Gamma – uncertainty estimation in dosimetry

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Standards

- **ISO/ASTM 51707:2002** *Guide for Estimating Uncertainties in Dosimetry for Radiation Processing*

- **ISO/ASTM 51261:2002** *Practice for Use of the Ethanol-Chlorobenzene Dosimetry System*

- **ASTM E 2303-03** *Guide for Absorbed-Dose Mapping in Radiation Processing Facilities*

- *Discussion paper on uncertainties in routine dosimetry for Gamma and EB plants*, **PANEL ON GAMMA & ELECTRON IRRADIATION**

Introduction

- The objective of a measurement is to determine the value of the measurand (e.g. absorbed dose).

- In general, the result of a measurement is only an approximation or estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty of that estimate.

Introduction

- For absorbed dose to be meaningful, the overall uncertainty associated with measurements must be estimated and its magnitude quantified.

- Uncertainty: parameter, associated with a measurand or derived quantity, that characterizes the distribution of the values that could be reasonably attributed to the measurand or derived quantity.

- Error: result of a measurement minus a true value of the measurand.

Classification of uncertainty

- Based on the type of effect causing uncertainty: random or non-random (systematic)

- Based on the method of evaluation of uncertainty: ***Type A*** or ***Type B***

Type of effects causing uncertainty

- **Random:** arises from unpredictable (stochastic) variation of influence quantities. It can be reduced (by increasing the number of observations) but not eliminated.

- **Non-random (systematic):** arises from a recognised effect of influence quantities. It can be reduced if the effect can be quantified.

Methods of evaluation

The purpose of the ***Type A*** and ***Type B*** classification is to indicate the two different ways of evaluating uncertainty components:

- **Type A** evaluation: method of evaluation of a standard uncertainty by the statistical analysis of a series of observations (u_A is obtained from a probability density function derived from an observed frequency distribution)
- **Type B** evaluation: method of evaluation of a standard uncertainty by means other than the statistical analysis of a series of observation (u_B is obtained from an assumed probability density)

Sources of uncertainty in dosimetry

- Uncertainty in the absorbed dose received by the dosimeters during system calibration
- Analysis of dosimeter response
- Fit of dosimetry data to a calibration curve
- Routine use of dosimeters in a production irradiation facility

Each source of uncertainty usually consists of several components of both **Type A** and **Type B**.

Combining uncertainties

For sources of uncertainty that are independent (not correlated), the combined uncertainty is obtained by combining all Type A and Type B standard uncertainties in quadrature. This combined standard uncertainty is designated as $\boldsymbol{u_c}$.

$$u_c = \sqrt{u_A^{\,2} + u_B^{\,2}}$$

For sources of uncertainty that are related, the effects of those correlation must be taken into account in determining the combined standard uncertainty.

The overall uncertainty ***U*** is obtained by multiplying the combined standard uncertainty $\boldsymbol{u_c}$ by a coverage factor ***k***:

$$U = k \cdot u_c$$

For probability distributions that are approximately normal:
***k* = 2** corresponds approximately to a confidence level of **95 %** and ***k* = 3** to **99 %**.

Ethanol-Chlorobenzene (ECB) Dosimetry System

The ECB dosimetry system is based on a process of radiolytic formation of HCl in aqueous ethanolic solution of CB by ionizing radiation.

The conductivity of a solution depends on the concentration of free ions in the solution. Irradiation causes changes in the concentration of conducting species in the dosimeter solution. Oscillometry method is an electro-analytical method of conductivity measurements; high-frequency, 1-600 MHz, alternating current is applied to measure changes in the composition of chemical systems. Oscillometry method is relative; calibration by means of ampoules irradiated to known doses is needed. This method is non-destructive.

- The system consists of:

- **dosimeters** - sealed ampoules containing dosimeter solution (24 vol. % CB, 4 vol. % water, 0.04 vol. % acetone, 0.04 vol. % benzene, and 71.92 vol. % ethanol)
- **oscillometric reader** Radelkisz OK 302 (Institute of Isotopes, Hungary)
- **reference standards**

Applicability

- dose range: [1, 100] kGy
- dose rate: <1 MGy/s
- for gamma-ray sources,
  the initial photon energy > 0.6 MeV
- irradiation temperature of the dosimeter:
  [-40, 80] °C

Influence Quantities

- **Temperature**

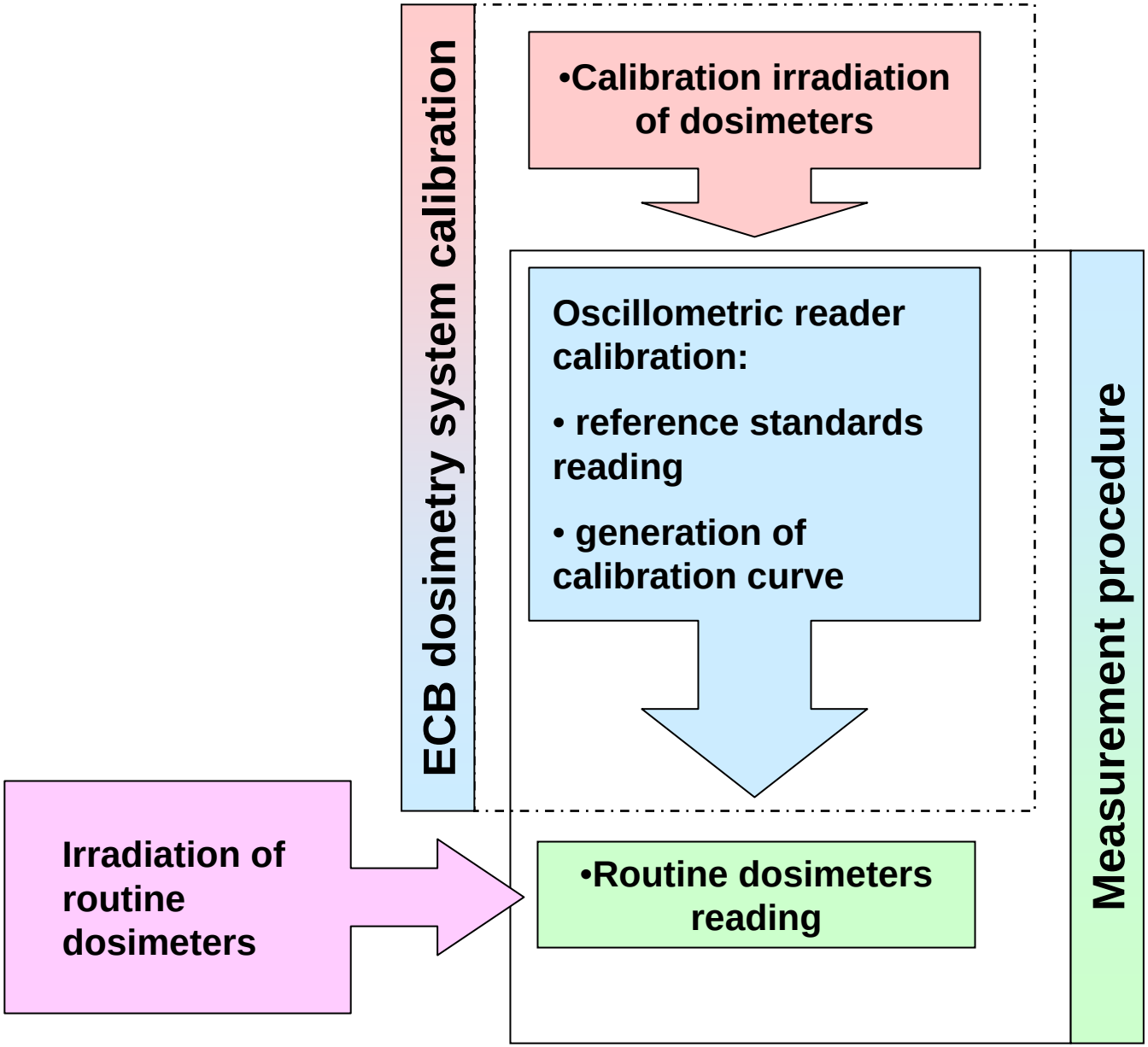
  ECB has a response which is independent of the irradiation temperature (-40 to 80 °C) and, also, of the post-irradiation storage temperature.

  Measurement temperature: the temperature of solution to be measured should be similar to that of the calibration ampoules.

- **Time**

  Dosimeter solutions are stable before and after irradiation (can be stored for years).

- Sensitivity to **impurities in dosimeter solution**: negligible
- **Dose dependence**: negligible (from 1 to 100 kGy)
- **Dose rate dependence**: negligible (up to 1 MGy/s)
- no influence of **humidity** and **oxygen** as dosimeter solutions are contained in sealed ampoules
- **UV** exposure should be avoided during storage



Standards and routine dosimeters are kept together for, at least, half an hour to get the same temperature

Uncertainty: calibration irradiation of dosimeters

- Calibration irradiation of dosimeters was performed by RISØ High Dose Reference Laboratory
- Three dosimeters at each dose point (1, 3, 5, 7, 10, 20, 30, 40, 50, 75, 100 kGy)
- Uncertainty of the nominal dose, given at $k=2$ (Irradiation Certificate no. 06C-50/20.09.2006):

Non-random: 2.2 %

Random: 2.0 %

Combined: 3.0 %

Uncertainty due to calibration irradiation of dosimeters:

$$u_{irr} = 1.5\ \%\ \text{at}\ k=1$$

Uncertainty: reference standard reading

- Two components:
  - batch variability
  - oscillometric reader variability

- **Evaluation of uncertainty due to batch variability, $u_{b,A}$ (*Type A*)**
  For every dose point, oscillometric signals of corresponding reference dosimeters were averaged and their coefficient of variation calculated.

$U_{b,A}$ is evaluated as follows:

$$u_b(\%) = \sqrt{\frac{\sum_{i=1}^{k} CV_{b,i}^2}{k}}$$

where $CV_{b,i}$ is the coefficient of variation of oscillometric signal for dose point ***i*** and ***k*** is the number of dose points

Oscillometric signal of reference standards - measurement temperature: 24.5±0.4 °C

Dosimeter ID	Dose point [kGy]	Averaged oscillometric signal [a.u.]	CV_b [%]
B1503, B2280, B2904	1	128.25	0.09
B1515, B2290, B2916	3	204.32	0.20
B1520, B2303, B2922	5	271.5	0.45
B1525, B2314, B2931	7	333.97	0.17
B1531, B2325, B2940	10	418.48	0.22
B1538, B2330, B2950	20	645.3	1.25
B1548, B2337, B2953	30	826.6	0.44
B1558, B2343, B2965	40	967.8	0.27
B1567, B2352, B2975	50	1082.5	0.20
B1574, B2363, B2988	75	1287.0	0.44
B1584, B2378, B2995	100	1422.9	0.48

$$u_{b,\,A}=0.49\ \%$$

Uncertainty: reference standard reading

- **Evaluation of uncertainty due oscillometric reader variability, $u_{eq,\,A}$ (*Type A*)** The signal of reference standard dosimeters was measured over a period of three days. For every reference standard dosimeter the signal was averaged and corresponding coefficient of variation calculated.

$U_{eq,\,A}$ is evaluated as follows:

$$u_{eq}(\%) = \sqrt{\frac{\sum_{j=1}^{l} CV_{eq,j}^{2}}{l}}$$

where $CV_{eq,\,j}$ is the coefficient of variation of oscillometric signal for dosimeter ***j*** and ***l*** is the number of reference standard dosimeters

Oscillometric signal of reference standards - measurement temperature: 24.5±0.4 °C

Dosimeter ID	Dose point [kGy]	Averaged oscillometric signal – over three days [a.u.]	CV_{eq} [%]
B 2223	0	89.83	0.74
B 1503	1	128.3	1.23
B 2280		128.1	1.45
B 2904		128.4	1.25
B 1515	3	203.9	1.26
B 2290		204.7	1.31
B 2916		204.4	1.44
…	…	…	…
B 1584	100	1421.3	0.18
B 2378		1417.0	0.32
B 2995		1430.5	0.47

$u_{eq,\,A}$=0.83 %

Curve fitting

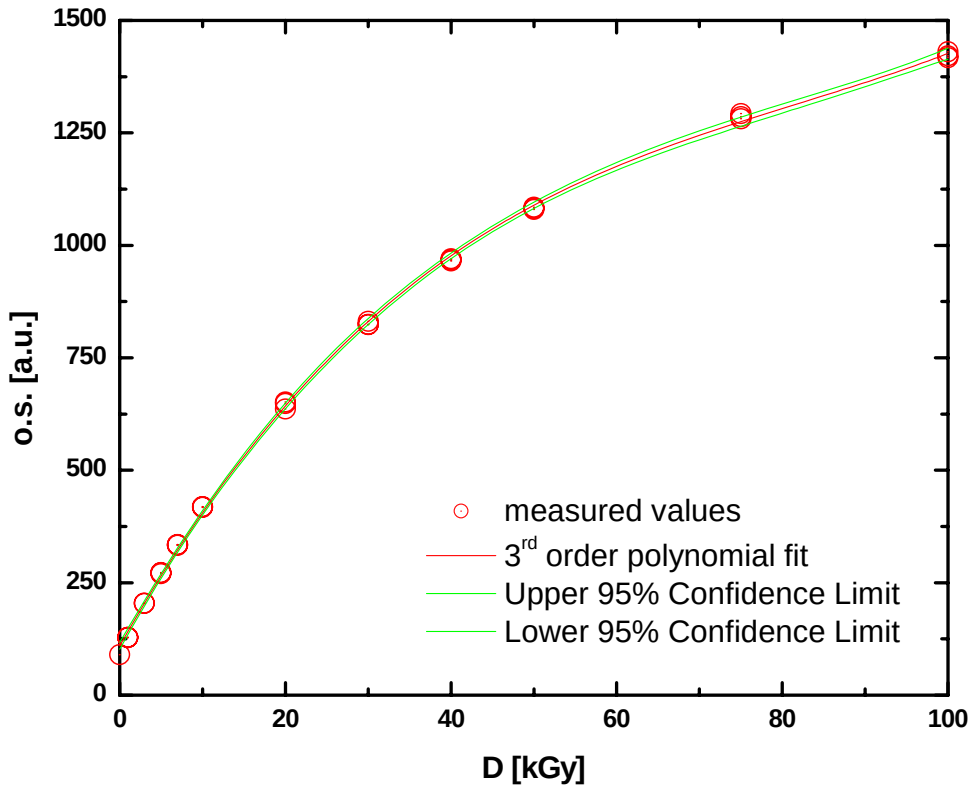
Polynomial fit test parameters

Degree of polynomial	r^2	*F*-value
2	0.99563	3530.9
3	0.99951	20391.9
4	0.99987	53812.4

- The goodness-of-fit can be evaluated by several parameters; two such parameters are the coefficient of determination, r^2 (or correlation coefficient), and the *F*-value (or *F*-statistic)
- A good fit is indicated by r^2 values close to 1 and larger *F*-value indicates better fit
- The degree of the polynomial selected should be the lowest order that gives a good fit to the data

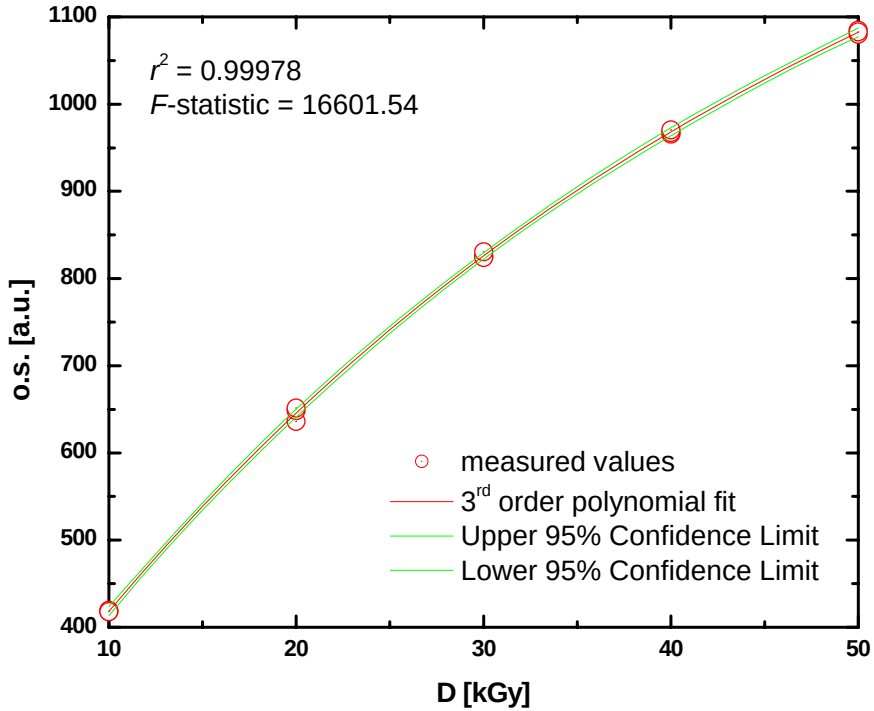
r^2 values for degrees 3 and 4 indicate essentially equally good fits. *F*-value test is much more sensitive than r^2. A 3rd order polynomial was selected for fitting calibration data.

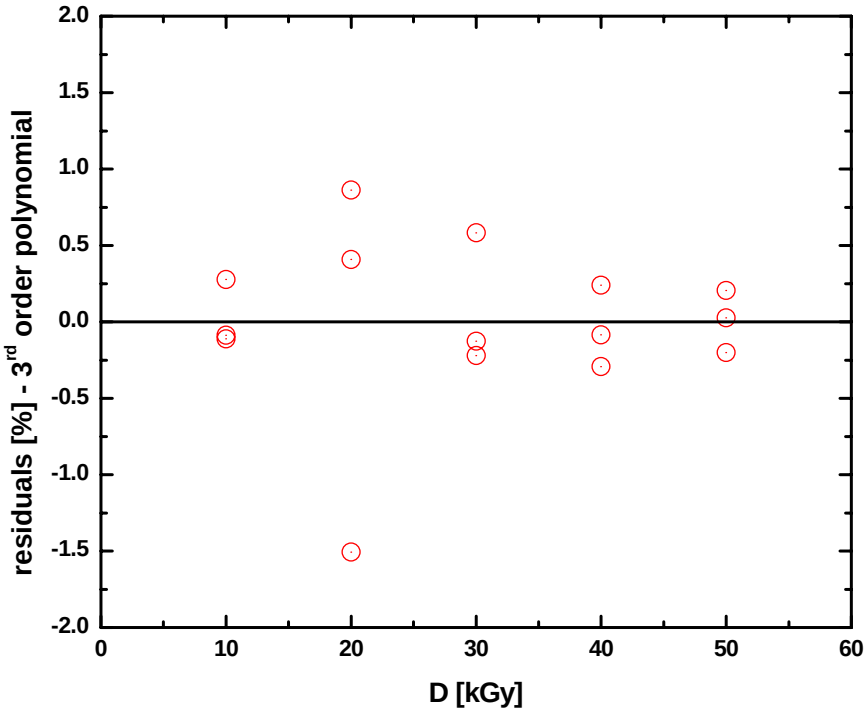
Calibration curve and confidence limits; [1, 100] kGy



$$o.s. = 109.83681 + 32.71021*D - 0.32963*D^2 + 0.00134*D^3$$

Calibration curve and confidence limits; 10-50 kGy





o.s. = 134.25333 + 31.5631*D - 0.33098*D^2 + 0.00158*D^3

Uncertainty: curve fitting

Dose [kGy]	o.s. - polynomial fit [a.u.]	U.C.L. 95% [a.u.]	L.C.L. 95% [a.u.]	$u_{f,B}$ [%]
24.89	739.25	743.34	735.16	0.277
24.93	739.97	744.06	735.88	0.276
24.97	740.69	744.77	736.61	0.276
25.00	741.16	745.04	736.88	0.275
25.02	741.41	745.49	737.34	0.275
25.06	742.13	746.2	738.06	0.274
25.1	742.85	746.91	738.79	0.274
25.14	743.57	747.62	739.51	0.273
25.18	744.28	748.34	740.23	0.272
25.22	745	749.05	740.95	0.272
25.26	745.72	749.76	741.67	0.271
25.3	746.43	750.47	742.4	0.270
25.34	747.15	751.17	743.12	0.270

$$u_{f,D}[\%] = \frac{U.C.L_D - L.C.L._D}{o.s._D} \cdot \frac{1}{4} \times 100$$

Components of Uncertainty

- Dosimetry system calibration:

1. Calibration irradiation: $u_{irr,B}$**=1.5 %** (dose)
2. Batch variability: $u_{b,\,A}$**=0.49 %** (o.s.)
3. Oscillometric reader variability: $u_{eq,\,A}$**=0.83 %** (o.s.)
4. Curve fitting: $u_{f,\,B}$ (o.s.)

- Routine dosimeters reading:

5. Batch variability, (2)
6. Oscillometric reader variability, (3)

Example: uncertainty for a measured value of 25 kGy

Component of uncertainty	*Type A*, %	*Type B*, %
Calibration irradiation, $u_{irr,\,B}$	-	1.5
Batch variability, $u_{b,\,A}$	0.93	-
Oscillometric reader variability, $u_{eq,\,A}$	1.57	-
Curve fitting, $u_{f,\,B}$	-	0.52
Dosimetry system calibration	**1.83**	**1.59**
	2.42	
Batch variability, $u_{b,\,A}$	0.93	-
Oscillometric reader variability, $u_{eq,\,A}$	1.57	-
Routine dosimeters reading	**1.83**	**-**
	1.83	
Combined uncertainty, u_c (1σ)	**3.03**	

$$u_c[\%] = \sqrt{u_{irr}{}^2 + u_b{}^2 + u_{eq}{}^2 + u_f{}^2 + u_b{}^2 + u_{eq}{}^2}$$

Reporting results

Combined uncertainty in the measurement of dose:

u_c[kGy]=(3.03/100) * 25 [kGy]=0.76 [kGy]

The overall uncertainty at $k=2$ (95% confidence level): U= 2*0.76 [kGy]=1.52 [kGy]

***D* = (25.0±1.5) kGy; *k*=2**

In the routine process control, measured values of dose are related to minimum/maximum dose delivered in the product. In this case, an additional component of uncertainty (evaluated in dose mapping) must be added to u_c when a minimum/maximum dose is reported.

Thank you for your attention!