

SUMMARY OF PERSONAL NEUTRON DOSEMETER RESULTS OBTAINED WITHIN THE EVIDOS PROJECT

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Within the EC project EVIDOS ('Evaluation of Individual Dosimetry in Mixed Neutron and Photon Radiation Fields'), different types of active neutron personal dosimeters (and some passive ones) were tested in workplace fields at nuclear installations in Europe. The results of the measurements which have been performed up to now are summarised and compared to our currently best estimates of the personal dose equivalent $H_p(10)$. Under- and over-readings by more than a factor of two for the same dosimeter in different workplace fields indicate that in most cases the use of field-specific correction factors is required.

INTRODUCTION

Neutron dosimeters used for the determination of the personal dose equivalent for neutrons in mixed neutron/photon fields are much less precise than those for photons. Usually readings are accepted which are lower or higher than the conventional true value up to a factor two. Passive dosimeters are used with field-specific correction factors and have dose detection thresholds in the order of 0.1–0.5 mSv. Active neutron personal dosimeters are used rather infrequently still in workplaces and have become available only during the past few years. Both types were tested in workplace fields within the EVIDOS project, and their readings are compared to estimates of the personal dose equivalent $H_p(10)$ which have been determined in the same fields by spectrometry.

DOSEMETERS USED

The personal dosimeters used in the EVIDOS project and their main characteristics are listed together with the HpSLAB, an instrument which uses a superheated drop detector at 10 mm depth in a slab phantom and which is expected to have a small energy dependence and thus may be developed into a reference instrument for $H_p(10)$, in Table 1.

The electronic personal dosimeters used are the few devices which have been commercially available

in the past few years (Thermo Electron EPD-N, Aloka PDM-313). They are dosimeters from first industrial prototype series (Thermo Electron EPD-N2, Saphydose-n) and laboratory prototypes which were in the stage of light-weight battery-operated instruments (PTB DOS-2002, DMC2000GN). In addition, dosimeters with (almost) immediate readout (BTI bubble detectors, Rados DISN) were used as well as passive dosimeters (nuclear track detectors from PSI and NRPB) and the TLD dosimeters of the facilities visited (Nuclear power plants Krümmel, Ringhals).

DOSEMETER READINGS IN WORKPLACE FIELDS

The dosimeters were irradiated in:

- two simulated workplace fields in Cadarache, France (SIGMA and CANEL),
- four workplace fields in Krümmel, Germany (two at the BWR: KKK Reactor top, KKK SAR, two at a cask: KKK Cask midline and KKK Cask side),
- two workplace fields at the Venus research reactor in Mol, Belgium (Venus control room, Venus reactor side),
- four workplace fields at the fuel facility Belgonucléaire in Mol, Belgium (Belgo P.1 Bare rods, Belgo P.2A Unshielded rack, Belgo P.2B Shielded rack, Belgo P.3 Stockroom) and in

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Table 1. Short description of the personal dosimeters used in the EVIDOS project.

Name of device	Short description	Neutron calibration	Neutron dose calculation	Status
HpSLAB	Superheated drop detector inside a slab phantom ⁽¹⁾	²⁴¹ Am-Be	$H_{p,n}(10) = 0.0915 \text{ (NU-1.0313 NC)} \mu\text{Sv}$	p
Thermo EPD-N	Electronic photon/thermal neutron dosimeter with three silicon detectors ⁽²⁾	Thermal		c
Thermo EPD-N2	Electronic photon/neutron dosimeter with three silicon detectors ⁽³⁾	Light water-mod. ²⁴¹ Am-Be	$H_{p,n}(10) = (10 \text{ FN} + \text{AN}) \mu\text{Sv}$	c
Aloka PDM-313	Electronic neutron dosimeter with one silicon detector ⁽⁴⁾	²⁴¹ Am-Be	$H_{p,n}(10) \cong (\text{N}/1.4) \mu\text{Sv}$	c
Saphydose-n	Electronic neutron dosimeter using a segmented silicon diode ⁽⁵⁾	²⁴¹ Am-Be	Algorithm using five count numbers	c
DOS-2002	Electronic photon/neutron dosimeter with one silicon detector ⁽⁶⁾	²⁵² Cf(D ₂ Omod.): 1.4	$H_{p,n}(10) = (2.602 \text{ N}) \mu\text{Sv}$	p
DMC2000GN	Electronic photon/neutron dosimeter with two silicon detectors	²⁵² Cf(D ₂ Omod.): 1.24	$H_{p,n}(10) = (1.263 \text{ N}) \mu\text{Sv}$	p
BTI-PND	Fast neutron bubble detector ⁽⁷⁾	²⁵² Cf(bare)		c
BTI-BDT	Thermal neutron bubble detector ⁽⁷⁾	Thermal BR I reactor		c
SCK-CEN PND + BDT	Combination of a fast and a thermal neutron bubble detector ⁽⁷⁾	²⁵² Cf(bare), thermal	$H_{p,n}(10) = 0.9 \text{ PND} + \text{BDT}$	a
PSI DISN 1.25%	Ionisation chamber with wall material A-150 + 1.25% BN ⁽⁸⁾	²⁴¹ Am-Be		p
PSI DISN 1.25%(2 mm)	Ionisation chamber with wall material A-150 + 1.25% BN and 2 mm boron shielding ⁽⁸⁾	²⁴¹ Am-Be		p
PSI DISN 4%	Ionisation chamber with wall material PE + 4% LiNO ₃ ⁽⁸⁾	²⁴¹ Am-Be		p
PSI DISN 4% (1 mm)	Ionisation chamber with wall material PE + 4% LiNO ₃ and 1 mm boron shielding ⁽⁸⁾	²⁴¹ Am-Be		p
NRPB PADC	Nuclear track detector (chemical + electrochemical etching) ⁽⁹⁾	²⁵² Cf(bare)	$H_{p,n}(10) = (\text{N}'-\text{B})/\text{R}_{\text{sys}}$	a
PSI CR-39	Nuclear track detector (chemical etching) ⁽¹⁰⁾	²⁴¹ Am-Be, thermal		a
KrümmeL TLD	TLD Albedo dosimeter with ⁶ LiF, ⁷ LiF ⁽¹¹⁾	¹³⁷ Cs, ²⁵² Cf(bare)	Field-specific correction factors	a
Ringhals TLD	TLD dosimeter with LiF/Li ₂ B ₄ O ₇ ⁽¹²⁾	¹³⁷ Cs	$H_{p,n}(10) = (\text{D}_{\text{pos}2}(\text{Li}_2\text{B}_4\text{O}_7) - \text{D}_{\text{pos}3}(\text{LiF}))/\text{OF}$	a

The status [commercial (c), prototype (p) or approved (a)] is given in the last column

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- four workplace fields in Ringhals, Sweden (two at the PWR Ringhals, Block 4: Pos L Entrance lock and Pos A Containment and two at a transport cask with used fuel: Pos D Cask midline, Pos N Cask end).

The criteria for selecting these fields were:

- Neutrons contribute with at least 20% to the ambient dose equivalent.
- The places are typical workplaces which are regularly visited for special jobs.

A more detailed description of the workplace fields is given in Refs^(13–15).

The dosimeters were attached to the front and back side of an ISO phantom (30 × 30 × 15 cm), with the reference point at the front surface. The front surface was usually directed towards the source (reactor, cask and fuel elements), with the exception of a position below the reactor in Krümmel where the front was directed towards the lock while the main source was above. The dosimeters were attached on the phantom in such a way that their active parts stayed in an area of 20 × 20 cm and the boron shielding of the neighbouring dosimeters were at least 5 cm apart. Some passive dosimeters (chiefly track detectors) were also mounted on the phantom sides and for more sensitive devices (HpSLAB and bubble detectors), additional irradiations at an angle of 45° right, 45° left, 45° up, 45° down were performed.

The results of the measurements for front direction are summarised in Table 2. The measured dose equivalent rates are given with one standard uncertainty containing the statistical uncertainties, the uncertainties introduced by the calibration procedures and—in case of the passive dosimeters—the uncertainties introduced by background subtractions. Since there was no time for repeated measurements, the statistical uncertainties were estimated from count numbers (when available) and experience. The uncertainties introduced by the calibration procedures were estimated in most cases in the order of 5–6% with exception of bubble detectors with uncertainties up to 20% for thermal neutron devices. Thus, high uncertainties as given for several measurement results are chiefly a result of small count numbers due to the limited time available for all measurements performed within the project. Our best estimates of the personal dose equivalent rate $\dot{H}_{p,DS}(10)$ (to which these results are compared) are those resulting from spectrometry measurements using the PTB directional spectrometer with silicon diodes (DS)⁽¹⁵⁾. As long as not all possible data available from other measurements are consistently interpreted, these values are only preliminary. A high uncertainty of 30% is assigned at the moment. $\dot{H}_{p,DS}(10)$ values which are considerably smaller (up to a factor of four, see Table 2) than the reference

values of the ambient dose equivalent rate $\dot{H}^*(10)$ indicate fields where neutrons do not chiefly impinge from the front. Both values— $\dot{H}_{p,DS}(10)$ and $\dot{H}^*(10)$ —are given in the first columns of Table 2. In addition, the workplace field is characterised by the ratio of neutron-to-photon dose equivalent rates $\dot{H}_n(10)/\dot{H}_\gamma(10)$, using the photon dose equivalent rate reading of a FHT 191 N ionisation chamber calibrated with ⁶⁰Co.

DOSEMETER RESPONSES IN WORKPLACE FIELDS

The dosimeter response, i.e., the measured value divided by the reference value, is shown for some selected dosimeters in Figure 1. The lowest spread of the results (but still a factor of 2–3) is obtained for the dosimeters which are based on the superheated drop detectors HpSLAB⁽¹⁾ and SCK-CEN PND + B DT⁽⁷⁾ and for those based on the nuclear track detectors NRPB PADC⁽⁹⁾. The HpSLAB and the SCK-CEN PND +BD T indicate mean values which are by a factor of 1.4 and a factor 1.8 higher and the NRPB PADC indicates mean values which are lower (factor 0.9) than the reference values $\dot{H}_{p,DS}(10)$ obtained from spectrometry.

The response of the electronic dosimeters (Thermo EPD-N2, Saphydose-n, PTB DOS-2002) varies by about a factor of ten. The ALOKA dosimeter shows a spread of response of two orders of magnitude. It overreads at reactors by up to a factor of 60.

The DISN 4% device is the favoured one among the devices with different wall material and shieldings⁽⁸⁾. Although its neutron response is comparable to—or even better than—those of the electronic devices, its main drawback is that a photon reading has to be subtracted. This, in fields with a high photon dose contribution (KKK SAR, see Table 1), resulted in zero readings. The DISN 1.25% devices were in most measurements used on the backside of the phantom.

The dosimeters which chiefly indicate thermal and epithermal neutrons (Thermo EPD-N and BTI-BDT) showed responses below unity. The response of the EPD-N was in all workplace fields (with the exception of SIGMA) lower than 0.3, indicating small dose contributions of thermal neutrons in these fields. The BTI-BTD in general showed higher response values than the EPD-N (0.99 for Ringhals Pos A Containment, see values in Table 1).

In general, the response values observed in reactor fields (full symbols in Figure 1) are higher than those found in fields at the transport casks and at the MOX fuel factory (open symbols in Figure 1). This allows a field-specific correction factor to be used for a special class of workplace fields. This can be done

Table 2. Personal dose equivalent rate measured in workplace fields.

Workplace	$H_{p,DS}(10)/\mu\text{Sv h}^{-1}$	$\dot{H}^*(10)/\mu\text{Sv h}^{-1}$	$\dot{H}_s^*(10)/\dot{H}_s^*(10)$	DIMNP HpSLAB	Aloka PDM-313	Thermo EPD-N	Thermo EPD-N2	Saphydose-n	PTB DOS-2002	DMC 2000 GN	BTI-BDT
Canel ^a	120.2 (6.4)	122.3 (6.0)		153 (21)	639 (35)	21 (20)	345 (22)	104 (21)	153 (11)		41 (8)
Sigma	131.9 (3.7)	143.6 (5.1)	3.6 (0.1)	148 (21)	648 (37)	53 (49)	800 (49)	160 (40)	178 (14)		85 (9)
KKK (SAR)	11 (3)	47.6 (1.7)	0.2 (0.01)	11 (2)		0 (1)	56 (3)	106 (19)	51 (3)		7 (1)
KKK (Reactor top)	24 (7)	40.0 (1.5)	4.4 (0.2)	47 (6)	300 (18)	5 (5)	114 (10)	119 (21)	68 (10)		8 (1)
KKK (Cask midline)	110 (33)	156.3 (4.9)		206 (29)	146 (10)	3 (3)	34 (6)	95 (24)	87 (17)		22 (5)
KKK (Cask side)	28 (8)	54.8 (2.0)	41.3 (1.5)	54 (7)	167 (11)	2 (2)	30 (6)	26 (6)	26 (5)		5 (2)
Venus (Control room)		14.1 (0.5)	1.3 (0.05)	10 (1)	22 (2)	1 (1)	33 (3)	15 (3)	7 (1)		2 (1)
Venus (Reactor side)	44 (13)	153.0 (5.1)	3.6 (0.1)	70 (10)	330 (22)	8 (8)	209 (23)	122 (21)	80 (14)		15 (3)
Belgo P.1 (Bare rods)	29 (9)	50.9 (1.6)	1.1 (0.03)		18 (2)	0 (1)	30 (7)	43 (7)	12 (3)		2 (1)
Belgo P.2A (Unshield.rack)	162 (49)	208.7 (6.7)	7.2 (0.23)	177 (25)	93 (6)	0 (1)	105 (14)	204 (32)	68 (7)		10 (2)
Belgo P.2B (Shielded rack)	21 (6)	33.2 (1.1)	6.4 (0.2)		27 (2)	1 (1)	15 (2)	19 (4)	13 (2)		2 (1)
Belgo P.3 (Stockroom)	17 (5)	31.9 (1.1)	2.6 (0.1)	20 (3)	34 (3)	0 (1)	19 (2)	31 (5)	10 (2)		2 (1)
Pos A (Entrance lock)	118 (35)	252.7 (8.1)	5.1 (0.16)	193 (26)	4386 (224)	20 (10)	462 (33)	1311 (197)	389 (30)	428 (29)	59 (10)
Pos A (Containment)	614 (184)	1845.1 (55.0)	5.5 (0.2)		37200 (1875)	176 (88)	3728 (208)	2735 (410)	2690 (181)	3033 (176)	608 (112)
Pos D (Cask midline)	36 (11)	49.0 (1.8)	0.7 (0.03)	48 (7)	338 (18)	3 (3)	103 (7)	132 (20)	86 (8)	89 (6)	24 (7)
Pos N (Cask end)	13 (4)	21.4 (0.8)	0.7 (0.03)	15 (2)	144 (8)	1 (1)	58 (4)	31 (5)	34 (3)	41 (3)	5 (2)

Workplace	BTI-PND	SCK-CEN PND + BDT	PSI DISN 1.25%	PSI DISN 1.25% (2mm)	PSI DISN 4%	PSI DISN 4% (1mm)	PSI CR-39	NRPB PADC	KKK TLD	Ringhals TLD
Canel ^a	140 (13)	167 (14)	918 (107)	73 (16)	289 (47)	64 (13)	40 (5)	114 (7.9)		
Sigma	101 (14)	176 (16)	3000 (350)	161 (19)	632 (79)	151 (18)	68 (21)	127 (7)		
KKK (SAR)	20 (5)	25 (5)		0 (?)		0 (?)		4.8 (0.7)	43 (6)	
KKK (Reactor top)	29 (4)	33 (3)			15 (15)			21 (8)	103 (21)	
KKK (Cask midline)	222 (36)	222 (33)		63 (19)	12 (10)		47 (24)	72 (12)	212 (95)	
KKK (Cask side)	64 (9)	63 (8)		13 (6)	10 (5)			18.4 (0.9)	17 (35)	
Venus (Control room)	10 (1)	11 (1)						8.3 (1.1)		
Venus (Reactor side)	83 (8)	89 (8)			116 (24)	24 (15)	63 (9)	32 (2)		
Belgo P.1 (Bare rods)	27 (3)	26 (3)					32 (10)	28 (2)		
Belgo P.2A (Unshield.rack)	237 (24)	223 (21)			132 (15)	117 (15)	110 (13)	124 (3)		
Belgo P.2B (Shielded rack)	42 (4)	40 (4)			28 (6)	13 (6)	27 (5)	14.3 (0.3)		
Belgo P.3 (Stockroom)	28 (3)	27 (3)			24 (6)	13 (6)	15 (2)	14.1 (1.6)		
Pos L (Entrance lock)	277 (25)	308 (25)			159 (19)	65 (8)	194 (26)	80 (7)		64 (28)
Pos A (Containment)	1653 (138)	2095 (167)			1541 (180)	620 (72)	1673 (349)	646 (60)		624 (156)
Pos D (Cask midline)	25 (10)	47 (12)			9 (4)	0 (?)	25 (8)	31 (4)		15 (15)
Pos N (Cask end)	16 (4)	19 (4)					18 (9)	10.0 (1.5)		10 (10)

Dosemeter readings are given in $\mu\text{Sv h}^{-1}$. The standard uncertainty (see text) is indicated in brackets. The first three columns indicate the preliminary reference values $\dot{H}_{p,DS}(10)$ for the personal dose equivalent rate, the reference values $\dot{H}^*(10)$ for the ambient dose equivalent rate and the ratio of photon-to-neutron dose equivalent rates $\dot{H}_s^*(10)/\dot{H}_s^*(10)$ ^amsv/ monitor count

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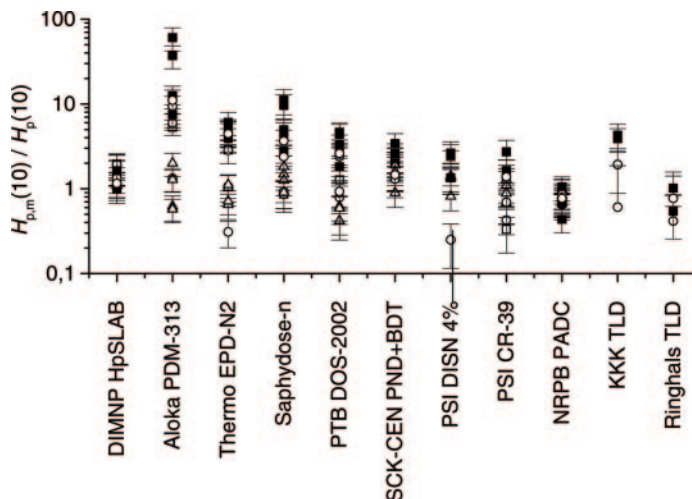


Figure 1. Response of different personal dosimeters in the simulated workplace field CANEL (□), the reactor fields (■), the fields at transport casks (○) and the fields at the fuel facility Belgonucléaire (△).

Table 3. Mean correction factor for reactor fields.

Device	Field-specific correction factor
DIMNP HpSLAB	0.64
Aloka PDM-313	0.034
Thermo EPD-N2	0.20
Saphydose-n	0.15
PTB DOS-2002	0.29
DMC 2000GN	0.23
SCK-CEN PND + BDT	0.43
PSI DISN 4%	0.46
PSI CR-39	0.52
NRPB PADC	1.32
KKK TLD	0.24
Ringhals TLD	1.28

either by using the calibration as indicated in Table 1 and the results of this campaign (see Tables 2 and 3 for reactor fields) or by using a more appropriate calibration field. In the case of the EPD-N2, a calibration using the simulated workplace field CANEL will give improved readings at reactor fields, whereas this is not the case for the dosimeters Saphydose-n⁽⁵⁾ and DOS-2002 which show responses that are close to unity at CANEL and, despite this fact, responses in reactor fields that are too high (see the values in Table 2).

In general, no trend of higher or lower response values depending on the photon contribution in the fields (see Table 1) was observed.

The HpSLAB device indicates our preliminary best estimate of $H_p(10)$ as obtained from spectrometry within a factor of 0.7–1.3, if the readings are adjusted

by dividing them by 1.4. It may be therefore suited as a reference instrument, if recently performed calculations⁽¹⁾ of the response matrix of this system are fully analysed.

LOCAL DEVICES

As TLD dosimeters usually require field-specific correction factors which depend on the dosimeter itself and on the characteristics of the fields, only the local devices as used in the facilities visited were used.

The albedo dosimeters at Krümmel were evaluated by means of calibration factors which for the measurements at the cask were by a factor of two higher than inside the reactor. The high uncertainties at the cask (see Figure 1) result from short irradiations of only ~2 h.

The dosimeters at Ringhals are usually used with field-specific correction factors. Three different over-response factors (OF, see Table 1), depending on where the person has been working, are used. These factors have been determined using knowledge from earlier spectrometric investigations of the workplaces at Ringhals⁽¹²⁾. Although the dosimeter uses no albedo shielding and chiefly detects thermal and epithermal neutrons, the spread of the measured responses is acceptable and the mean response close to unity. The results of the campaign will be used to improve the field-dependent correction factors.

The local dosimeters used at Belgonucléaire and at the VENUS reactor for routine personnel monitoring are the BTI-PND and the SCK-CEN PND + BDT bubble detectors [see Ref.⁽⁷⁾ for a more detailed analysis].

Table 4. Predicted and measured dose rates for the PTB DOS-2002.

Workplace	$\dot{H}_{p,\text{pred.}}(10)/\mu\text{Sv h}^{-1}$	$\dot{H}_{p,\text{m}}(10)/\mu\text{Sv h}^{-1}$	$\dot{H}_{p,\text{pred.}}(10)/\dot{H}_{p,\text{m}}(10)$
KKK (SAR)	40 (20)	51 (3)	0.78 (39)
KKK (Reactor top)	51 (25)	68 (10)	0.75 (38)
KKK (Cask midline)	47 (25)	87 (17)	0.54 (27)
KKK (Cask side)	14 (7)	26 (5)	0.54 (27)
Venus (Reactor side)	55 (27)	80 (14)	0.68 (34)
Belgo P.1 (Bare rods)	14 (7)	12 (3)	1.12 (56)
Belgo P.2A (Unshielded rack)	77 (39)	68 (7)	1.13 (56)
Belgo P.2B (Shielded rack)	11 (5)	13 (2)	0.83 (42)
Belgo P.3 (Stockroom)	9 (5)	10 (2)	0.95 (47)
Pos L (Entrance lock)	430 (215)	389 (30)	1.10 (55)
Pos A (Containment)	1835 (918)	2690 (181)	0.68 (34)
Pos D (Cask midline)	50 (25)	86 (8)	0.58 (29)
Pos N (Cask end)	24 (12)	34 (3)	0.71 (35)

The uncertainties stated correspond to one standard deviation

COMPARISON WITH THE PREDICTED RESPONSE

The high deviations of the readings from $H_p(10)$ in workplaces can be explained by the monoenergetic response functions of the dosimeters which are not ideal. A first estimate of the response in workplace fields has been obtained for the dosimeter PTB DOS-2002 by folding the response of the dosimeter [as a function of energy and angle, see Ref.⁽¹⁶⁾] by the direction-dependent neutron spectra having been obtained within the project [see Ref.⁽¹⁵⁾].

By folding this response matrix with the direction-dependent neutron spectra, predicted readings were obtained. Since the integral dose values obtained from the directional spectrometer already have uncertainties of about 30%⁽¹⁵⁾ and additional uncertainties add to these in determining the dosimeter response, the values obtained have an estimated uncertainty of about 50%. In Table 4, the results of the predicted dose rates are compared with the measured dose rates for the investigated workplace fields. The agreement is satisfactory within the uncertainties estimated. The high over-readings observed in the reactor fields are a result of high dosimeter overresponses for intermediate energy neutrons and an appreciable contribution of these neutrons in the fields.

UNCERTAINTIES

As the time available for all experiments was limited, some dosimeters could be irradiated for a short period of time only (~ 1 h), in other cases (especially for the passive devices) irradiations were performed overnight and the uncertainties of the dose rate values indicated in Table 2 do not allow the low dose limits of the dosimeters to be compared.

The statistical uncertainties can, however, be estimated quite easily from the algorithms given in Table 1. For a personal dose equivalent reading of 100 μSv , the relative uncertainty (1 SD) is 8.4% for Aloka PDM-313, 16.1% for PTB DOS-2002 and 11.4% for DMC2000GN.

In the case of the Thermo EPD-N2, the readings depend on two count numbers: one (FN) corresponds to a fast neutron reading, the other one (AN) to an albedo neutron reading. Since in most of the workplace fields these readings were also determined, the relative uncertainty for a measured personal dose equivalent of 100 μSv has been determined for the different workplace fields. At the transport casks and reactors, it is in the order of 10–20%, whereas for the fields with unshielded MOX fuel, it is higher (up to 29%).

In reactor fields, the readings of 100 μSv correspond—with appropriate correction factors—to personal dose equivalent values of about 20 μSv (see Table 3). Hence, in reactor fields, the personal dose equivalent of 20 μSv can be determined with a low standard deviation of about 10%.

TECHNICAL PERFORMANCE

Most of the devices were used without problems. In the case of the laboratory type device PTB DOS-2002 care had to be taken as the instrument was still shock-sensitive. The DISN devices could not be used in fields with a high photon dose contribution.

CONCLUSION

For the determination of the neutron dose equivalent, the electronic personal dosimeters still require field-specific correction factors. The measurements

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performed within the EVIDOS project in 14 real workplace fields and two simulated ones reveal that mean correction factors can be used for some classes of workplace fields, such as reactors, transport casks and MOX fuel. In reactor fields, most of the electronic dosimeters overrespond by more than a factor of 3. The measured readings have been compared with predictions and yielded reasonable agreement. The electronic dosimeters indicate a personal dose equivalent of about 20 μSv in reactor fields with a standard uncertainty of about 10%.

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