# EVIDOS: Optimisation of Individual Monitoring in Mixed Neutron/Photon Fields at Workplaces of the Nuclear Fuel Cycle

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## INTRODUCTION

Within its 5th Framework Programme, the EC is funding the project EVIDOS ("Evaluation of Individual Dosimetry in Mixed Neutron and Photon Radiation Fields"). The aim of this project is the optimisation of individual monitoring at workplaces of the nuclear fuel cycle with special regard to neutrons. Various dosemeters for mixed field application – passive and new electronic devices – are tested in selected workplace fields in nuclear installations in Europe. The fields are characterised using a series of spectrometers that provide the energy distribution of neutron fluence (Bonner spheres) and newly developed devices that provide the energy and directional distribution of the neutron fluence. Results from the first measurement campaign, carried out in simulated workplace fields (IRSN, Cadarache, FR), and those of a second measurement campaign, carried out at workplaces at a boiling water reactor and at a storage cask with used fuel elements (Kernkraftwerk Krümmel, DE), are described.

## SELECTION OF WORKPLACE FIELDS

A first important task of the project was the selection of workplace fields. There were two main aims: One was to select places with significant contributions of neutrons to the personal dose equivalent but which differ with respect to neutron energy and direction, neutron to photon dose ratio and environmental conditions in terms of noise, temperature, vibrations and electromagnetic interference. The second aim was to involve the radiation protection officers at the facilities and to promote discussions. Some of the first project meetings, either with all members of the project or within smaller task groups, were held at the envisaged facilities. The workplaces were visited and their suitability discussed. The facilities considered are listed in Table 1.

The campaign C0 was carried out at the simulated workplace fields at Cadarache. These fields are particularly attractive for performance tests of electronic dosemeters which may not present a perfect response in quasi-mono-energetic neutron fields but respond with sufficient accuracy in practical fields with broader energy distributions. Secondly, these fields have been characterized with extensive MCNP calculations of energy and directional distributions of neutron fluence(1) and are thus well suited for testing of the performance of the new spectrometers.

Electronic neutron personal dosemeters are especially needed for operational dosimetry in nuclear power plants and there is also an upcoming need for neutron monitoring around casks that contain spent fuel. Places which are routinely visited for control measurements at the Krümmel Nuclear Power Plant were chosen for

**Table 1.** *List of sites for the measurements*

| | Facility | Place | Measurement period |
|---|---|---|---|
| C0 | Canel and Sigma simulated workplace neutron fields | Cadarache, France | October/November 2002 |
| C1 | BWR Krümmel | Krümmel, Germany | April 2003 |
| C2 | Venus Research Reactor, SCK-CEN and Nuclear Fuel Facility Belgonucléaire | Mol, Belgium | June 2003 |
| C3 | PWR Ringhalsverket | Ringhals, Sweden | planned for fall 2004 |
| C4 | Fuel processing plant / Magnox Reactor | Sellafield, U.K. | planned for spring 2005 |

measurement campaign C1: a position in the control room underneath the reactor, another position near the top of the reactor and two places close to a cask containing spent fuel.

In Mol, the measurements for the C2 campaign were performed at two facilities. At the VENUS Research Reactor one location was chosen where personnel need to read a gauge next to the reactor and another in the control room. At the Belgonucléaire fuel processing plant, four positions were chosen: bare plutonium rods, plutonium-rods in a rack with and without shielding and inside a stock room.

The measurement campaign C3 is foreseen to take place at the PWR Ringhalsverket. This reactor is of a different type (PWR) from the Krümmel reactor (BWR). Positions with extremely severe environmental conditions are selected. This allows the performance of dosemeters and spectrometersto be tested under harsh conditions. In addition, these fields have been extensively investigated by spectrometric methods several years before, thereby providing additional information and comparisons.

Finally, campaign C4 is intended to take place at a fuel processing plant at Sellafield in the UK.

## DOSEMETERS AND SPECTROMETERS USED

The dosemeters used in the EVIDOS project are listed in Table 2. Recent publications concerning their performance are given in the references in Table 2 and some recent overviews(11-13).

The IRSN Bonner sphere spectrometer is used for reference spectrometry. It consists of an $^{3}$He filled proportional counter and 12 polyethylene spheres. The five smallest spheres are used bare and also with a cadmium shield. This system is well characterized by calculations and measurements at monoenergetic fields(14). The measurements were performed at the PTB and NPL standard laboratories and at the SIGMA IRSN thermal neutron facility(15).

The simultaneous measurement of neutron fluence as a function of energy and direction is performed with two novel instruments: one based on Si-diodes mounted on a stationary polyethylene sphere and one using a SDD-spectrometer inside a rotatable collimator.

The directional spectrometer based on silicon detectors(16) consists of six detector capsules, each containing a stack of 4 silicon detectors, mounted onto the surface of a 30 cm diameter polyethylene sphere and electronics to amplify and record the pulse height spectra of all detectors. The response function of this device has been determined for a series of directions using measurements in quasi-mono-energetic neutron fields and MCNP calculations for neutrons in the energy range from thermal up to 15 MeV, and using measurements for photons in the energy region from 80 keV to 6 MeV. The pulse height spectra measured in workplace fields are analysed using unfolding codes with respect to energy and direction, for both neutrons and photons(16,17).

One of the codes (MIEKE) works without explicit pre-information on energy and directional distribution, the

**Table 2.** *Short description of the devices used in the EVIDOS project. The status (commercial (c) or prototype (p)) is given in the last column.*

| Name of Device | Short description | |
|---|---|---|
| BAE SYSTEMS | novel area monitor for H*(10) and $H_p(10,\alpha)$ measurements(2) | p |
| Berthold LB 6411 | moderator type area monitor | c |
| Harwell N91 | moderator type area monitor | c |
| Sievert instrument | low pressure proportional counters (one of tissue-equivalent plastics and one of graphite) evaluated according to the variance/covariance technique(3) | p |
| Studsvik 2200's | moderator type area monitor | c |
| Wendi-II | moderator type area monitor with tungsten loaded moderator(4) | c |
| Aloka PDM-313 | electronic neutron dosemeter with 1 silicon detector | c |
| BTI-PND | fast neutron bubble detector(5) | c |
| DISN | differential reading of two ionisation chambers, based on Direct Ion Storage two types, each type with and without boron plastic shieldings(6) | p |
| DOS-2002 | electronic photon/neutron dosemeter with 1 silicon detector(7) | p |
| HpSLAB | superheated drop detector inside a slab phantom(8) | p |
| PADC (CR-39) | track etch detector (chemical + electrochemical etching)(9) | c |
| PND+BDT | combination of fast and thermal neutron bubble detector | c |
| Saphydose-n | electronic neutron dosemeter using a segmented silicon diode(10) | c |
| Siemens EPD N | electronic photon/thermal neutron dosemeter with 3 silicon detectors | c |
| Siemens EPD N2 | electronic photon/neutron dosemeter with 3 silicon detectors | c |

other one (MAXED) takes pre-information into account: with respect to the neutron energy, primarily the spectra measured at the same places by Bonner spheres were taken for pre-information. For the direction, initial estimates were derived from the raw detector readings of the directional spectrometer itself.
The directional spectrometer with superheated drop detectors[18] uses a "telescope design" with a single detector at the centre of a 30 cm diameter moderating-sphere of nylon-6. The system views a narrow solid angle of about 1/6 steradians since the hydrogenous sphere effectively attenuates laterally incident neutrons, thus providing a strong angular dependence of the response. By changing the temperature of the superheated drop detector from 25°C to 55°C, a series of responses with threshold behaviour is obtained as a function of neutron energy. The response functions have been determined experimentally using quasi-monoenergetic neutrons for frontal incidence and using MCNP calculations for higher angles of incidence. First analyses of the energy and direction of neutrons were performed using the MAXED unfolding code[17,18].

## RESULTS IN SIMULATED WORKPLACE FIELDS

First results of dosemeter readings obtained in the Cadarache simulated workplace fields were presented at the 9th Symposium on Neutron Dosimetry in Delft[19]. Two fields were discussed: the thermal field SIGMA[15] , with 43% of the ambient dose equivalent arising from thermal neutrons, and the CANEL[20] field with a broad energy distribution showing a maximum contribution to the dose equivalent in the range of a few hundred keV and additional significant contributions of thermal and intermediate energy neutrons. Reference values were obtained from Bonner sphere measurements and MCNP calculations.
All personal dosemeters were attached to ISO phantoms for irradiation. For normal incidence, the dosemeters Aloka PDM-313 and Siemens EPD N2 showed over-readings by more than a factor of two compared to the reference values, while others (Saphydose-n, DOS-2002, PADC track detectors from NRPB and devices based on superheated drop detectors like HpSLAB and BTI PND) showed deviations less than 30%. DIS-N dosemeters were used with and without boron plastic shielding. Without shielding over-responses of up to a factor of 20 were recorded, while with shielding responses between 0.5 and 1.1 were obtained. The Siemens EPD N, a dosemeter which is intended only for the measurement of thermal and intermediate energy neutrons, responded well to the thermal part of the spectrum at SIGMA but showed under-readings by more than a factor of two at CANEL.
The readings of the ambient dose equivalent devices deviated by less than 30% from the reference values, except for one case: BAE systems at SIGMA showed a response value of 0.59.
Both directional spectrometers were used at SIGMA and CANEL. Due to time consuming variations of the temperature of the superheated drop detectors and the small effective opening of the "telescope device" measurements were performed only in one direction (frontal) at SIGMA and two directions (frontal and 30°) at CANEL. The analysis using unfolding codes is still in progress.
The results of the directional spectrometer with silicon detectors were analysed and first results published[16]. Figure 1 shows the directional distribution obtained at CANEL. $H^*(10)$ contributions per angular interval, derived from MCNP calculations, decrease sharply above 30°, whereas the results of the directional spectrometer show significant contributions up to 60°. This shows the limited angular resolution of the experimental device. Each of the six capsules mounted onto the surface of the sphere chiefly extracts information on neutron fluence impinging on a solid angle cone corresponding to roughly one sixth of the

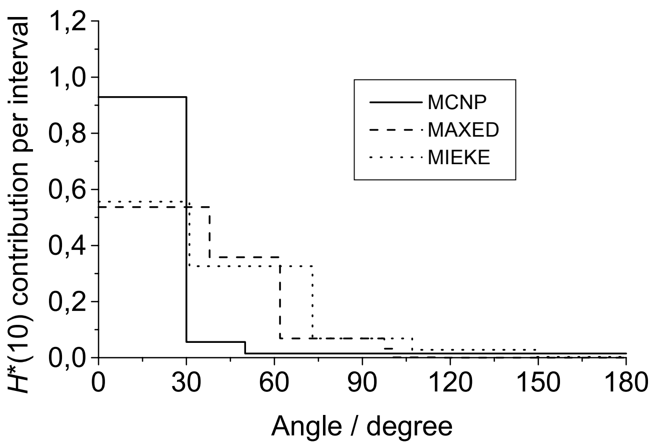


**Figure 1.** *H*(10) contribution per angular interval as calculated by MCNP for the CANEL field and derived from the directional spectrometer using the unfolding codes MIEKE and MAXED.*

total solid angle. The angle integrated fluences and ambient dose equivalent showed agreement with the reference values within 20%.

## RESULTS AT KRÜMMEL

The measurements were performed at two positions inside the boiling water reactor and at two positions near an NTL11 cask with spent fuel (see Figure 2 and Table 3).

**Table 3.** *Measuring positions at Krümmel*

| Position | Distance 1 | Distance 2 | Height above floor | Front direction |
|---|---|---|---|---|
| KKK TOP, 40 m level | to door: 0.8 m | to wall: 0.68 m | 1.50 m | towards reactor |
| KKK SAR | centre of room | centre of room | 1.20 m | towards lock |
| Cask midline | centre of cask | to cask: 1.0 m | 2.65 m | towards cask |
| Cask side | $10^{th}$ ring, left side | to cask: 1.35 m | 1.50 m | towards cask |

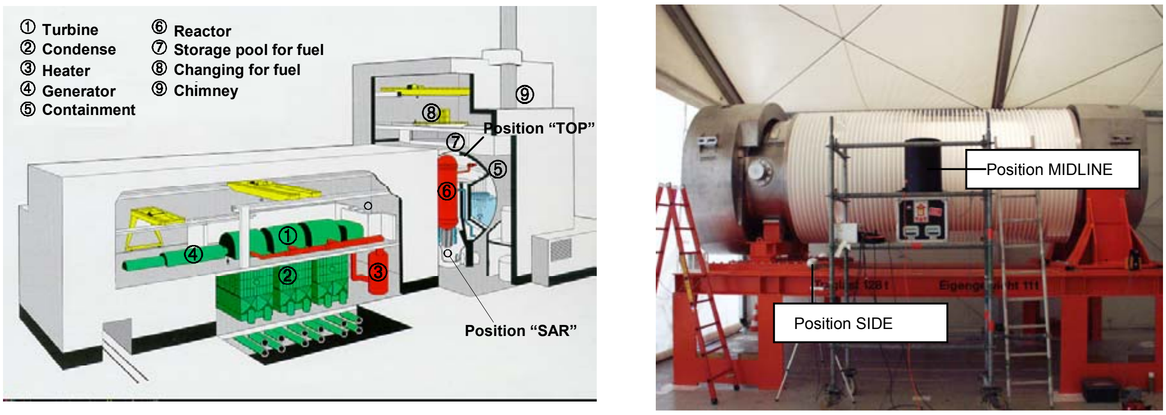


**Figure 2.** *Measuring positions at Krümmel*

The results obtained with the Bonner sphere spectrometer for the energy distribution of neutrons are shown in Figure 3 together with angle integrated spectra obtained from analysis of the directional spectrometer with silicon detectors. The spectra at the cask are quite hard, with a main fluence contribution at a few hundred keV, while the spectra at the reactor contain a considerable amount of thermal and intermediate energy neutrons.

Reference values for $\dot{H}^*(10)$ were obtained by multiplying the spectra by fluence-to-ambient dose equivalent conversion coefficients (see Table 4). The results of the ambient dose equivalent meters agree with the reference values $\dot{H}^*(10)$, within 30%, except for Wendi-II (1.75 at KKK SAR) and for BAEsystems (0.66 at KKK TOP). More detailed information on results of ambient dose equivalent meters measured at "cask midline" and at SAR is given in Reference 19.

$\dot{H}^*(10)$ values obtained by the directional spectrometer with silicon detectors agree within 30% with the reference values in case of the MAXED unfolding (see also Figure 3) and showed deviations up to 50% for unfolding without pre-information (MIEKE). Preliminary estimates for $\dot{H}_p(10)$ were derived using the following approach: The spectra, obtained for different directions from measurements with the directional

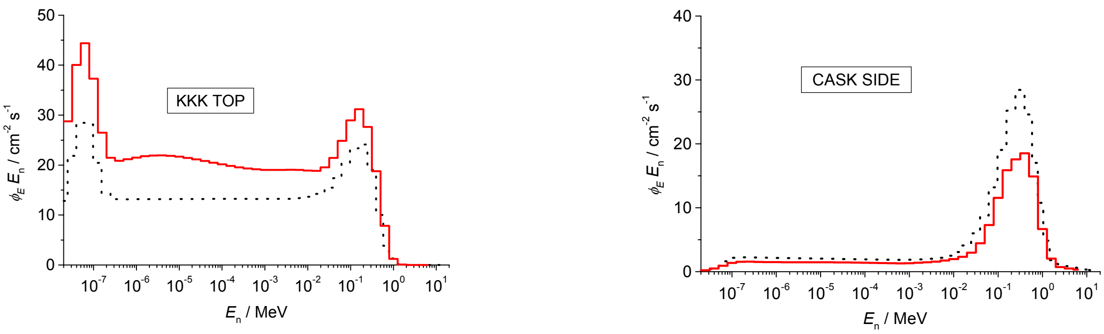


**Figure 3.** *Spectral neutron fluence per logarithmic bin-width as a function of energy at two workplaces investigated during C1 (Krümmel) using Bonner spheres (dotted line)*[(19)] *and the directional spectrometer with silicon detectors (full line, MAXED unfolding).*

spectrometer, were multiplied with fluence-to-personal dose conversion coefficients (new ones calculated also for backward directions[21]) and fluence-to-ambient dose equivalent conversion coefficients, and ratios $\dot{H}_p(10)/\dot{H}^*(10)$ were calculated. Values derived from the directional spectrometer using both unfolding codes (MAXED and MIEKE) are given in Table 4. Low values for the ratio $\dot{H}_p(10)/\dot{H}^*(10)$ were obtained in the field with almost isotropic distribution of neutron fluence, at the SAR. Preliminary estimates for $\dot{H}_p(10)$ were obtained by multiplying the $\dot{H}^*(10)$ reference values obtained using the Bonner spheres with values of $\dot{H}_p(10)/\dot{H}^*(10)$ obtained using the angular spectrometer and MAXED and MIEKE unfolding (mean value). Estimate of $\dot{H}_p(10)$ for the front direction are given in Table 4. The last column in Table 4 contains the ratio of neutron and photon contributions of ambient dose equivalent (latter measured by a FHT 191N ionisation chamber).

**Table 4.** *$\dot{H}^*(10)$ reference values and estimates of $\dot{H}_p(10)$ (latter for front direction) for the measurement positions at Krümmel. Preliminary values of uncertainties are given.*

| Position | $\dot{H}^*(10)$ / µSv h$^{-1}$ | $\dot{H}_p(10)/\dot{H}^*(10)$ MAXED, front | $\dot{H}_p(10)/\dot{H}^*(10)$ MIEKE, front | $\dot{H}_p(10)$/µSv h$^{-1}$ front | $\dot{H}^*_n(10)$ / $\dot{H}^*_\gamma(10)$ |
|---|---|---|---|---|---|
| KKK TOP | 39.0 ± 5.8 | 0.52 | 0.60 | 21.8 ± 6.5 | 4.20 |
| KKK SAR | 46.8 ± 7.0 | 0.33 | 0.29 | 14.5 ± 4.4 | 0.24 |
| Cask midline | 152 ± 23 | 0.69 | 0.85 | 117 ± 35 | |
| Cask side | 54.6 ± 8.2 | 0.52 | 0.85 | 37.4 ± 11.2 | 40 |

The personal dosemeters were irradiated on ISO phantoms in the positions "cask side", "cask midline" and "KKK TOP" for about 2 hours and inside the SAR under nitrogen atmosphere for 38 hours. In the latter case, the track dosemeters were sealed in air in order to avoid track fading due to oxygen deficiency. The readings of the personal dosemeters attached on the front side are shown in Figure 4. In all cases also dosemeters were attached on the back side of the phantom. The readings were mostly zero or close to the detection limit of the dosemeters and are not shown in Figure 4 besides those measured at the SAR, where the radiation field was much more isotropic.

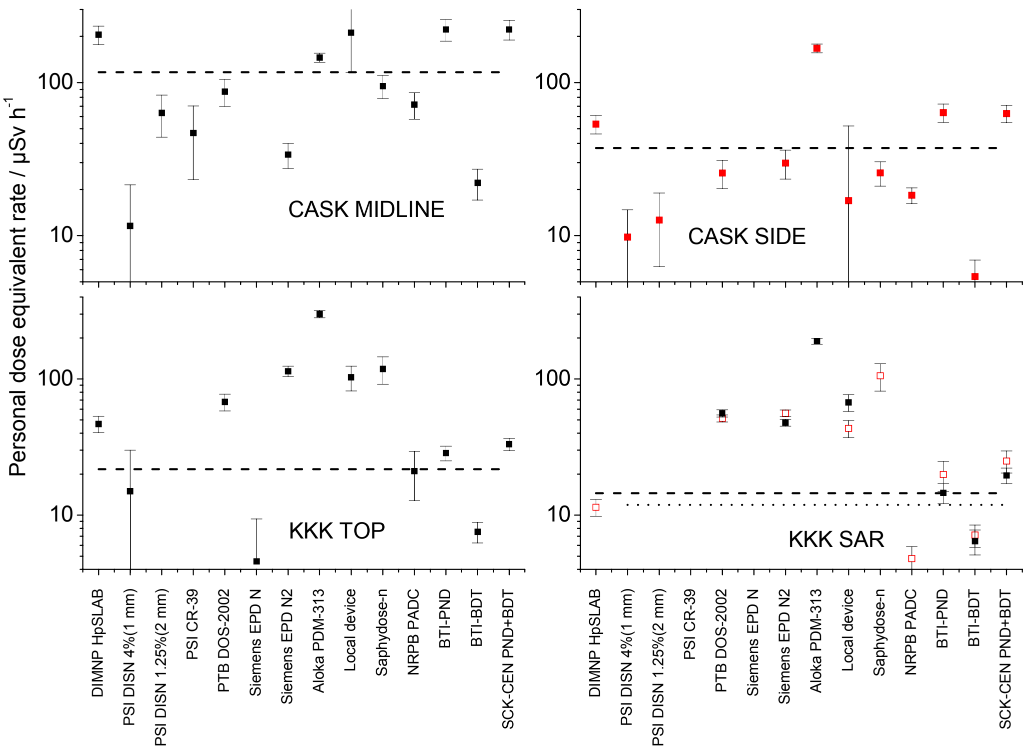


**Figure 4.** *Personal dose equivalent rates $\dot{H}_p(10)$ of dosemeters at Krümmel. The dashed lines indicate estimated values of $\dot{H}_p(10)$. The local device was a TLD albedo dosemeter. The full / open symbols indicate values measured at the front side/back side of the phantom ($\dot{H}_p(10)$ value dotted for back side).*

The estimated values of $\dot{H}_p(10)$ are indicated by dashed/dotted lines. In both reactor fields some of the personal dosemeters seem to over-respond $\dot{H}_p(10)$ by more than a factor of two. This is probably due to over-responses of these dosemeters for thermal and intermediate energy neutrons. Please note that the uncertainties of the estimated values of $\dot{H}_p(10)$ are still of the order of 30% (one standard deviation).

## OUTLOOK

To achieve the aim of the project a consistent description and understanding of all measurements and results is necessary. This implies a deeper understanding of the dosemeter responses in workplace fields by multiplying the spectral information by the angle dependent response of the dosemeters. Equally important is the knowledge of energy and direction distribution of neutrons for the investigated fields. Such additional information can be obtained by analysis of the results measured by superheated drop detectors and PADC track detectors mounted in different directions on the sides of the phantom.

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