparisons with graphite calorimeters made at National Bureau of Standards, U.S.A., and at Risø. Irradiations were made at National Physical Laboratory, England, and at Risø. The NPL measurements in general showed good agreement between the NBS graphite calorimeters and the Risø water calorimeters, but the details are reported elsewhere (Morris, 1983; Humphreys and McLaughlin, 1983).

The measurements at Risø were made on the 10 MeV linear accelerator, both using scanned beam on a conveyor and fixed beam in a "straight ahead" configuration.

The thicknesses of both kinds of calorimeters (water and graphite) are about 1.7 g/cm^2, and they are not totally absorbing for the 10 MeV electron beam. Stopping-power corrections for 10 MeV electrons are therefore applied for comparison of water and graphite calorimeter readings (using stopping-power values of Seltzer and Berger (1982)).

$$(3)\quad S_G^W = \frac{\left(\frac{1}{\rho}\cdot\frac{dE}{dx}\right)_W}{\left(\frac{1}{\rho}\cdot\frac{dE}{dx}\right)_G} = 1.133$$

In three separate series of irradiations at the Risø 10 MeV linac, the following ratios were obtained:

$$\frac{D_W}{S_G^W \cdot D_G} \pm \sigma$$

1. 1.11 ± 0.06 Scanned beam
2. 1.09 ± 0.04 Straight ahead beam
3. 1.07 ± 0.02 Scanned beam

D_W is dose as measured by the Risø water calorimeter, and D_G is dose as measured by the NBS graphite calorimeter.

Following these measurements 4 graphite calorimeters were made at Risø, partly in order to make comparisons with the water calorimeter, and partly in order to use the graphite calorimeters as routine dosimeters for lower doses

at the linear accelerator, and if possible also at the 400 keV accelerator. The lower specific heat of graphite should make it possible to measure doses down to 0.5 kGy and assuming a homogeneous distribution of heat in the calorimeter shortly after irradiation, application on the low penetrating 400 keV electrons is possible.

The graphite calorimeters are made as a disk with the same diameter (~ 14 cm) as the water calorimeter and with the thickness (1.7 $g \cdot cm^{-2}$) also equal to the water calorimeter. The density of the graphite is measured to be 1.78 $g \cdot cm^{-3}$.

The dose may be calculated as for the water calorimeter, but since there is no encapsulation of the graphite and the thermistor is a nonencapsulated type with thin wires and negligible influence on the temperature measurement, eq. (1) reduces to:

$$(4)\quad D_G = \Delta T \cdot C_G$$

The specific heat of graphite, C_G, was measured as a function of temperature as shown in Fig. 11. The temperature rise of the calorimeter is expected not

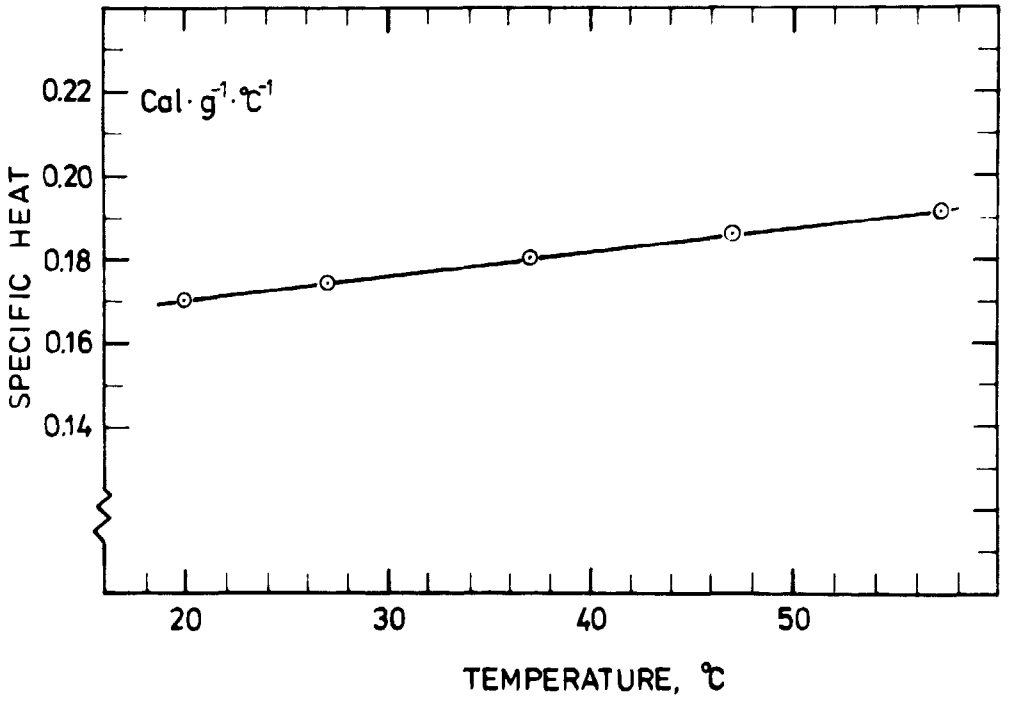

Fig. 11. Specific heat of the graphite used for construction of calorimeters at Risø.

to exceed 10-15°C and an average value of C_G is accordingly chosen to 0.174 $Cal \cdot g^{-1} \cdot °C^{-1}$ = 730 $J \cdot kg^{-1} \cdot °C^{-1}$.

For use at the linear accelerator the graphite disk was isolated by ~ 5 cm polystyrene foam.

Several series of irradiations were made on the conveyor where 4 water calorimeters were irradiated together with the 4 graphite calorimeters. The doses were generally between 10 kGy (~ upper limit of graphite calorimeter) and 5 kGy (~ lower limit of water calorimeter). Measurement of temperature was made 1-2 minutes before irradiation and again 1-2 minutes after irradiation.

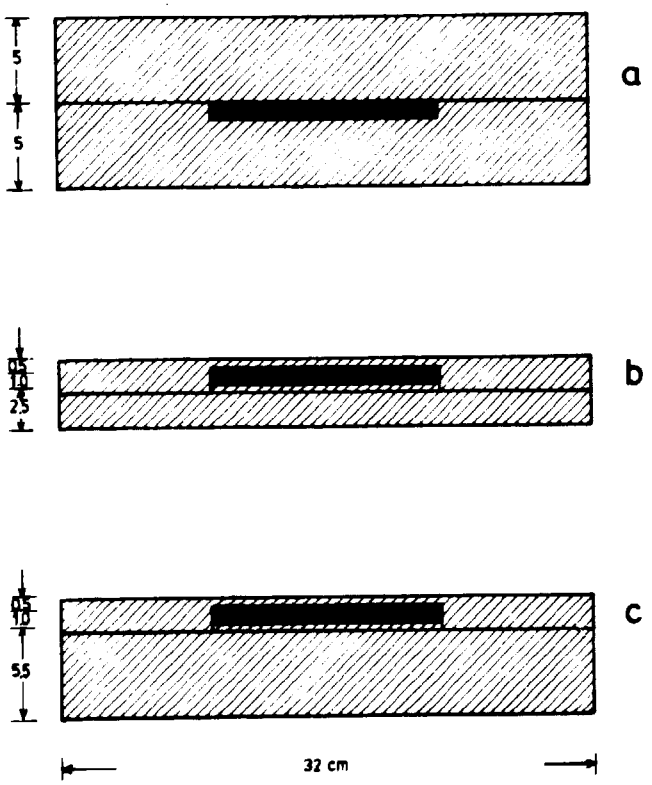

Fig. 12. Graphite calorimeters with different isolation configurations.

The following ratios were found between the dose as measured by the water calorimeters D_W, and the dose as measured by the individual graphite calorimeters, but multiplied by the stopping power ratio:

$$\frac{D_W}{D_C \cdot S_C^W} \pm \sigma$$

1. 1.04 ± 0.04
2. 1.04 ± 0.03
3. 1.03 ± 0.03
4. 1.08 ± 0.03

No significant variation of the ratio could be seen as the dose was varied, and that was also the case if the average dose rate was lowered by shortening of the beam pulse to 1 μsec.

Thinner layers of isolation were used as shown in Fig. 12 in order to test the validity of the dose measurement when the calorimeter is to be used at low energy electron beams. No significant change of the ratio was found.

The differences between individual measurements may be due to the construction of the calorimeters, in particular with respect to the mounting of the thermistor, and it is likely that in value number 4 above the temperature measurement is inaccurate.

The deviation of the ratio from unity may be due to heat exchange between the foam insulation and the graphite. The specific heat of the foam is higher than that of graphite, and the foam is therefore not heated as much as the graphite. After irradiation the temperature of the graphite therefore decreases. The decrease was measured to 0.5% per minute at 10 kGy. If a few grams of the insulation is taken into account when calculating the dose, the ratio will be brought close to unity, but there may be other causes for the deviations. The change in temperature with time for both the water and graphite calorimeters may account for about 2%, so that the ratio becomes 1.02 rather than 1.04. The remaining 2% difference seems hardly worth reducing, but it is realized that at least one possible source of oerror still excists: Correction with a simple stopping power ratio (eq. 3) may not be adequate. Cavity theories for electron beam irradiations have been questioned (see e.g. Horowitz (1981)), and it is possible that additional corrections must be included.

For the moment we have assumed that the water calorimeter is estimating a correct dose and the reading of the graphite calorimeters will be calibrated against the reading of the water calorimeters. It is realized that Domen finds errors in dose interpretation using a water calorimeter of the order of 3-4%. Domen, however, uses low doses (1-10 Gy) and we do not feel that these findings can be extrapolated to the kGy region.

The following calibration factors have been obtained for the four graphite calorimeters:

	Dose to graphite	Dose to water (10 MeV electrons)
1)	757 $Gy \cdot °C^{-1}$	858 $Gy \cdot °C^{-1}$
2)	757 $Gy \cdot °C^{-1}$	858 $Gy \cdot °C^{-1}$
3)	750 $Gy \cdot °C^{-1}$	850 $Gy \cdot °C^{-1}$
4)	786 $Gy \cdot °C^{-1}$	891 $Gy \cdot °C^{-1}$

These values are used for routine determination of dose at the 10 MeV linear accelerator.

Based on these measurements there is no evidence that the water calorimeter is inaccurate. Possible sources of error include:

a) Heat defect <1% (see section 3.5)
b) Thermistor calibration error <0.2%
c) Determination of masses <1%
d) Uncertainty of specific heat values <1%
e) Temperature changes not observed between readings <1%.

It seems thus acceptable to assume that the accuracy is within ± 5%.

3.4 400 keV accelerator

There is no radiation measurement device available for measuring in absolute terms the absorbed dose from high-intensity, low-energy accelerators under product-irradiation conditions, as is done with water calorimeters at the 10 MeV accelerator.

Preliminary measurements have been made with the graphite calorimeters in order to test if this may be applied as reference dosimeter for 400 keV electrons. About 5 mm insulation between graphite body and accelerator window was used, but measurements have also been made with a 15 μm PE-foil covering the graphite front surface.

The dose from the 400 keV accelerator may be calculated approximately according to the method of Proksch et al., (1979) using the following parameters:

$E = 400$ kV

$\eta_E = 0.89$ (voltage efficiency)

$\eta_I = 0.80$ (current efficiency)

$R_{eq} = 0.0625$ g·cm^{-2} (equivalent range)

$Y_{eq} = 100$ cm (equivalent scan width)

$$k = \frac{E \cdot \eta_E \cdot \eta_I}{R_{eq} \cdot Y_{eq}} = \frac{400 \cdot 10^3 \cdot 0.89 \cdot 0.8}{0.0625 \cdot 100} = 45.6 \cdot 10^3 \text{ kGy(cm·sec}^{-1})\text{A}^{-1}$$

$$D = k \cdot \frac{I}{V}$$

At $I = 6$ mA and $V = 5$ cm/sec, the dose is calculated to be $D = 45.6 \cdot \frac{6}{5} \approx 54.7$ kGy.

Measurement with Nylon radiochromic dye films, which were calibrated at the Cobalt-60 and at the linear accelerator and assumed dose rate independent, measure 50 kGy at this setting of irradiation parameters and are thus in reasonable agreement with the calculations.

The graphite calorimeter measures average dose in the calorimeter body. At 400 keV electrons, only a small fraction of the total body is actually irradiated, and in order to make a dose measurement it must be assumed that the temperature is equalized over the full graphite disk. Tests have been made that indicate this being the case within 20 sec after irradiation.

In order to determine the surface dose based on knowledge of the average dose, the depth dose curve in graphite must be known. The depth dose curve was measured previously in a stack of dosimeter films (McLaughlin et al., 1975), but it was suspected that the depth dose curve might be different in electrical conducting graphite, as compared to electrically isolating dosimeter films. The dose was therefore measured under different thicknesses of

conducting plastic (Fig. 13), but as can be seen there is no appreciable difference.

Based on the depth-dose curve, a simple approximation (Fig. 13) is used to integrate this curve in order to find the ratio between the surface dose D_S, and the average dose for the full thickness of the disk, $D_{G,a}$.

$$\frac{D_S}{D_{G,a}} = 27.4$$

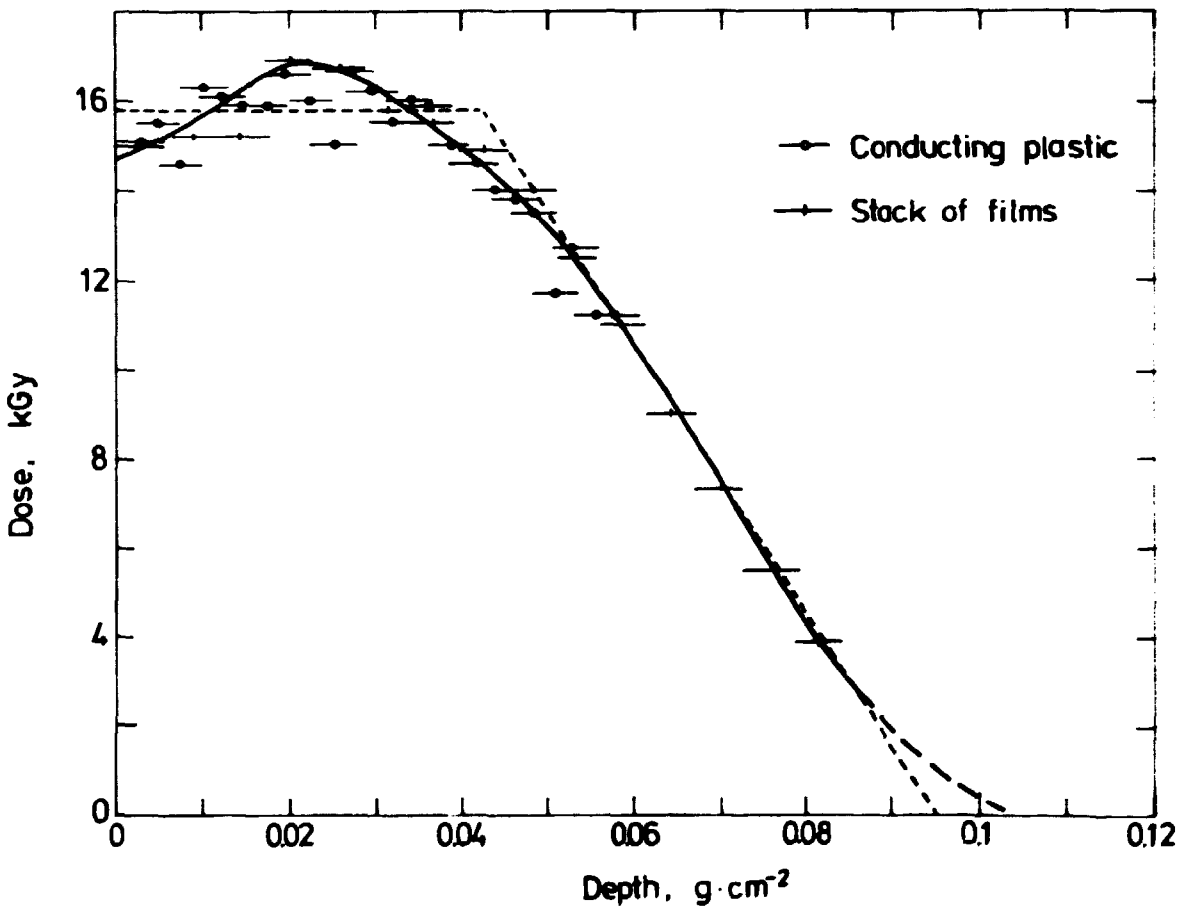

Fig. 13. Depth dose measurements at the 400 keV electron accelerator at Risø. One set of measurements were carried out with a stack of 50 μm electrically isolating dosimeter films, while another set of measurements was made with dosimeter films at different depths of electrically conducting plastic.

$D_{G,a}$ is calculated by application of eq. (4) and no stopping power correction is made because the calorimeter is totally absorbing. The first few measurements of this ratio, assuming D_S to be equal to the dose usually measured by film dosimeters and calculated as shown above, seem uncertain, but most values have been around 19, indicating either a too high $D_{G,a}$ (measured), or a too low D_S (assumed). Further investigations are being made trying to solve this problem.

Another calorimetric approach for calibration of dosimeters at the 400 keV electron accelerator has been used by Radak et al. (1973), and with small modifications this method has been tried again (Miller, 1982a). The calorimeter is shown in Fig. 14. The temperature difference between the irradiated and the non-irradiated body is measured on-line for fixed irradiation times. Following calibration irradiations with the calorimeter, stacks of dosimeter films are irradiated under equal conditions, and calibration curves are constructed.

The calorimeter is equipped with an electrical calibration heater, and a new calibration curve was made (Fig. 15).

The calorimeter was irradiated at 400 keV at 2, 5, and 10 mA and irradiating times were varied from 20 to 60 seconds.

When the irradiation time is increased the signal increases proportionally as shown in Fig. 16, but when the time is fixed and the beam current is increased, there does not seem to be proportionality as shown in the other half of Fig. 16. Various attempts have been made to resolve this discrepancy, but without success, and we have therefore concluded that beam measurements can be extrapolated and interpolated in terms of irradiation time, but not in terms of beam current. Measurements at each beam current in question should therefore be made.

Dosimeters, which are calibrated at this calorimeter, are not irradiated under processing conditions, where they are going to be used, and the procedure for evaluation of the calibration curve is rather troublesome. Even with these and the previously mentioned drawbacks this calorimeter may still be the best available for low-energy electron beams, and its application as a calibration instrument is still being considered.

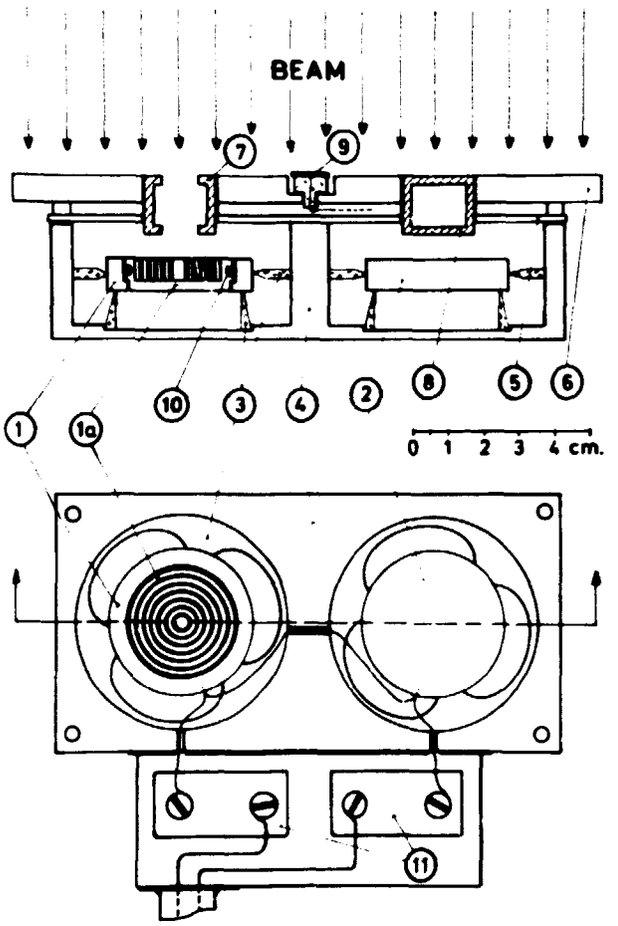

Fig. 14. Calorimeter for calibration of dosimeters irradiated at low energy electrons (Radak et al., 1973).

(1) Calorimetric body; fixed part.
(1a) Calorimetric body; exchangeable part.
(2) Reference body.
(3) Perspex supports.
(4) Aluminium matrix.
(5) Aluminium lid.
(6) Aluminium shield.
(7) Brass collimator.
(8) Dummy collimator.
(9) Beam current monitor.
(10) Calibration heater.
(11) Copper connectors.

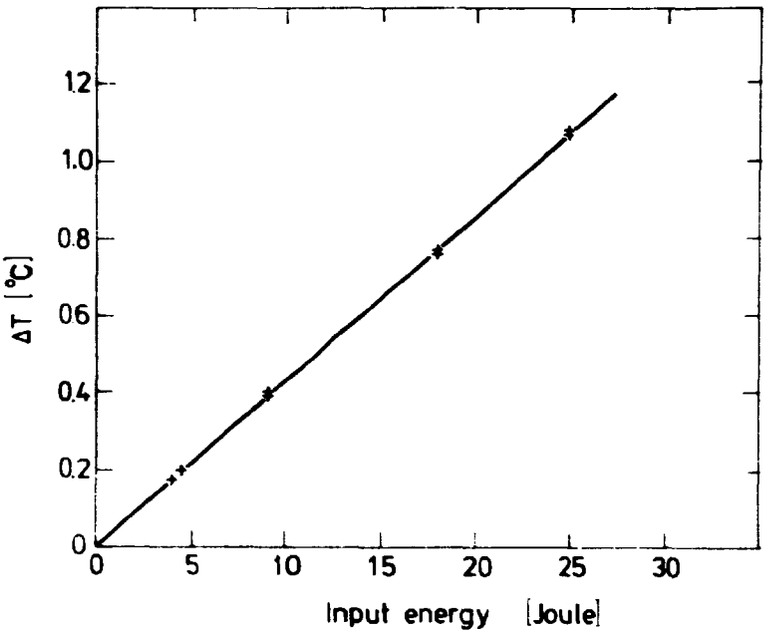

Fig. 15. Electrical calibration of the calorimeter of Fig. 14.

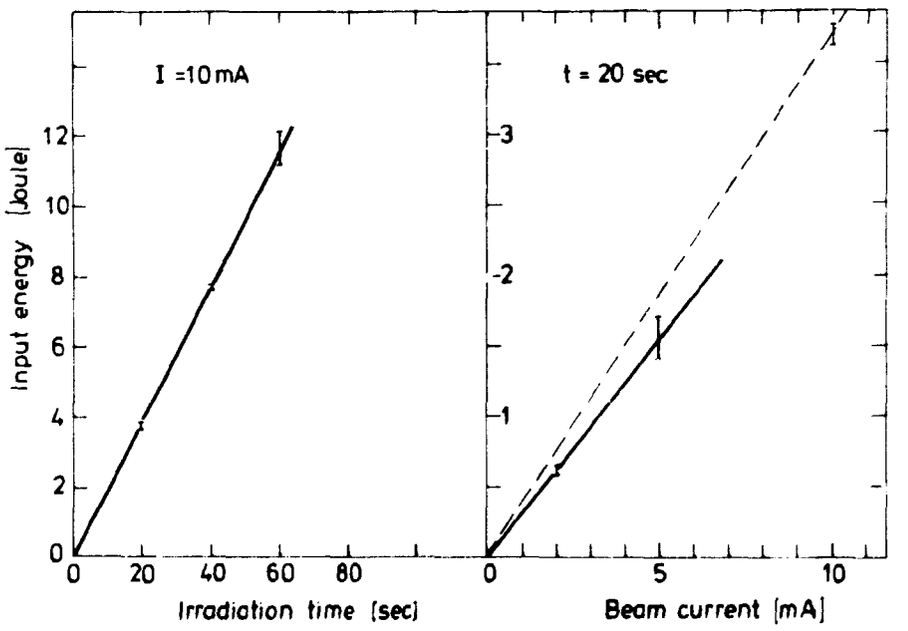

Fig. 16. Electron beam measurements with the calorimeter of Fig. 14.

3.5 Heat Defect

It has been suggested that endo- or exo-thermal chemical reactions in the water calorimeter might give rise to erroneous dose readings (Fletcher, 1982) (for the graphite no chemical reactions are assumed to take place).

The yields of O_2, H_2 and H_2O_2 by irradiation of water have been calculated by a computer code developed here (Bjergbakke and Lang Rasmussen, 1984), and the amounts of energy consumed or released in the reactions were found. We have considered 5 different irradiation conditions:

Source	Dose	Irr. time	Heat defect (exothermal)	Consumption H_2O 10^{-5} M	Formation H_2O_2 10^{-5} M
1. Cobalt	1 kGy	1 hour	1.1 %	8.47	7.1
2. Cobalt	10 kGy	1 hour	0.16%	12.2	9.9
3. Electron	1 kGy	3.6 sec	1.4 %	9.15	6.7
4. Electron	10 kGy	3.6 sec	0.25%	18.7	15.2
5. Electron	0.4 kGy	4 μsec	2.7 %	7.07	4.95

We consider 5) the worst case where the correction will be high due to the initial conditions. By successive pulsing the corrections will be less, depending on the time scale.

We have considered a closed system (the water calorimeter), but we do not expect larger corrections in an open system, in particular not at the short time scales involved with the electron irradiation. We therefore conclude that "heat defects" will amount to less than 1% for irradiations of 5 kGy or higher under these irradiation conditions.

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DOSIMETRY FOR ELECTRON BEAM APPLICATIONS

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32 pages + tables + 16 illustrations

Abstract

This report describes two aspects of electron beam dosimetry, on one hand development of thin film dosimeters and measurements of their properties, and on the other hand development of calorimeters for calibration of routine dosimeters, e.g. thin films. Two types of radiochromic thin film dosimeters have been developed in this department, and the properties of these and commercially available dosimeters have been measured and found to be comparable. Calorimeters, which are in use for routine measurements, are being investigated with reference to their application as standardizing instruments, and new calorimeters are being developed.

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