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Study on the uncertainty of passive area dosimetry systems for environmental radiation monitoring in the framework of the EMPIR “Preparedness” project

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ABSTRACT

One of the objectives of the EMPIR project 16ENV04 “Preparedness” is the harmonization of methodologies for the measurement of doses with passive dosimetry systems for environmental radiation monitoring in the aftermath of a nuclear or radiological event. In such cases, measurements are often performed at low radiation dose rates, close to the detection limit of the passive systems.

The parameters which may affect the dosimetric results of a passive dosimetry system are analyzed and four laboratories quantitatively evaluate the uncertainties of their passive dosimetry systems. Typical uncertainties of five dosimetric systems in four European countries are compared and the main sources of uncertainty are analyzed using the results of a questionnaire compiled for this specific purpose.

To compute the characteristic limits of a passive dosimetry system according to standard ISO 11929, the study of the uncertainty of the system is the first step. In this work the uncertainty budget as well as the characteristic limits (decision thresholds and detection limits) are evaluated and the limitations and strengths of a complete analysis of all parameters are presented.

1. Introduction

While environmental dosimetry in routine application requires the measurement of low dose levels in long monitoring periods (i.e. three or six months) (Duch, 2017), different methodologies are required in emergency situations. In the framework of the “Preparedness” project (Neumaier, 2019), the passive dosimetry systems are studied for their application of monitoring artificial sources of radiation in the environment (after a radiological or nuclear event). A detailed study on the results of a “Preparedness” intercomparison investigates the long-term behavior of 38 dosimetry systems which may be used in the aftermath of a radiological or nuclear event at three dosimetric reference sites which are operated by the Physikalisch-Technische Bundesanstalt (PTB) (Dombrowski, 2019).

The dose rate level is the most important reference value to determine potential protective actions in the early phase of a nuclear or radiological event and also in the intermediate and late phase. In the area close to the nuclear power plant of Fukushima the dose rates measured two months after the accident were in the range of 0.3 μSv/h to 19.3 μSv/h (ICRU, 2015).

In this work, the study of the uncertainties of passive area dosimetry systems used for environmental monitoring is presented. Data is collected from five dosimetry systems of the four EMPIR “Preparedness” partners: ENEA (Italy), VINS (Serbia), CLOR (Poland) and RBI (Croatia).

The results of this study are used as a starting point for the quantification of the characteristic limits of the dosimetry systems by applying the ISO standard 11929 (ISO, 2019). Several studies on the characteristic limits can be found in literature (Ling, 2010; Roberson and Carlson,

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1992; Ondo Meye, 2017; Saint-Gobain, 2002) but the majority of these studies refer to personal dosimetry systems. Currently it is also possible to find specific application software to evaluate the characteristic limits of measurement systems (UncertRadio, 2014; LIMCAR, 2020).

It is well known that the identification of a nuclear or radiological event by means of environmental radiation monitoring is only possible if the related radiation dose increment, quantified by the measurand of a measurement system, is higher than the decision threshold. Furthermore, the detection limit is defined as the smallest true value of the measurand for which the probability to obtain a measurement result smaller than the decision threshold is less than a predefined value (in most cases this value is set at 5%). In this context, it is worth noting that the computation of the detection limit is necessary to determine if a passive dosimetry system is suitable for dose measurements in emergency situations. The computation of the characteristic limits is presented in section 2.3.

2. Estimation of the ambient dose equivalent with passive area dosimetry systems for environmental monitoring

2.1. Model function of ambient dose equivalent

According to the standard IEC 62387:2020 (IEC, 2020), when area dosimeters are used to estimate effective dose, they need to be capable to measure H*(10) due to photon radiation, in the unit sievert (Sv). The standard is applicable for the photons within the energy range between 12 keV and 7 Mev, but the minimum energy range is between 80 keV and 1.25 MeV.

According to ISO standard 11929-1 (ISO, 2019), the evaluation of a measurement consists of an estimation of a measurand and the associated standard uncertainty. The measurand is generally determined from other quantities by a formula. The symbol H is considered equivalent to $H^*(10)$ in this application, and h is the estimate of the measurand H.

The simplified model function of the measurand $H^*(10)$ for a dosimetry system can be deduced starting from the computation of the dose of an issued detector H_{gross}:

$$H_{gross} = M \cdot k_{ref} \cdot k_{det} \cdot k_{E,\alpha} \cdot k_n \cdot k_{env} \quad (1)$$

where:

- M is the reader signal from the detector (x) minus the contribution of the background (z) of the dosemeter reading system:

$$M = x - z$$

- $k_{ref} = \frac{1}{r_{ref}}$ is the inverse of the reader sensitivity r_{ref}: the quotient of the average net signal of N reference dosemeters (e.g. N = 5) and a reference dose which is metrologically traceable;

$$r_{ref} = \frac{\overline{x - z}}{H^*(10)_{ref}}$$

(x is the reader signal from the i^{th} detector, z is the blank signal of the reader);

- $k_{det} = \frac{1}{r_{det}}$ is the inverse of the detector normalization factor r_{det} (also called element correction coefficient of the single dosemeter, specific calibration factor or individual sensitivity correction factor); it is the quotient of the response of a single dosemeter and the average response of the simultaneously irradiated reference dosemeters

$$r_{det} = \frac{x - z}{\eta - z}$$

(x is the reader signal from the detector, z the reader blank signal and η the average signal from the detectors of the reference group);

- $k_{E,\alpha} = \frac{1}{r_{E,\alpha}}$, where $r_{E,\alpha}$ is the relative response due to energy and angle of incidence;
- $k_n = \frac{1}{r_n}$, where r_n is the correction factor for non-linearity of the detector's response with the dose variation;
- $k_{env} = \frac{1}{r_{env}}$, where $r_{env}$is the correction factor for environmental influences (e.g. ambient temperature, relative humidity, atmospheric pressure, light exposure).

The fading effect of the signal should be taken into account in the evaluation of k_{env} because, as it is known, it is closely related to environmental factors (for example, in a TLD, the temperature and time of storage are the main factors that influence the probability of escaping of charge carriers from trapping centers). Further parameters such as mechanical effects and electromagnetic fields compatibility are not taken into account in this simplified model.

Then, the contribution of the local average dose is subtracted from H_{gross} to calculate H', the net dose according to the following formula:

$$H' = H_{gross} - t \cdot \dot{H}_{BG} \quad (2)$$

where:

- t is the number of days between annealing and reading (this time period includes the transportation times, exposure time and other days after annealing or before reading, if the case warrants);
- $\dot{H}_{BG}$ is the local average dose rate (μSv per day) due to the radiation background.

Finally, the contribution of the dose accumulated during the transport of the dosemeter is subtracted from H' as:

$$H = H' - H_{trs} \quad (3)$$

where:

- H_{trs} is the transport (or transit) dose.

For a passive dosemeter also the local average dose and transport dose can be calculated employing Eq. (1) and the corresponding input quantities have to be taken into account in their uncertainty budgets.

Some dosemeters consist of two or three detectors in the same holder (n detectors), so the algorithm should be applied to each detector reading and the mean value of the available data is the final result:

$$\overline{H} = \frac{1}{n} \sum_{i=1}^{n} H_i \quad (4)$$

2.2. Uncertainty of ambient dose equivalent

The correct evaluation of the uncertainty of $H^*(10)$ is crucial for the evaluation of the detection limit of the dosimetry system. The uncertainty is computed through the law of propagation of uncertainties, in a simplified example with independent input or influence quantities. We use the following formula:

$$u(H) = \sqrt{\sum_i c_i^2 \cdot u^2(x_i)} \quad (5)$$

where X_i are the input and influence quantities and $c_i = \left.\frac{\partial H}{\partial X_i}\right|_{X_1 = x_1, \ldots, X_m = x_m}$ are the partial derivatives (JGCM, 2008). These partial derivatives are often called sensitivity coefficients; they describe how the output H varies with changes in the value of the input quantities X_i.

The sensitivity coefficients characterize the dispersion of the true value of the quantity H. It is assumed that the input parameters X_i are not correlated. Currently, most of the reports from the dosimetric laboratories do not specify the characteristic limits of the dosimetric systems but only report the uncertainty of the measurements with the coverage factor $k=2$. According to a study on the status of passive environmental dosimetry in Europe, 17% of the analyzed dosimetry services did not give information about the overall measurement uncertainty (Duch, 2017). The measurement of small dose increments due to artificial radiation release is a challenge in the field of passive dosimetry.

It is relevant to note that the detection limit shall be smaller than the reporting level that could be defined in practical application according to radiation protection requirements.

2.3. Calculation of decision threshold and detection limit

The uncertainty of natural radiation background raises the question whether or not a contribution of physical phenomena could be identified using a defined model of the evaluation.

This analysis is treated by decision theory allowing for a predefined probability α of a wrong decision.

The decision threshold h^* (ISO, 2019) is defined by the condition that the probability to obtain a result $h > h^*$ is equal to α when the true value of the measurand $\tilde{h}$ is zero:

$$P\left(h > h^* \middle| \tilde{h} = 0\right) = \alpha. \tag{6}$$

According to ISO standard 11929, the decision threshold is given by the following formula:

$$h^* = k_{1-\alpha} \cdot \tilde{u}(0) \tag{7}$$

where $k_{1-\alpha}$ is the (1-α) quantile of the standardized normal distribution and $\tilde{u}(0)$ is the standard uncertainty of the result for the true value $\tilde{h}$ is equal to zero. For the following studies α is set at 5%. The corresponding value of $k_{1-\alpha}$ is $k_{1-\alpha} = k_{0.95} = 1.645$.

As explained in the introduction, the detection limit (ISO, 2019) indicates the smallest true value of the measurand which can still be detected with a specified probability using the specific measurement procedure. This characteristic limit gives a decision on whether or not the applied procedure satisfies the purpose of the measurement.

The detection limit $h^\#$ is defined as the smallest true value of the measurand fulfilling the condition that the probability to obtain a result h, that is smaller than the decision threshold h^*, is equal to β if in reality the true value $\tilde{h}$ is equal to $h^\#$.

$$P\left(\left(h < h^* \middle| \tilde{h} = h^\#\right) = \beta \tag{8}$$

According to ISO 11929, the detection limit is given by the following formula:

$$h^\# = h^* + k_{1-\beta} \cdot \tilde{u}(h^\#) \tag{9}$$

with $k_{1-\beta}$ being the (1-β) quantile of the standardized normal distribution. For the following studies β is 5%. The corresponding value of $k_{1-\beta}$ is $k_{1-\beta} = k_{0.95} = 1.645$. In most cases Eq. (9) can be solved only numerically or by applying the dedicated application software (UncertRadio, 2014; LIMCAR, 2020) mentioned above.

In this specific application, starting from Eq. (1) and Eq. (2), it is possible to rewrite Eq. (3) as follow:

$$H = M \cdot k_{tot} - H_{B\&T} \tag{10}$$

where $k_{tot} = k_{ref} \cdot k_{det} \cdot k_{E,\alpha} \cdot k_n \cdot k_{fad} \cdot k_{env}$ and $H_{B\&T} = H_{BG} + H_{trs}$.

It is then possible to write the square of the uncertainty on H as:

$$u^2(H) = k_{tot}^2 \cdot u(M)^2 + M^2 \cdot u(k_{tot})^2 + u(H_{B\&T})^2 \tag{11}$$

Following ISO 11929, we need to express $u(H)$ as a function of $\tilde{h}$; with this aim, it is possible to write M as:

$$M = x - z = \frac{H + H_{B\&T}}{k_{tot}}$$

and:

$$u^2(M) = u^2(x) + u^2(z) = x^2 \cdot \left(\frac{u(x)}{x}\right)^2 + u^2(z) = \left(z + \frac{H + H_{B\&T}}{k_{tot}}\right)^2 \cdot u_{rel}^2(x) + u^2(z). \tag{12}$$

where $u_{rel}(x) = \frac{u(x)}{x}$.

It is now possible to write Eq. (11) as function of true value $\tilde{h}$:

$$\tilde{u}^2\left(\tilde{h}\right) = k_{tot}^2 \left[\left(z + \frac{\tilde{h} + H_{B\&T}}{k_{tot}}\right)^2 \cdot u_{rel}^2(x) + u^2(z)\right] + \left(\frac{\tilde{h} + H_{B\&T}}{k_{tot}}\right)^2 \cdot u^2(k_{tot}) + u^2(H_{B\&T}) \tag{13}$$

Starting from the hypothesis that the uncertainty $u(0)$ and $u(h^\#)$ are approximately equal and $k_{1-\alpha} = k_{1-\beta}$, it is a common practice the approximation $h^\# = 2 \cdot \tilde{h}$. However the uncertainty for any measurement with net dose greater than zero would be larger, in absolute value, than the $u(0)$, and this is also true for our specific case.

If the decision threshold for this simplified model can be calculated as:

$$h^* = k_{1-\alpha} \sqrt{k_{tot}^2 \left[\left(z + \frac{H_{BG}}{k_{tot}}\right)^2 \cdot u_{rel}^2(x) + u^2(z)\right] + \left(\frac{H_{BG}}{k_{tot}}\right)^2 \cdot u^2(k_{tot}) + u^2(H_{B\&T})} \tag{14}$$

the detection limit can be calculated, in a more precise way, by solving the following equation by iteration (ISO,2019):

$$h^\# = h^* + k_{1-\beta} \sqrt{k_{tot}^2 \left[\left(z + \frac{h^\# + H_{BG}}{k_{tot}}\right)^2 \cdot u_{rel}^2(x) + u^2(z)\right] + \left(\frac{h^\# + H_{BG}}{k_{tot}}\right)^2 \cdot u^2(k_{tot}) + u^2(H_{B\&T})}. \tag{15}$$

3. Method

The four partners of the EMPIR project "Preparedness" involved in this study are:

- ENEA (Agenzia Nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile, Italy);
- CLOR (Centralne Laboratorioum Ochrony Radiologicznej, Poland);
- RBI (Ruđer Bošković Institute, Croatia);
- VINS (Institut Za Nuklearne Nauke Vinca, Serbia).

The dosimetry systems are based on thermo-luminescence (TL) detectors (four types) and radio-photoluminescence (RPL) detectors (one type).

A detailed questionnaire (see Annex A) was distributed to the partners which included 40 questions addressing four topics:

- technical data of dosimetry systems for environmental monitoring;
- elements of dose calculation for environmental monitoring;
- uncertainty budget of dose calculation for environmental monitoring;
- current typical coverage factor applied for uncertainty of dose calculation for environmental monitoring.

To identify the highest contributions to the total uncertainty, the laboratories investigated the uncertainties of their passive dosimetry systems starting from a simulation of a selected dose rate in a fixed measurement period. It is useful to specify that the measurement period is the time of exposure of the detector in the place of measurement. For a passive dosemeter it is necessary to specify also the number of days between annealing and reading (t). To limit the divergences due to the selection of these different time parameters, the simulation is done for a one month measurement period (30 days) and two extra periods of 10 days are conservatively added in the final interval between annealing and reading of a single device (the parameter t is set equal to 50 days). The $\dot{H}_{BG}$ used in the algorithms of the laboratories is around 2 μSv/day. This value is commonly used as European average dose (European Commission, 2009) and it takes into account the annual mean values of external dose from cosmic and terrestrial radiations in Europe, respectively 0.34 mSv per year and 0.48 mSv per year (Cinelli, 2019).

The decision threshold and the detection limit of the five dosimetry systems are computed according to the ISO standard 11929, for these measurement conditions.

The capability of the five investigated passive detector systems to measure an additional annual dose in $H^*(10)$ of approximately 2 mSv per year within a short measuring period of one month in the natural environment is chosen as the reference scenario.

The choice of this reference scenario is based on the following considerations:

- Only the external exposure to the public has been taken into account starting from the assumption that the internal doses following a nuclear or radiological accident should largely be avoided by implementing restrictions on food and drinking water (IAEA, 2015).
- The external exposure rate has been determined for this scenario on the basis of the theoretical environmental monitoring data by the use of the calculation model in which the natural shielding of buildings and the human indoor occupation time are considered (IAEA, 2013).

The external exposure rate can be computed applying the following formula:

$$H^*(10)_{ext} = H^*(10)_{outdoor} + H^*(10)_{indoor} =$$

$$= \left(H^*(10)_{detect.} - H_{BG}\right)\cdot(1-F_0) + \left(H^*(10)_{detect.} - H_{BG}\right)\cdot F_0 \cdot F_S \quad (16)$$

Where:

- $H^*(10)_{ext}$ is a conservative estimate of the effective dose of a person exposed to the same photon radiation field;
- $H^*(10)_{detect.}$ is the result of measured data;
- H_{BG} is the contribution of the natural radiation background;
- F_0 is the indoor occupancy factor;
- F_S is the general building shielding factor: it is the ratio of indoor to outdoor dose rate and its value is assumed to be equal to 0.2 (UNSCEAR, 2000).

In order to combine indoor and outdoor dose rates to compute total doses, the UNSCEAR uses an indoor occupancy factor $F_0 = 0.8$ which implies that on average, people around the world spend 20% of their time outdoors (UNSCEAR, 2000). In case of a nuclear emergency, the indoor occupancy factor may even be higher (people may be requested to stay indoors according to the sheltering protective action) and the total exposure is therefore even less than the one calculated in the following for $F_0 = 0.8$.

The selected scenario for all following calculations considers an artificial increment of the outdoor dose rate of $H^*(10) \approx 0.165$ mSv for a measurement period of one month.

This value is chosen starting from the hypothesis that in this condition the detectable external gamma dose rate could be approximately 0.3 μSv/h, which corresponds to a conservatively estimated additional effective dose of 0.7 mSv per year for the scenario described above. This value of the effective dose is even slightly less than the limit for the public exposure of 1 mSv per year, according to the European Council Directive 2013/59 (EURATOM, 2013). It is important that, for the scenario described, the passive dosimetry systems are able to reliably measure the related external dose, even with a low exposure time of only one month.

Therefore, the main goal of this work is to study the factors which affect the uncertainty of the doses measured with these dosimetry systems for environmental monitoring.

4. Results and discussion

Significant differences and some conformances are found between the laboratories in the answers to the questionnaire. The operational quantity $H^*(10)$ for gamma radiation is measured in different rated dose ranges (from a minimum value of 0.01 mSv to a maximum value of 10 Sv) and rated energy ranges (from a minimum value of 13 keV to a maximum value of 1.25 MeV) in all laboratories. The measuring period for environmental radiation monitoring varies from a minimum of 1 to a maximum of 6 months. Table 1 summarizes the principal characteristics of five passive dosimetry systems for environmental monitoring analyzed in this study.

Regarding dose calculation procedures (see Fig. 1) all laboratories take into account the reader sensitivity factor of the dosimetry system and three systems consider the detector normalization factor. Two systems take into account the relative response due to energy and angle of incidence and no one makes correction for non-linearity and environmental influences.

All laboratories consider the effect of a non-linearity due to dose dependence to be negligible for environmental monitoring of measurement (Shih-Ming Hsu, 2006; Ranogajec-Komor, 2008). Furthermore the long term stability under varying environmental conditions (little fading effect) of TLD and RPL help to simplify the model function used by the laboratories for monitoring period from 1 to 6 months (Shih-Ming Hsu, 2006; Trousil, Spurn,1999; Phakphum Aramrun, 2017).

The background of the dosemeter reader is taken into account in three algorithms. Furthermore, the background dose contribution is subtracted from $H^*(10)$ as a mean background dose value in standard procedure of three laboratories. Only one laboratory applies transport dose corrections for two passive dosimetry systems.

In the uncertainty budgets of dose calculation, the laboratories routinely apply the uncertainty of all parameters taken into account in their procedure. To compare the five dosimetry systems used by four laboratories, all partners simulated the measurement of the specific low dose $H^*(10) \approx 0.165$ mSv/month. The number of days between two consecutive readings is assumed to be 50 days for a measurement period of one month. In Table 2 the decision thresholds and detection limits of the five systems are presented for this selected measurement condition. All laboratories applied the model function of the measurand $H^*(10)$ described above (see Eqs. (1)–(3)) considering only the components that each laboratory actually evaluates (as indicated in the questionnaire)

Table 1
Features of five passive dosimetry systems for environmental monitoring of ENEA, CLOR, RBI and VINS.

Technical data of passive dosimetry systems for environmental monitoring	TLD-ENEA	TLD-CLOR	TLD-RBI	RPL-RBI	TLD-VINS
Dosimetry quantity	$H^*(10)$	$H^*(10)$	$H^*(10)$	$H^*(10)$	$H^*(10)$
Type of radiation	photons	photons	photons	photons	photons
Energy rated range	13 keV to 1.25 MeV	33 keV to 1.25 MeV	13 keV to 1.25 MeV	33 keV to 1.25 MeV	20 keV to 1.25 MeV
Angular rated range	0°–60°	–	–	–	0°–60°
Detector Type	LiF:Mg,Cu,P (GR200A) SDDML - China	LiF:Mg,Cu,P (MCP-N); RADCARD	I: CaF_2:Mn (TLD-IJS-05); II: Al_2O_3:C (TLD-500); III: LiF:Mg,Cu,P (TLD-100H)	RPL (FD-7), Ag activated phosphate glass (AGC Techno Glass Co.)	LiF:Mg,Cu,P (TLD-700H)
Number of detectors for each dosemeter	1	1	3	1	1
Dosimetry reader	Harshaw 6600PLUS Automated - TLD Card Reader - Thermo Fisher Scientific	RADOS RE 2000	TOLEDO 654 (Vinten)	FDG-202E	Harshaw 6600PLUS, WinREMS
Measuring period	45 days	3 months	6 months	6 months	1-3-6 months
Number of dosemeters for each measurement point	1	1	1	1	2
Additional remark:			1 dosemeter system includes: (TLD-100H + Al_2O_3:C + CaF_2Mn) + RPL		

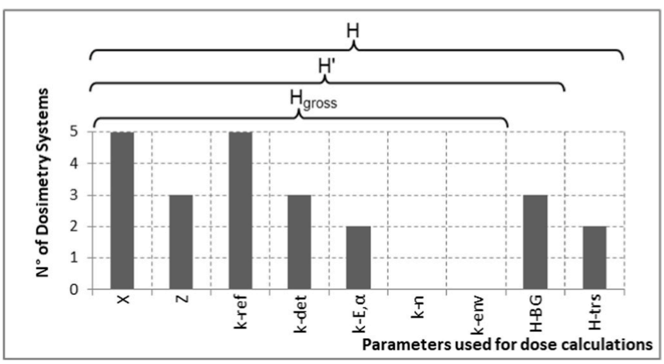

Fig. 1. Number of laboratories which use the parameters for dose calculation procedures according to Eqs (1)–(3) for the five passive dosimetry systems.

Table 2
Information about decision threshold (h^*) and detection limit ($h^{\#}$) for *H*(10)* for photons and 1 month measuring period for environmental monitoring for each dosemeter system. The values are computed according to the standard ISO 11929-1 (as explained in 2.3).

	TLD-ENEA	TLD-CLOR	TLD-RBI	RPL-RBI	TLD-VINS
h^* (μSv/period)	32	31	I:35; II:32; III:30	25	35
$h^{\#}$ (μSv/period)	76	67	I:80; II:72; III:65	51	86

with the exception of background subtraction which was applied for all dosimeter systems. In the following Tables 3–7 the analysis of the combined uncertainty (European Commission, 2009) of the five dosemeter systems is presented.

The uncertainty budget is studied in three fundamental steps of the dose calculation: the computation of H_{gross} (see Fig. 2), the determination of the artificial contribution to the dose in the period of measurement (see Fig. 3), and the final evaluation of $H^*(10)$ considering all detectors which are part of the same dosemeter (see Fig. 4).

Currently the decision threshold (h^*) and detection limit ($h^{\#}$) for *H*(10)* for photons are not reported in the dose rate reports for environmental monitoring of the five passive dosimetry systems.

For this case study, the analytical method of the IEC TR 62461 is applied (IEC, 2015). In Tables 3–7 all uncertainties of presented values have level of confidence $k = 1$ and only the final combined uncertainty have $k = 2$ as specified in the last line of each table.

Consecutive detector readings are not possible for TLD, so every laboratory analyzed the data according their internal procedure. For example, in ENEA laboratory, $u(x)$ is calculated from the standard deviation of 10 measurements taken on the same dosimeter, exposed to 1 mSv in the assumption of normal distribution and $u(z)$ is calculated from the standard deviation of 10 measurements on different dosimeters, not exposed to radiation. Otherwise, in the RBI laboratory $u(x)$ is depending on the integration of the glow curve (the lower and upper integration limit can be changed) and uncertainty shown in Table 5 is estimated with respect to that; furthermore the reader signal from the detector z is not taken into account.

For RPL-IRB detector (see Table 6) the value of the quantities x and z are calculated as the 5 consecutive readings of the same detector and each uncertainties are represented as standard deviations of the 5 readings.

The statistical distribution of k_{ref} is considered a normal distribution (European Commission, 2009) and includes the uncertainty of the reference irradiation in each laboratory.

Usually a triangular distribution should be considered for k_{det} (IEC, 2015) but in three laboratories (ENEA,CLOR and IRB) it is considered normal. This approach is based on data experimental distribution but don't reflect the restrictive requirement that detectors with a too low or too high response are rejected for routine use as a measure of quality assurance (European Commission, 2009). Currently this requirement on detectors homogeneity is indeed practical applied on the batch of detectors used in the measurement for all five dosimetry systems.

The statistical distributions of $k_{E,\alpha}$ and k_n are computed starting from the data of type-test for *H*(10)* for photon energies, angle and dose rate variation (these data are also provided by the manufacturers in technical specifications). By way of illustration, in ENEA laboratory, for $k_{E,\alpha}$, difference between the maximum and the minimum response value of the reference dosimeters is calculated for four energy values E (15.7 keV, 78 keV, 205 keV and 1250 keV) of the incident radiation, and 4 radiation incidence angle values α (0°, 20°, 40 °and 60°). The standard uncertainty associated with $k_{E,\alpha}$ has been calculated with the assumption of normal distribution.

The period t is recorded in terms of day with a discretization error of 1 or 2 days, so the rectangular statistical distribution is applied. In the

Table 3
Analysis of the combined uncertainty of ENEA dosemeter system.

TLD-ENEA						
Quantity	Unit	Value	Uncertainty $u(x_i)$	Relative Uncertainty	Distribution	Sensitivity Coefficient $c(x_i)$
Z	nC[1]	8.29E+00	3.50E+00	42%	normal	5.50E-01
X	nC	4.90E+02	9.81E+00	2%	normal	5.50E-01
M	nC	4.82E+02	1.04E+01	2%		
k_{ref}	μSv/nC	5.50E-01	2.75E-02	5%	normal	4.82E+02
k_{det}	–	1.00E+00	7.00E-02	7%	normal	2.65E+02
$k_{E,\alpha}$	–	1.00E+00	8.83E-02	9%	normal	2.65E+02
t	d	5.00E+01	5.80E-01	1%	rectangular	2.00E+00
$\dot{H}_{BG}$	μSv/d	2.00E+00	3.00E-01	15%	normal	5.00E+01
H_{trs}		N.A.				
Combined Uncertainty of H = 165 μSv/month				44% (k = 2)		

[1] nC = nanoCoulomb

Table 4
Analysis of the combined uncertainty of CLOR dosemeter system.

TLD-CLOR						
Quantity	Unit	Value	Uncertainty u(xi)	Relative Uncertainty	Distribution	Sensitivity Coefficient c(xi)
Z	counts	3.00E+03	9.00E+01	3%	normal	1.10E-03
X	counts	2.51E+05	5.83E+03	2%	normal	1.10E-03
M	counts	2.48E+05	5.83E+03	2%		
k_{ref}	μSv/counts	1.10E-03	4.40E-05	4%	normal	2.48E+05
k_{det}	–	1.00E+00	7.00E-02	7%	normal	2.73E+02
$k_{E,\alpha}$		N.A.				
t	d	5.00E+01	5.80E-01	1%	rectangular	2.16E+00
$\dot{H}_{BG}$	μSv/d	2.16E+00	3.24E-01	15%	normal	5.00E+01
H_{trs}	μSv	N.A.				
Combined Uncertainty of H = 165 μSv/month				34% (k = 2)		

Table 5
Analysis of the combined uncertainty of RBI TLD dosemeter system.

TLD-RBI						
Quantity	Unit	Value	Uncertainty u(xi)	Relative Uncertainty*	Distribution	Sensitivity Coefficient c(xi)
Z		N/A				
X	counts	I: 7.06E+04 II: 3.60E+05 III: 4.18E+05	I: 4.17E+03 II: 6.48E+03 III: 2.09E+03	I: 6% II: 2% III: 1%	normal	I: 4.25E-03 II: 8.20E-04 III: 6.74E-04
M	counts	I: 7.06E+04 II: 3.60E+05 III: 4.18E+05	I: 4.17E+03 II: 6.48E+03 III: 2.09E+03	I: 6% II: 2% III: 1%		
k_{ref}	μSv/counts	I: 4.25E-03 II: 8.20E-04 III: 6.74E-04	I: 2.71E-04 II: 4.40E-05 III: 2.90E-05	I: 6% II: 5% III: 4%	normal	I: 7.06E+04 II: 3.60E+05 III: 4.18E+05
k_{det}	–	I: 1.00E+00 II: 1.00E+00 III: 1.00E+00	I: 5.60E-02 II: 7.00E-02 III: 6.70E-02	I: 6% II: 7% III: 7%	normal	I: 3.00E+02 II: 2.95E+02 III: 2.82E+02
$k_{E,\alpha}$		N.A.				
t	d	5.00E+01	5.80E-01	1%	rectangular	2.00E+00
$\dot{H}_{BG}$	μSv/d	2.00E+00	3.00E-01	15%	normal	5.00E+01
H_{trs}	μSv	I:3.50E+01 II: 3.00E+01 III: 1.70E+01	I: 6.00E+00 II: 5.00E+00 III: 3.60E+00	I: 17% II: 17% III: 21%	normal	I: 1.00E+00 II: 1.00E+00 III: 1.00E+00
Combined Uncertainty of H = 165 μSv/month				I (k = 2): 42%; II(k = 2): 37%; III (k = 2): 33% Final value** (k = 2): 22%		

* I. CaF_2:Mn (TLD-IJS-05); II. Al_2O_3:C (TLD-500); III. LiF:Mg,Cu,P (TLD-100H).
** Uncertainty for $\overline{H}$, mean value of three detectors: types I, II and III.

end the two quantities H_{trs} and H_{BG} are considered statistically distributed with a normal distribution (European Commission, 2009).

The study of five dosimetry systems revealed that the uncertainty for environmental doses in emergency situations is relatively high at low dose rate levels (for a dose rate of 0.165 mSv/month the uncertainty is in the range of 19%–50% with k = 2).

The data presented are not easy to compare because of the differences in the number of parameters for the dose calculation procedures according to equations (1)–(4) used by the five laboratories. Only ENEA and VINS used the same parameters and it is evident that these two passive dosimetry systems have very similar results.

The use of more detectors for each dosemeter can help in reducing

Table 6
Analysis of the combined uncertainty of RBI RPL dosemeter system.

RPL-RBI						
Quantity	Unit	Value	Uncertainty u(xi)	Relative Uncertainty	Distribution	Sensitivity Coefficient c(xi)
Z	μSv	1.60E+01	1.00E+00	6%	normal	1.00E+00
X	μSv	2.96E+02	2.81E+00	1%	normal	1.00E+00
M	μSv	2.80E+02	2.99E+00	1%		
k_{ref}	–	1.00E+00	1.40E-02	1%	normal	2.80E+02
k_{det}	–	N.A.				
$k_{E,\alpha}$	–	N.A.				
t	d	5.00E+01	5.80E-01	1%	rectangular	2.00E+00
$\dot{H}_{BG}$	μSv/d	2.00E+00	3.00E-01	15%	normal	5.00E+01
H_{trs}	μSv	1.45E+01	2.30E+00	16%	normal	1.00E+00
Combined Uncertainty of H = 165 μSv/month				19% (k = 2)		

Table 7
Analysis of the combined uncertainty of VINS TLD dosemeter system.

TLD-VINS						
Quantity	Unit	Value	Uncertainty u(xi)	Relative Uncertainty	Distribution	Sensitivity Coefficient c(xi)
Z	μSv	2.00E+01	1.00E+00	5%	normal	1.00E+00
X	μSv	2.85E+02	4.00E+00	2%	normal	1.00E+00
M	μSv	2.65E+02	4.12E+00	2%		
k_{ref}	–	1.00E+00	2.30E-02	2%	normal	2.65E+02
k_{det}	–	1.00E+00	4.00E-02	4%	triangular	2.65E+02
$k_{E,\alpha}$	–	1.00E+00	1.35E-01	14%	normal	2.65E+02
t	d	5.00E+01	5.80E-01	1%	rectangular	2.00E+00
$\dot{H}_{BG}$	μSv/d	2.00E+00	3.00E-01	15%	normal	5.00E+01
H_{trs}	μSv	N.A.				
Combined Uncertainty of H = 165 μSv/month				50% (k = 2)		

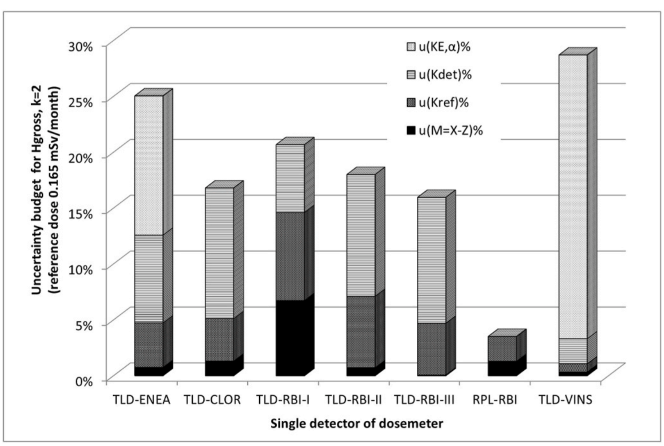

Fig. 2. Uncertainty of H_{gross} for seven detectors of five passive dosimetry systems* obtained from a simulation of a hypothetical dose of 0.165 mSv/month. For each dosemeter the different colours represent the factors taken into account with their relative contribution in the uncertainty budget analysis. (* The three data of TLD-RBI refer to three detectors of a single dosemeter).

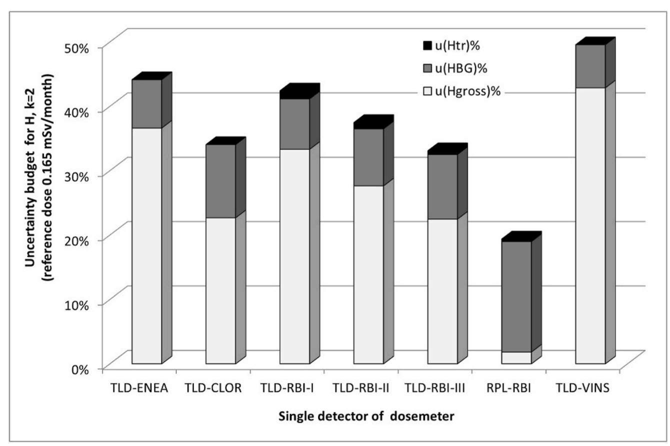

Fig. 3. Uncertainty of H for seven detectors of five passive dosimetry systems* with k = 2 obtained from a simulation of a hypothetical dose of 0.165 mSv/month. For each dosemeter the different colours represent the factors taken into account with their relative contribution in the uncertainty budget analysis. * The three data of TLD-RBI refer to three detectors of a single dosemeter).

the final uncertainty, for example, 22% is the uncertainty for the mean value of three detectors with uncertainties for a single detector in the range of 33%–42%.

The contribution of the background to a measurement of 0.165 mSv/month is within the range of 33%–40% of the dose value for the five systems analyzed, and its contribution to relative uncertainty budget of H is within 3%–9%.

The contribution of the transport dose to H_{gross} computed on RBI dosimetry systems is less than 12%. Even if not commonly analyzed, it is recommendable to use a reference dosemeter to trace possible anomalies during the shipment.

This study shows the importance of analyzing the factors which contribute to the uncertainty and several improvements are necessary in each laboratory to harmonize the methodologies for environmental dose measurement with passive dosimetry systems in emergency situations.

The uncertainty of H is above 50% with k = 2 for a low dose rate (e.g. 0.165 mSv/month) if all components of formula (1), (2) and (3) are taken into account. For a high dose rate (e.g. 2 mSv/month) the uncertainty can be in the order of 30% for k = 2 for a single detector in the dosemeter.

Some laboratories don't take all components of formula (1), (2) and (3) into account in their standard procedures and the result is a large variation of the uncertainty in the measurements report.

Lastly, two parameters affecting the uncertainties are studied in the unchanged assumption of a measurement performed at a low dose rate of about 0.3 μSv/h.

The first parameter is the measuring period already analyzed in literature (Romanyukha, 2008; Tang, 2002; Traino, 1998; Dombrowski,

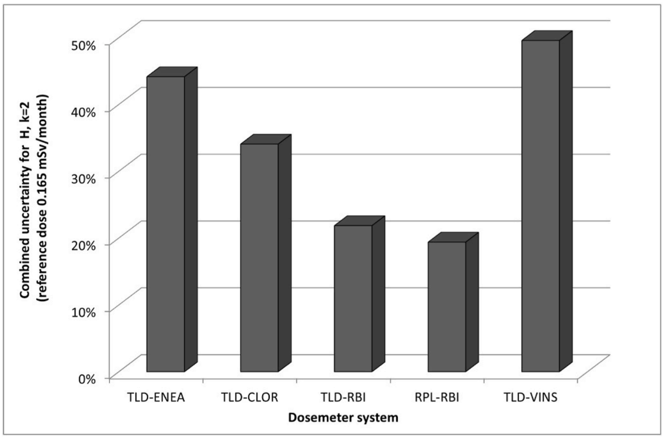

Fig. 4. Uncertainty of H for five passive dosimetry systems with k = 2 obtained from a simulation of a hypothetical dose of 0.165 mSv/month. As specified in Table 1 the TLD-RBI data refers to the mean value of three detectors which are part of a single system. All the other dosimetry systems have a dosemeter based on only one detector.

Table 8
Analysis of the variation of the uncertainty with the increment of the measurement period for the ENEA dosemeter system.

Measure Period	t (days)	H (μSv/period)	relative u(H) (k = 2)
1 month	50	165	44%
3 months	111	495	39%
6 months	202	990	37%

Table 9
Analysis of the variation of the uncertainty with the reference value of background in the measurement point for the ENEA dosemeter system.

Reference H_{BG} value	H_{BG} (μSv/day)	relative u(H_{BG})	H (μSv/month)	relative u (H) (k = 2)
European [a]	2.00	15%	165	44%
Italian [b]	2.28	15%	165	47%
Regional [c]	2.26	5%	165	43%

[a] (European Commission, 2009).
[b] Median value from regional value (Dionisi, 2017)
[c] Turin area (Losana, 2001)

2017). The data reported in Table 8 show that a longer measuring period can lead to a lower uncertainty.

The second parameter taken into account is the background dose. In Table 9 the variations of the final uncertainty (k = 2), the different values of the background dose and the relative uncertainties are presented. The three values of background dose refer to values available in literature with reference to dose rate measured in a very large area like Europe, in the Italian country and in the specific Regional area like Turin district (Italy). Variations of background uncertainty are related to different measurement techniques and homogeneity of the rate dose values acquired in big or small areas, with different contributions of the cosmic radiation and terrestrial radiation.

The higher the value of the background dose (with comparable relative uncertainty), the greater the final uncertainty of $H^*(10)$. For comparable values of background doses, the lower H_{BG} uncertainty can reduce the final uncertainty of $H^*(10)$.

5. Conclusions

In order to apply the ISO standard 11929, the uncertainties in dose measurements have to be assessed. Therefore, the uncertainty budget calculation is the first step towards the correct evaluation of the characteristic limits of a passive dosimetry system in order to optimize the procedure for the calculation of environmental doses in normal as well as in emergency situations.

The detection limit depends on the number of parameters taken into account in the uncertainty budget. To compare the detection limit for more systems, it is necessary to verify that the parameters used in the uncertainty budget are the same.

Substantial differences and some conformances are found in the methodologies between the four participating laboratories.

The reader sensitivity factor of the dosimetry system is the only common factor used in all five dose measurement procedures, while no laboratory applies correction factors for non-linearity, signal fading and environmental influences. Furthermore, the environmental background dose is subtracted from $H^*(10)$ as a common (location independent) background dose value.

The five dosimetry systems studied show that the uncertainty of environmental dose determinations in emergency situations is relatively high at low dose rate levels and the use of more detectors for each dosemeter can help in reducing the final uncertainty.

An important contribution to the final combined uncertainty, in case of a low dose measurement, is found to be given by the background dose uncertainty (European Commission, 2009). Therefore, in monitoring networks near a nuclear facility, it is recommended to perform direct background measurements near the dosemeter location to reduce this contribution. Alternatively, historical data from a set of passive dosemeters placed in the same location could be used to calculate a more accurate value of the background dose and its variations.

Furthermore it is recommended to use a reference dosemeter to trace any anomalies during the shipment of the dosemeters.

A longer measurement period can lead to results with lower uncertainty, but this is not always applicable in emergency situations because more frequent measurements could be required for radiation protection purpose.

Nevertheless, even with a short measuring period of 1 month the detection limits of all systems, varying between 51 μSv/period and 86 μSv/period (see Table 2), are sufficiently low to measure an increase of $H^*(10)$ of 1 mSv per year. As pointed out in section 3 (Eq. (8)) even in case of a significantly higher outdoor exposure rate the limit for the effective dose for the public exposure of 1 mSv per year, according to the European Council Directive 2013/59 (EURATOM, 2013) would be meet, due to the shielding effects of buildings during the indoor exposure (about 80% of the time).

Despite this positive result, a reduction of the overall uncertainties of the investigated passive dosimetry systems at low doses is desirable.

This study shows how important it is to analyze the factors which affect this uncertainty and several improvements are necessary in each laboratory in order to harmonize the methodologies of environmental dose measurements with passive dosimetry systems in normal as well as in emergency situations. A future investigation could take into consideration the spurious effect in the glow curves due to background signals as sources of uncertainty in low dose radiation measurement and its application in measurements of H*(10).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex A.

A questionnaire was distributed to ENEA, CLOR, RBI and VINS laboratories to provide data on dose calculation, uncertainty budget and current typical uncertainty of dose calculations for environmental monitoring. The answers to this questionnaire are reported in this annex with all details used for the work.

Table A. 1
Information about algorithm applied for environmental monitoring with passive dosemeters

Data of dose calculation for environmental monitoring	TLD-ENEA	TLD-CLOR	TLD-RBI	RPL-RBI	TLD-VINS
Is the reader sensitivity factor of the dosimetry system taken into account?	Yes	Yes	Yes	Yes	Yes
a- Where does the reader sensitivity factor of the dosimetry system come from?	irradiation of “reference group” dosemeters at 5 mGy Co-60	irradiation of “reference group” of dosemeters with reference dose	irradiation of “reference group” dosemeters with 5 mGy Cs-137 at RBI SSDL	irradiation of “reference group” dosemeters with 5 mGy Cs-137 at RBI SSDL	VINS SSDL
b- Are there specific, irradiated background dosemeters used (also to get information on fading)?	Experimentally evaluated fading: 2 per thousand for each thermal cycle	No	background dosemeters are taken into account; fading is negligible	background dosemeters are taken into account; fading is negligible	No
Is a single detector normalization factor (also called element correction coefficient of single dosemeters or specific calibration factors) taken into account?	Yes	No	Yes	No	Yes
Is the relative response due to energy and angle of incidence taken into account?	Yes	No	No	No	Yes
Is a correction factor for non-linearity taken into account?	No	No	No	No	No
Is the background of the dosemeter reader subtracted?	Yes	Yes	No	No	Yes
Is a fading correction taken into account?	No	No	No	No	No
Is the background dose subtracted in $H^*(10)$ calculations?	Yes	Yes	Usually No, but Yes for the purpose of this study	Usually No, but Yes for the purpose of this study	Yes
a- Is the Background dose measured at a comparable location?	No	No	No	No	No
b- Is the Background dose measured earlier at the same location?	No	No	No	No	No
c- Is the Background dose estimated or computed considering a standard background dose?	Yes	Yes	Yes	Yes	Yes
Is the relative response due to environmental influences taken into account in $H^*(10)$ calculations?	No	No	No	No	No
Is a correction for the transport dose applied?	No	No	Yes	Yes	No
a- Is the transport dosemeter an active dosemeter?	not applicable	not applicable	No	No	not applicable
b- Is the transport dosemeter a passive dosemeter?	not applicable	not applicable	Yes	Yes	not applicable

Table A. 2
Information about the uncertainty budget of dose calculation for environmental monitoring with passive dosemeters

Uncertainty budget of dose calculation for environmental monitoring	TLD-ENEA	TLD-CLOR	TLD-RBI	RPL-RBI	TLD-VINS
Is the uncertainty of the reader sensitivity factor of the dosimetry system taken into account?	Yes	Yes	Yes	Yes	Yes
Is the uncertainty of the detector normalization factor (also called element correction coefficient of single dosemeters or specific calibration factor) taken into account?	Yes	No	Yes	No	Yes
Is the uncertainty of the relative response due to energy and angle of incidence taken into account?	Yes	No	No	No	Yes
Is the uncertainty of the correction factor for non-linearity taken into account?	No	No	No	No	No
Is the uncertainty of the background of the dosemeter reader system taken into account?	Yes	Yes	Yes	Yes	Yes
Is the uncertainty of the fading correction taken into account?	No	No	No	No	No
Is the uncertainty of the background dose taken into account in H*(10) calculations?	Yes	Yes	Yes	Yes	Yes
Is the uncertainty of the relative response due to environmental influences taken into account in H*(10) calculations?	No	No	No	No	No
Is the uncertainty of the transport dose taken into account?	No	No	Yes	Yes	No
Coverage factor k	2	2	1	1	2

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