

INDIVIDUAL NEUTRON MONITORING IN WORKPLACES WITH MIXED NEUTRON/PHOTON RADIATION

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EVIDOS ('evaluation of individual dosimetry in mixed neutron and photon radiation fields') is an European Commission (EC)-sponsored project that aims at a significant improvement of radiation protection dosimetry in mixed neutron/photon fields via spectrometric and dosimetric investigations in representative workplaces of the nuclear industry. In particular, new spectrometry methods are developed that provide the energy and direction distribution of the neutron fluence from which the reference dosimetric quantities are derived and compared to the readings of dosimeters. The final results of the project will be a comprehensive set of spectrometric and dosimetric data for the workplaces and an analysis of the performance of dosimeters, including novel electronic dosimeters. This paper gives an overview of the project and focuses on the results from measurements performed in calibration fields with broad energy distributions (simulated workplace fields) and on the first results from workplaces in the nuclear industry, inside a boiling water reactor and around a spent fuel transport cask.

INTRODUCTION

EVIDOS is an European Commission (EC)-sponsored project which, over the course of almost 4 y, will perform an 'evaluation of individual dosimetry in mixed neutron and photon radiation fields'. One of the primary aims of the project is to establish whether innovative electronic dosimeters with direct reading allow improved determination of personal dose equivalent. This objective requires preliminary investigations in calibration fields followed by extensive in-field measurements in representative workplaces of the nuclear industry. Seven European research laboratories with recognised expertise in radiation protection and in detector development are involved in the project.

Reference methods for the determination of personal dose equivalent in workplace fields are a central part of this project. Because no current dosimeter gives correct results in all neutron fields, reference values have to be derived from spectrometry (with respect to the energy and direction of the radiation) and fluence-to-dose equivalent conversion coefficients.

Various measurement campaigns have already been performed, comprising 2 simulated workplace fields and 10 workplace fields in the nuclear industry.

While these complex measurements require a detailed analysis, which is still in progress, a selection of the results is already available and is presented here.

MEASUREMENT CAMPAIGNS AND INSTRUMENTS USED

In the early phases of the project, a series of representative workplaces in the nuclear industry in which workers can receive significant neutron doses were selected. For each workplace, some measurement points were selected in collaboration with the radiological safety officers of the inspected facilities. These workplaces permit a thorough test of the dosimeters since they differ widely in terms of dose rates, neutron/photon relative intensity, energy/direction distributions and also temperature, pressure, humidity, acoustic noise, vibration, electromagnetic fields, etc.

The area monitors and the personal dosimeters employed in the project are listed in Table 1⁽¹⁻¹⁷⁾. These instruments comprise commercial devices as well as laboratory prototypes developed by some of the partners. Only prototype dosimeters have reached the stage of well-characterised, light-weight battery-operated instrumentation with direct reading⁽¹⁸⁾ are utilised in the project.

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Table 1. Short description of the devices used in the EVIDOS project.

Name of device	Short description	Commercial (c) or prototype (p)
Sievert instrument	Low pressure proportional counters (one of tissue-equivalent plastic and one of graphite) evaluated according to the variance/covariance technique ⁽¹⁾	p
Berthold LB 6411	Moderator type area monitor	c
Harwell N91	Moderator type area monitor	c
Wendi-2	Moderator type area monitor with tungsten loaded moderator ⁽²⁾	c
Studsvik 2200's	Moderator type area monitor	c
BAE SYSTEMS	Novel area monitor for $H^*(10)$ and $H_p(10,x)$ measurements ⁽³⁾	p
Aloka PDM-313	Electronic neutron dosimeter with one silicon detector ⁽⁴⁾	c
Siemens EPD N	Electronic photon/thermal neutron dosimeter with three silicon detectors ⁽⁴⁾	c
Siemens EPD N2	Electronic photon/neutron dosimeter with three silicon detectors ⁽⁴⁾	c
PADC(CR-39)	Track-etch detector(chemical + electrochemical etching) ⁽⁵⁾	c
Saphydose-n	Electronic neutron dosimeter using a segmented silicon diode ⁽⁶⁾	c
DISN 1.25% (2 mm)	Differential reading of two ionisation chambers that are based on Direct Ion Storage ⁽⁷⁾	p
DISN 4% (1 mm)	Differential reading of two ionisation chambers that are based on Direct Ion Storage ⁽⁷⁾	p
DOS-2002	Electronic photon/neutron dosimeter with one silicon detector ⁽⁸⁾	p
HpSLAB	Superheated drop detector inside a slab phantom ⁽⁹⁾	p
BTI-PND	Fast neutron bubble detector ⁽¹⁷⁾	c
PND + BDT	Combination of fast and thermal neutron bubble detector ⁽¹⁷⁾	c

For a complete analysis of the results, the estimates provided by the individual devices are compared with the reference values for dose equivalent quantities determined using neutron and, eventually, photon spectrometry. In the case of neutrons, direction-differential fluence distributions are determined along with the energy-differential values. These are needed to correlate isotropic quantities, such as ambient dose equivalent, to non-isotropic ones, such as personal dose equivalent and effective dose. Reference field spectrometry providing energy-differential, direction-integrated fluence distributions are primarily performed with a Bonner-sphere system⁽¹⁰⁾ for the entire energy range. The measurements of the double-differential (energy and direction) neutron fluence are performed with novel instruments based, respectively, on SDD-spectrometers⁽¹¹⁾ and Si-diodes⁽¹²⁾, and employing dedicated numerical procedures (unfolding methods) for data analysis⁽¹⁶⁾. Information on the direction distribution of the fields is also derived from PADC track-etch detectors mounted on different sides of the slab phantom and from analysis of the different detector readings for a novel design of neutron survey instrument (BAE SYSTEMS)⁽³⁾.

In October 2002, prior to the campaigns in the workplaces, an intercomparison exercise was performed at the IRSN simulated workplace facility CANEL/T400^(13,14) and at the thermal neutron source SIGMA⁽¹⁵⁾. The purpose of the exercise was

to test some novel instruments and to verify the behaviour of all instruments in a well-established reference field similar to some of those encountered at workplaces. Following the intercomparison, two measurement campaigns have been performed:

- (1) Campaign number 1 (April 2003) was carried out in Krümmel, Germany, inside a boiling water reactor building and around a storage cask containing spent fuel elements.
- (2) Campaign number 2 (June 2003) was carried out in Mol, Belgium, at the Belgonucléaire MOX fuel element manufacturing plant and at the SCK•CEN VENUS research reactor.

One or two additional campaigns are scheduled for the year 2004: at the BNFL plutonium re-processing plant and thermal oxide re-processing plant in Sellafield (UK), and/or inside a pressurised water reactor building and around a transport cask in Ringhals, Sweden.

PRELIMINARY RESULTS FROM MEASUREMENTS IN SIMULATED WORKPLACE FIELDS

The responses of area monitors and personal dosimeters in the SIGMA thermal field and at the CANEL simulated workplace field are reported in Tables 2 and 3, respectively. The personal dosimeters were irradiated on an ISO PMMA

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Table 2. Ambient dose equivalent response of area monitors, $R_{H^*} = H^*(10)_{\text{measured}}/H^*(10)_{\text{reference}}$ and relative standard uncertainties.

Name of device	Facility			
	CANEL		SIGMA	
	R_{H^*}	$u(R_{H^*})/R_{H^*}$ (%)	R_{H^*}	$u(R_{H^*})/R_{H^*}$ (%)
BAE SYSTEMS	1.11	7	0.58	8
Berthold LB 6411	0.85	7	0.88	6
Harwell Leake N91	1.26	7	–	–
SSI Sievert A	1.10	17	1.28	11
SSI Sievert B	0.97	17	0.97	11
Studsvik 2202D	1.26	7	0.75	6

The references values of $H^*(10)$ at CANEL and SIGMA are obtained from Refs (15) and (14), respectively. The Sievert instrument used the following approximate relation between quality factor, Q , and dose mean lineal energy, y_D : $Q = 0.52 + 0.28y_D$.

Table 3. Personal dose equivalent response of personal dosimeters, $R_{Hp} = H_p(10)_{\text{measured}}/H_p(10)_{\text{reference}}$ and relative standard uncertainties.

Name of device	Facility			
	CANEL		SIGMA	
	R_{Hp}	$u(R_{Hp})/R_{Hp}$ (%)	R_{Hp}	$u(R_{Hp})/R_{Hp}$ (%)
Aloka PDM-313	5.1	11	4.3	6
BTI-PND	1.11	14	0.69	15
DISN 1.25%	7.3	15	20	12
DISN 1.25% (2 mm)	0.58	24	1.1	12
DISN 4%	2.3	19	4.2	13
DISN 4% (1 mm)	0.50	23	1.0	12
DOS-2002	1.21	12	1.19	7
HpSLAB	1.21	17	0.99	14
PADC (NRPB)	0.95	13	0.85	9
PADC (PSI)	0.32	15	0.45	31
PND + BDT	1.32	13	1.19	10
Saphydose-n	0.82	14	1.07	13
Siemens EPD N	0.16	97	0.36	93
Siemens EPD N2	2.7	12	5.4	7

The references values at CANEL and SIGMA are obtained from Refs (15) and (14), respectively.

water-filled phantom at angles of 0° , 45° and 75° (angles are stated with respect to the normal on the front face of the phantom). Only the results for 0° are presented here since the reference dose values for 45° and 75° are not yet available. The readings are those provided directly by the instruments based on their specific calibration procedures as established by manufacturers or developers. No attempt has been made yet to harmonise the calibration procedures of the different instruments. The uncertainties given in this paper represent first estimates of standard uncertainties although a comprehensive analysis is in progress. It is important to note that the uncertainties of the instruments' readings do not include

the contributions from the energy and direction dependence of their response. For area monitors, type A uncertainties are generally negligible whereas for the personal dosimeters they are significant. The type B uncertainties are mostly due to uncertainties from the calibration of the instruments ($\sim 5\%$).

The SIGMA facility has been recently characterised by comparing MCNP-4C simulations with activation foil and spectrometer results⁽¹⁵⁾. In Table 2, the ambient dose equivalent rates measured by the area monitors are compared with a reference value $dH^*(10)/dt = (143.6 \pm 5.1) \mu\text{Sv h}^{-1}$. Most of the area monitors appear to underestimate the ambient dose equivalent for thermal neutrons. The personal

dose equivalent rates measured by personal dosimeters are compared (Table 3) with a reference value $dH_p(10)/dt = (149.4 \pm 5.3) \mu\text{Sv h}^{-1(15)}$. Many personal dosimeters show agreement with the reference value within $\pm 50\%$, but one device significantly underestimates whereas five significantly overestimate.

The CANEL facility⁽¹³⁾ simulates, using an accelerator generated field, neutron spectra representative of some workplaces of the nuclear industry. The neutron fluence and ambient dose equivalent $H^*(10)$ as a function of the energy were determined using MCNP-4C and compared with experimental values derived from spectrometry in the framework of the EUROMET intercomparison⁽¹⁴⁾. The reference value used here is the experimental one, $H^*(10) = 122.3 \pm 6.1$ pSv per monitor count. Because of the complex irradiation conditions, dedicated computations of personal dose equivalent $H_p(10)$ are required, which are extremely time consuming and only preliminary results are available at present⁽¹³⁾. Thus, the reading of the personal dosimeters can only be compared with the personal dose equivalent value derived from the EUROMET spectrometry data⁽¹⁴⁾: $H_p(10) = 126.5$ pSv per monitor count, i.e. assuming a broad and parallel irradiation of the phantom. The relative standard uncertainty is estimated to be $\sim 10\%$. The responses of the area monitors presented in Table 2 show agreement with the reference dose rate within 30%. Of the 14, 8 personal dosimeters, show readings that deviate by less than $\pm 50\%$ from the reference values (Table 3).

PRELIMINARY RESULTS FROM MEASUREMENTS IN WORKPLACE FIELDS OF NUCLEAR INDUSTRY

This paper presents preliminary results of 2 of the 10 workplaces investigated to date. The analysis of direction and energy spectrometry is not complete yet so reference values are available for $H^*(10)$ but not for $H_p(10)$. The first campaign took place at the nuclear power plant in Krümmel (Germany). Measurements were performed at four workplaces. Two positions were measured at a spent fuel cask of type NTL11 ('cask midline' and 'cask side') and two other positions close to the boiling water reactor inside the reactor building: one was situated in the control rod room underneath the reactor ('reactor SAR') and the other near the top of the reactor outside the safety vessel ('reactor top'). The neutron fluence as a function of energy was measured with the IRSN Bonner-sphere spectrometer. At the cask midline, the distribution of fluence as a function of energy (Figure 1, dashed line) shows a rather hard spectrum in which 75% of the neutrons have energies between 50 keV and 1 MeV. The ambient dose equivalent rate derived from the spectrum at this point is $dH^*(10)/dt = 141 \mu\text{Sv h}^{-1}$. The energy spectrum at the position reactor SAR (Figure 1, full line) shows a thermal and a fast peak but also a non-negligible epithermal and intermediate energy neutron contribution. The ambient dose equivalent rate calculated from this spectrum is $dH^*(10)/dt = 46 \mu\text{Sv h}^{-1}$. A complete uncertainty analysis for these results is not

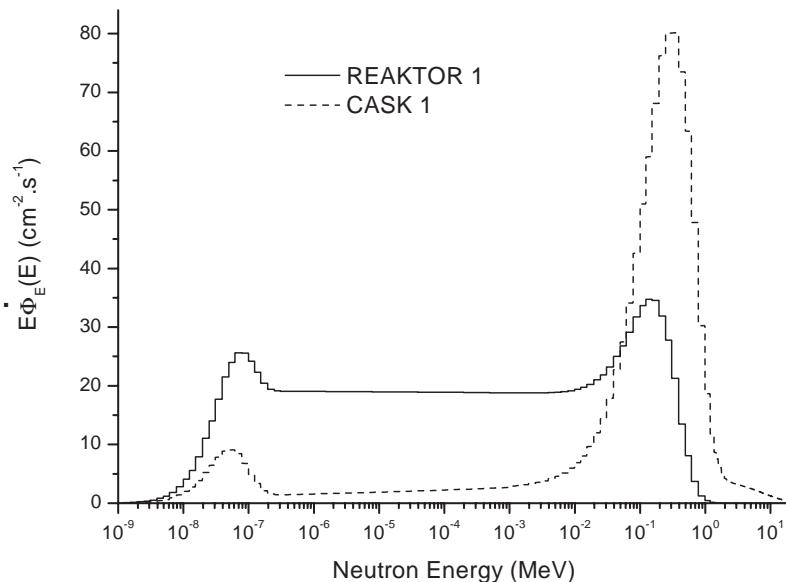


Figure 1. Relative spectral neutron fluence per logarithmic bin-width as a function of energy at Krümmel transport cask midline (CASK 1, dashed line) and reactor control rod room (SAR—reactor 1, solid line)

Table 4. Ambient dose equivalent response of area monitors: $R_{H^*} = H^*(10)_{\text{measured}}/H^*(10)_{\text{reference}}$ and relative standard uncertainties measured at two workplaces in Krümmel.

Name of device	Workplace			
	Cask midline		Reactor SAR	
	R_{H^*}	$u(R_{H^*})/R_{H^*}$ (%)	R_{H^*}	$u(R_{H^*})/R_{H^*}$ (%)
BAE SYSTEMS	0.71	16	0.92	16
Berthold LB 6411	0.91	16	1.30	16
Harwell Leake N91	0.91	16	1.30	16
SSI Sievert B	0.84	22	1.28	22
Studsvik 2200's	0.79	16	1.09	16
Wendi-2	0.93	16	1.79	18

The reference values are derived from the Bonner-sphere measurements of the neutron energy distribution. The Sievert instrument used the following approximate relation between quality factor, Q , and dose mean lineal energy, y_D : $Q = 0.52 + 0.28y_D$.

yet possible. Based on previous experience with Bonner-sphere spectrometers, a conservative estimate of the relative standard uncertainty is 15%.

Table 4 shows the ambient dose equivalent response of the area monitors at the two measurements positions. Except for one case, the deviations from the reference value are <30%.

The $H_p(10)$ reference value is being evaluated using direction and energy spectrometry. This work is still in progress. However, for the cask midline position the radiation field is almost unidirectional and the reference value for $H_p(10)$ can be approximated by $dH_p(10, 0^\circ)/dt \approx 147 \mu\text{Sv h}^{-1}$, derived from Bonner-sphere measurements. A large uncertainty of 30% is attributed to this value. The actual value of the $H_p(10)$ rate is likely to be lower since the oblique components of the field will have conversion coefficients that are lower than that for 0° . Except for two dosimeters with negligible response, the personal dosimeter results agree within ~50% with the reference values (Table 5). The results may improve once the dosimeter calibrations at the CANEL facility are fully analysed using the MCNP-computed as well as the experimental energy and direction spectra. For the measurement point under the reactor (SAR), the reference values of $H_p(10)$ cannot be deduced from the Bonner-sphere measurements because the irradiation field was coming from the top and from room scattering on several structures surrounding the measurement point. In this case, direction spectrometry is needed to assess the behaviour of the personal dosimeters.

CONCLUSIONS

The EVIDOS programme has currently reached its mid-term. One calibration campaign and two workplace campaigns have been performed. A large

Table 5. Personal dose equivalent response of personal dosimeters, $R_{Hp} = H_p(10)_{\text{measured}}/H_p(10)_{\text{reference}}$ and relative standard uncertainties measured at Krümmel, cask midline.

Name of device	R_{Hp}	$u(R_{Hp})/R_{Hp}$
Aloka PDM-313	0.96	31
BTI-PND	1.46	34
HpSLAB	1.35	33
Local device (TLD albedo)	1.39	54
PADC (NRPB)	0.47	36
PND + BDT	1.46	33
PSI CR-39	0.31	>59
PSI DISN 1.25% (2 mm)	0.42	43
PSI DISN 4% (1 mm)	0.08	90
PTB DOS-2002	0.57	36
Saphydose-n	0.62	34
Siemens EPD N	0.02	115
Siemens EPD N2	0.22	35

The personal dosimeter readings are compared with $H_p(10)$ obtained from the Bonner sphere measurement and assuming a broad, parallel incidence of neutrons.

quantity of data has already been collected and data are being analysed. Preliminary results show reasonable behaviour of several radiation protection instruments, in particular the area monitors but also several novel personal dosimeters. But they also highlight the well-known necessity to apply, for several instruments, a field-specific correction factor to derive sufficiently accurate results in workplace fields. Knowledge of the direction and energy distribution of the irradiation field is essential to understand and improve the response of the instruments used. To improve the response of personal dosimeters, a well-characterised (in energy and direction) workplace-simulated reference field is needed.

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