

**DOSIMETER OVERVIEW AND THE USE OF D_{μ}
FOR CALIBRATION**

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1. INTRODUCTION

Irradiation with low-energy electrons (75 – 300 keV) results in dose gradients across the thickness of the dosimeters that are typically used for dose measurement at these energies. This leads to different doses being measured with different dosimeter thicknesses irradiated at the same energy, resulting in difficulties in providing traceable dose measurements using reference dosimeters. This paper will discuss different dosimeter systems and how to use the D_{μ} to calibrate and measure doses from low energy electron irradiations with measurement traceability to national standards.

2. DOSE

The transfer of energy from the electron beam into material is specified by four parameters:

- Depth of penetration
- Absorbed dose
- Beam uniformity
- Throughput

2.1 Depth of penetration

The penetrating power of the electron beam is related to the accelerating voltage and the density of the processed material. Higher voltage causes deeper penetration, and denser material reduces the depth of penetration. The Depth Dose Curves (see fig 1) are convenient aids for estimating the penetration depth. These curves show the penetration for different accelerating voltages to the depth of penetration in a material with mass density equal to that of water, i.e. $\rho = 1 \text{ g/cm}^3$.

Penetration into materials of different density can be estimated by multiplying the penetration depth, found from the normalized curves, by the ratio of the density of water to the density of the material. For example, a 200 kV beam will have a 50 % dose point at 0,246 mm in water and 0,123 mm in a material twice as dense ($\rho = 2 \text{ g/cm}^3$).

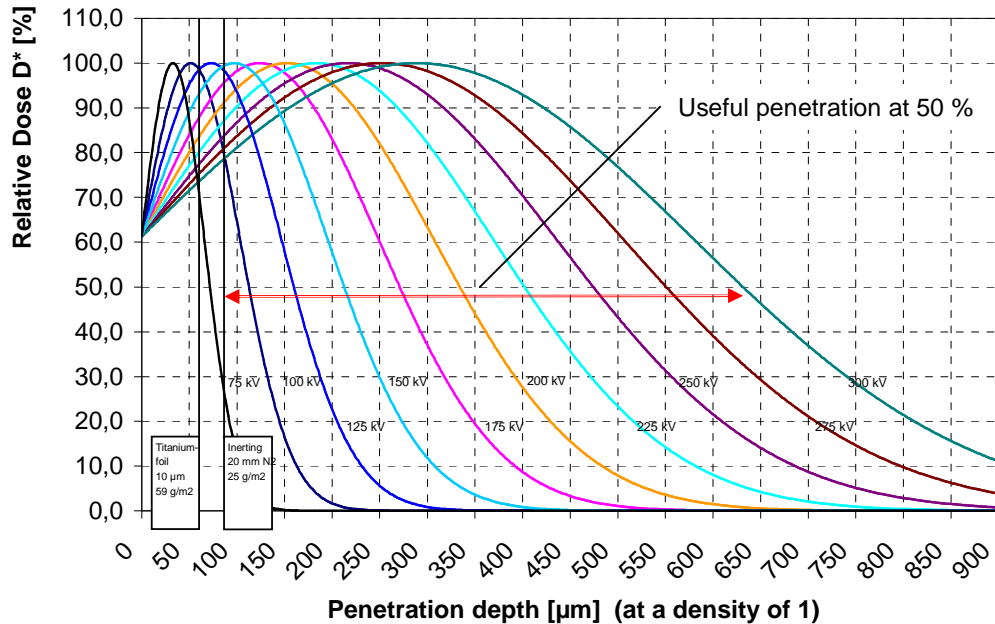


Figure 1. Range of penetration with different accelerating voltages, 13 µm titanium foil and 20 mm of nitrogen. [9]

At accelerating voltages of 150, 180 and 250 kV, curing depths of 86, 138 and 277 g/m², respectively, are achieved at 80 % dose level.

Experienced values for industrial accelerating voltages are as follows:

- 80 – 150 keV thin layers in the field of printing inks or silicon-release materials, surface sterilisation
- 165 – 180 keV furniture foil, pressure-sensitive adhesives
- 180 – 250 keV boards, parquet, panels, lamination
- 250 – 300 keV composite

2.2 Absorbed Dose

Absorbed dose is defined as the amount of energy deposited into a specified mass of material. The unit of absorbed dose is gray (Gy), defined as the number of joules (J) of energy deposited into 1 kilogram (kg) of material. An older, but frequently used unit is megarad (Mrad).

$$1 \text{ Gy} = 1 \text{ J/kg}$$

$$1 \text{ kGy} = 1 \text{ kJ/kg}$$

1 Mrad = 10 kGy = 10 J/g = 2,4 cal/g

- Heating of water 1 degree 1 cal/g
- Evaporation of water 540 cal/g
- EB-curing of lacquer approx. 10 cal/g

At a fixed electron accelerating voltage, the dose is directly proportional to the electron beam current. The dose D [kGy] is proportional to electron current I [mA] and inverse to web speed v [m/min] as by equation 1.

$$D = k \times \frac{I}{v} \quad (1)$$

The k factor depends on the equipment and the accelerating voltage.

- The formula above shows that dose and electron current are directly proportional. If the ratio of electron current and speed are kept constant the dose is constant.

Typical values of the dose needed for practical applications are:

- Drying/curing of inks and coatings 15-30 kGy
- Crosslinking of plastic films 25-150 kGy
- Sterilization of medical products 7.5-35 kGy

2.3 Beam Uniformity

Beam uniformity describes how the electron beam is distributed over the working width. It is specified as a percentage deviation from the average value, e.g. 20 kGy \pm 10%.

2.4 Throughput

Throughput is a measure of the energy deposition rate and relates directly to the amount of material that can be processed within a given time interval. It is measured in kilo gray per second, abbreviated kGy/s.

An accelerator specified to 10 000 kGy m/min can provide a dose of 25 kGy when the web speed is 400 m/min, or 50 kGy at 200 m/min, etc. The processor will automatically adjust the beam intensity as the web speed changes so that the dose remains constant, see equation 1.

3. DOSIMETER SYSTEM

There are some systems available on the market using different measuring principles. The principles are based on physical or chemical changes in a substance.

- temperature
- colour
- luminescence
- radical concentration

In the past most dosimeter systems and applicable standards were made for high energy applications, i.e. electron irradiation at 5 – 10 MeV and for gamma radiation from cobalt-60.

An example of a dosimeter used for high energy electron irradiation applications is the calorimeter. In a high energy system of several MeV the penetration depth is enough to extend through the calorimeter. This is not the case for low energy systems due to the limited penetration.

3.1 Calorimeter

The calorimeter is a foam insulated calorimeter body that can contain water or is made of graphite. In the calorimeter body a thermistor is placed that measures the temperature. By reading this temperature before and after irradiation the dose can be calculated. This type of calorimeter is only used in high energy application and can not be used in the low energy range, but it is used as a standard dosimeter in many standards. In point 2.2 we learned that 10 kGy corresponds to 2,4 cal/g of matter that will give us a temperature change of 2,4° per 10 kGy in water. The picture below shows a standard calorimeter available from Risø High Dose Reference Laboratory - HDRL in Denmark.



Figure 2. Risø Calorimeter

Principle: Measures change in temperature
Dose range: 1.5 kGy –50 kGy
Reproducibility less than 1%, 1.s.d
Measurement: Digital Volt Meter
Use: Routine dosimetry and local reference dosimetry in high energy applications
Ref: ISO/ASTM 51631 [7]

3.2 Alanine dosimeter

Alanine dosimetry is an approved technique for the dose measurement in various radiation fields. In the amino acid alanine irradiation with ionizing radiation causes the production of free radicals (unpaired electrons), of which the number is proportional to the dose absorbed over a wide dose range. The crystalline structure of the tissue equivalent dosimeter material counteracts the recombination of radicals.

The readout of the radiation induced measuring signal is performed by the procedure of electron spin resonance (ESR).

The dosimeter are characterized by low influence of temperature, humidity and dose rate as well as a wide measuring range, which makes them applicable as a reference dosimeter. The picture below shows both pellets and the film dosimeter from Kodak.



Figure 3. Alanine pellets and films for electron or gamma reference dosimetry

Principle: Measures free radical concentration by EPR (= ESR)

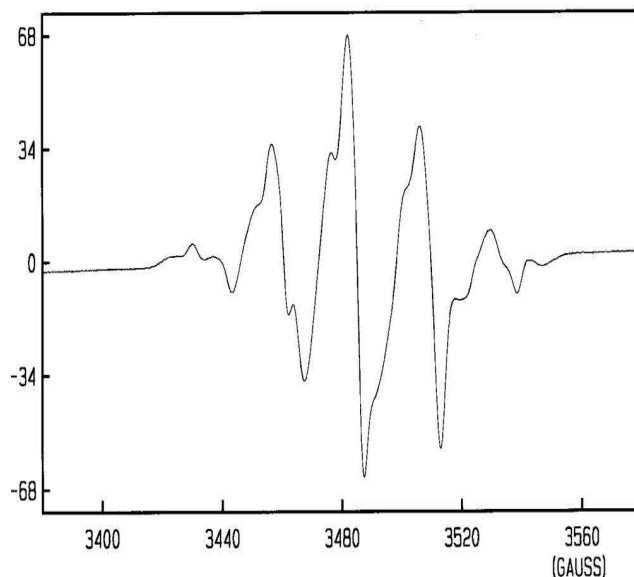


Figure 4. EPR Electron Paramagnetic Resonance spectrum of irradiated alanine pellet.

Dose range: 10 Gy – 100 kGy
 Stable signal for more than one year
 Reproducibility less than 0.5%, 1.s.d
 Thickness of alanine pellet dosimeter: 3 mm
 Thickness of alanine film dosimeter: 130 μ m

Measurement: EPR spectrometer

Use: Reference dosimetry

Ref.: ISO/ASTM 51607 [6]

For the low energy range of 75 – 300 keV even the alanine film becomes almost totally absorbing, limiting the practical use of these dosimeters in this energy range.

3.3 Risø B3 Film dosimeters

The production of the B3 is cooperation between Risø High Dose Reference Laboratory - HDRL in Denmark and Tesa AG (formerly Beiersdorf AG) in Germany [1]. The radiochromic dye is synthesized by Risø and sent to Tesa where it is cast in a continuous process. The B3 dye is dissolved in polyvinyl butyral (PVB) and cast over a knife edge onto a polyester backing materials that carries the liquid radiochromic material through the drying tunnel. After the drying a thin layer of radiochromic film is left clinging to the polyester backer. The principle of the film bases on the color change of para rosaniline nitrile with exposure to radiation. This color change is detected by measurement of the transmission of the film at 550 nm. This system is available from Risø High Dose Reference Laboratory - HDRL in Denmark.



Figure 5. Risø B3 dosimeter film

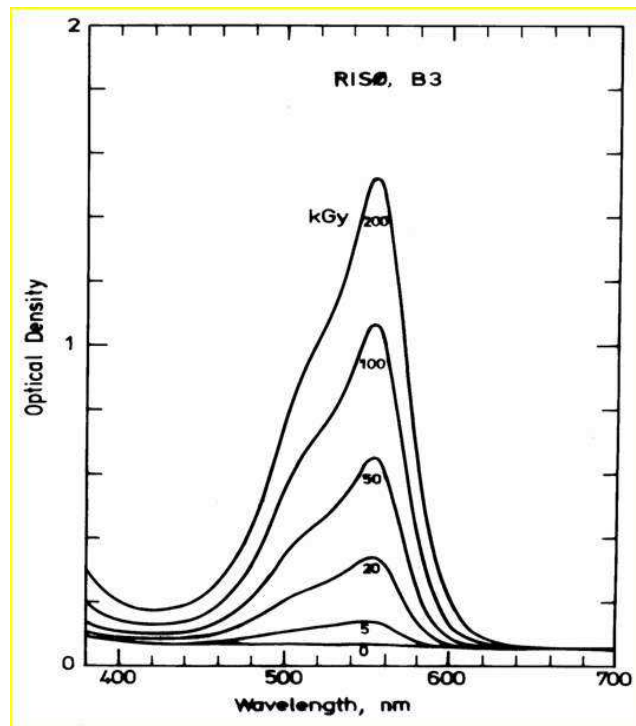


Figure 6. Absorption spectrum of Risø B3 dosimeter film Measured at 554 nm,

Principle: Measures change of colour
Thickness: 20 μm
Dose range: 3 kGy – 100 kGy
Measurement Spectrophotometer or scanner
Use: Dose mapping

Ref: ISO/ASTM 51275 [5]

3.4 GEX Dosimeter

The dosimeter materials used in the GEX dosimeter is the Risø B3 film. All dosimeters are numbered and packaged in protective foil punches, also bearing matching bar codes. The picture below shows the B3WINDose and the B3 DoseStrix dosimeter.

The read out of the dosimeters is done with an spectrophotometer. This dosimeter system is available from the GEX Corporatin in US.



Figure 7. B3WINDose Dosimeters

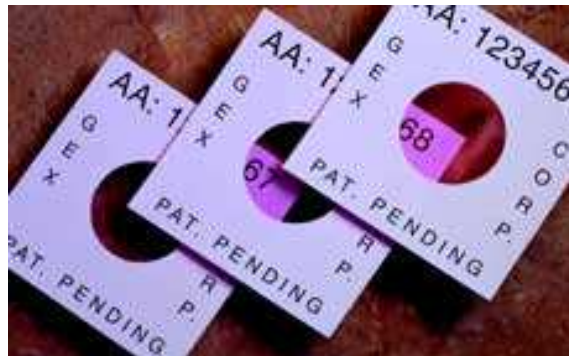


Figure 8. B3 DoseStrix Dosimeters

Sealed packaged to protect from influence from humidity and UV

Principle: Measures change of colour
 Thickness: 20 μm
 Dose range: 3 kGy – 100 kGy
 Measurement: Spectrophotometer or Readers
 Use: Dose map
 Routine dosimetry

Ref: ISO/ASTM 51275 [5]

3.5 FWT dosimeter

The FWT series of dosimeters use hexa(hydroxyethyl) aminotriphenylacetonitrile (HHEVC) dye. These colourless films gradually change to deep blue in relation to absorbed dose. The reading is done in a photometer or spectrophotometer. The wavelengths in general use are 510 nm and 600 or 605 nm. The FWT dosimeters are available from Far West Technology Inc. in US.



Figure 9. FWT-60-00: 1 cm x 1 cm x 42-52 microns

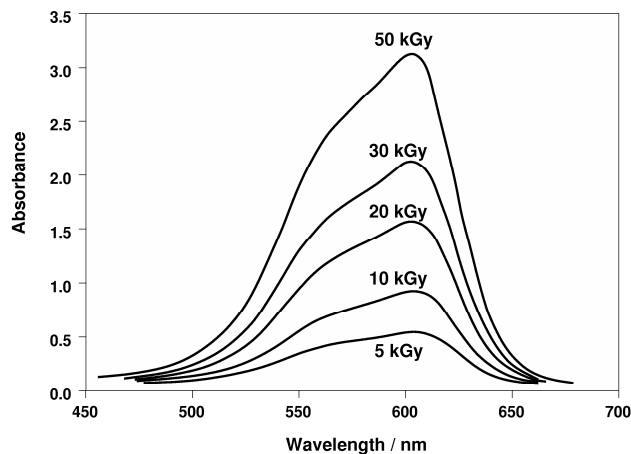


Figure 10. Absorption spectrum of FWT dosimeter film Measured at 605 nm,

Principle: Measures change of colour
 Thickness: 50 or 10 μ m
 Dose range: 1 kGy – 100 kGy
 Measurement: Spectrophotometer or Readers
 Use: Dose map
 Routine dosimetry

Ref: ISO/ASTM 51275 [5]

3.6 CROSSLINKING dosimeter

Tesa AG have used the experience from the development of the B3 and used the same type of dye as in 3.3 [2]. But because the transmission depends on the thickness of the film, a further variant of the film (grey film) contains in addition a pigment, which does not react to radiation. So with the extinction by the pigment, measured at 650 nm, the thickness of the film is calibrated. In the dose reader this is used to correct the readings for thickness variation of the casted film. This dosimetric film and dosereader are available from Electron Crosslinking AB in Sweden.

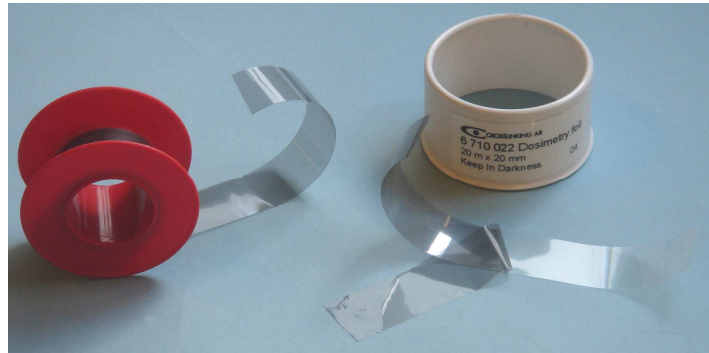


Figure 11. Roll of dosimeter film 20m x 20 mm



50

25

0 kGy

Figure 12. Irradiated dosimeter film 10 µm



Figure 13. Dosereader DR-020

Principle: Measures change of colour with thickness correction
Thickness: 20 or 10 μm
Dose range: 5 kGy – 75 kGy
Measurement: Dosereader DR-020
Use: Dose map
Routine dosimetry

Ref: ISO/ASTM 51275 [5]

4. DOSIMETER CALIBRATION

Any of the dosimeters mentioned must be calibrated. The response of thin film dosimeters depends on temperature and humidity during irradiation, and whenever possible the dosimeters should be irradiated at the same facility where they will be used [8] together with reference dosimeters. The reference dosimeter is issued by a calibration laboratory, and its measurement of dose is traceable to national standards.

For this in-plant irradiation to work it is necessary that the reference dosimeter and the routine dosimeter to be calibrated receive the same dose. This requirement can be fulfilled without difficulty at high energy electron irradiation, but in the low energy range this can sometimes be a problem due to the limited penetration of the electrons.

Even the thinnest reference dosimeter available – alanine film coated on a substrate – has a thickness (130 μm) that is similar to or larger than the range of low-energy electrons. As a consequence significant dose gradients will occur over the thickness of the dosimeter. The routine dosimeter is often a radiochromic thin film dosimeter with thickness in the range between 10 and 50 μm . The routine and the reference dosimeter will therefore not receive the same dose when irradiated with low-energy electrons. In-plant irradiation for calibration can therefore not be carried out at low-energy electron accelerators without the introduction of a measurement error. The figure 14 illustrates the problem.

It shows a typical depth dose distribution for an electron accelerator operating at 125 keV. Three commonly used dosimeters (18 μm Risø B3, 50 μm FWT-60 and 130 μm alanine film) are shown, each with thickness and measured average dose for irradiation at this accelerator indicated. The average dose for each dosimeter is based on a 10-MeV calibration, and it is shown how the different dosimeter thicknesses give rise to significant differences in measured average doses.

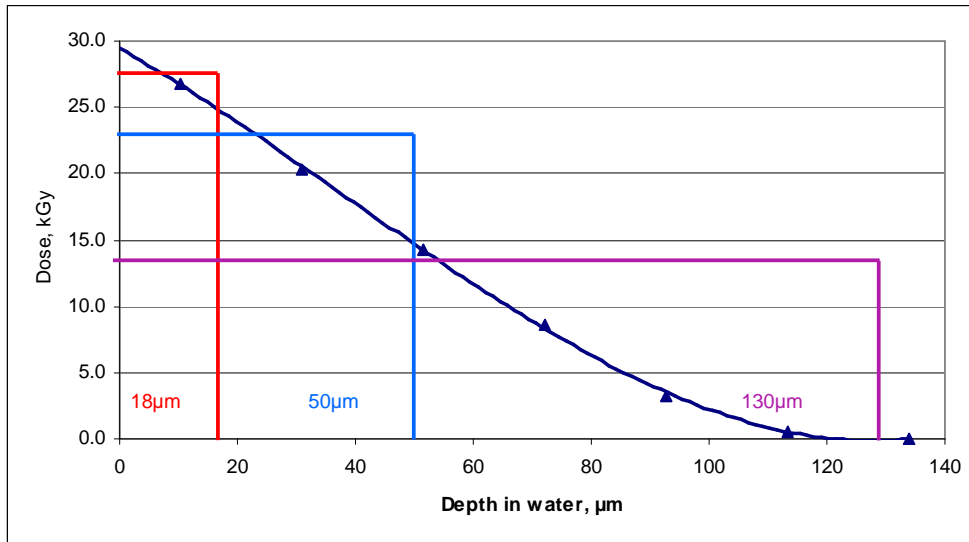


Figure 14. Typical depth dose distribution for a 125 keV electron accelerator. Three used dosimeters (18 μm Risø B3, 50 μm FWT-60 and 130 μm alanine film) are shown, each with thickness and measured average dose for irradiation at this accelerator.

In order to overcome this problem has been suggested [3] that all dose measurements are specified as average dose to water in the first micrometer of water equivalent absorbing material – in most cases equal to the dose in the first micrometer of the absorbing material. This dose is given the symbol D_{μ} and is independent of dosimeter thickness. A thickness of one micrometer was chosen as a finite thickness that will receive almost the same dose as an infinitely thin layer.

The calibration laboratory will measure the irradiated reference dosimeter and issue certificates stating the delivered dose in terms of D_{μ} . The user of the routine dosimeter will measure the response of his dosimeter and a calibration function can be established based on measured response and D_{μ} .

4.1 Determining D_{μ} .

Details of the method of determining D_{μ} are given in a paper by Helt-Hansen et al (2009). The value of D_{μ} depends strongly on dosimeter response function, dosimeter thickness, dose, radiation energy, accelerator window material and thickness, window to dosimeter distance, and temperature of the air between electron beam window and dosimeter.

Three correction factors are considered in order to obtain D_{μ} from the measured apparent dose D_{app} . The relationship is described by equation 2:

$$D_{\mu} = \frac{k_{water / dosimeter}}{k_{\mu} \cdot \eta} D_{app} \quad (2)$$

The backscatter correction factor $k_{water/dosimeter}$ is found by Monte-Carlo calculations. It corrects for differences in backscattered electrons from the different materials upon which the dosimeter might be placed. By applying $k_{water/dosimeter}$ it is ensured that the dose measured by the dosimeter is expressed as dose to water as if the dosimeter was placed on water. The value of $k_{water/dosimeter}$ is close to 1 when low atomic number materials are used as backing materials, and in most practical situations it can be ignored.

The dose gradient correction factor k_{μ} corrects for the geometrical difference in dose caused by the dose gradient through the thickness of the dosimeter. Calculation of the value of k_{μ} is based on a measured depth dose curve. k_{μ} is almost always less than 1 in low-energy applications.

The sensitivity correction factor η corrects for the fact that the response functions of the dosimeters are not linear. The dose gradient over the thickness of the dosimeter leads to different parts of the dosimeter being irradiated with different doses. The relative response of the dosimeter decreases as the dose increases because of the non-linear response function, and the measured average response does therefore not correspond to the average dose. The calculation of the value of η is based on the measured depth dose function and the response function of the dosimeter. A response function obtained by irradiation at high energy electrons or at gamma can be used for this purpose. η is always equal to or less than 1 for the dosimeters used in low energy dosimetry.

4.2 Measurements

We have carried out a series of measurements to verify the D_{μ} approach when applied to dosimetry at industrial low-energy facilities [10]. The complete work has been submitted to the Radiation Physics Chemistry for publications. The aim was to show that using high-energy calibrations for different types of dosimeters would lead to the same value for D_{μ} when these dosimeters were used for dose measurements at 100-300 keV electron irradiations.

The used dosimeters that were used are given in table 1.

Table 1. Dosimeters used in this work

<i>Dosimeter</i>	<i>Crosslinking EC-LAB 400</i>	<i>3M</i>	<i>Thickness</i>	<i>Measurement</i>
Alanine film, Kodak	Batch 307	Batch 308	130 μm	Bruker EMS- 104 Risø
Risø B3 (not packaged)	Batch B3-02, 8.200.1		17 μm	Scanner + RisøScan
Crosslinking G1A10 (grey films)	Batch, 6 710 023		12 μm	DR 020 Crosslinking
GEX DoseStix without package		Batch BB	18 μm	Genesys 20 Risø
GEX DoseStix without package		Batch BA	17 μm	Genesys 20 GEX
FWT-60		1081	47 μm	Genesys 20 GEX

The dosimeters were placed on 1-mm polystyrene plates for the irradiation at the two accelerators (see fig 15.).

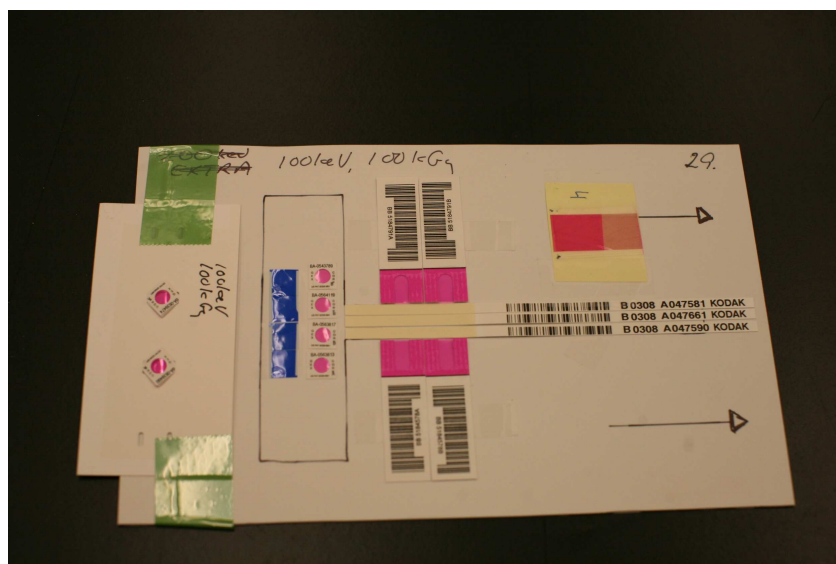


Figure 15. Polystyrene plate with dosimeters for irradiation

Irradiations were carried out at two electron accelerators: Electron Crosslinking AB, Halmstad, Sweden and 3M Corporate Research, St. Paul, MN, USA. The general data for the two accelerators are given in table 2.

Table 2. General characteristics of the electron accelerators used in this work

	<i>Crosslinking EC-LAB 400</i>	<i>3M</i>
Energy range	75 – 300 keV	100 – 300 keV
Beam current range	1 – 50 mA	2-20 mA
Product speed through beam zone	30 m/min	10 m/min
Extended beam	Scanned	Long cathode
Beam window	12 μm Titanium	13 μm Titanium
Distance window – dosimeter	33 mm	47 mm

The Electron Crosslinking EC-LAB 400 accelerator is a laboratory model with a vertical, scanned beam (see fig 16). Samples or dosimeters are placed on a tray that is passed under the beam at the selected speed. The tray height can be adjusted to different window-to-dosimeter distances.

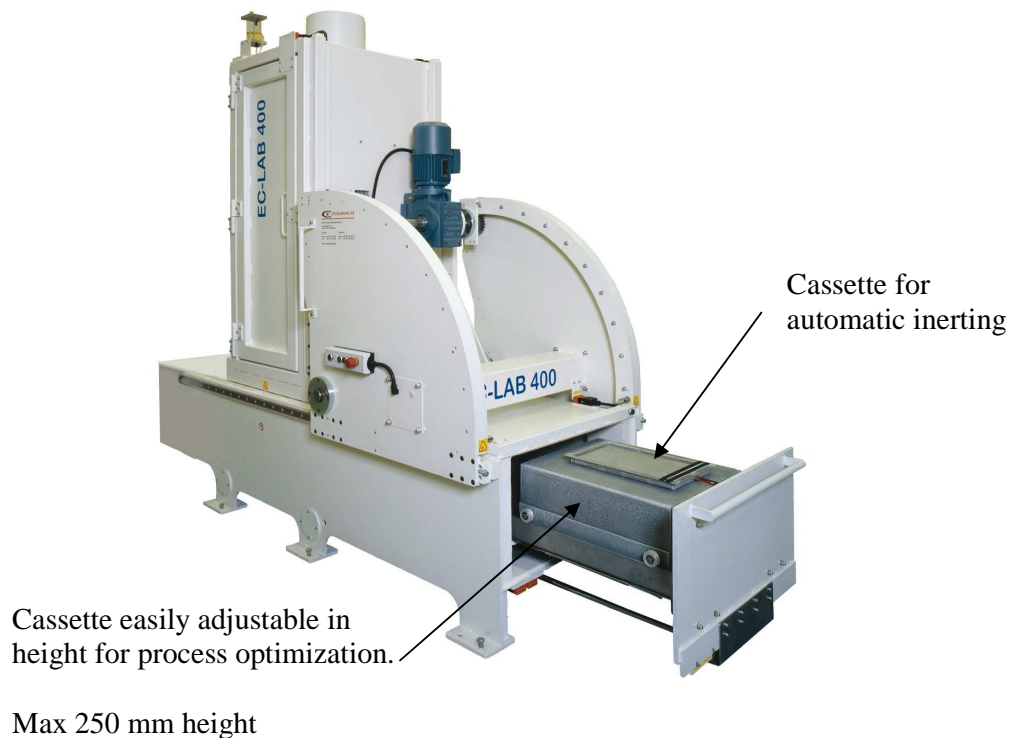


Figure 16. EC-LAB 400 in load position for the cassette (80–300 kV, 5-30 m/min, 400 mm).

The 3M accelerator is a pilot scale machine for experiments where long webs of materials are passing at constant speed under the beam (see fig 17). In this experiment plates with dosimeters were affixed to the web and moved under the beam. A constant window-to-dosimeter distance was ensured as the web moved under the beam in close contact with a metal backing.

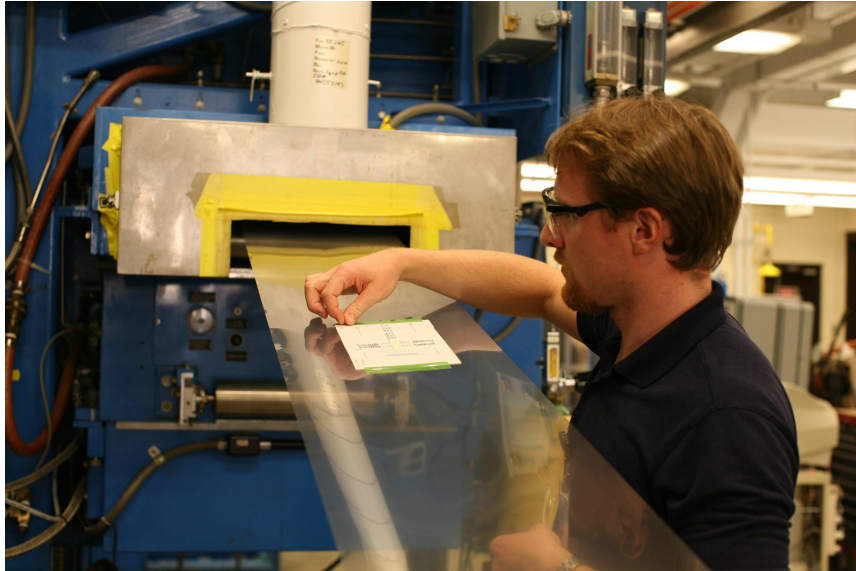


Figure 17. Plate with dosimeters placed on the web for irradiation at the 3M electron accelerator.

Depth dose curves were measured with stacks of Risø B3 dosimeter films for both accelerators at each energy used in this experiment. The dosimeter films were measured with a scanner and RisøScan software [4]. The depth dose curves in fig. 18 (Crosslinking) and fig.19 (3M) show significant differences for the same energies at the two accelerators. These differences are caused by differences in window material and thickness, by differences in window-to-dosimeter distance and by differences in temperature of the air between window and dosimeter.

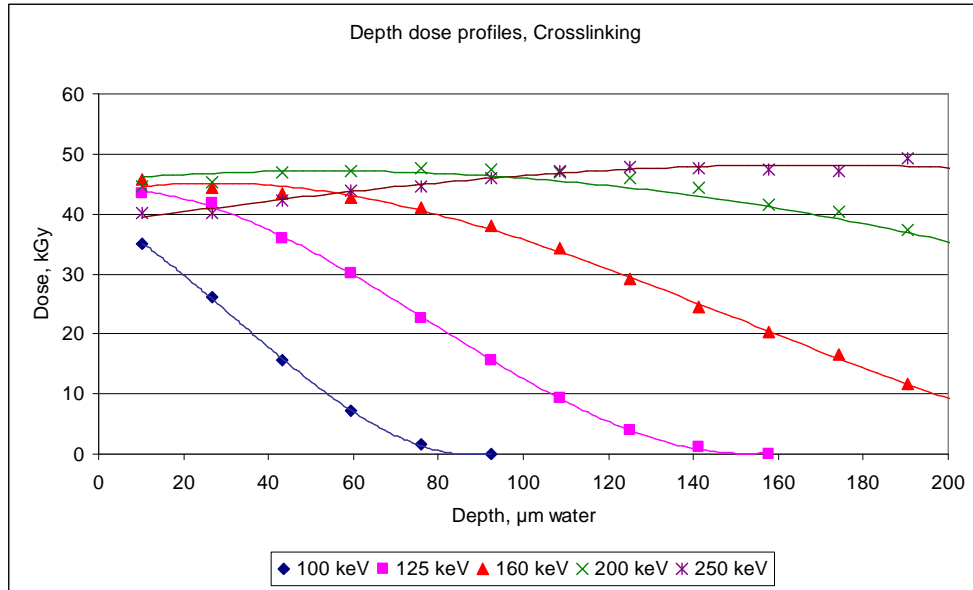


Figure 18. Measured depth dose curves at the Electron Crosslinking accelerator

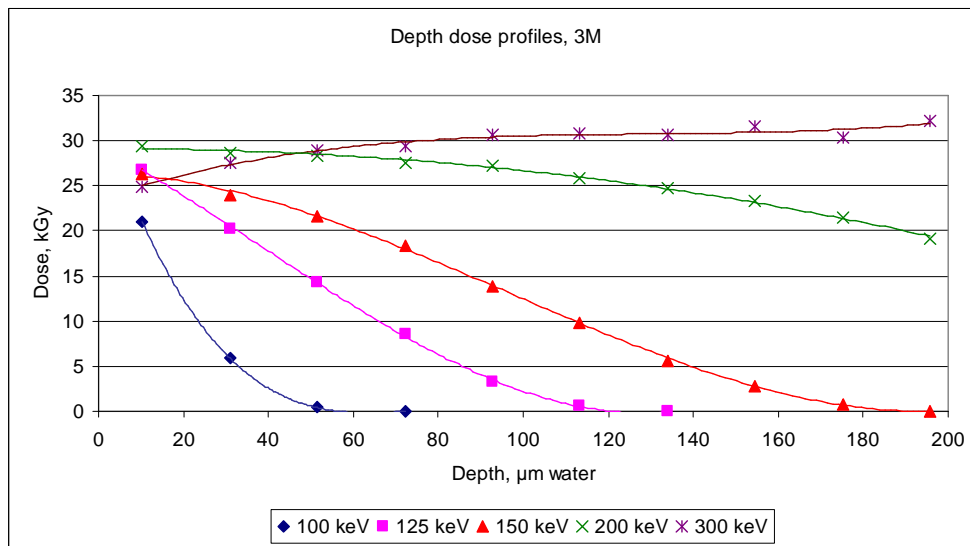


Figure 19. Measured depth dose curves at the 3M accelerator

An example of the results is given in table 3 for irradiation at the Crosslinking electron accelerator at 100 keV. The correction by k_{μ} (dose gradient) is large at this low energy, in particular for the thickest dosimeter (the alanine film). The alanine film dosimeter was considered as the reference dosimeter, and the doses measured by the other dosimeters were compared with the dose found by the alanine dosimeter with all doses expressed as D_{μ} .

Table 3. Correction factors and calculation of D_{μ} for irradiation at the Crosslinking accelerator at 100 keV.

Crosslinking 100 keV	D_{app}	D_{avg}	k_{μ}		$D_{\mu}(water)$			
Dosimeter	kGy	kGy	Dose gradient correction factor	Combined Correction factor $1/(k_{\mu}*\eta)$	kGy	Ratio to alanine		
							Average	St. dev
Alanine 132 μ m	2,82	2,95	0,19	5,51	15,5			
	3,68	3,91	0,19	5,59	20,6			
	5,12	5,59	0,19	5,75	29,4			
	6,89	7,80	0,19	5,96	41,1			
Risø B3 18 μ m	12,8	12,8	0,89	1,12	14,4	0,93		
	17,0	17,0	0,89	1,12	19,1	0,93		
	25,8	25,8	0,89	1,12	28,9	0,98		
	35,1	35,1	0,89	1,12	39,4	0,96	0,95	0,03
Crosslinking G1A10 12 μ m	14,5	14,5	0,88	1,14	16,6	1,07		
	18,7	18,7	0,88	1,14	21,4	1,04		
	27,4	27,4	0,88	1,14	31,3	1,06		
	35,6	35,6	0,88	1,14	40,7	0,99	1,04	0,04

Table 4 shows an example for irradiation at the 3M electron accelerator which leads to the same conclusions as for the irradiations at the Crosslinking accelerator, only in this case the corrections from D_{app} to D_{μ} are larger due the lower effective energy of the 3M accelerator.

Table 4. Correction factors and calculation of D_{μ} for irradiation at the 3M accelerator at 100 keV.

3M, 100 keV	D_{app}	D_{avg}	k_{μ}		$D_{\mu}(water)$			
Dosimeter	kGy	kGy	Dose gradient correction factor	Combined Correction factor $1/(k_{\mu}*\eta)$	kGy	Ratio to alanine		
							Average	St. dev
Alanine 128 μ m	2,06	2,21	0,10	11,33	23,3			
	2,85	3,17	0,10	11,70	33,4			
	3,26	3,69	0,10	11,91	38,9			
	4,53	5,43	0,10	12,61	57,2			
FarWest 43.5 μ m	5,63	5,72	0,36	2,82	15,9	0,68		
	9,32	9,57	0,36	2,85	26,6	0,80		
	10,8	11,2	0,36	2,86	31,0	0,80		
	21,7	23,1	0,36	2,96	64,3	1,12	0,85	0,19
B3 BB DoseStix (Risø) 17.6 μ m	15,8	15,9	0,67	1,51	23,9	1,02		
	24,5	24,7	0,67	1,51	37,1	1,11		
	30,5	30,8	0,67	1,51	46,2	1,19		
	43,3	43,8	0,67	1,52	65,7	1,15	1,12	0,07
B3 BA DoseStix (GEX) 17.0 μ m	13,1	13,2	0,68	1,48	19,4	0,83		
	18,1	18,2	0,68	1,49	26,9	0,81		
	21,9	22,1	0,68	1,49	32,6	0,84		
	29,9	30,2	0,68	1,49	44,6	0,78	0,81	0,03

All results from the two electron accelerators are averaged in table 5. The closeness of the overall ratio to unity is a good indication of the validity of the approach.

Table 5. Average ratios $D_{dosimeter}$ to $D_{alanine}$ in terms of D_{μ} for all dosimeters irradiated at the two electron accelerators.

Overall average		
	Ratio	St. dev.
All	1,00	0,08
Crosslinking	0,97	0,04
3M	1,02	0,10

The average correction factors for each energy are given in table 6 (Crosslinking) and table 7 (3M). The corrections to be applied to D_{app} to obtain D_{μ} are relatively small for the thinnest dosimeters (DoseStix and G1A10) and become more significant for increasing thickness of the dosimeter.

Table 6. Crosslinking accelerator. Average correction factors $1/(k_{\mu}*\eta)$

Energy →	100	125	160	200	250
Alanine	5,70	2,75	1,39	0,98	0,89
DoseStix	1,12	1,02	1,01	0,97	0,99
G1A10	1,14	1,02	1,01	0,95	0,99

Table 7. 3M accelerator. Average correction factors $1/(k_{\mu}*\eta)$.

Energy →	100	125	150	200	300
Alanine	11,89	3,92	2,08	1,13	0,84
Far West	2,87	1,35	1,10	1,02	0,88
DoseStix	1,50	1,11	1,03	1,01	0,94

5. CONCLUSION

We have introduced a new dosimetric term D_μ , the average dose to water in the first micrometer of a water equivalent absorber that eliminates the effects of dose gradients through the thickness of the dosimeter when irradiated with low energy electrons.

We have shown that calibration of routine dosimeters can be carried out by in-plant irradiation at low-energy electron accelerators by irradiating the routine dosimeters and the reference dosimeters together so that they receive the same dose. The response function for the routine dosimeter can be generated in terms of its measured response versus D_μ as measured with the reference dosimeter. In subsequent dose measurements, the dose measured with the routine dosimeter will be in terms of D_μ .

Verification that a calibration of a routine dosimeter obtained by gamma or by 10-MeV electron irradiation is valid at low energy irradiation can be carried out in the same way as an in-plant calibration. In this case it is necessary to calculate D_μ for both the reference dosimeter and for the routine dosimeter, but as described above, for dosimeters that are thinner than approximately 20 μm the difference between D_{app} and D_μ is small and at energies above 125 keV it may be acceptable not to apply corrections to D_{app} .

In most practical situations the user does therefore not have to carry out corrections to the routine dosimetry system in order to report dose as D_μ . The calibration laboratory must be able to provide dose measurements in terms of D_μ , and the user can then calibrate in terms of dosimeter response versus D_μ .

6. ACKNOWLEDGEMENT

This paper is based on the work that has been done for the “a new concept in industrial low energy electron dosimetry” together with the co-authors below. The co-authors are also thanked here for their assistance with the planning and carrying out of the experiments. The complete document has been submitted to Rad Phys Chem.

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