Characterization of the neutron fields around Cernavoda NPP

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In the environment near a nuclear reactor, a fuel container or a particle accelerator, mixed neutron/gamma fields are very common, necessitating routine neutron dosimetry. Accurate neutron dosimetry is complicated by the fact that the neutron effective dose E and neutron personal dose equivalent $H_p(10)$ is strongly dependent both on the neutron energy and the direction distribution of the neutron fluence. Therefore, neutron field characterization is indispensable if one wants to obtain a reliable estimate for the neutron dose. A measurement campaign in CANDU NPP in Cernavoda, Romania, was set up in November 2010 to characterize the neutron fields in four different locations and to investigate the behavior of different personal neutron dosemeters. Neutron field characteristics, such as energy and angular distributions, were determined using different neutron monitors. The energy distribution was measured using a BTI Mycrospec and Nprobe combination, the angular distribution was measured by placing personal dosemeters on five faces of a slab phantom. The results were combined together to obtain a reference value for the personal dose equivalent $H_p(10)$. The obtained values were compared to the readings of the personal monitors in order to choose a suitable neutron dosimetry system at Cernavoda nuclear power plant.

1 Introduction

When individuals are exposed in mixed neutron/gamma environments it is necessary, in addition to routine gamma dosimetry, to perform accurate routine neutron dosimetry. It would be optimal to have neutron dosemeters capable of measuring the dose equivalent with the same accuracy as the existing dosemeters for gamma radiation. But the fact that the neutron equivalent dose is strongly dependent on the neutron energy implies extra features to the neutron detectors. Most ambient and personal neutron dosemeters lack the requirement of providing a combined standard uncertainty of less than 50% (Garcia-Alves et al 2009).

In addition to the energy dependence of neutron dose measurements, the directional distribution of the neutron fluence strongly affects neutron dose measurements as well; the personal dose equivalent $H_p(10, \theta)$ and the effective dose E depend strongly on the direction of the incident radiation field (ICRP 74 1996). To make accurate estimations of the ambient and personal dose equivalent, neutron field characterization, taking into account both the energy and angular distribution, is indispensable.

In this work neutron field characterization was performed at four different locations in Cernavoda Nuclear Power Plant (NPP), which is a CANDU type reactor. The main goal of this collaboration was to characterize the neutron fields and to derive a reference value for the neutron ambient and personal dose equivalent, $H^*(10)$ and $H_p(10)$. This allowed us to investigate the behavior of different personal monitors in the chosen measurement locations by comparing the measured values with the estimated reference values. This provided information for a well informed choice of a neutron dosimetry system at the power plant.

2 Materials and methods

2.1 Measurement locations

Measurements were performed at different locations, including locations inside and outside the containment structure of unit 1. The locations were chosen taking into account dose rate estimates and the occupancy level of workers.

Measurements inside the containment structure were performed in the heat transport auxiliary room (R-405) and in the boiler room (R-501). The boiler room is situated at the top level, near the heat exchanger. Outside the containment structure, measurements were performed in the D_2O vapour recovery room (S-146).

In order to obtain a reliable value for the personal dose equivalent, several measurements were performed intended to:

- Derive the energy distribution of the neutron fluence
- Determine the directional distribution of the neutron fluence
- Estimate a reference value for the ambient and the personal dose equivalent rate $\mathrm{d}H^*(10)/\mathrm{d}t$ and $\mathrm{d}H_p(10)/\mathrm{d}t$

2.2 Energy distribution of the neutron fluence

The energy spectrum was determined using a Microspec-2 Nprobe, developed by BTI bubble Technologies. Thermal and epithermal neutrons are measured with a ^{3}He counter encased within a special ^{10}B shield, separated in two energy bins. Fast neutrons are measured and presented in 16 energy bins by using a liquid scintillator. (Ing 2007)

2.3 Directional distribution of the neutron fluence

The directional distribution of the neutron fluence was estimated using the readings of different active and passive personal dosemeters. The detectors were placed on five faces of a slab phantom, being front, left, right, back and top, as shown in Figure 1. The fluence incident in different directions $P(\vartheta, \phi)$ on the phantom, indicated in Figure 1, was estimated using linear interpolation techniques in steps of 15° in the perpendicular directions.

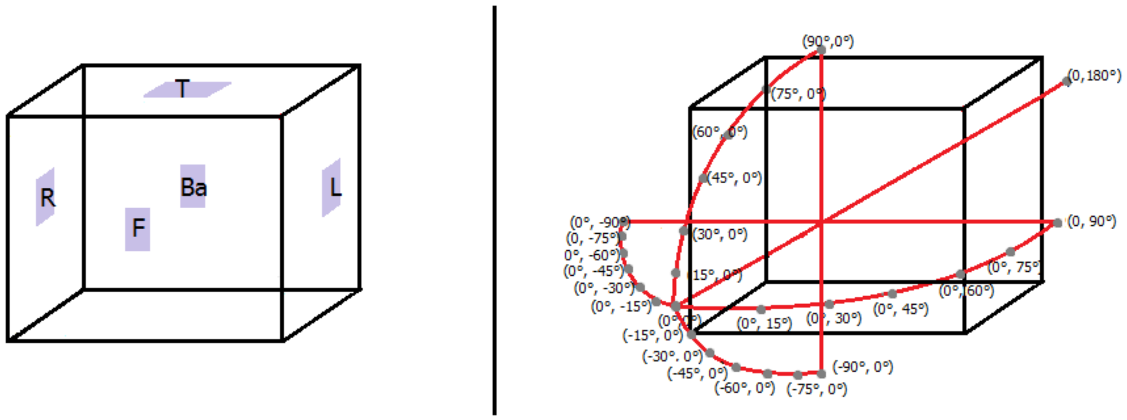

Figure 1: Both active and passive dosemeters were placed on all sides of a slab phantom (left figure) to estimate the angular distribution of the neutron fluence incident in different directions P(ϑ, ϕ) (right figure). This latter was done using linear interpolation techniques under the assumption that the energy distribution remains the same in all orientations.

2.4 Reference value for ambient dose equivalent rate d*H*(10)*/d*t*

A reference value for the ambient dose equivalent was determined using three different ambient monitors, Studsvik 2202D (Andersson and Braun 1964), Wendi II (Therom Scientific), and Eberline NRD ASP2. These detectors are all proportional counters based on the $^{3}He(n,p)^{3}H$ or $^{10}B(n,\alpha)^{7}Li$ reaction.

A reliable estimation for each monitor of the ambient dose equivalent rate d*H*(10)*/d*t* was obtained by taking into account the energy response of the monitors (shown in Figure 2) normalized to the proper calibration sources (Schumacher et al 2006), (IAEA 2001), (Tanner et al 2007) and the spectral information obtained with the Nprobe. The average of the energy corrected values was considered to be the reference value for d*H*(10)*/d*t*.

d*H*(10)*/d*t* was used to obtain the reference for the total neutron fluence $d\Phi_{total}/dt$, by dividing d*H*(10)*/d*t* with the site specific average neutron fluence to ambient dose equivalent conversion coefficient $<h^*(10)>$. The latter was obtained by using the Nprobe data and the ICRP *h*(10)* values (ICRP 74 1996) in the following way:

$$<h^*(10)> = \frac{\sum_i h^*(10)_i \Phi_i}{\sum_i \Phi_i} \qquad \textbf{Eq1}$$

In this equation, Φ_i represents the fluence in the *i*th energy bin and $h^*(10)_i$ the average conversion coefficient for energy bin *i* taken from the ICRP/ICRU conversion factors (ICRP 74 1996; ICRU 1997).

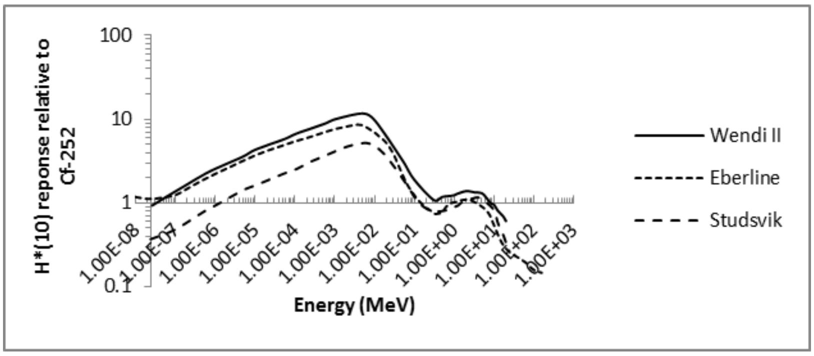

Figure 2: *H*(10)* response relative to Cf-252 of the ambient monitors used in the measurement campaign.

2.5 Reference value for personal dose equivalent rate d$H_p(10)$/d*t*

A reference value for personal dose equivalent rate was obtained by combining the information on the directional distribution of the neutron field and the reference value for the total neutron fluence $d\Phi_{total}/dt$.

In a first approach a dose estimation was made under static conditions, meaning a person present in a certain location is not moving. The front of the phantom will therefore represent the front of the person. Partial dose rates were estimated by multiplying partial fluences $d\Phi(\vartheta, \phi)/dt$, derived from the directional distribution and the total neutron fluence, with an average personal dose equivalent conversion coefficient $<h_p(10, \theta)>$. The latter was calculated as explained previously in Eq1. For plane parallel irradiation from the front with an angle of incidence θ, $<h_p(10, \theta)>$ values were calculated from 0° to 90° in 15° increments using the data of (d'Errico et al 2007). A reference value for d$H_p(10)$/d*t* was obtained by summing together all partial dose rates.

$$
\begin{aligned}
&\frac{\mathrm{d}H_p(10,0°)}{\mathrm{d}t} = \frac{\mathrm{d}\Phi_{(0°,0°)}}{\mathrm{d}t} < h_p(10,0°) > \\
&\frac{\mathrm{d}H_p(10,\theta)}{\mathrm{d}t} = \frac{\mathrm{d}\Phi_{(0°,\theta°)} + \mathrm{d}\Phi_{(0°,-\theta°)} + \mathrm{d}\Phi_{(\theta°,0°)} + \mathrm{d}\Phi_{(-\theta°,0°)}}{\mathrm{d}t} < h_p(10,\theta) > \\
&\text{where } \theta = (15°,30°,45°,60°,75°,90°) \qquad \textbf{Eq 1} \\
&\frac{\mathrm{d}H_p(10,180°)}{\mathrm{d}t} = \frac{\mathrm{d}\Phi_{(0°,180°)}}{\mathrm{d}t} < h_p(10,180°) > \\
&\frac{\mathrm{d}H_p(10)}{\mathrm{d}t} = \sum \frac{\mathrm{d}H_p(10,\theta)}{\mathrm{d}t} \text{ where } \theta = (0°,15°,30°,45°,60°,75°,90°,180°)
\end{aligned}
$$

The values obtained were compared to each other and to the readings of the personal monitors to evaluate the behavior of the monitors in the chosen locations.

3 Results

3.1 Energy distribution of the neutron fluence

In three out of four measurement locations, soft spectra were observed. In the boiler room a rather large contribution from neutrons spanning energies from 0.5 to 1 MeV were observed.

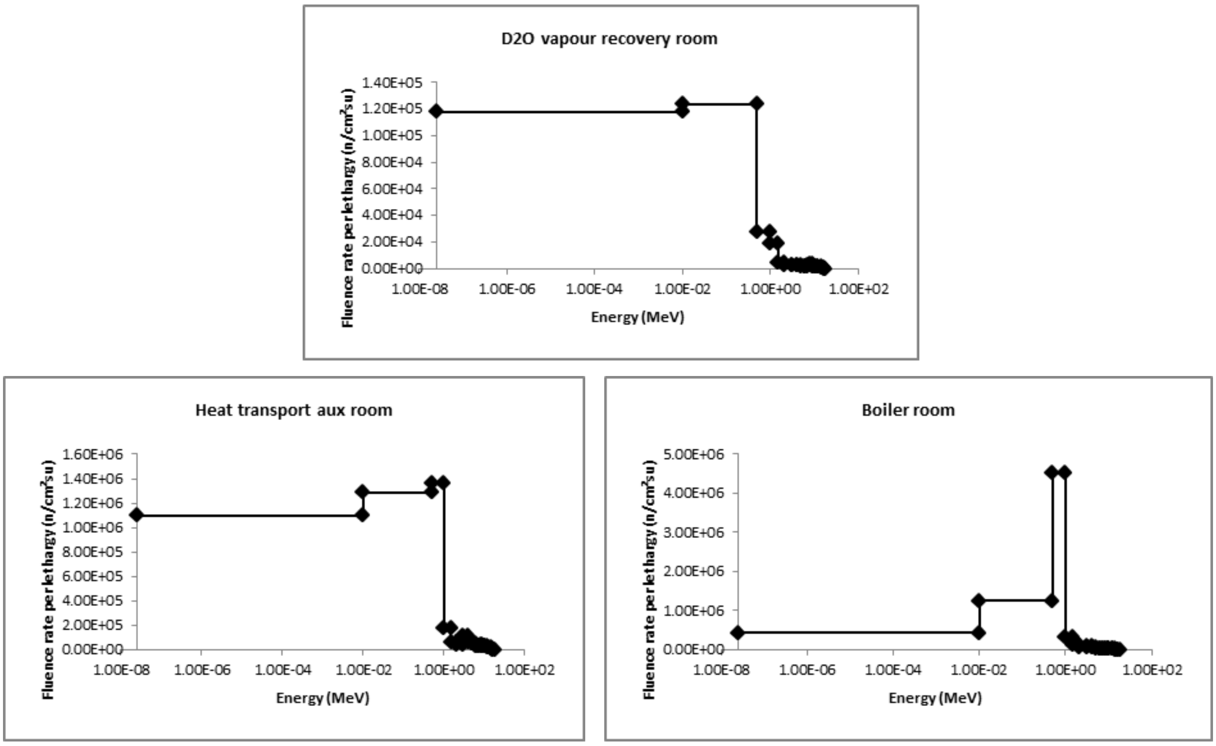

Figure 3: The spectra obtained with the Nprobe are in general soft spectra. An exception to this is the spectrum obtained in the boiler room, where there is a rather large contribution from neutrons having energy from 0.5 to 1 MeV.

3.2 Directional distribution of the neutron fluence

The directional distribution of the neutron fluence was estimated by placing different personal monitors on five faces of a slab phantom. The measured values from all detectors are presented in Table 1. These values were used to calculate the relative neutron fluence incident in different directions $P(\vartheta, \phi)$ on the phantom using linear interpolation.

Table 1: Measured values from all the personal monitors in all the measurement locations.

Location		*Thermo EPDN2 (µSv/h)*	*DMC 2000 GN (µSv/h)*	*HPA PADC (µSv/h)*	*Landauer PADC (µSv/h)*	*Landauer FNTD (µSv/h)*
D2O vapour recovery room	**Front**	77 ± 11	46 ± 6	10 ± 2	13	11 ± 1
	Back	28 ± 4	19 ± 3	1 ± 1	5	2.6 ± 0.3
	Left	57 ± 11	67 ± 13	6 ± 2	3	4.4 ± 0.5
	Right	47 ± 9	31 ± 6	4 ± 1	7	1.9 ± 0.2
	Top	62 ± 12	34 ± 7		5	
Heat transport aux room	**Front**	383 ± 54	251 ± 36	76 ± 4	133	40 ± 5
	Back	66 ± 9	26 ± 4	4 ± 2	9	4.4 ± 0.5
	Left	160 ± 32	156 ± 31	12 ± 3	20	16 ± 2
	Right	164 ± 33	184 ± 37	10 ± 2	26	
	Top	160 ± 32	161 ± 32	18 ± 3	18	
Boiler room	**Front**	127 ± 18	101 ± 20	44 ± 3	80	17 ± 2
	Back	54 ± 8	36 ± 5	4 ± 1	14	
	Left	83 ± 17	69 ± 14	9 ± 2	19	
	Right	80 ± 16	81 ± 16	17 ± 2	33	
	Top	99 ± 20	57 ± 11	7 ± 2	20	

In the D_2O vapour recovery room the neutron fluence can be considered isotropic; in the boiler room and the heat transport aux room, the neutron fluence is mainly coming from the front of the phantom.

3.3 Reference value for ambient dose equivalent rate d*H*(10)*/d*t*

As explained in the "Materials and Methods" section of this paper, the ambient dose equivalent rate was measured using ambient monitors. The spectral information of the Nprobe was used together with the energy response of the monitors to obtain energy corrected values. The values are presented in Table 2. The average of the energy corrected values was considered the reference value for the ambient dose equivalent rate d*H*(10)/*d*t*.

Table 2: Measured values for the ambient dose equivalent rate, together with the corrected values, taking into account the energy response of the monitors. The average value of the energy corrected values is considered the reference value for the ambient dose equivalent rate.

	Ambient monitor	*Measured dose rate (µSv/h)*	*Energy corrected dose rate (µSv/h)*	*Average dose rate (reference dose rate) (µSv/h)*
D_2O vapour recovery room	*Wendi II*	41 ± 8	17 ± 3	16 ± 2
	EberlineASP2	44 ±9	17 ± 3	
	Studsvik2202D	23 ± 1	14 ± 1	
Heat transport aux room	*Wendi II*	150 ± 30	78 ± 16	97 ± 9
	EberlineASP2	218 ± 44	105 ± 21	
	Studsvik2202D	154 ± 4	107 ± 3	
Boiler room	*Wendi II*	126 ± 25	97 ± 19	92 ± 9
	EberlineASP2	139 ± 28	103 ± 21	
	Studsvik2202D	86 ± 2	77 ± 2	

As explained in section 2.4, the ambient dose equivalent rate was used to estimate the total neutron fluence dΦ/d*t*, by dividing d*H*(10)/*d*t* with the site specific average neutron fluence to ambient dose equivalent conversion coefficient $< h^*(10) >$. The latter was obtained by using the Nprobe data and the ICRP $h^*(10)$ values (ICRP 74 1996). The values are presented in Table 3.

Table 3: Reference value for the ambient dose equivalent rates, average fluence to ambient dose equivalent conversion coefficient and reference value for the total fluence rate, calculated for every measurement location.

	$dH^*(10)/dt$ ($\mu Sv/h$)	$\langle h^*(10)\rangle$ ($\mu Svcm^2$)	$d\Phi/dt$ (n/cm^2h)
D_2O vapour recovery room	16 ± 2	4.02E-05	(4.0 ± 0.4) E+05
Heat transport aux room	97 ± 9	5.57E-05	(1.7 ± 0.2) E+06
Boiler room	92 ± 9	1.37E-04	(6.8 ± 0.7) E+05

3.4 Reference value for personal dose equivalent rate $dH_p(10)/dt$

Reference values for personal dose equivalent rate were estimated using a static approach, meaning a person present in a certain location is not moving. Partial dose rates were estimated by multiplying partial fluences $d\Phi(\vartheta,\phi)/dt$, derived from the directional distribution and the total neutron fluence, with an average personal dose equivalent conversion coefficient $\langle h_p(10, \theta)\rangle$.

Table 4 represents the average $\langle h_p(10, \theta)\rangle$ conversion coefficients calculated using the Nprobe data and the ICRP $h_p(10)$ values (ICRP 74 1996).

Table 1: average $\langle hp(10, \theta)\rangle$ conversion coefficients, obtained using the Nprobe data, and the ICRP $h_p(10)$ values.

	D_2O vapour recovery room	***Heat transport aux room***	***Boiler room***
$\langle h_p(10,0°)\rangle$ pSvcm²	42.3	58.2	141.4
$\langle h_p(10,15°)\rangle$ pSvcm²	40.5	53.7	122.5
$\langle h_p(10,30°)\rangle$ pSvcm²	39.2	55.1	137.7
$\langle h_p(10,45°)\rangle$ pSvcm²	33.5	48.1	123.5
$\langle h_p(10,60°)\rangle$ pSvcm²	24.4	36.4	97.6
$\langle h_p(10,75°)\rangle$ pSvcm²	10.7	17.1	48.0
$\langle h_p(10,90°)\rangle$ pSvcm²	0.9	1.4	2.7
$\langle h_p(10,180°)\rangle$ pSvcm²	2.1	2.9	5.4

Table 5 summarizes the values for the total personal dose equivalent rate estimations, calculated using a static approach.

Table 5: Personal dose rate estimations, under a static approach. The front of the phantom is considered the front of a person.

	D2O vapour recovery room		***Heat transport aux room***		***Boiler room***	
	Hp(10, x)	**u**	**Hp(10, x)**	**u**	**Hp(10, x)**	**u**
$H_p(10)$	11.3	1.2	73	11	65	9

As a final step, the calculated values for personal dose equivalent rate were compared with the readings of different detectors. Site specific correction factors for each detectortype were proposed and presented in in Table.

For proper evaluation, the readings of the monitors in the front of the phantom were compared to the calculated values of the personal dose equivalent rates.

Table 6: Comparison between the calculated static dose equivalent rates and the readings from the front detectors.

	D_2O vapour recovery room		*Heat transport aux room*		*Boiler room*	
	$H_p(10)$ (µSv/h)	**Site specific correction factor**	**$H_p(10)$ (µSv/h)**	**Site specific correction factor**	**$H_p(10)$ (µSv/h)**	**Site specific correction factor**
Reference	11.3 ± 1.2		73 ± 11		65 ± 9	
Thermo EPD N2 - Front	77 ± 11	6.8 ± 1.2	383 ± 54	5.2 ± 1.1	127 ± 18	2.0 ± 0.4
DMC 2000 GN - Front	46 ± 6	4.0 ±0.7	251 ± 36	3.4 ± 0.7	135 ± 20	2.1 ± 0.4
HPA CR 39 - Front	10.5 ± 2.0	0.9 ± 0.2	76 ± 4	1.0 ± 0.2	44 ± 3	0.7 ± 0.1
Landauer CR 39 - Front	13.1	1.2 ± 0.1	133	1.8 ± 0.3	80	1.2 ± 0.2
Landauer FNTD - Front	11.3 ± 1.4	1.0 ± 0.2	40 ± 5	0.6 ± 0.1	17 ± 2	0.27 ± 0.05

4 Conclusion

The measurements conducted in this project were intended to estimate reference values for $dH_p(10)/dt$ and $dH^*(10)/dt$. In order to obtain reliable reference values, information on energy and direction distribution is of great importance in the case of neutron dosimetry. Measurements were performed with an Nprobe to determine the energy distribution of the neutron fluence.

Information on the directional distribution was obtained by placing personal dosemeters in 5 faces of a slab phantom. It is clear that the neutrons do not come from one direction. In one location, most neutrons come from the top, which can give rise to underestimations of the effective dose.

A reliable value for $\mathrm{d}H^*(10)/\mathrm{d}t$ was estimated using different ambient monitors. After energy dependency corrections, consistent values for $\mathrm{d}H^*(10)/\mathrm{d}t$ were obtained in every location, with an exception for the basement perimeter. The reference values for ambient dose equivalent rate were used to determine reference values for the total neutron fluences $\mathrm{d}\Phi/\mathrm{d}t$ in each of the considered locations.

Using $h_p(10,\theta)$conversion coefficients (for every 15° in perpendicular directions, up to 90°), partial fluences, obtained using the information about the total fluence and the direction distribution, are converted into partial dose rates and combined together to a reference value for $\mathrm{d}H_p(10)/\mathrm{d}t$. The obtained values are compared with the readings of the personal monitors involved in the measurement campaign in order to propose site specific correction factors.

When comparing the calculated values with the detector readings, the PADC detectors perform relatively well in all considered locations. In general, Landauer PADC detectors have to tendency to overestimate the dose with an average of 20%, while HPA PADC detectors underestimate the dose with an average of 20%, meaning an overall correction coefficient could be used for this detector type.

The performance of the other detectors seem to differ depending on the location, which necessitates the use of different correction factors that are quite substantial. This limits the use of the passive Landauer FNTD detectors, but is relatively easy to overcome with active detectors.

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