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INVITED PAPER

EVALUATION OF INDIVIDUAL DOSIMETRY IN MIXED NEUTRON AND PHOTON RADIATION FIELDS (EVIDOS). PART I: SCOPE AND METHODS OF THE PROJECT

F. d'Errico[1,*], D. Bartlett[2], T. Bolognese-Milsztajn[3], M. Boschung[4], M. Coeck[5], G. Curzio[1], A. Fiechtner[4], J.-E. Kyllönen[6], V. Lacoste[3], L. Lindborg[6], M. Luszik-Bhadra[7], M. Reginatto[7], H. Schuhmacher[7], R. Tanner[2] and F. Vanhavere[5]
[1]Dipartimento di Ingegneria Meccanica, Nucleare e della Produzione, Università di Pisa, I-56126 Pisa, Italy
[2]Health Protection Agency, Chilton, Didcot OX11 0RQ, UK
[3]Institut de Radioprotection et de Sûreté Nucléaire, F-92265 Fontenay-aux-Roses, France
[4]Paul Scherrer Institut, CH-5232 Villigen, Switzerland
[5]Studiecentrum voor Kernenergie-Centre d'Étude Nucléaire, B-2400 Mol, Belgium
[6]Swedish Radiation Protection Authority, SE-171-16 Stockholm, Sweden
[7]Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig, Germany

Supported by the European Commission, the EVIDOS project started in November 2001 with the broad goal of evaluating state of the art dosimetry techniques in representative workplaces of the nuclear industry. Seven European institutes joined efforts with end users at nuclear power plants, at fuel processing and reprocessing plants, and at transport and storage facilities. A comprehensive programme was devised to evaluate capabilities and limitations of standard and innovative personal dosemeters in relation to the mixed neutron-photon fields of concern to the nuclear industry. This paper describes the criteria behind the selection of dosimetry techniques and workplaces that were analysed, as well as the organisation of the measurement campaigns. Particular emphasis was placed on the evaluation of a variety of electronic personal dosemeters, either commercially available or previously developed by the partners. The estimates provided by these personal dosemeters were compared to reference values of dose equivalent quantities derived from spectrometry and fluence-to-dose equivalent conversion coefficients. Spectrometry was performed both with conventional multisphere and with some original instrumentation providing energy and direction resolution, based on silicon detectors and superheated drop detectors mounted on or in spherical moderators. The results were collected in a large, searchable database and are intended to be used in the harmonisation of dosimetric procedures for mixed radiation fields and for the approval of dosimetry services in Europe.

INTRODUCTION

The EVIDOS project was a comprehensive evaluation of different methods for individual dosimetry in mixed neutron-photon workplaces in the nuclear industry. This required investigating the capabilities and limitations of personal dosemeters and establishing methods to determine sufficiently accurate values of personal dose equivalent from spectrometers, area survey instruments, routine personal dosemeters and in particular, novel electronic personal dosemeters. The development of reference methods for the determination of personal dose equivalent in workplace fields was a central part of the project. Because no current dosemeter can provide correct results in all neutron fields, reference values had to be derived from spectrometry (with respect to energy and direction of the radiation) and fluence-to-dose equivalent conversion coefficients. In order to achieve this goal, we selected a series of workplaces in the nuclear industry where workers can receive significant neutron doses, and the following tasks were carried out: (1) determination of the energy and direction distribution of the neutron fluence; (2) derivation of the (conventionally true) values of radiation protection quantities; (3) determination of the readings of routine and innovative personal dosemeters and of area monitors; (4) comparison between dosemeter readings and values of the radiation protection quantities.

The project aimed at establishing whether innovative electronic dosemeters with direct reading allow an improved determination of personal doses. A related goal was setting up a compendium of dosimetric and spectrometric data for a representative selection of European nuclear fuel cycle workplaces. Electronic dosemeters are part of a more general innovative approach to dose assessment, in which a significant role is played by advanced computational methods developed to analyse the monitoring information. Indeed, new unfolding methods were developed in the course of the EVIDOS project to determine energy- and direction-differential fluence distributions and to derive non-isotropic quantities, such as personal dose equivalent and effective dose from the spectrometer readings.

Due to the extent and complexity of the work to be performed to reach the aims of the project, the

*Corresponding author: francesco.derrico@ing.unipi.it

work-plan was structured into five workpackages: (1) Measurement campaigns, (2) Reference spectrometry, (3) Neutron fluence as a function of energy and direction, (4) Dosimetric reference data and dosemeter results, (5) Analysis and recommendations. This first overview paper describes the scope and methods of the first four workpackages, whereas the second overview paper[1] summarises the analysis of the data and the recommendations that were derived from the project.

MEASUREMENT CAMPAIGNS

The measurements took place in selected mixed radiation environments representative of the nuclear fuel cycle, including reactors, fuel processing, reprocessing, transport and storage facilities. These environments allowed a thorough testing of the dosemeters since they differed widely in terms of radiation dose rates, neutron/photon relative intensity, energy distributions, as well as temperature, pressure, humidity, noise, vibration, electromagnetic fields, etc.

The different nuclear installations visited during five measurements campaigns are shown in Figures 1–3. They include a fuel element factory (Belgonucléaire) and a research reactor (VENUS) in Mol, Belgium, a pressurised water reactor and a transport cask in Väröbacka, Sweden, a boiling water reactor and another type of two types of transport cask in Krümmel, Germany, and a further undisclosed European nuclear facility (visited after the presentation of this paper). Before these campaigns, the responses of the instruments were investigated in neutron reference fields at IRSN Cadarache, France.

The selection of the measurement positions, the measurements and the analysis of the dosimetric results was done in collaboration with the radiological safety officers of the inspected facilities during visits before the campaigns. The managers of the visited installations were all interested in having these investigations made and the cooperation with the radiation protection officers was in general excellent. To increase the value for the local health physicists, personal dosemeters and area monitors in use at the installations were included and evaluated as part of the investigation. This way, knowledge was exchanged, thus enhancing the quality of the local radiation protection procedures.

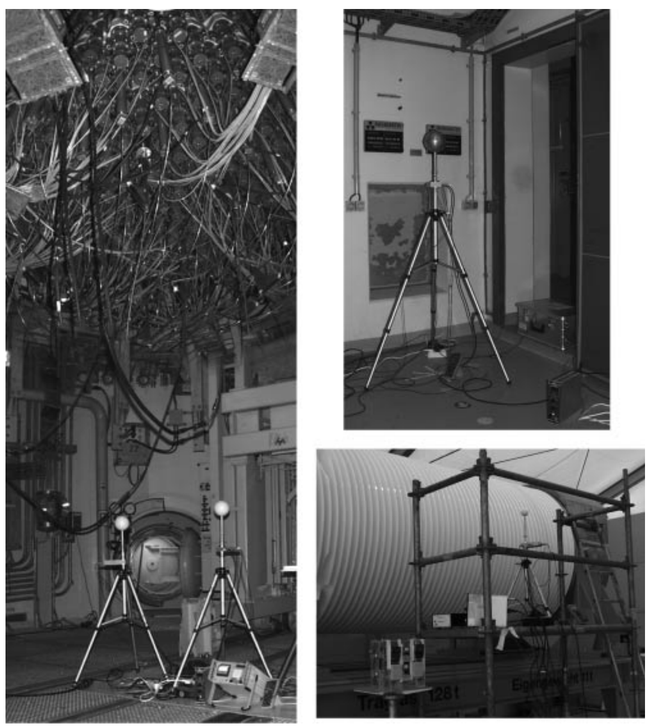

Figure 1. Workplaces investigated during campaign C1 at the Krümmel Nuclear power plant: (a) The field BWR SAR (Steuerstab-Antriebsraum) was located in the centre of the control rod room; (b) BWR T was located next to the top of the reactor containment; (c) Cask NTL M was at the centre, while Cask NTL S was at the end of the long side of the cask.

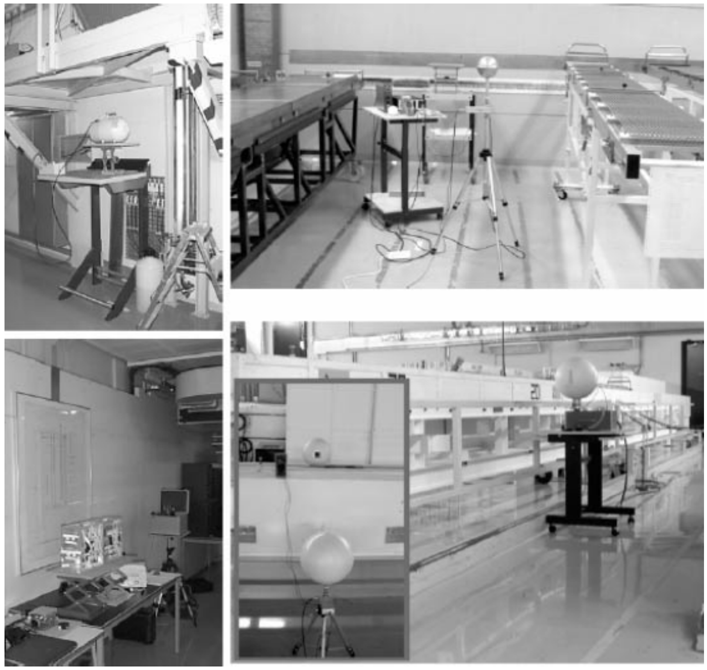

Figure 2. Workplaces investigated during campaign C2 in Mol, Belgium: (a) The field SCK•CEN VENUS F was next to the concrete shielding wall of the reactor, at the height of the core; (b) SCK•CEN VENUS C was located behind an additional polyethylene shield protecting the workers in the control room during a reactor run; (c) Belgonucléaire 1 was located in the proximity of a rack holding bare MOX fuel rods; (d) Belgonucléaire 2A and 2B were on the two sides of a rack (one shielded and one unshielded) were fuel boxes are manipulated before they enter the storage room.

The measurements were usually made during a period of 3–4 d during which a very tight measurement plan had to be followed. Among the limiting factors was the radiation dose to the accompanying radiation protection officers. Thus, if complications occurred with an instrument there was usually no time to repeat a measurement or to replace it by another instrument. Due to the limited time available, instrument positioning was often less precise than in a laboratory environment but it was deemed sufficiently accurate in relation to the fairly constant fields investigated.

In general, the detector placement was chosen to be relevant for a person working in the area. This meant that the instruments were at about 1 m above the floor and away from the nearest wall. Before measurements could start in controlled areas, the instruments had to be examined and approved by the local management. In order to enable a comparison of results from different dates, the radiation fields and some influence quantities, such as temperature, pressure and humidity were monitored during the whole measurement period.

Altogether, about 500 measurements were made at the nuclear sites. An Excel™ database was created into which the data were introduced. This became quite useful and allowed quick access to the results, as soon as they had been introduced.

SPECTROMETRY AND REFERENCE VALUES FOR $H^*(10)$

Neutron reference spectrometry was performed using the IRSN Bonner sphere (BS) system, which includes 12 polyethylene spheres with diameters between 2.5 and 12 inches[2] This is a well-characterised system, whose MCNP-calculated response functions have been validated at the NPL and PTB primary standard laboratories with monoenergetic reference neutron fields.

The BS measurements were analysed by means of two unfolding codes. First, the program NUBAY was used. This is based on Bayesian parameter estimation methods and provides posterior probability densities for a set of parameters used to describe a given neutron spectrum. In addition, it can provide probability densities for integral quantities, which is useful for estimating the integral quantities and their associated uncertainties.

The energy distributions were assumed to comprise three components: a thermal peak—modelled using a Maxwellian distribution, an intermediate

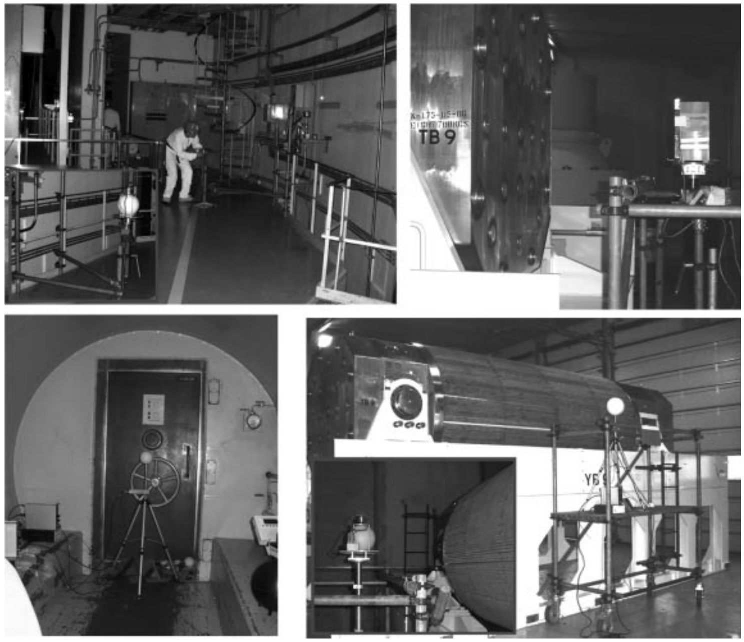

Figure 3. Workplaces investigated during campaign C3 at Ringhals, Sweden: (a) The field PWR Ringhals A was located inside containment a few meters above the core; (b) PWR Ringhals L was located close to an entrance lock door; (c) Cask TN N was located at the centre of the end plate of the cask; (d) Cask TN D was located at the centre of long side of the cask.

region—modelled as a straight line in lethargy representation, and a high energy peak—modelled using a fission Maxwell distribution. This solution spectrum was further used as one of the default spectra for the second unfolding code GRAVEL(3), a modification of SAND-II. GRAVEL is an iterative algorithm, which generates a solution spectrum starting from an initial default spectrum (DS) that is provided as input to the code. Unlike NUBAY, GRAVEL provides a 'freeform' solution (i.e., the solution spectrum does not have to fit any pre-determined parameterisation of the spectrum), which depends however to some extent on the prior information (i.e., the initial estimate) used.

The reference values of neutron ambient dose equivalent were finally determined by convolution of the reference spectra with the relevant fluence to ambient dose equivalent coefficients(4).

The reference photon ambient dose equivalent rate was determined using two different instruments: a commercial ionization chamber FHT 191 calibrated in a ^{60}Co photon beam at the PTB, and the Sievert instrument, comprising a tissue-equivalent proportional counter (TEPC) and a graphite proportional counter, whose results were evaluated according to the variance-covariance method(5).

DIRECTION SPECTROMETRY AND REFERENCE VALUES FOR $H_p(10)$ AND E

Double differential neutron fluence spectra—determined in terms of energy and direction, were measured using two novel direction spectrometers(6,7). For the simulated workplace field CANEL(8) and for the VENUS research reactor(9) the double differential spectra were also calculated with Monte Carlo transport calculations. The reference values of $H^*(10)$, $H_p(10)$ and E were then derived(10–13) by folding the energy distributions with conversion coefficients as given by ICRP 74(4) and as derived from recent calculations for higher angles of incidence(14).

The main direction spectrometer used in the EVIDOS project was an original device based on silicon detectors(6). This consists of six detectors and of the related electronics to amplify and record the pulse height spectra. The detector capsules, each containing a stack of four silicon detectors, are mounted onto the surface of a 30 cm diameter polyethylene sphere. Silicon detectors with a sensitive depleted layer of 40 μm are used. They are covered with converters required for neutron detection in different energy regions. One detector of the stack is only covered by polyethylene, whereas the others are covered by a combination of fast/thermal neutron converters consisting of 30 μm polyethylene and 0.3 mm ^{6}LiF. On the latter detectors, boron shielding is also used to provide different attenuation of thermal neutrons. The full spectrometer response is a complex matrix containing information for the four detectors in a capsule, for different pulse height thresholds and for different angles of a capsule with respect to the incident radiation.

An additional direction spectrometer, developed within the EVIDOS project, is based on a 'telescope-design' and uses a variable-threshold superheated drop detector at the centre of a 30 cm diameter nylon-6 sphere(7). The sphere absorbs most of the neutrons, except for those incident into the telescope window covering a solid angle of about 15°. The central superheated drop detector is utilised at different temperatures, corresponding to well-defined neutron energy thresholds in the 0.1–10 MeV range. During the measurement campaigns it was observed that the temperature-regulation, sphere rotation and bubble counting cycles of the telescope spectrometer were too time consuming to allow a complete set of measurements in the limited time available. Therefore, data from this device exist only for few workplace fields and the reference results on direction spectrometry were based on the silicon detector instrument which was used in virtually all measuring positions.

The measured data were analysed using dedicated unfolding programs(6,15). For this purpose, programs for deriving fluence distributions in terms of energy (MIEKE and MAXED) were further developed in order to unfold simultaneously fluence distributions in terms of energy and direction, for neutrons and photons. In particular, a general-purpose program based on MAXED unfolding was set-up. This program utilises maximum entropy neutron/photon unfolding taking into account prior information in an optimised way. The use of prior information on the energy spectrum (typically from the Bonner sphere spectrometer) was found to be necessary, since the response functions of the devices, especially of the direction spectrometer with silicon detectors, overlap in such a way that in general the direction distribution is not independent of the energy distribution. Results of the unfolding program based on MAXED are energy distributions in 20 directions.

AREA MONITORS AND PERSONAL DOSEMETERS

Four conventional moderator-type neutron monitors and a TEPC device were used in almost all of the workplaces(16). The moderator-type monitors were all commercial devices, whereas the TEPC is a prototype survey instrument initially developed for measurements on board aircraft. The device is based on microdosimetric measurement principles and consists of a TEPC and a graphite proportional counter, both filled with low-pressure tissue-equivalent propane based gas simulating a mean chord-length of 2 μm.

Figure 4. Some personal dosimeters for neutrons or for mixed neutron/photon radiation used within the EVIDOS project.

A broad selection of personal dosemeters were used in the EVIDOS project, their main characteristics are detailed in other publications(13,17). The electronic personal dosemeters we used are those devices which have been commercially available in the past few years (EPD-N, Aloka), devices from first industrial production series (EPD-N2, Saphydose-n, DMC 2000 GN) or laboratory prototypes at the stage of light-weight battery-operated instruments (DOS-2002) (Figure 4). In addition, dosemeters with an (almost) immediate readout (BTI bubble detectors, DIS-N) were used, along with passive dosemeters (nuclear track detectors from PSI and NRPB/HPA) and the TLD dosemeters in use at the visited facilities (Nuclear power plants Krümmel and Ringhals).

An additional, experimental device was used, which was meant to provide a small energy and angle dependence of the dose equivalent response and thus serve as reference instrument for $H_p(10)$(14). Called HpSLAB, it consists of a $30 \times 30 \times 15$ cm polymethyl methacrylate slab with a halocarbon-12 superheated drop detector embedded at a depth of 10 mm. The device is based on the fundamental principle that, under charged particle equilibrium and negligible uncharged-radiation losses, neutron dose equivalent in tissue can be measured by a detector whose fluence response is proportional to the quality-factor weighted kerma factor, such as neutron superheated drop detectors based on halocarbon-12.

CONCLUDING REMARKS

The EVIDOS project evaluated state of the art dosimetry techniques in representative workplaces of the nuclear industry with mixed neutron/photon radiation. The results from the project are summarised in the second part of this paper[1] and discussed in detail in a series of separate publications. They include spectra and dosimetric reference values for 17 different workplace fields (boiling water reactor, pressurised water reactor, research reactor, fuel processing, storage of spent fuel), instruments and procedures to derive reference values for personal dose equivalent and other radiation protection quantities, and results on the dosimetric and technical performance of personal dosemeters for mixed radiation. These dosimetric results represent important information for the users of these devices, to whom they indicate advantages and limitations of these devices, as well as for their manufacturers, to whom our results indicate possible avenues for improvement of their products.

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