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Neutron field correction coefficients for active and passive dosimeters in Cernavoda NPP

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This work evaluated the Hp(10)dose for the personnel exposed in mixed field inside several locations of reactor 1 building at Cernavoda NPP. In order to achieve this we used active (EPD N2 and DMC 2000GN) and passive (TLD 8806) personnel dosimeters and one ambient neutron monitor for H*(10) evaluation. The dose correction coefficients vary from one room to another depending on the neutron spectra. The obtained values range from 1.6 to 4 meaning that all dosimeters are over evaluating the exposure.

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1. Introduction

Personal neutron doses in mixed neutron/ gamma field are still very hard to evaluate a strong energy dependency of the neutron dose. The energy response of ambient monitors approximates the energy response of the neutron fluence to ambient dose equivalents, but are heavy and impractical to use. Since they provide only a measure for ambient dose equivalent, they are also unsuited to evaluate the personal dose equivalent Hp(10). In order to evaluate Hp(10), personal monitor should be used. The disadvantage of this monitor is the poor energy response, necessitating the use of site specific correction factor.

.As CANDU reactors usually have lower energy spectra that other reactor designs, this complicates even more the required personnel dosimetry.

The method applied in this article is proposed by SCK•CEN [2, 3, 10] who was also one of the partners within the EVIDOS [1] international project for the Evaluation of Individual Dosimetry in Mixed neutron-gamma workplace fields.

The experimental values were obtained for several locations inside the Unit 1 Reactor building at Cernavoda NPP using active (EPD N2 detectors from Cernavoda NPP) and passive (8806TLD from University of Bucharest) detectors and one neutron monitor (FHT 752 from University of Bucharest) used for evaluation of ambient dose rate *dH*(10)/dt*.

2. Methods and materials

The locations used in this article to irradiate the chosen dosimeters with respect to the work previously done in [4] and taking into account dose rate estimates and the possible presence of workers:

- R-009: Basement Perimeter
- R-405: Heat Transport Auxiliary Room
- R-501: Boiler Room nearby one primary heat transport pump

The energy spectra for these locations was determined in a previous measurement campaign [4] and was repeated in 2007 [5] obtaining the spectra presented in Fig. 1.

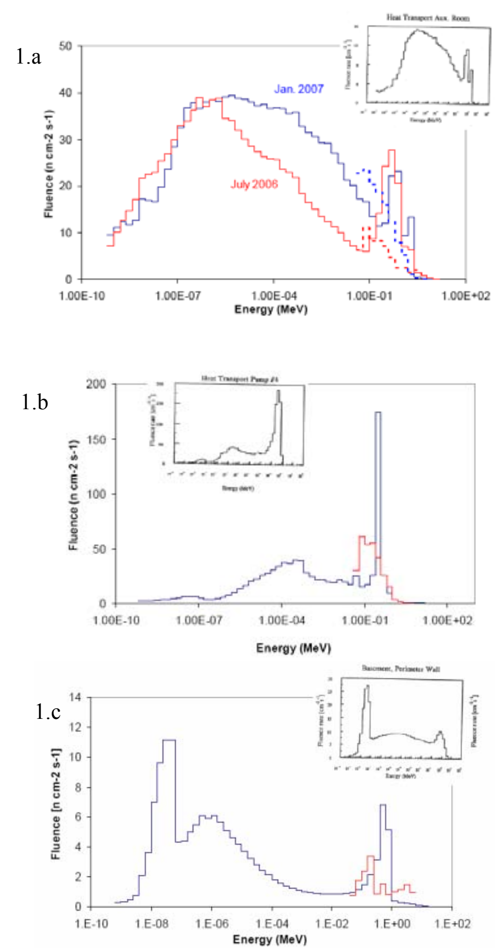

Fig. 1a). Neutron spectra in the R-405, b) Neutron spectra in the R-501, 1c). Neutron spectra in the R-009.

Fig. 1 contains the 2007 measured spectra (big frame) and literature reference (small frame) spectra [4]. Those spectra are used to determine the average (per neutron) $\overline{h^*(10)}, \overline{h_p(10,0°)}, \overline{h_p(10,90°)}$ and $\overline{h_p(10,180°)}$ fluency to dose conversion factors for each considered location. In order to achieve this, average values from the ICRP [5] conversion factors were used for each energy bin i:

$$\overline{h^*(10)} = \frac{\sum_i h^*(10)_i \varphi_i}{\sum_i \varphi_i} \tag{1}$$

Where $h^*(10)_i$ the average conversion coefficient for energy bin i, φ_i the fluency measured in energy bin i and $\overline{h^*(10)}$ the average conversion coefficient for a specific location (for the whole spectra). The same approach is used to obtain an average value for the others conversion coefficients.

2.1 Dosimeters

The ambient dose rate *dH*(10)/dt* is evaluated using an dosimeter Thermo FHT 752 (University of Bucharest, Faculty of Physics). FHT 752 is a proportional counter with cylindrical geometry using a BF_3 proportional counters, based on $^{10}B(n,\alpha)^7Li$ reaction. The field is moderated by a large hydrogenous mass with the use of a perforated thermal neutron absorbing layer, made of cadmium or boron-loaded rubber.

The angular distribution of the neutron fluency is estimated using both active and passive personal dosimeters. Therefore the dosimeters are placed in five angular orientations on a slab phantom, namely front, back, left, right and top[Fig. 2].

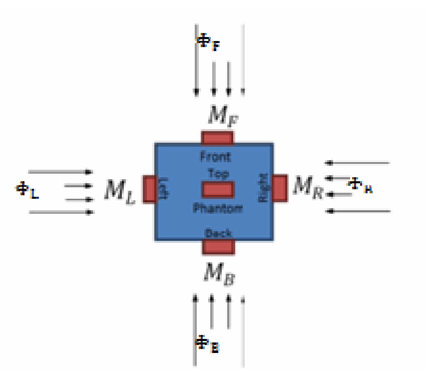

Fig. 2 Personal dosimeter placement on 30 cm SLAB water phantom.

Experimental dose values obtained for the personnel dosimeters (H_F, H_B, H_L, H_R, H_T - foreach of the phantom sides) are presented in table 4. Dose fractions (F_F, F_B, F_L, F_R, F_T - foreach of the phantom sides) are computed using

$$F_F = \frac{H_F}{H_F + H_B + H_L + H_R + H_T}$$

Fractional fluencies are presented in table 6 and computed according to $\Phi_F = F_F \Phi$ with the values from table 4

The active dosimeters used are Thermo EPD-N2™ and MGPI DMC-2000GN™ (Cernavoda NPP) and the passive are TLD 8806 (Faculty of Physics)

The EPD-N2's are based on three silicon detectors; two of them are being used for neutron detection: one of them is covered with a plastic layer for the detection of fast neutrons via recoil protons, and the other is covered with ^6LiF for the detection thermal, epithermal and intermediate neutrons. Boron-loaded plastic in front of the dosimeter acts to suppress an over-response to incident thermal neutrons. The sensitivity of the fast neutron detector is 0.1 counts μSv^{-1} and for the thermal, epithermal and intermediate is 1 count μSv^{-1} [6].

DMC 2000 GN, developed by MGP Instruments under PTB license, uses two silicon detectors for the determination of photon and neutron personal dose equivalent. The neutron detector is covered by converters and absorbers to improve its energy response (polyethylene and ^6LiF) and an albedo shield that surrounds the detector/converter assembly.

The Harshaw TLD 8806 is equipped with two pairs of TLD-600 (^6LiF) and TLD-700 (^7LiF). TLD-600 has sensitivity for both the neutron and gamma component of the radiation field, while TLD-700 has sensitivity for the gamma component. To distinguish between thermal and epithermal neutrons, one TLD-600 and one TLD-700 are covered with Cd; TLD-600 covered with Cd interacts with epithermal neutrons, while TLD-600 without Cd cover interacts with both thermal and epithermal neutrons. Since ^6Li only interacts with thermal and epithermal neutrons, albedo neutrons from the body, which are representative for the fast neutrons of the primary field, are measured as well to cover the complete energy range. The Harshaw TLD 8806 detectors were calibrated using a ^{137}Cs source. A conversion factor for moderated ^{252}Cf was used to convert the ^{137}Cs response to a neutron dose equivalent Hp(10).

2.2 Methods of evaluation

In this approach we consider the static (subject is not moving) dose estimation. The angular information is used to determine a reference value for dHp(10)/dt, by combining partial dose rates dHp(10, 0°)/dt, dHp(10, 90°)/dt, dHp(10, 180°)/dt and dHp(10,270°)/dt . This method is presented in [7].The partial dose rates are estimated using $\overline{hp(10,0°)}$ $\overline{hp(10,90°)}$ and $\overline{hp(10,180°)}$ (table 1) in combination with the fractional fluencies from table 6:

$$\begin{aligned} dH_p(10,0°)/dt &= \Phi_F\, \overline{h_p(10,0°)} \\ dH_p(10,90°)/dt &= (\Phi_L + \Phi_R + \Phi_T) h_p(10,90°) \\ dH_p(10,180°)/dt &= \Phi_B\, hp(10,180°) \\ dH_p(10)/dt &= dH_p(10,0°)/dt + dH_p(10,90°)/dt + dH_p(10,180°)/dt \end{aligned} \tag{2}$$

The obtained values were used to correct the measured dH_p/dt with the personal monitors and to evaluate locations specific dependant albedo detector correction coefficients.

3. Results and discussion

In Table 1 we have the average $\overline{h^*(10)}$ and $\overline{hp(10,x^o)}$ conversion factors (Eq 1).

Table 1. Average fluence to dose conversion coefficients for each of the rooms

	$\overline{h^*(10)}$	$\overline{hp(10,0^o)}$	$\overline{hp(10,90^o)}$	$\overline{hp(10,180^o)}$
	pSv*cm^2			
R009	54.9 (55)	57.0	4.31	7.4
R405	38.3 (43)	40.2	3.67	6.51
R501	81.8 (119)	85.5	5.11	8.29

Note: The values in the brackets are taken from [4]

For these locations, we have used the obtained ambient doses with FHT-752. The experimental values are corrected with the relative response for FHT 752 obtained from Fig. 3. With these values we compute (Table 3) the integral fluencies for each location using the $\overline{h^*(10)}$ values presented in table 1.

Table 2. Ambient dose rates dH(10)/dt measured with FHT 752*

Dose rate [μSv/h]	R-009	R-405	R-501
Measured	36 ± 7	442 ± 88	181 ± 36
Correction coefficient (k)	1.09±0.05	1.62±0.06	1.16 ± 0.05
Corrected	33±7	272.8±55	156±32

Table 3. The actual integral fluencies computation in the considered rooms and the fluencies from [4].

	$dH^*(10)/dt$ μSv*h^{-1}	$\overline{h^*(10)}$ μSv*cm^2	ϕ n*cm^{-2}*h^{-1}	φ_{2007} [4] n*cm^{-2}*h^{-1}
R009	33±7	5.49E-5	6.0E+5 ± 1.3E+5	5.1E+5
R405	272.8±55	3.83E-5	71.2E+5 ± 14.3E+5	44.8E+5
R501	156±32	8.18E-5	19.1E+5 ± 3.9E+5	33.9E+5

Exposures have been made inside each of the rooms using the personnel dosimeters and the results are presented in Table 4.

*Table 4. Experimental results for dose rate (μSv*h^{-1}) in the exposure on SLAB phantom.*

	Pos	EPD N2	TLD #1	TLD #2	DMC-2000G N
R009	Front	16.5±3	16±3	17±3	16±3
	Back	17±4	13±3	13±3	11±2
	Left	17±4	16±3	16±3	10±2
	Right	21.5±4	21±4	22±4	23±5
	Top	34±7	35±7	31±6	18±4
R405	Front	383±83	513±102	514±103	261±52
	Back	66±13	68±14	64±13	27±5
	Left	160±32	228±46	136±27	156±31
	Right	164±33	195±39	107±22	184±37
	Top	160±32	307±61	200±41	161±32
R501	Front	131±25	144±29	135±27	168±34
	Back	54±11	54±11	65±13	39±8
	Left	83±17	96±19	74±15	69±14
	Right	80±16	101±20	115±23	81±16
	Top	22±4	85±17	61±12	17±3

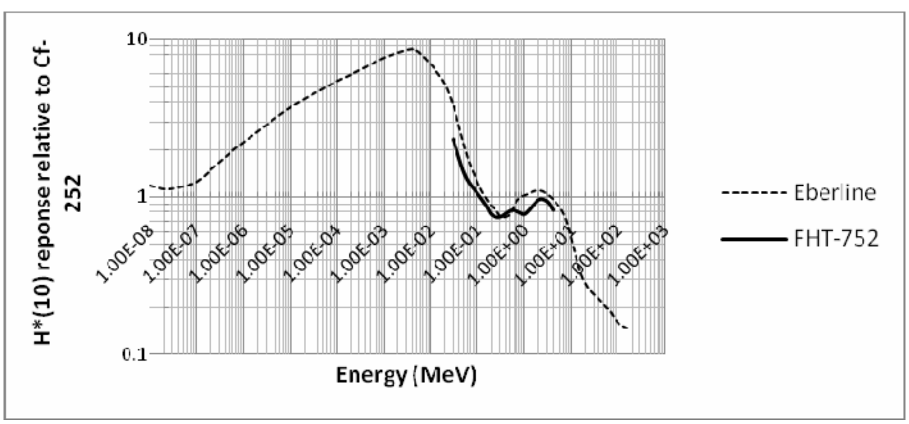

Fig. 3. H(10) response relative to Cf-252 of the ambient monitors used in the measurement campaign. Our FHT 752 is a Eberline class detector with efficiency experimentally validated in the 3×10^{-2} MeV and $4\times10^{+2}$ MeV energy range.*

Table 5. Dose fraction for each SLAB size calculated under the assumption that the energy spectrum remains constant in every orientation and that the angular response of the personal detectors is perfect.

Location		*Thermo EPD N2*	*TLD 8806*	*TLD 8806*	*DMC-2000GN*	*Average*	*Stdev*
R-009	Front	15.5%	15.8%	17.1%	20.5%	17.2%	2.3%
	Back	16.0%	12.8%	13.1%	14.1%	14.0%	1.4%
	Left	16.0%	15.8%	13.1%	12.8%	14.4%	1.7%
	Right	20.2%	20.7%	21.2%	29.5%	22.9%	4.4%
	Top	32.0%	34.6%	31.3%	23.1%	30.3%	5.0%
R-405	Front	41.0%	39.1%	50.3%	33.1%	40.9%	7.1%
	Back	10.0%	5.2%	6.3%	3.4%	6.2%	2.8%
	Left	20.0%	17.4%	13.3%	19.8%	17.6%	3.1%
	Right	20.0%	14.9%	14.9%	23.3%	18.3%	4.1%
	Top	10.0%	23.4%	23.4%	20.4%	19.3%	6.4%
R-501	Front	35.0%	30.0%	30.0%	44.9%	35.0%	7.0%
	Back	15.0%	11.0%	14.0%	10.4	12.6%	2.2%
	Left	22.0%	20.0%	16.0%	18.4	19.1%	2.5%
	Right	22.0%	21.0%	26.0%	21.7	22.7%	2.3%
	Top	6.0%	18.0%	14.0%	4.6	10.7%	6.4%

Table 6. d H(10)/dt to dHp(10)/dt conversion using coefficients from Table 3 into equations (2).*

	dH(10/dt) (μSv/h)*	*□ (n/cm²h)**	*Position*	□ $\left(\frac{n}{cm^2 h}\right)$	$\overline{h_p(10,x)}$ *μSvcm²*	*$dH_p(10,x)/dt$ (μSv/h)*	*$dH_p(10)/dt$ (μSv/h)*
Basement perimeter	33±7	6E+5 ± 1.3E+5	front	10.3E+4 ± 2.22E+4	5.7E-5	5.9 ± 1.3	8.4 ± 1.9
			back	8.4E+4 ± 1.81E+4	7.4E-6	0.7 ± 0.2	
			left	8.66E+4 ± 1.87E+4	4.3E-6	0.4 ± 0.1	
			right	13.7E+4 ± 2.96E+4	4.3E-6	0.6 ± 0.1	
			top	18.2E+4 ± 3.93E+4	4.3E-6	0.8 ± 0.2	
Heat transport aux room	272.8±55	71.2E+5 ± 14.3E+5	front	29.1E+5 ± 77.3E+5	4E-5	116 ± 30.9	134 ±37
			back	4.41E+5 ±21.8E+5	6.5E-6	2.9 ± 1.4	
			left	12.5E+5 ± 33.5E+5	3.7E-6	4.6 ± 1.2	
			right	13.0E+5 ± 39.2E+5	3.7E-6	4.8 ± 1.5	
			top	13.7E+5 ± 5.3E+5	3.7E-6	5.1 ± 1.9	
Boiler room	156±32	1.91E+6 ± 3.9E+5	front	6.68E+5 ± 1.36E+5	8.6E-5	57.4 ± 11.7	64.5 ± 13.2
			back	2.41E+5 ± 0.49E+5	8.3E-5	2.0 ± 0.4	
			left	3.65E+5 ± 0.74E+5	5.1E-6	1.9 ± 0.4	
			right	4.33E+5 ± 0.88E+5	5.1E-6	2.2 ± 0.5	
			top	2.03E+5 ± 0.41E+5	5.1E-6	1.0 ± 0.2	

When the assumption is made that the personal monitors only respond to neutrons perpendicular to the monitor's axis, similar conclusions about the angular distributions can be drawn.

The results show that in the basement perimeter, there is a main contribution of neutrons coming from the top. The same conclusions were drawn in the study conducted by [4]. This is of major importance when estimating the personal dose equivalent, since personal dosimeters are always worn on a person's chest. In the boiler room and the heat transport aux room, the neutron fluency is mainly coming from the front of the phantom.

The personal dose rate dHp(10)/dt presented in Table 6 is calculated using the values for the partial dHp(10,x)/dt dose rates under static conditions.

Considering a static person, having the same orientation as the phantom we can compute the values presented in Table 7.

Table 7. Correction coefficient for albedo dosimeters.

	Basement perimeter-R009		
	dHp(10)/dt (μSv/h)	u (μSv/h)	Site specific correction factor
Angular Static – Reference	8.4	1.9	
Thermo EPD N2	16.5	3	1.96±0.57
TLD 8806	16	3	1.90±0.56
DMC-2000GN	16	3	1.90±0.56
	Heat transport aux room-R405.		
	dHp(10)/dt (μSv/h)	u (μSv/h)	Site specific correction factor
Angular Static – Reference	134	37	0.0729
Thermo EPD N2	383	83	2.86±0.99
TLD 8806	513	102	3.83±0.46
DMC-2000GN	216	53	1.61±0.21
	Boiler room-R009		
	dHp(10) (μSv/h)	u (μSv/h)	Site specific correction factor
Angular Static – Reference	64.5	13.2	0.0418
Thermo EPD N2	131	25	2.03±0.57
TLD 8806	144	29	2.23±0.64
DMC-2000GN	168	34	2.60±0.75

For the case that the person is constantly moving in the field and his orientation is uniformly distributed with respect to the phantom orientation (the person si either rotating to the left, to the right or at a complete turn – 180^{o} with respect to the phantom positionig. By assuming these is posible to compute the average correction coefficients presented in Table 8.

Table 8. Dinamic dose evaluation for a person moving within the specified room.

Room 009	
0 degrees	8.24±1.78
90 left	7.29±1.57
90 Right	7.37±1.59
180 degrees	10±2.17
Average	8.2±1.78
Room 405	
0 degrees	175±35.2
90 left	92.7±18.6
90 Right	526±106
180 degrees	151±30.3
Average	236±47.4
Room 501	
0 degrees	82.6±16.8
90 left	81.3±16.5
90 Right	73±14.8
180 degrees	73.2±14.9
Average	77.5±15.8

4. Conclusions

The effected measurements estimate reference values for *dHp(10)/dt* and *dH*(10)/dt* in order to obtain reliable reference values and information on energy and angular distribution in the case of neutron dosimetry. To estimate a reliable value for *dH*(10)/dt*, measurements were performed with FHT752 ambient monitor. After energy dependency corrections, consistent values for *dH*(10)/dt* were obtained in every location.

A proper estimation for the personal dose equivalent *dHp(10)/dt*, can only be made when information is available on the angular distribution. This information is obtained by placing personal dosimeters in the front, back, left, right and top of a slab phantom. Assuming that the energy spectrum doesn't change for the different orientations considered (front, back, left, right and top) and a perfect angular dependency of the EPD's, the relative fluency coming from each one of the considered orientations (front, back, left, right, top), is calculated using as information the measured dose rate and the fluency-to-dose conversion factors [9].

Because directional spectrometry was not available it was not possible to know the spectra from all the directions; the assumption that they are all the same is the only possibility to estimate the contribution of the different sides.

Using $\overline{h_p(10,0°)}$, $\overline{h_p(10,90°)}$ and $\overline{h_p(10,180°)}$ conversion coefficients, the partial fluencies are converted into partial dose rates *dHp(10,0°)/dt*, *dHp(10,90°)* and *dHp(10,180°)* and combined together to a reference value for *dHp(10)/dt*.

Another important aspect is the evaluation of personnel deep dose rate dHp(10)/dt by the means of the neutron flow that we previously done.

In case of a preference for the use of active or passive personal dosimeters, one must use different correction factors, depending on the location and the dosimeter.

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