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DIRECTION DISTRIBUTIONS OF NEUTRONS AND REFERENCE VALUES OF THE PERSONAL DOSE EQUIVALENT IN WORKPLACE FIELDS

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Within the EC project EVIDOS, double-differential (energy and direction) fluence spectra were determined by means of novel direction spectrometers. By folding the spectra with fluence-to-dose equivalent conversion coefficients, contributions to $H^*(10)$ for 14 directions, and values of the personal dose equivalent $H_p(10)$ and the effective dose E for 6 directions of a person's orientation in the field were determined. The results of the measurements and calculations obtained within the EVIDOS project in workplace fields in nuclear installations in Europe, i.e., at Krümmel (boiling water reactor and transport cask), at Mol (Venus research reactor and fuel facility Belgonucléaire) and at Ringhals (pressurised reactor and transport cask) are presented.

INTRODUCTION

Within the EC project EVIDOS ('Evaluation of Individual Dosimetry in Mixed Neutron and Photon Radiation Fields'), various personal dosemeters for mixed field applications—passive and new electronic devices—were tested in selected workplace fields in nuclear installations in Europe.

The individual monitoring quantities to which the readings of personal dosemeters have to be compared depend not only on the energy distribution of the neutrons but also on their direction distribution. This work describes the direction spectrometers used within the EVIDOS project and discusses the energy and direction distributions of neutrons derived from the measured data. It also gives our current best estimates for the personal dose equivalent $H_p(10)$ and the effective dose E in these fields, including estimates of the uncertainties. The results are compared to those from the HpSLAB, an instrument which uses a superheated drop detector at 10 mm depth in a slab phantom and which is being developed as a reference instrument for personal dosemeter readings.

DIRECTION SPECTROMETERS

Two direction spectrometers were used.

DIMNP has developed a direction spectrometer with a superheated drop detector. It uses a 'telescope-design' with a single detector at the centre of a moderating sphere of nylon-6, 30 cm in diameter. By changing the temperature of the superheated drop detector, a series of responses with a threshold behaviour as a function of the neutron energy is obtained. By rotating the sphere into selected directions, neutrons chiefly incident into a cone corresponding to a solid angle of about 1/6 steradians are registered. The response functions of the spectrometer were determined by measurements and calculations$^{(1)}$. Due to time constraints, for most of the workplace measurements the spectrometer could only be used facing the assigned front direction. A more complete set of measurement was performed during the last measurement campaign inside the Ringhals reactor containment, but these data have not been analysed yet.

PTB has developed a direction spectrometer which consists of six detector capsules each containing a stack of 4 silicon detectors, mounted onto the surface of a 30 cm diameter polyethylene sphere. The response matrix of the full detector set-up has been determined from measurements and calculations for different directions of incidence (0°–180°) in the energy range from thermal up to 15 MeV for neutrons and from 65 keV to 7 MeV for photons$^{(2)}$. Information on the neutron radiation incident from different directions can be obtained in a sufficiently short time, but due to the broad and overlapping nature of the response functions, some prior information is required to get optimal results.

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The energy and the direction distributions of the neutron fluence were derived from the measured pulse height spectra of all 24 silicon detectors using four different unfolding methods. In this way, the sensitivity of the results to different ways of unfolding could be studied and the uncertainty associated with the unfolding procedure estimated:

- MAXED, BS: maximum entropy neutron/photon unfolding code specially adapted to this system$^{(3)}$, with prior information on the energy distribution of neutrons based on the results of the Bonner sphere measurements performed in the same fields$^{(4)}$. This method makes optimum use of the prior information that is available and therefore provides the best estimate of the spectrometric quantities.
- MAXED, 0.5 MeV: maximum entropy neutron/photon unfolding, using in all cases a simple parameterised model spectrum as an initial estimate for the neutron spectra. The parameterised model assumed peaks at thermal energies and 0.5 MeV and an intermediate region that is flat in the lethargy representation.
- MIEKE, N + G: Monte Carlo neutron/photon unfolding without site-specific prior information.
- MIEKE, N: Monte Carlo neutron unfolding (without photons). This unfolding uses only the pulse height information with deposited energies above 800 keV.

The unfolding codes produced neutron fluence spectra in 20 (MAXED) or 14 (MIEKE) direction intervals.

The following dosimetric results were calculated from the unfolded distributions:

- ambient dose equivalent $H^*(10)$ and contribution to $H^*(10)$ for 14 directions;
- personal dose equivalent $H_p(10)$ corresponding to 6 directions;
- effective dose E corresponding to 6 directions;
- effective dose E_{new} with new w_R values as given in Reference 7.

The dose values were determined by folding the fluence energy distributions with conversion coefficients $h^*(10)$ and $h_{p,slab}(10)$ as given by ICRU 57$^{(5)}$ and as derived for higher angles of incidence from recent calculations$^{(6)}$. The difference between $H_p(10)$ in the slab phantom and that in the body of a person is thought to be small for neutrons incident from front direction. For the calculations of the effective dose E, the fluences were folded using the conversion coefficients for AP, PA, LLAT and RLAT, and values for the directions 'Up' and 'Down' were estimated by setting them equal to (3·ISO–2·ROT). In addition, revised w_R values were also used (as recently proposed$^{(7)}$), and their influence on the values of the effective dose estimated. For this, the fluence-to-dose conversion coefficients given in ICRU 57 for AP, PA, LLAT, RLAT, ISO and ROT were divided by the w_R values as given in ICRP 74 and multiplied by the newly recommended values.

MEASUREMENTS IN WORKPLACE FIELDS

The measurements were performed in two simulated workplace fields in Cadarache and in workplace fields in nuclear installations in Europe, i.e., at Krümmel (boiling water reactor and transport cask), at Mol (Venus research reactor and fuel facility Belgonucléaire) and at Ringhals (pressurised reactor and transport cask). More detailed information on the measurement positions is presented elsewhere$^{(4,8)}$.

RESULTS OF THE DIRECTIONAL SPECTROMETER OF THE PTB

Figures 1–4 show the contributions to $H^*(10)$ from 14 different directions for all the workplace fields that were investigated, obtained by folding the fluence energy distributions from the MAXED, BS unfolding with fluence-to-ambient dose conversion coefficients. The FRONT direction was usually assigned towards the source (reactor, cask and fuel elements), except for a position below the reactor in Krümmel where the FRONT direction was assigned towards the lock. The directions LEFT, RIGHT and BACK correspond to the directions as described by a person facing the source. The positions in between are indicated by abbreviations.

The distributions were strongly-directed forwards for the simulated workplace fields CANEL and SIGMA (see Figure 1, note the logarithmic scale) and for the 'Cask midline' positions (see Figure 2), and directed less strongly forwards for the positions 'Krümmel Cask side', 'Ringhals Pos N Cask end' (see Figure 2), 'Krümmel Reactor top' and 'Ringhals Pos. L Lock' (see Figure 3) and the workplace fields

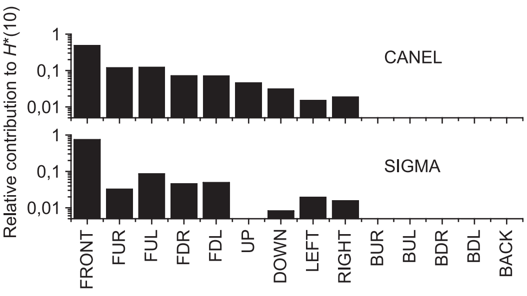

Figure 1. Relative contribution to $H^*(10)$ from 14 different directions as measured in simulated workplace fields.

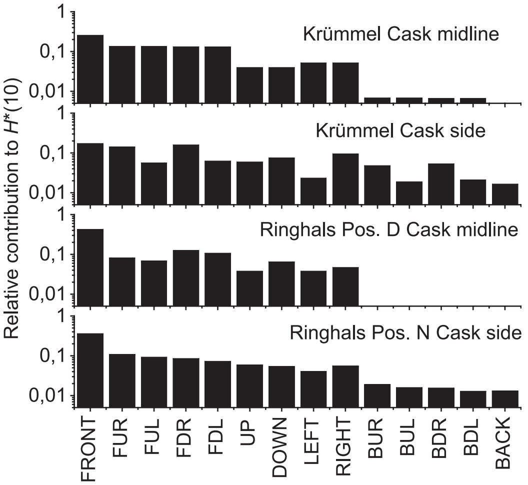

Figure 2. Relative contribution to $H^{*}(10)$ from 14 different directions as measured near casks with used fuel.

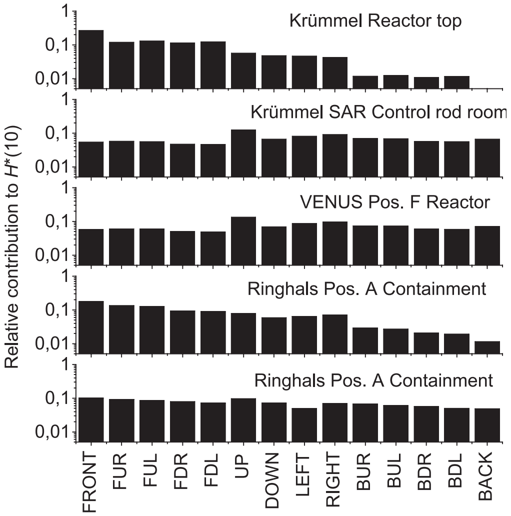

Figure 3. Relative contribution to $H^{*}(10)$ from 14 different directions as measured in reactor fields.

in the MOX fuel storage at Belgonucleaire (see Figure 4). Distributions were almost isotropic for the reactor fields 'Krümmel, SAR Control rod room', 'VENUS Pos. F Reactor' and 'Ringhals Pos. A Containment' (see Figure 3).

The broader distributions arised chiefly from extended sources and from room scattered neutrons produced either by the proximity to the floor or by concrete walls close to the measuring position. In case of the almost isotropic reactor fields, slightly higher contributions were observed from the top, either arising due to the source being above ('Krümmel, SAR Control rod room') or due to sky-shine radiation ('VENUS Pos. F Reactor', 'Ringhals Pos. A Containment') (see Figure 3). In the case of the 'Krümmel Cask side' position, where the centre of the cask was on the right hand side, higher contributions were observed from the right (see Figure 2). In case of 'Belgonucleaire Pos.1 Bare rods', MOX fuel rods in a rack behind the measuring position contributed to the dose equivalent on the back side (see Figure 4).

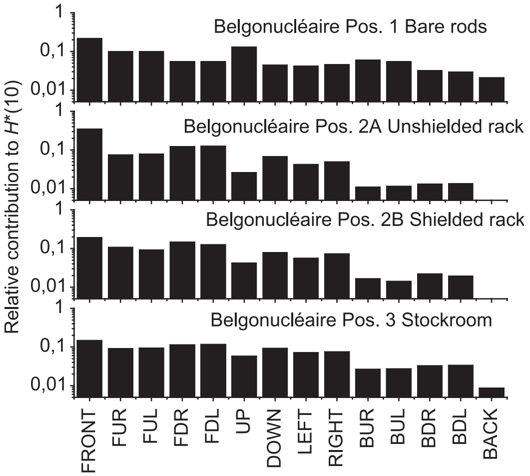

Figure 4. Relative contribution to $H^{*}(10)$ from 14 different directions as measured in a MOX fuel storage at Belgonucléaire.

Table 1 contains dose values using spectral fluences as determined by means of the direction spectrometer (index DS) and by means of Bonner spheres (index BS). Values of the personal dose equivalent $H_{\mathrm{p,DS}}(10)$ and of E_{DS}, both divided by $H^{*}_{\mathrm{DS}}(10)$ are given in column 2 and 3 for a person facing the front direction. These values are our best estimates, as derived from the MAXED, BS unfolding. The values in brackets indicate the standard deviation of the results obtained with the four different unfolding methods described above. The ratio $H_{\mathrm{p}}(10)/\ H^{*}(10)$ is close to 1 (0.7–0.9) in the case of the strongly-directed fields, but much lower (0.2–0.3) in the case of the almost isotropic reactor fields. This is due to the fact that in these reactor fields low-energy neutrons incident at higher angles contribute with lower conversion coefficients to $H_{\mathrm{p}}(10)$ and those incident on the backside of the phantom give almost no contribution. The effective dose E is in all cases much lower than $H^{*}(10)$, in most cases also lower than $H_{\mathrm{p}}(10)$. In the case of the more isotropic reactor fields, $H_{\mathrm{p}}(10)$ is a slightly non-conservative estimate of the effective dose E (see column 4).

Table 1. Ratio of dose values for different workplace fields (see text).

Workplace	$H_{p,DS}(10)/H^*_{DS}(10)$	$E_{DS}/H^*_{DS}(10)$	$E_{DS}/H_{p,DS}(10)$	$H^*_{BS}(10)/H^*_{DS}(10)$
CANEL	0.83 (21)	0.52 (8)	0.63	1.08 (20)
SIGMA	0.91 (26)	0.67 (19)	0.73	0.98 (36)
Krümmel SAR control rod room	0.22 (2)	0.32 (3)	1.43	1.11 (33)
Krümmel reactor top	0.60 (2)	0.45 (3)	0.75	1.02 (39)
VENUS Pos. F reactor	0.29 (3)	0.33 (2)	1.14	1.19 (22)
VENUS Pos. C control room[a]				
Ringhals Pos. L lock	0.47 (4)	0.42 (3)	0.89	1.19 (25)
Ringhals Pos. A containment	0.33 (3)	0.35 (3)	1.06	1.41 (35)
Krümmel cask midline	0.70 (8)	0.36 (5)	0.51	0.96 (32)
Krümmel cask side	0.52 (12)	0.30 (7)	0.59	1.41 (30)
Ringhals Pos. N cask end	0.61 (4)	0.39 (2)	0.64	1.05 (31)
Ringhals Pos. D cask midline	0.73 (14)	0.40 (3)	0.55	0.72 (15)
Belgonucléaire Pos. 1 Bare rods	0.57 (11)	0.43 (13)	0.75	1.05 (25)
Belgonucléaire Pos. 2A Unshielded rack	0.78 (2)	0.48 (7)	0.62	1.02 (30)
Belgonucléaire Pos. 2B Shielded rack	0.64 (3)	0.39 (5)	0.61	1.09 (36)
Belgonucléaire Pos. 3 Stockroom	0.54 (2)	0.36 (2)	0.66	1.35 (30)

[a] No measurements performed with the directional spectrometer because of limited time and low dose rates

Table 2. $H_p(10)$ and E divided by $H^*(10)$ for different directions of a person's orientation at Ringhals, Pos. L (Lock).

Position	FRONT	UP	DOWN	LEFT	RIGHT	BACK
$H_p(10)/H^*(10)$	0.47 (4)	0.29 (4)	0.21 (3)	0.23 (2)	0.24 (4)	0.08 (2)
$E/H^*(10)$	0.42 (3)	0.34 (3)	0.33 (2)	0.34 (2)	0.35 (2)	0.34 (2)
$E_{new}/H^*(10)$	0.24 (2)	0.20 (2)	0.19 (1)	0.20 (2)	0.21 (2)	0.20 (1)

$H_P(10)$ AND E FOR DIFFERENT DIRECTIONS OF A PERSON'S ORIENTATION

In Table 2, values of $H_p(10)/H^*(10)$, $E/H^*(10)$ and $E_{new}/H^*(10)$ are given for a person facing the directions FRONT, UP, DOWN, LEFT, RIGHT and BACK. In the case of the position 'Ringhals Pos. L (Lock)', $H_p(10)$ becomes a non-conservative estimate of E for directions different from FRONT. By using the newly recommended w_R values, $H_p(10)$ becomes a conservative estimate of E_{new} for all directions except for the direction BACK (compare values in Table 2).

PRELIMINARY REFERENCE VALUES OF $H_p(10)$

For the MAXED, BS unfolding, the values of ambient dose equivalent $H^*(10)$ obtained by the direction spectrometer agree well with those obtained by the Bonner spheres (see Table 1, last column). However, the values of $H^*(10)$ deviated from those obtained by the Bonner sphere spectrometer by up to a factor of two when the Bonner sphere spectra were not used as prior information. Our current best estimates of the reference values are derived from a combination of results from the Bonner sphere spectrometer—$H^*(10)$ values—with results from the directional spectrometer—ratios $H_{p,DS}(10)/H^*_{DS}(10)$, obtained by unfolding with prior information of spectral shape from Bonner spheres:

$$H_p(10) = H^*_{BS}(10) \cdot (H_{p,DS}(10)/H^*_{DS}(10)).$$

The $H^*_{BS}(10)$ values have been determined with standard uncertainties of about 5%$^{(4)}$ and the standard uncertainty for the ratios $H_{p,DS}(10)/H^*_{DS}(10)$ using the four unfolding codes resulted in 10–20% for values determined for the front direction (see Table 1). For the uncertainty of $H_p(10)$, we estimate a relative uncertainty of 30% (one relative standard uncertainty) for the front direction. These reference values should be regarded as preliminary, since additional information from other measurements within the project still needs to be analysed. A comparison of the readings of the HPSLAB device with the values above indicates that these values are consistent within a range 0.7–1.3 if the HpSLAB values are lowered by a factor of 1.4 [see Ref. (9)]. For the reference fields CANEL and SIGMA, the ratios $H_p(10)/H^*(10)$ obtained by the direction spectrometer for the front direction (0.83 for CANEL and

0.91 for SIGMA, see Table 1) can also be compared to reference values that have been determined for these fields by measurements and calculations [0.98 for CANEL(10) and 1.04(11) for SIGMA]. They agree within 10%.

CONCLUDING REMARKS

The direction distributions of neutrons varied strongly in the workplace fields investigated. For strongly-directed fields, ratios $H_\mathrm{p}(10)/H^*(10)$ close to 1 were determined, reflecting the fact that fluence-to-personal dose equivalent and fluence-to-ambient dose equivalent conversion coefficients are similar for normally incident low-energy neutrons. In almost isotropic fields, ratios $H_\mathrm{p}(10)/H^*(10)$ considerably lower than 1 (0.2–0.3) were determined, reflecting the fact that the fluence-to-personal dose equivalent conversion factors decrease strongly for low-energy neutrons incident at higher angles, while the fluence-to-ambient dose equivalent coefficients are not angular dependent. Folding fluences with fluence-to-effective dose conversion coefficients resulted in values for the effective dose E, which were found in most cases lower than $H_\mathrm{p}(10)$, thus conservative estimates of E, for the assigned front directions.

Our current best estimates of $H_\mathrm{p}(10)$ values, which are needed for the interpretation of personal dosemeter results within the EVIDOS project, are derived from a combination of Bonner sphere measurements and measurements with the direction spectrometer of the PTB, and should be regarded as preliminary until all the data from the project becomes available and is fully analysed.

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