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1 Results of the EURADOS 2022 intercomparison for neutron personal 2 dosimeters (IC2022n)

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10 performance testing.

11 ABSTRACT

12 The European Radiation Dosimetry Group (EURADOS) has initiated a regular, self-sustaining interlaboratory
13 comparison scheme to test the performance of individual monitoring services. The 2022 intercomparison for
14 neutron personal dosimeters (IC2022n) was the third campaign involving devices routinely applied to measure
15 personal dose equivalent, $H_p(10)$, in neutron fields. The exercise was attended by 29 laboratories from 19 countries
16 (more than half outside the European Union). The 31 registered dosimetry systems were categorized according to
17 their detection principle into albedo and track dosimeters. Participants were given the option to request simplified
18 *a priori* information on the energy distribution of the neutron reference fields to enable application of the proper
19 calibration factor for the dosimeter response, in compliance with their routine practice. As a novelty, the
20 interlaboratory comparison also investigated false positive response. The irradiation plan comprised a combination
21 of standard calibration and simulated workplace neutron fields, aimed to provide information on the dosimeter
22 performance regarding linearity, reproducibility as well as energy and angle dependence of response. The
23 irradiations were carried out at accredited metrology laboratories for ionizing radiation in accordance with the ISO
24 8529 and ISO 29661 series of standards. Evaluation of results applied the performance limits and the approval
25 criterion of ISO 14146:2018 to provide a comprehensive overview of the status of neutron personal dosimetry for
26 individual monitoring of occupational exposure.

27 1. Introduction

28 In response to a requirement for individual monitoring services (IMSs) to periodically engage in performance
29 testing, the European Radiation Dosimetry Group (EURADOS) Working Group 2 has been organising a regular,
30 economically self-sustainable interlaboratory comparison (ILC) scheme since 2008 (Romero et al., 2016). The
31 initiative aims to improve dosimetric quality assurance in individual monitoring for external radiation and provide
32 evidence of dosimetric performance (Bartlett et al., 2001). Participation in ILCs provides for an independent
33 assessment of the competence, impartiality, and harmonization of operating procedures of testing laboratories. It
34 also represents essential evidence to support IMS approval and accreditation by national authorities, demonstrating
35 a laboratory's capability to generate technically valid results (ISO/IEC, 2017). The EURADOS 2022
36 intercomparison for neutron personal dosimeters (IC2022n) built on the success of two previous ILCs conducted
37 in 2012 (Fantuzzi et al., 2014a, 2014b) and 2017 (Mayer et al., 2020; 2021).

38 An organisation group (OG) was appointed by EURADOS to prepare and implement IC2022n. The
39 coordinating organization was the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) in Fontenay-aux-
40 Roses, France. The coordinator was tasked to receive the dosimeters from the IMSs registered for the exercise,
41 manage their transport to the irradiation facilities and return them to participants for evaluation and dose reporting.

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42 The coordinator also carried out all communication between the IMSs, the irradiation laboratories and the OG.
 43 Registration and data exchange was processed via a secure online platform, which has proven practicable in
 44 previous ILCs. The cloud-based tool enabled the participants to monitor the status of their dosimetry systems in
 45 real-time and download relevant information and documents. To prevent disclosure and ensure that the data are
 46 used only for the purpose of the ILC, OG members have signed a confidentiality clause. All information that could
 47 potentially lead to the identity of the participants was separated from the published results.

48 2. Materials and methods

49 2.1. Dosemeter systems

50 Similar to previous campaigns, IC2022n encompassed whole-body dosimeters routinely applied to measure
 51 personal dose equivalent, $H_p(10)$, in neutron fields. Prototype dosimeters were not accepted. The exercise was
 52 attended by 29 laboratories from 19 countries, more than half of which were from outside the European Union.
 53 The 31 registered dosimetry systems were categorized by the OG according to their detection principle into albedo
 54 (11 systems) and track dosimeters (20 systems). The former category included thermoluminescence dosimeters
 55 with boron or cadmium-loaded shields as well as an active neutron/photon personal dosimeter equally exploiting
 56 the albedo technique. The latter group employed etched track detectors, which were mostly equipped with thermal
 57 neutron converters or sensors. IMSs were requested to provide a total of 44 dosimeters, including eight spare and
 58 eight background/transit control dosimeters. As stated in the terms and conditions of the exercise, up to four
 59 dosimeters might have been used to test for false positive response.

60 2.2. Irradiation plan

61 As summarized in Table 1, the irradiation plan included a combination of standard calibration and simulated
 62 workplace neutron fields, aimed to provide information on the dosimeter performance regarding reproducibility,
 63 energy and angle dependence of response. The irradiations were carried out in accordance with the ISO 8529 (ISO,
 64 1998; 2000; 2001) and ISO 29661 (ISO, 2012) series of standards in low-scatter areas at the following accredited
 65 metrology laboratories for ionizing radiation, which are considered as internationally recognized Calibration and
 66 Measurement Capabilities (CMCs) by the Bureau International des Poids et Mesures (BIPM): Institut de
 67 Radioprotection et de Sûreté Nucléaire (IRSN), St-Paul-lez-Durance, France, and Physikalisch-Technische
 68 Bundesanstalt (PTB), Braunschweig, Germany. The reference personal dose equivalent, H_{ref} , was calculated from
 69 the fluence rate of direct and in-scattered neutrons and the corresponding fluence-to-personal-dose-equivalent
 70 conversion coefficients (ICRP, 1996; ISO, 1998; Jetzke and Kluge, 1997). The neutron emission rates of the
 71 sources used have been determined using manganese sulphate bath measurements validated in key international
 72 comparisons.

73 **Table 1**

74 IC2022n irradiation plan and simplified *a priori* information to enable correction for albedo dosimeter response. The
 75 conventional quantity value, H_{ref} , is reported with the expanded measurement uncertainty at a 95% confidence level, which has
 76 been determined by the metrology laboratories in accordance with the ISO/IEC Guide 98-3 (ISO/IEC, 2008) and stated on the
 77 irradiation reports received from IRSN and PTB.

Radiation quality	H_{ref} / mSv	Irradiation laboratory	<i>A priori</i> information
^{252}Cf at 0°	0.30 ± 0.03	IRSN	Bare radionuclide source
^{252}Cf at 0°	5.00 ± 0.17	IRSN	Bare radionuclide source
^{252}Cf at 30°	0.50 ± 0.03	IRSN	Bare radionuclide source
^{252}Cf at 45°	0.50 ± 0.03	IRSN	Bare radionuclide source
^{252}Cf (D_2O -moderated, 1 mm Cd)	0.80 ± 0.09	PTB	Radionuclide source, significantly moderated
^{252}Cf with additional thermal field	0.63 ± 0.04	PTB	Radionuclide source, significantly moderated
$^{241}\text{Am-Be}$ at 0°	1.00 ± 0.09	IRSN	Bare radionuclide source
$^{241}\text{Am-Be}$ at 30°	0.50 ± 0.04	IRSN	Bare radionuclide source

79 The thermal neutron field was obtained from a high-purity graphite block (H 1.5 m × W 1.5 m × D 1.8 m)
80 accommodating sixteen ^{241}Am -Be neutron sources assembled in depths of 1.15 m, 1.25 m and 1.35 m from the
81 front surface at heights of 0.65 m and 0.85 m above the floor (Luszik-Bhadra et al., 2018). Because of the low
82 thermal neutron dose equivalent rate of $2.13 \pm 0.15 \mu\text{Sv h}^{-1}$, it was decided to perform the irradiations without
83 cadmium plate and accept a minor contamination of the field by neutrons with energies $E_n > 0.5 \text{ eV}$, corresponding
84 to a dose equivalent of $0.03 \pm 0.01 \text{ mSv}$. Consequently, for irradiations performed in a ^{252}Cf reference field with
85 an additional thermal component, the major fraction of dose equivalent was contributed by fast neutrons
86 ($0.48 \pm 0.02 \text{ mSv}$), with the thermal dose equivalent amounting to $0.15 \pm 0.01 \text{ mSv}$.

87 Participants were given the opportunity to request simplified *a priori* information on the energy distribution of
88 the neutron reference fields (Table 1) to enable application of the proper calibration factor for dosimeter response,
89 in compliance with their routine practice. This request had to be clearly stated during the registration process and
90 re-confirmed to the coordinator before the dosimeters were returned for analysis to the IMS after irradiation. More
91 than 70% of IMSs participating with albedo systems had made use of this option, compared to 40% of participants
92 using track dosimeters. Services who had not opted for receiving *a priori* information, were notified of the identity
93 of irradiated and unirradiated dosimeters.

94 As a novelty, the interlaboratory comparison also investigated false positive response. For that purpose, four
95 dosimeters from each participating IMS were misleadingly reported to have been irradiated with bare radionuclide
96 sources, while they had only been subject to ambient background exposure. This specific test was performed as a
97 matter of scientific interest, and the participants had been informed that the corresponding dosimeters would not
98 be considered in the evaluation of dosimeter performance according to the ISO 14146 standard.

99 3. Results and discussion

100 Dosimeter performance was analysed in terms of response, R , defined as the quotient between the measured
101 personal dose equivalent value, G , as reported by the IMSs, and the conventional quantity value, H_{ref} , in accordance
102 with the irradiation plan (Table 1). The box plots in Fig. 1 provide estimates for the central value of the distributions
103 of response (arithmetic mean, median) and an indication of their spread (coverage intervals, extreme values) for
104 all radiation qualities tested. A few IMSs reported zero response, which cannot be shown in logarithmic scaling.
105 The mean response, \bar{R} , is presented separately for each category of dosimeter system in Table 2. While track
106 dosimeters showed an almost perfect response to fast neutrons from ^{252}Cf , the mean response of both albedo and
107 track dosimeters tended to be somewhat less than 1 for ^{241}Am -Be. For irradiations performed at 30° and 45° angles
108 of incidence, the decrease in response compared to normal incidence was more pronounced for track than for
109 albedo dosimeters. A similar tendency was seen in previous ILCs (Fantuzzi et al., 2014a, 2014b; Mayer et al.,
110 2020, 2021). Few albedo dosimeters exhibited exceptional over-response by up to a factor of 40 to neutron fields
111 with significant moderation or thermal contribution, becoming most evident for bare ^{252}Cf with an additional
112 thermal field. While low-energy neutrons provided a minor contribution to personal dose equivalent, they
113 contributed considerably to the readings of albedo dosimeters, which are characterized by enhanced personal dose
114 equivalent response at lower energies, and thus caused the dosimeters to over-respond. The mean response of
115 track dosimeters showed considerably less over-estimation.

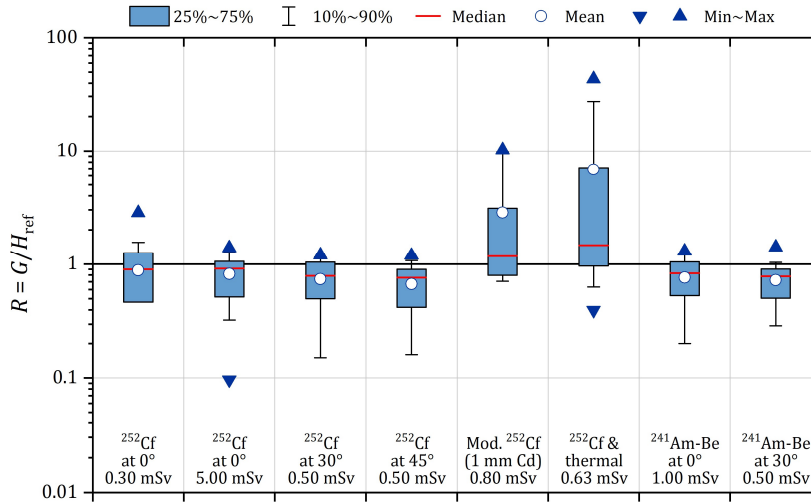


Fig. 1. Distributions of dosemeter response grouped by radiation qualities.

Table 2

Performance of albedo and track dosimeters in terms of mean response, \bar{R} , as evaluated for IC2022n. The errors represent one standard deviation.

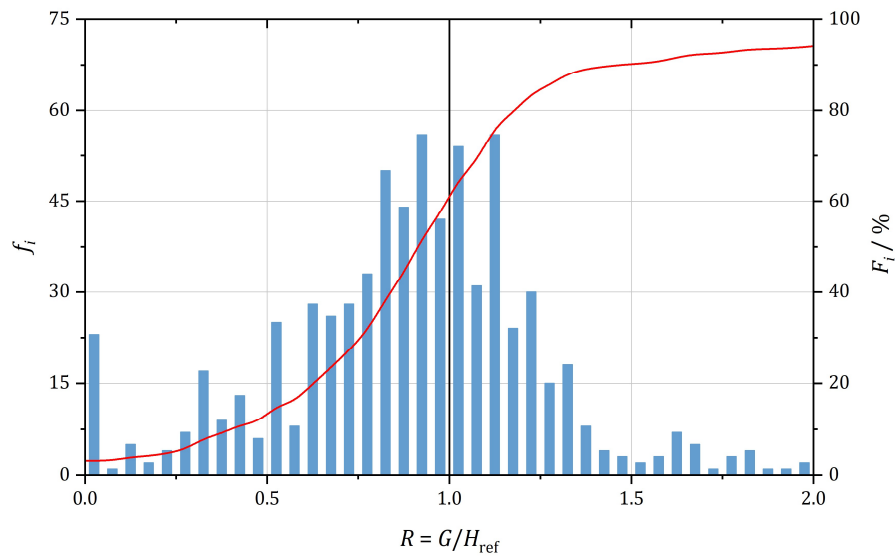
Radiation quality	H_{ref} / mSv	\bar{R}	
		Albedo dosimeters	Track dosimeters
^{252}Cf at 0°	0.30 ± 0.03	0.86 ± 0.52	1.3 ± 0.6
^{252}Cf at 0°	5.00 ± 0.17	0.85 ± 0.37	0.95 ± 0.23
^{252}Cf at 30°	0.50 ± 0.03	0.75 ± 0.39	0.82 ± 0.29
^{252}Cf at 45°	0.50 ± 0.03	0.72 ± 0.35	0.63 ± 0.24
^{252}Cf (D_2O -moderated, 1 mm Cd)	0.80 ± 0.09	3.7 ± 4.0	1.0 ± 0.3
^{252}Cf with additional thermal field	0.63 ± 0.02	8 ± 14	1.8 ± 1.6
$^{241}\text{Am-Be}$ at 0°	1.00 ± 0.09	0.72 ± 0.37	0.82 ± 0.25
$^{241}\text{Am-Be}$ at 30°	0.50 ± 0.04	0.72 ± 0.36	0.76 ± 0.30

The responses reported cover a wide range from 0 to 43.68, with a pronounced maximum near unity. Fig. 2 shows the distributions of absolute frequency, f_i , and cumulative frequency, F_i , of the dosimeter responses. Of those 744 values, 42 were outside the range of the figure, corresponding to 5.6% of all results. Applying the performance limits of ISO 14146 (ISO, 2018) for neutron personal dosimeters,

$$0.5 \cdot \left(1 - \frac{2 \cdot H_0 / 1.5}{H_0 / 1.5 + H_{ref}}\right) \leq R \leq 2 \quad (1)$$

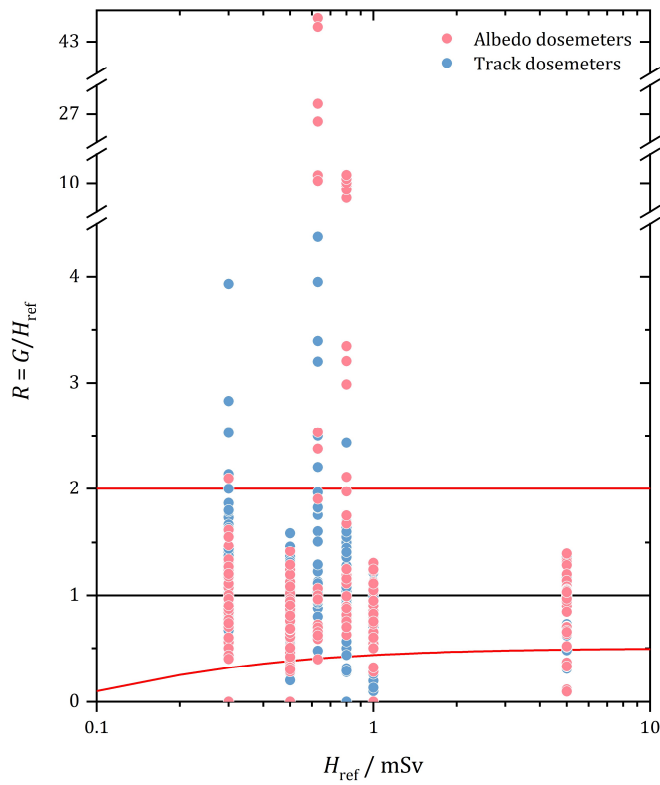
where $H_0 = 0.1$ mSv, 45% of albedo and 80% of track systems met the approval criteria, with a maximum of one-tenth of the dosimeters irradiated exceeding the limits (Figs 3 and 4). Fig. 4 presents the results from individual dosimeter systems identified by reporting number to maintain confidentiality. From the figure, it becomes apparent how the outliers are grouped among certain systems, while others essentially show acceptable results. The choice of H_0 corresponds to the value specified for whole-body dosimeters measuring $H_p(10)$ in ISO 14146 (ISO, 2018). Acknowledging the diversity of national requirements, EURADOS refrained from issuing a conformity statement in the Certificate of Participation awarded to each service, leaving it to the participant to decide about the performance limits and approval criterion to be applied. The Certificate included information on the irradiation qualities, doses, dosimeter responses and overall uncertainties for all irradiations carried out.

Under consideration of the applicable recording levels, below which values of personal dose equivalent are not entered into individual exposure records, 18% of albedo and 35% of track dosimeters indicated false positive response. The highest personal dose equivalent that was reported for an unirradiated dosimeter amounted to 0.59 mSv and originated from a track detector system, for which no *a priori* information on the energy distribution of the neutron reference fields had been requested.



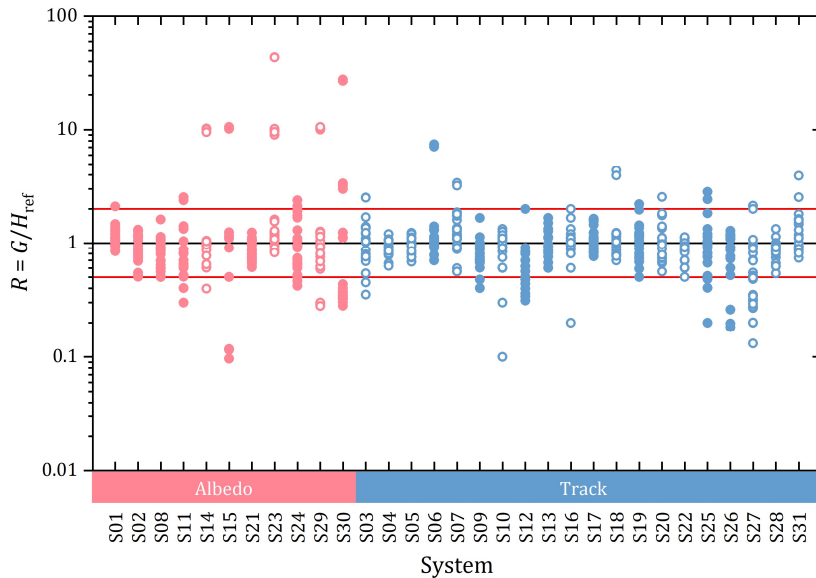
141

142 **Fig. 2.** Distributions of absolute frequency, f_i , (left axis – histogram) and cumulative frequency, F_i , (right axis –
 143 solid line) of dosemeter responses R .



144

145 **Fig. 3.** Responses of albedo and track doseimeters as a function of conventional reference quantity value, H_{ref} . The
 146 solid lines represent the performance limits of ISO 14146:2018.



147

148 **Fig. 4.** Responses of albedo and track dosimeters grouped by confidential reporting number. Full symbols
 149 represent dosimeter systems for which *a priori* spectral information had been requested. The $R = 0.5$ and $R = 2$
 150 criteria are indicated by solid lines to guide the eye.

151 **4. Conclusions**

152 Interlaboratory comparisons are a key tool that allows individual monitoring services to independently
 153 demonstrate compliance with performance limits during quality audits and to validate their measurement methods.
 154 IC2022n was the third ILC for neutron personal dosimeters carried out under coordination of EURADOS. The
 155 median of all responses reported (0.94) was reasonably close to unity, confirming that the calibration procedures
 156 and traceability were largely established without significant bias. Overall, 68% of dosimeter systems met the
 157 approval criterion of ISO 14146 (ISO, 2018). No systems were identified with outliers for all radiation qualities
 158 tested. However, the results also emphasized that a substantial number of services could improve the response of
 159 their dosimeter systems through enhanced dosimetric characterization and calibration. For the tested radiation
 160 qualities, track systems generally provided better estimates of neutron personal dose equivalent with less
 161 uncertainty, while albedo dosimeters showed significant over-response to moderated and thermal neutrons.

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