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INSTRUMENT INTERCOMPARISON IN THE HIGH-ENERGY MIXED FIELD AT THE CERN-EU REFERENCE FIELD (CERF) FACILITY

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This paper discusses an intercomparison campaign performed in the mixed radiation field at the CERN-EU (CERF) reference field facility. Various instruments were employed: conventional and extended-range rem counters including a novel instrument called LUPIN, a bubble detector using an active counting system (ABC 1260) and two tissue-equivalent proportional counters (TEPCs). The results show that the extended range instruments agree well within their uncertainties and within 1σ with the *H(10) FLUKA value. The conventional rem counters are in good agreement within their uncertainties and underestimate *H**(10) as measured by the extended range instruments and as predicted by FLUKA. The TEPCs slightly overestimate the FLUKA value but they are anyhow consistent with it when taking the comparatively large total uncertainties into account, and indicate that the non-neutron part of the stray field accounts for ∼30 % of the total *H**(10).**

INTRODUCTION

Monitoring of stray radiation at workplaces characterised by mixed fields with radiation spectra extending over a wide energy range is a difficult task. These mixed fields are usually dominated by neutrons with a more or less pronounced photon contribution, but other radiation components (electrons, muons, pions and protons) cannot always be neglected. Measurements in such complex radiation environments can lead to huge variations in detector readings, due to differences in their energy response function and sensitivity. With the aim of evaluating the performance of various active monitors in a well-characterised mixed field, an intercomparison campaign was carried out in 2012 at the CERN-EU reference field (CERF) facility[(1)].

The CERF stray radiation field is generated by a positive hadron beam (2/3 protons and 1/3 positive pions) with momentum of 120 GeV c^{-1} impinging on a copper target placed inside an irradiation cave. The secondary particles produced in the target traverse an 80-cm concrete shield on top. This roof shield produces an almost uniform radiation field over an area of 2×2 m^2 located at 90° with respect to the incoming beam direction, divided in 16 squares of 50×50 cm^2. Each element of this 'grid' represents a reference exposure location (concrete top, CT). The energy distributions of the particles (mainly neutrons) at the various exposure locations were obtained in the past by Monte Carlo simulations performed with the FLUKA code[(2,3)].

The beam is delivered to the CERF facility from the super proton synchrotron (SPS) with a typical intensity of 10^8 particles per SPS spill. The spill duration (beam extraction time) is ∼10 s over an SPS cycle of ∼45 s. The beam spot is approximately rectangular, ∼30 mm × 40 mm. The beam monitoring is provided by an air-filled ionisation chamber (IC) placed in the beam a few meters upstream of the target. One IC count corresponds to $2.2\cdot10^4$ beam particles[(1)].

INSTRUMENTATION

The measurements were performed behind a 80-cm thick concrete shield in the CT7 reference exposure location[(1)]. At this location the neutron spectral fluence is characterised by a low-energy peak with an energy around 0.4 eV, an intermediate region between the thermal and the evaporation peak located at ~1 MeV and a high-energy peak centred at ~100 MeV[1]. Both commercial and prototype detectors were employed, which can be divided in three classes:

(1) Conventional and extended-range rem counters: the LINUS used at CERN[4–7]; the Thermo Wendi-2, the Berthold LB6411[8, 9]; the Thermo BIOREM FHT 752, whose response to high-energy neutrons can be enhanced by adding an external lead shell; the LUPIN prototype employed in its BF_3 version[10, 11];

(2) Other neutron detectors: the Thermo RadEye NL, employed with its small-size polyethylene moderator to increase the efficiency to fast neutrons (the main purpose of this instrument is to detect radiation sources more than estimating a neutron dose rate); the ABC 1260-1 neutron dosemeter, a bubble detector using an active counting system, whose response can be extended to several hundred MeV with the addition of a 1-cm thick cylindrical lead shell placed around the detector cap[12–14];

(3) Tissue-equivalent proportional counters (TEPCs): the PNNL TEPC[15], with the quality factor chosen to give an estimate of $H_p(10)$; the Far West Technology HAWK FW-AD2[16].

Table 1 summarises the detectors employed in the intercomparison and the institutes participating in the experiment. A description of the detectors can be found in ref. (17). Table 2 provides the calibration details for each detector. For commercial detectors it gives the operating range in terms of dose rate and neutron energy as declared by the manufacturer.

While for the rem counters the calibration procedure and the related coefficient is unambiguous, for the TEPCs one can refer to different calibration processes: using an internal ^{244}Cm alpha source (for the calibration of the lineal energy scales, to convert

Table 1. Summary of detectors employed and institutes participating in the intercomparison.

Detector name	Detector type	Institute
Wendi-2	Extended range rem counter	CERN
LB6411	Conventional rem counter	CERN
Biorem FHT 752	Conventional rem counter	CERN
LINUS	Extended range rem counter	CERN
LUPIN	Prototype extended range rem counter	CERN/POLIMI
RadEye NL	Pocket meter	CERN
ABC 1260-1	Bubble detector	CERN
TEPC	TEPC	PNNL
HAWK FW-AD2	TEPC	ASCR
BIOREM FHT 752	Conventional rem counter	HZB
BIOREM FHT 752+Pb shell	Extended range rem counter	HZB

Table 2. Summary of the calibration details and the operating range of the detectors.

Detector	Calibration coefficient [nSv/count]	Calibration spectrum	Measured operational quantity	Declared operating range (for commercial detectors)	
				Dose rate	Neutron energy
Wendi-2	0.32 ± 0.03	Pu–Be	$H^*(10)$	10 nSv h^{-1}–100 mSv h^{-1}	0.025 eV–5 GeV
LB6411	0.72 ± 0.06	Pu–Be	$H^*(10)$	10 nSv h^{-1}–100 mSv h^{-1}	0.025 eV–20 MeV
BIOREM (CERN)	0.67 ± 0.05	Pu–Be	$H^*(10)$	10 nSv h^{-1}–400 mSv h^{-1}	0.025 eV–10 MeV
LINUS	0.88 ± 0.07	Pu–Be	$H^*(10)$	n.a.	n.a.
LUPIN	0.48 ± 0.04	Pu–Be	$H^*(10)$	n.a.	n.a.
RadEye	3.00 ± 0.24	Pu–Be	$H^*(10)$	n.s.	n.s.
ABC 1260	195.0 ± 15.6	Pu-Be	$H^*(10)$	n.s.	0.025 eV–20 MeV (200 MeV with Pb)
PNNL TEPC	6.80 ± 0.27	^{252}Cf	$H_p(10)$	n.a.	n.a.
HAWK	0.39 ± 0.04	^{252}Cf	$H^*(10)$	n.a.	n.a.
BIOREM (HZB)	0.67 ± 0.05	Pu–Be	$H^*(10)$	10 nSv h^{-1}–400 mSv h^{-1}	0.025 eV–10 MeV

The calibration coefficient takes into account the uncertainty on the calibration source. n.a., not available; n.s., not specified.

channel numbers from the pulse-height spectrum and to check the gas gain), an external photon source (typically ^{137}Cs or ^{60}Co, for the calibration of the low-LET component) or an external ^{252}Cf source (to verify the response to the high-LET component). Since in these measurements the interest is focused on the neutron component of the stray field, the values in Table 2 refer to the calibration with the ^{252}Cf source.

MEASUREMENTS

Experiment

The aim of the measurements was to intercompare the response of the detectors amongst them and with the FLUKA value. All measurements were performed by placing each detector in turn in the CT7 reference location. The integrated counts of each detector were normalised to the IC counts. The internal clock of each detector was synchronised with the internal clock of the PC used for data acquisition before the start of each measurement, so as to allow an off-line normalisation of the data. Data acquisition for all the detectors was controlled remotely.

RESULTS

Table 3 shows the measured quantity ($H^*(10)$ for all the detectors, except for the PNNL TEPC which measured $H_p(10)$), normalised to the beam intensity expressed in IC counts. For the HAWK, the data have been recalculated into REM500 equivalent readings to allow a direct comparison with the other instruments employed in the experiment. The FLUKA value for the reference exposure location CT7 is also shown. The values always refer to the neutron component of the radiation field. For the TEPCs the value refers to the high-LET contribution of the field (>8.2 keV μm^{-1} for the HAWK and >10 keV μm^{-1} for the PNNL TEPC). The authors assume that the neutron contribution to the radiation field coincides with the high-LET component, even if it cannot be excluded that other particles contribute to the high-LET component, causing an overestimation of the $H^*(10)$. At the same time, it cannot be excluded that neutrons may contribute to the low-LET part of the spectrum. The HAWK also provides an estimation of the total $H^*(10)$, 351.9 ± 36.7 pSv/IC count, determined according to the procedure explained in ref. (18).

The BIOREM (CERN) was tested in two different orientations to verify its known anisotropic response, indicated in Table 3 as V (i.e. with the vertical axis of the detector normal to the concrete top shielding) and H (i.e. with the vertical axis parallel to the shielding), and in two versions (with and without the external lead shell). The ABC 1260 was used in two versions: with and without the cylindrical lead shell.

The total uncertainty has been calculated as the sum of the statistical and the systematic ones. The uncertainty on the reproducibility of the positioning has been set to 2 %, i.e. 1/10 of the maximum difference between the reference value of $H^*(10)$ in CT7 and in the adjacent locations CT3/6/8/11 (Figure 1b). The systematic uncertainty of the HAWK includes a 3 %

Table 3. Normalised values of $H^*(10)$ or $H_p(10)$ due to neutrons as measured in CT7 by each detector with the related uncertainties, compared with the FLUKA reference value.

Detector	$H^*(10)$ or $H_p(10)$ [pSv IC count^{-1}]	Uncertainty [pSv IC count^{-1}]				Total
		Stat.	Systematic			
			Posit.	Calibr.	Other	
Wendi-2	251.51	1.25	5.03	20.1	/	26.4
LB6411	148.62	0.62	2.97	11.9	/	15.5
BIOREM (CERN) H [°]	173.59	1.52	3.47	13.9	/	18.9
BIOREM (CERN) V [°]	162.76	1.47	3.26	13.0	/	17.7
LINUS	224.04	1.98	4.48	17.9	/	24.4
LUPIN	220.00	1.06	4.40	17.6	/	23.1
RadEye	490.41	5.47	9.81	39.2	/	54.5
ABC 1260	190.57	3.60	3.81	15.3	/	22.7
ABC 1260+Pb	248.61	14.0	4.97	19.9	/	38.9
PNNL's TEPC	313.00	22.0	6.26	/	56.0	84.3
HAWK	275.60	0.10	5.51	27.6	8.30	41.5
BIOREM (HZB)	170.00	4.08	3.40	13.6	/	21.1
BIOREM (HZB)+Pb	236.00	3.64	4.72	18.9	/	27.3
FLUKA	267.00	/	/	/	/	26.7[a]

[a]Derived from the uncertainty on the beam monitor.

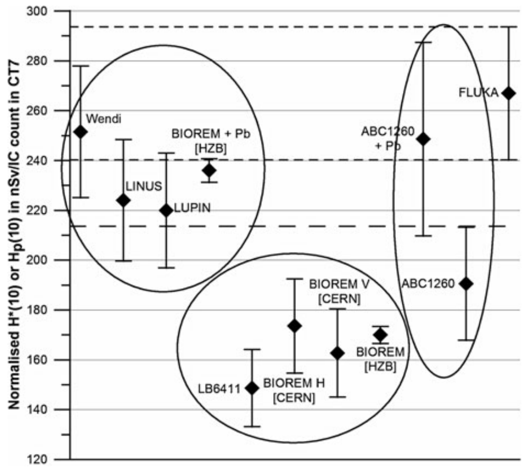

Figure 1. Comparison between the $H^*(10)$ values measured by the extended range rem counters (left), conventional rem counters (centre) and the ABC 1260 detector (right). The reference value derived from FLUKA simulations is also shown, together with the $\pm 1\sigma$ (small dashed line) and the $\pm 2\sigma$ deviations (big dashed line).

uncertainty coming from reproducibility issues, as declared by the manufacturer. The systematic uncertainty of the PNNL TEPC is a rough and conservative estimation based on the fact that there was no previous experience with the use of the detector in high-energy stray fields. The uncertainty deriving from the beam monitor calibration is not included in any of the results, except for the FLUKA value, since this is a correlated uncertainty which is the same for all measurements.

DISCUSSION

The discussion is presented in two parts: the first regarding the detectors whose readings explicitly refer to the $H^*(10)$ coming only from the neutron component of the stray field and the second about the TEPCs.

Rem counters and detectors alike

The results of the extended range rem counters (Wendi-2, LINUS, LUPIN and BIOREM (HZB)+Pb) are in good agreement within their uncertainties and also agree within 1σ with the value of $H^*(10)$ obtained with FLUKA. The readings of the conventional rem counters (LB6411, BIOREM (CERN) and BIOREM (HZB)) are in good agreement within their uncertainties and underestimate $H^*(10)$, as measured by the extended range instruments and as calculated by FLUKA, by 35–45 %. This is due to the reduced sensitivity of these detectors for neutrons with energies >10 MeV. Past measurements carried out at CERF with similar detectors in several reference locations on the concrete top showed underestimations of the $H^*(10)$ in the range of 30–50 %[19–21]. The BIOREM (CERN) showed a limited dependence of the response on the orientation, with a difference in the readings well below the uncertainty. This dependence is lower than the one declared by the manufacturer when the detector is calibrated with a ^{252}Cf source, i.e. a ratio of 1.33 in its reading in the vertical and horizontal orientations. This could be explained if the neutron field emerging from the shield would be isotropic, but this is not really the case, as past measurements with cylindrical phantoms had shown that the radiation field on the roof shield is predominantly from underneath[23]. Nonetheless, scattered neutrons from nearby shielding structures and the hall roof certainly provide an isotropic contribution. This behavior needs further investigations. The RadEye overestimates the FLUKA $H^*(10)$ value by a factor of 2. This confirms, as seen in other measurements[22], that this monitor, even when embedded in the polyethylene moderator, has limited reliability. The results from the ABC 1260 bubble detector confirm that the detector efficiently measures $H^*(10)$, showing a good agreement with the FLUKA value (within $\pm 1\sigma$) if employed with the lead shell. Otherwise the detector underestimates $H^*(10)$ by 30 %. This is consistent with the results obtained at CERF in the past employing a similar detector[20,21].

Figure 1 compares all the measured values of $H^*(10)$ and the FLUKA reference value. The experimental data are grouped in circles according to their type: extended range rem counters, conventional rem counters and the bubble detector. The result of the RadEye has been excluded from the analysis since it is an outlier and it is not shown in the graph.

TEPCs

The agreement of the results of the measurements performed with the TEPCs ($H_p(10)$ for the PNNL TEPC and $H^*(10)$ for the HAWK, both due only to the neutron component) is good within their range of uncertainty. Both results are higher than the FLUKA value (Figure 2) but the large total uncertainties (around 25 % for both TEPCs) well encompass it. The slight overestimation of the average measured values is probably a result of two contributions. The first is due to the potential presence of a non-neutron component in channels with energies >8.2–10 keV μm^{-1} (i.e. the energy limits set to subtract the low-LET events). The second is due to the well-known TEPC shortcomings when measuring thermal and low-energy neutrons (i.e. with a LET < 100 keV μm^{-1}). The only available estimation for the total $H^*(10)$ is given by the HAWK and this is 30 % higher than the FLUKA value, which refers

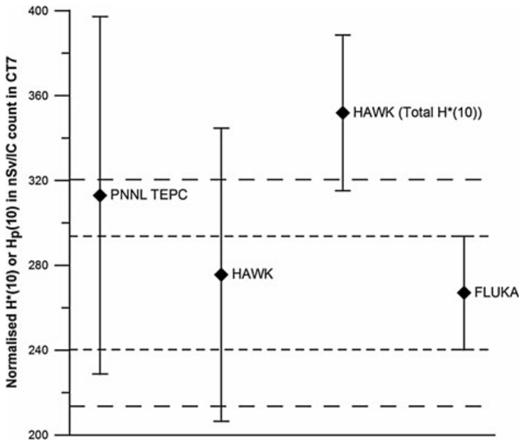

Figure 2. Comparison between the dose equivalent values due to neutrons measured with the TEPCs. For the HAWK also the total $H^*(10)$ is shown. The reference value derived from FLUKA simulations is plotted together with the $\pm 1\sigma$ (small dashed line) and the $\pm 2\sigma$ deviation (big dashed line).

only to the neutron component. Therefore, from the HAWK reading one can estimate the contribution of the non-neutron part of the stray field. These results confirm what obtained in the past at CERF with TEPCs exposed in similar reference locations (see for example ref.[23]), where the FLUKA value was overestimated by 20 %.

CONCLUSIONS

A comparison of the measured values of $H^*(10)$ ($H_p(10)$ for the PNNL TEPC) shows that:

(a) all the classes of detectors (extended range rem counters, conventional rem counters, TEPCs) agree well amongst them within the range of uncertainty;

(b) the conventional rem counters underestimate $H^*(10)$ by ~40 % with respect to the extended range rem counters and the FLUKA value;

(c) the results of the ABC 1260 bubble detector are consistent with those obtained with the conventional rem counters (with an underestimation of the dose of ~30 %) when used without the lead shell, and consistent with those of the extended range detectors (and with the FLUKA value) when the lead shell is employed;

(d) the BIOREM (CERN) does not show a significant difference in its reading when the detector is employed in the vertical or horizontal orientations, indicating that the stray field should be quasi-isotropic after crossing the concrete top shielding. However, this is in contrast with what one expects and with past measurements;

(e) the TEPCs results slightly overestimate the FLUKA value, confirming what observed in the past with similar detectors at CERF, but they are anyhow consistent with it when taking the comparatively large total uncertainties into account;

(f) the HAWK indicates that the non-neutron part of the stray field accounts for ~30 % of the total $H^*(10)$.

As expected, a clear distinction is seen in the response between instrumentation designed for neutron energies up to ~10 MeV and extended-range detectors. The difference in the results is evident also for instrumentation designed in two different versions (with a supplementary shell of high-Z material added when the detector is used in high-energy stray fields). The apparent inconsistency of the data obtained via the BIOREM on the stray field directionality could be ascribed to the different neutron energy distribution at CERF if compared with ^{252}Cf, but further investigations are needed.

The large total uncertainty related to the PNNL TEPC is due to the fact that the detector is usually employed for estimating personal dose equivalent in lower energy neutron fields, such as moderated fission spectra found in commercial reactors or plutonium facilities, and there was no previous experience in high-energy fields such as those produced at accelerators. Nevertheless, since the uncertainty encompasses the FLUKA value, the TEPC showed a consistent behaviour also in this unusual working field. In comparison with the PNNL TEPC, the HAWK was developed as a detector for aircrew dosimetry purposes, i.e. for radiation fields similar to the one present at CERF. Hence, being the difference between the measured $H^*(10)$ and the FLUKA value <10 %, the result is more than satisfactory when considering the complexity of the radiation field.

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