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# APPLICATION OF WORKPLACE CORRECTION FACTORS TO DOSEMETER RESULTS FOR THE ASSESSMENT OF PERSONAL DOSES AT NUCLEAR FACILITIES

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**Ratios of $H_p(10)$ and $H^*(10)$ were determined with reference instruments in a number of workplace fields within the nuclear industry and used to derive workplace-specific correction factors. When commercial survey meter results together with these factors were applied to the results of the locally used personal dosemeters their results improved and became within 0.7 and 1.7 of the reference values or better depending on the response of the survey meter. A similar result was obtained when a correction was determined with a prototype reference instrument for $H_p(10)$ after adjustment of its response. Commercially available survey instruments both for photon and neutron $H^*(10)$ measurements agreed with the reference instruments in most cases to within 0.5–1.5. Those conclusions are derived from results reported within the EC supported EVIDOS contract.**

## INTRODUCTION

Neutron dosimetry is quite complicated and there is still no perfect dosemeter. To improve the situation, workplace-specific correction factors are sometimes applied to account for the performance limitations of neutron dosemeters. However, methods to determine such factors are not standardised.

Neutron personal dosimetry services within the EU are usually approved by national authorities in the same way as dosimetry services for other radiations. The services are also the subject of regular checks by the authorities. Neutron dosemeters are usually tested in reference radiation fields, which may have a neutron energy distribution that deviates from that in the workplace and the direction distribution of the neutrons will most likely be different as well[(1)]. As a consequence, the accuracy achieved in workplace situations may not be well reflected by a test or calibration made under standardised laboratory conditions. As neutron standards laboratories are not available in all countries, calibrations perhaps occur less frequently than for photons and the transfer of knowledge on neutron dosimetry is hampered.

When 17 neutron personal dosimetry services were tested in unknown fields under laboratory conditions, seven services were inside or just outside the range 0.5 and 2 with respect to the dose-equivalent response (dosemeter reading divided by the reference value), in spite of some pre information being given about the radiation fields[(2)]. In another comparison in workplace fields at a nuclear plant, five personal dosimetry services participated with seven dosemeter systems. Here, four of the systems were within 0.5 and 2, the others were outside this range[(3)].

A basic goal within the EVIDOS project was to estimate values of the quantities ambient, $H^*(10)$, and personal, $H_p(10)$, dose equivalent rates, termed hereafter, reference values. The latter requires that the energy and direction distributions of the neutrons at those locations are first determined. The conclusion reached by the EVIDOS consortium was that the reference values for $H^*(10)$ and $H_p(10)$ were those derived from spectroscopic fluence distribution measurements with a Bonner sphere system from

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IRSN and a directional spectrometer developed at the PTB for the two quantities[4]. Another important goal was to test, in workplace situations, the accuracy of novel electronic personal dosemeters, either commercially available or those under final development. The investigation was limited to instruments known and made available to the group. Several commercial survey instruments for neutrons as well as one for photons were also tested. At three of the sites visited, the local personal dosimetry service took part and their results are now reported. The outcome of all dosemeter results was recently reported[5] and is only partly covered here. All measured results and detailed descriptions of measurement positions and instruments can be found in a PTB report[6].

In this paper, the reference values are used to derive workplace-specific correction factors, which could be used for workplace field calibrations. A way to apply those factors in practice is discussed here with reference to the local personal dosemeter results. Also the commercial survey meter results are compared with those of the reference instruments.

## INSTRUMENTS AND METHODS

The instruments and the evaluation of them were first tested in the well-characterised simulated workplace fields SIGMA and CANEL provided by IRSN in Cadarache, France. Measurements were then made at a boiling water reactor in Krümmel, Germany, a pressurized water reactor in Ringhals, Sweden, a research reactor VENUS in Mol, Belgium, a fuel processing plant and its storage facility at Belgonucléaire, Mol, Belgium and at a European nuclear facility. In total 17 different workplace fields were investigated. The measurement positions are described in detail elsewhere[6]. The fluence spectra and direction distributions can be found in other reports[4,6].

The survey instruments used during the campaigns and the neutron personal dosemeters used locally are listed in Tables 1 and 2. Four of the neutron survey meters are of the traditional moderator type, whereas the fifth is a twin detector instrument—one tissue equivalent proportional counter (TEPC) and one identical in size graphite proportional counter both with reduced gas pressure. It is evaluated according to the variance–covariance method. This instrument (the Sievert-instrument) is optimised for cosmic ray measurements and is less suitable for the lower neutron energies that dominate in the nuclear industry. However, both detectors are well suited to determine the gamma $H^*(10)$ component and they were used as reference dosemeter for this component. The method used for separation of the neutron and photon dose-equivalent component has been reported earlier[7]. The second gamma survey instrument was a commercially available ionisation chamber. Details concerning calibration of the dosemeters are found in the main report[6] and in ref. 5.

**Table 1. Survey meters used during the campaign.**

| Instrument | Type of instrument | Type of radiation |
|---|---|---|
| Studsvik 2202D | Moderator type | Neutrons |
| Harwell Leake N91 | Moderator type | Neutrons |
| Berthold LB 6411 | Moderator type | Neutrons |
| Wendi-2 | Moderator type | Neutrons |
| Sievert instrument | A tissue equivalent and a graphite proportional counter and the variance covariance method | Neutrons and gammas |
| FHT 191 | Ionisation chamber | Gammas |

**Table 2. Neutron personal dosemeters used locally.**

| Site and short description | Calibration source | Neutron dose calculation |
|---|---|---|
| *Krümmel* | | |
| TL Albedo dosemeter with $^{6}LiF$,$^{7}LiF$ | $^{137}Cs$ and $^{252}Cf$(bare) | Field-specific correction factors |
| *Ringhals* | | |
| TL dosemeter with $LiF/Li_2B_4O_7$ | $^{137}Cs$ | Field-specific correction factors |
| *Belgonucléaire* | | |
| BTI bubble detector BD-PND | Calibrated at BTI | Local correction factors |

The personal neutron dosemeters used locally are issued by the approved dosimetry services. Two of them used workplace-specific correction factors to improve the accuracy (Table 2). This approach is useful if the neutron fluence distributions in energy and direction remain the same over an extended period of time.

A local corrected value, $H_{p,\mathrm{loc,cor}}$, for the personal dose equivalent may be defined as

$$H_{p,\mathrm{loc,cor}} = H^*_{\mathrm{loc}}[H_p/H^*]_{\mathrm{ref}} \quad (1)$$

The index loc means an $H^*(10)$ value measured in the workplace field with a commercial survey meter, whereas the index ref means the corresponding value determined with a reference instrument (the Bonner sphere spectrometer or the directional spectrometer). The ratio $[H_p/H^*]_{\mathrm{ref}}$ in equation (1) may define a workplace-specific correction factor and

$$k_{w,1} = [H_p/H^*]_{\mathrm{ref}} \quad (2)$$

Of course, the direct relation between the results of the neutron directional spectrometer, $H_{p,DS}$, can also

be used to define a workplace-specific correction factor and

$$k_{w,2} = H_{p,DS}/H_{p,\mathrm{loc}} \quad (3)$$

A local corrected value may then be derived from either of the following two equations

$$H_{p,\mathrm{loc,cor}} = k_{w,1} H^*{}_{\mathrm{loc}} \quad (4)$$

$$H_{p,\mathrm{loc,cor}} = k_{w,2} H_{p,\mathrm{loc}} \quad (5)$$

## MEASUREMENTS

The dominant direction of incidence of the neutrons was identified by judgment of the irradiation geometry. The directional spectrometer was oriented according to this and it determined the directional distribution of the neutrons and usually confirmed the early judgments. All other instruments were positioned and aligned accordingly. For instance, the personal dosemeters were mounted on the slab surface facing the dominant direction with one exception. At the BWR SAR, the main direction was from above, whereas in the comparison the results relevant for the front surface, which faced the entrance lock to the SAR, was used as this is a situation more like the practice, in which a person is wearing the dosemeter on the trunk.

## RESULTS

Figure 1 presents the results for the photon dose component of $H^*(10)$. It shows the ratio of the ionisation chamber results, $H^*{}_{\mathrm{FHT}}$, to the Sievert instrument results, $H^*{}_{\mathrm{Sv}}$. For the two calibration fields at Cadarache, reference values were available from measurements with GM-tubes and Monte Carlo simulations[8], $H^*{}_{\mathrm{PTB}}$. Those values divided by $H^*{}_{Sv}$ are also included in the figure. The $H^*{}_{\mathrm{Sv}}$ results agree with the $H^*{}_{\mathrm{PTB}}$ results within 12%. If the results at SIGMA and at the Cask NTL S are excluded, the average ratio of $H^*{}_{\mathrm{FHT}}/H^*{}_{\mathrm{Sv}}$ is $1.01 \pm 0.15$ (one standard deviation).

At SIGMA, the fluence of thermal neutrons is large. The FHT 191 is known to respond also to thermal neutrons. This explains the much larger ratio here. At the Cask NTL S the gamma dose rate was low (1–3 μSv/h) which resulted in a higher uncertainty in particular for the ionisation chamber. This discrepancy was not analysed in any detail and the average of the two instrument values was instead regarded as the reference result. It is concluded that in most workplace situations a gamma dose component of $H^*(10)$ may be determined with sufficient accuracy with commercial instruments.

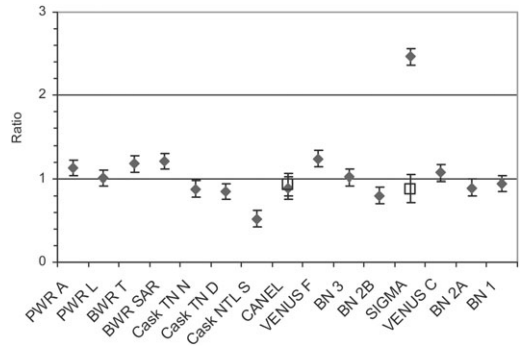


Figure 1. Ratios of the gamma dose component of $H^*(10)$ as determined with the ionization chamber FHT 191 and the Sievert instrument. For Canel and Sigma, the ratios between the reference values, $H^*(10)_{\mathrm{PTB}}$, and $H^*(10)_{\mathrm{Sv}}$ are also shown as open squares.

The neutron survey instrument results are presented in Figure 2. It shows the ratio of the results of each instrument divided by the reference $H^*(10)$ value from the Bonner Sphere spectrometer. With the exception of the Studsvik instrument, all results are observed in a single measurement lasting sufficiently long to avoid statistical fluctuations being important. All survey instruments were aligned with their reference direction towards the dominant direction of the neutrons. Because the Studsvik has relatively strong angle dependence of response the result here is the average of two readings with the instrument turned 90° in the horizontal plane between the measurements. The average ratio with one relative standard uncertainty given in parentheses was for the different instruments: Studsvik 0.86 (±16%), LB6411 0.91 (±14%), Leake 0.96 (±27%), Wendi 1.13 (±0.24%) and Sievert 0.90 (±38%). With the exception of a couple of positions for the Wendi and the Sievert-instrument, the agreement is well within the range 0.5–1.5. It is concluded that also the neutron $H^*(10)$ component may be determined with sufficient accuracy with commercial instruments.

The three local personal dosemeter systems were all approved. Each local personal dosemeter service took part only in the measurements at their own facility. Figure 3 shows the local personal dosemeter results. A line connects all the results in the figure as an eye guide. The results are within the range 0.5–4. The local results are comparable to or better than those of some new active dosemeters[4].

## COMPARISON WITH EARLIER RESULTS

For two of the measurement positions at Ringhals, similar measurements had been performed before[2]. Measurements around a similar transport cask as used at Ringhals but with other fuel elements and

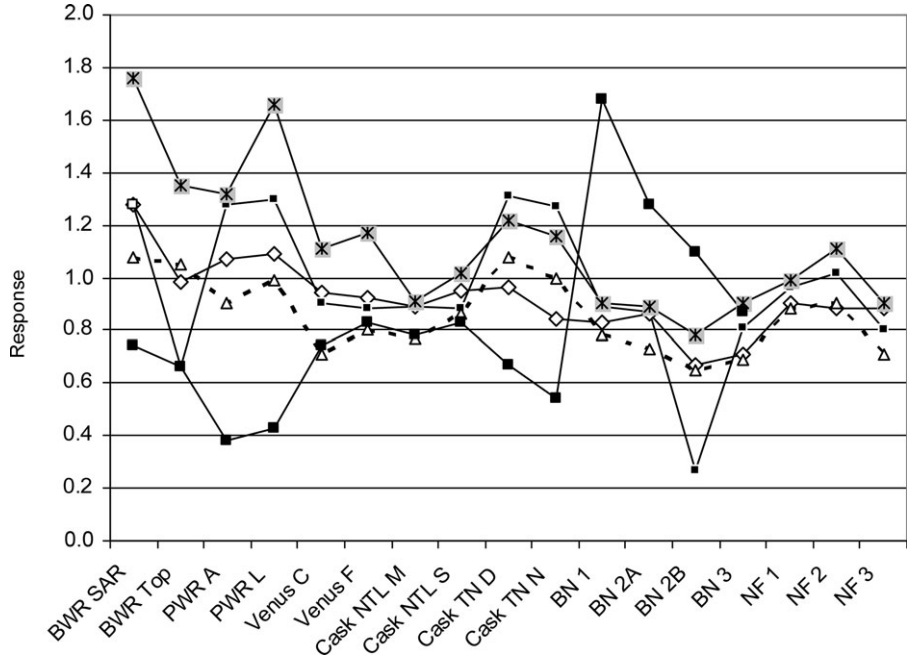


Figure 2. Ambient dose equivalent response of survey meters: Wendi (stars), Leake (small filled squares), Sievert (large filled squares), Studsvik (dashed line and open triangles) and LB (open diamonds).

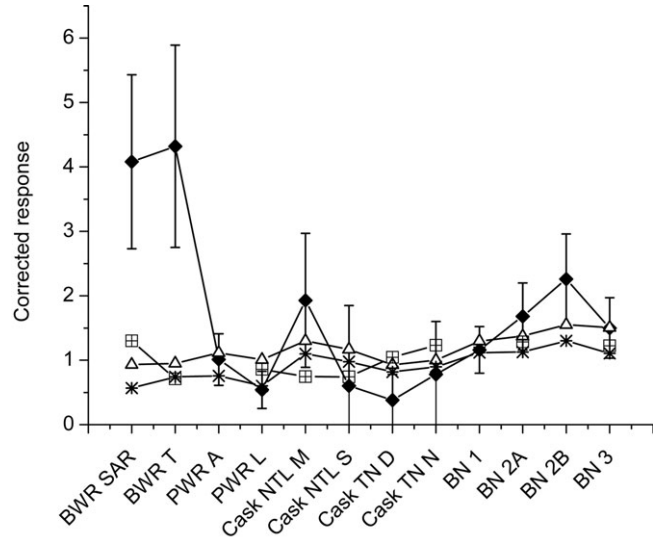


Figure 3. Personal dose equivalent response of the local personal dosemeter systems as delivered by the local staff and related to $H_p(10)$ (filled diamonds, with uncertainties corresponding to the readings) , after correction according to equation (4) with the Studsvik 2002D instrument (open triangles) and the WENDI 2 instrument (stars), after correction according to (5) and the $H_{P,\mathrm{SLAB}}$ instrument (+ inside open squares, this instrument did not measure in all fields).

with the cask positioned in another but similar area had also been reported. For the first two positions, L and A, Tables 3 and 4 present a comparison of the fractions of the fluence and ambient dose equivalent in different energy intervals as observed in 1992 and 2005. In the measurements in 1992 four

**Table 3. Fraction of the neutron fluence and $H^*(10)$ in three different energy intervals measured at PWR Ringhals Position L in 1992 and 2005.**

| Energy interval | $H^*(10)$ 1992 (%) | Fluence 1992 (%) | Fluence 2005 (%) |
|---|---|---|---|
| $E_n < 0.4$ eV | 3.5 | 11.7 | 13.7 |
| 0.4 eV $< E_n <$ 0.1 MeV | 29.7 | 75.8 | 72.7 |
| 0.1 MeV $< E_n$ | 66.9 | 12.5 | 13.6 |

**Table 4. Fraction of the neutron fluence in three different energy intervals measured at PWR Ringhals Position A in 1992 and 2005.**

| Energy interval | $H^*(10)$ 1992 (%) | Fluence 1992 (%) | Fluence 2005 (%) |
|---|---|---|---|
| $E_n < 0.4$ eV | 11.3 | 28.2 | 35.8 |
| 0.4 eV $< E_n <$ 0.1 MeV | 31.5 | 64.2 | 54.4 |
| 0.1 MeV $< E_n$ | 57.2 | 7.5 | 9.8 |

**Table 5. Ratios of $H_P/H^*$ determined 2005 and 1992 at Ringhals PWR and the Positions L, A and at Cask TND.**

| Position | $dH^*(10)/d\dot{t}$(mSv/h) | $H_P/H^*$ 1992 | $H_P/H^*$ 2005 |
|---|---|---|---|
| PWR L | 0.3 | 0.42 | 0.47 |
| PWR A | 1.8 | 0.42 | 0.33 |
| Cask TND | 0.02 | 0.49 | 0.73 |

different Bonner sphere systems took part and a best value was derived after a thorough evaluation. The results from 1992 are the best set of data. The results show good agreement. This is in particular the case for the important energy interval above 0.1 MeV. The contribution to ambient dose equivalent in the three energy intervals from 1992 is also shown.

Also the direction characteristics of the fields were determined in 1992[9] and the results from the two occasions are shown in Table 5. In the earlier measurements, passive personal dosemeters—Albedo TLD from Ringhals and track etched dosemeters from NRPB—were used to determine the direction characteristics of the fields using crude assumptions. The dose rate at the cask was quite small on both occasions (Table 5) and the statistical uncertainty was hence larger. The uncertainty in the new ratio of $H_p/H^*$ is 30%. The uncertainty is not smaller for the old ones. The results then agree within the uncertainties for the positions L and A, and most likely also at the cask due to the larger uncertainties.

The results in Tables 3–5 demonstrate that workplace fields may be fairly constant over longer time periods, particularly at a reactor facility, which should make workplace field-specific correction factors or workplace calibrations meaningful to use. However, this assumption may not apply to other workplaces where the source and shielding may vary with time.

## DISCUSSION

As the survey meters were found to be sufficiently accurate (Figure 2) a workplace calibration of the local personal dosemeters could be made according to equation (4). The responses calculated using the corrected personal dose equivalent results are shown in Figure 3, when $H^*(10)$ is determined with the Studsvik 2202D and the Wendi-2 instruments. Very similar results will appear if the Berthold LB 6411 replaces the former and the Harwell Leake N91 instrument the latter instrument. In both cases, the results improve and become within 0.7–1.1 and 0.8–1.7 for the two instruments, respectively. The corrected results now reflect the response of the survey meter in the workplace fields.

The alternative approach, to make use of a reference personal dosemeter and equation (5), would lead to a similar result. The corrected results will show a response equal to the inverse of the response of the personal dosemeter used as reference. The response of the reference neutron personal dosemeter $H_{p,\mathrm{SLAB}}$ under development at DIMNP[10] was the instrument with best response to $H_p(10)$ in the test. It consists of a super heated drop detector positioned in a polymethylmethacrylate slab phantom, which had been calibrated using a $^{241}$Am–Be neutron source. If its over-response (the response was in the range 1.07–2.3) is corrected for by dividing all results by 1.4[6], the range becomes 0.7–1.3. Those adjusted response values are used together with equation (3) or (5) to correct the local personal dosemeter results and the outcome is also presented in Figure 3. The statistical uncertainty of the readings of $H_{p,\mathrm{SLAB}}$ was typically 14%. Both methods would, if applied to $H_{p,\mathrm{loc}}$, have improved the accuracy to a range which is common for photon dosemeters.

In practice, a person may not be working constantly with his/her front facing the main direction of the neutrons. The influence on the dosemeter result of irradiations in other directions may be investigated by directing the phantom to other directions and compare with the reference meter for that direction. A suitably averaged calibration factor may then be derived.

The reference directional spectrometer used in this investigation is quite complex and is not expected to become a routine instrument. In the investigation

from 1992[9], quite similar ratios of $H_p/H^*$ were found at the higher dose rates (Table 5) with technically much simpler techniques, and other instruments and methods could be expected to appear. One such instrument could be the reference $H_{p,\mathrm{SLAB}}$ prototype detector used here. Such an instrument would be valuable also when neutron dosemeters are periodically checked for accuracy. It should be evident from the discussion that it is important that the reference instruments have a known response and that their results are traceable to national standards.

## CONCLUSIONS

The test has demonstrated that both photon and neutron ambient dose equivalent in workplace fields in the nuclear industry may be determined in the range 0.5–1.5 or better with commercial instruments. A comparison of neutron fluence energy distributions measured at the same locations but with a time difference of more than 10 y demonstrate that the neutron fluence as well as the direction distributions had not changed significantly. Workplace field calibrations are therefore a method of improving the accuracy of neutron personal dosimetry in locations where higher accuracy is of importance. It was demonstrated that workplace radiation field-specific factors defined by the ratio $H_p/H^*$ can be used together with commercial neutron survey meters to provide meaningful workplace calibrations. In this way, the local neutron personal dose-equivalent results improved from a range of 0.5–4 to a range 0.7–1.7 or better depending on the choice of survey meter used. A similar result was seen if the local dosemeters were directly calibrated to a prototype reference $H_{p,\mathrm{SLAB}}$ detector[10]. Those conclusions are strictly valid only for the investigated workplace fields. However, the different workplaces showed a great variety of energy distributions and it is believed that the investigated workplaces cover most situations in the nuclear industry. It is important that the survey instrument or reference personal dosemeter used has traceability to national standards and have response functions that are well known.

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