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CHARACTERIZATION OF AN EXTENDED RANGE REM COUNTER BASED ON MICRO STRUCTURED NEUTRON DETECTOR

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Abstract. *This study undertakes a comprehensive characterization of an extended range rem counter. Traditionally, these instruments adopt a gas thermal neutron detector surrounded by a polyethylene neutron moderator. Recently, Microstructured Semiconductor Neutron Detectors have garnered attention due to their advantageous traits: minimal voltage requirements high photon-neutron discrimination, cost-effectiveness, and the overall ease of use. Monte Carlo simulations using FLUKA were performed to assess the detector's response curve as function of neutron energy. The aim was to ensure its alignment with the fluence to ambient dose equivalent conversion factors across an extended range. The calibration coefficient, determined experimentally at the Czech Metrology Institute (CMI) in Prague, underwent validation at CERN's calibration facility. Furthermore, to assess the detector's response in high-energy mixed fields, it underwent irradiation at the CERN-EU high-energy References Field (CERF) facility. The results suggest the rem counter's proficiency in intense mixed fields, validating its applicability for both ambient dose monitoring and beam loss monitoring applications.*

Keywords: *Neutron Detector, Neutron Dosimetry, Radiation Protection, Rem Counter.*

1. INTRODUCTION

The complexity of neutron ambient dose equivalent evaluation arises from the wide energy spectrum of neutrons, ranging from meV to GeV. Rem counters, the main instruments adopted for this purpose, consist of a thermal neutron detector surrounded by a moderator designed to slow down high-energy neutrons. The detection mechanism involves nuclear reactions that emit charged particles, leading to a measurable current pulse. Currently, numerous rem counters based on gas neutron detectors have been developed [1]-[5]. Thermal neutron reactions involving BF_3, ^{6}LiF, and ^{3}He are commonly utilized in these detectors. The counts registered by the thermal neutron detector are subsequently multiplied by a calibration factor to evaluate the ambient dose equivalent value, denoted as H*(10). This calibration factor is determined through experimental measurements conducted at accredited institutes. Furthermore, the H*(10) response of each rem counter as a function of incident neutron energy can be evaluated using Monte Carlo codes.

A first implementation of a rem counter is known as the Andersson-Braun [1]. Its moderator consists of a polyethylene cylinder with boron inserts and a BF_3 neutron detector. This detector is capable to detect neutrons up to 15 MeV.

To enhance the detection capability for high-energy neutrons, extending up to a few GeVs, extended range rem counters were introduced [2]-[5], in which modified versions of the moderator have been used, incorporating high atomic number elements like lead and cadmium. The Long Interval NeUtron Survey-meter (LINUS) [2] marked the initial introduction of extended-range rem counters, enabling detection up to tens of MeV. Subsequently, the Wide Energy Neutron Detection Instrument (WENDI) [3]-[4] and Long Interval, Ultra-wide dynamic Pile-up free Neutron rem counter (LUPIN) [5] models were developed, extending the response to a few GeVs. Notably, the LUPIN rem counter integrates unique logarithmic electronics, enabling the detection of highly intense pulsed fields, reaching up to 16 nSv/burst. Other implementations of rem counters share common features such as gas detectors and a high-voltage electronic setup involving amplification, a single-channel analyzer, and a counter.

In this paper, the characterization of an extended-range rem counter based on a Micro-Structured Neutron Detector (MSND) manufactured by Radiation Detection Technologies has been conducted [6]. This implementation comprises a

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polyethylene moderator with cadmium and lead insertions, along with a diode-based neutron detector featuring low-voltage onboard electronics. The response function of the detector as a function of the incident neutron energy is assessed using the Monte Carlo code FLUKA [7]-[8]. An experimental campaign was conducted at the Czech Metrology Institute (CMI) in Prague [9] to evaluate the calibration factor of the detector and to perform a linearity test. Subsequently, the calibration factor was validated at the radiation protection calibration facility at CERN [10], and the detector's reliability in high-rate mixed fields was tested at the CERN-EU High-Energy References Field (CERF) facility [11]

2. Materials and Methods

The rem counter consists of a diode surrounded by a 12.5 cm polyethylene sphere with cadmium and lead insertions for an extended range response. The diode adopted is the DOMINO® neutron detector composed of four Micro-Structured Neutron Detectors (MSND) manufactured by Radiation Detection Technologies. The diode is then connected to a Raspberry Pi in order to supply power to the diode and control the entire detector. Figure 1 shows the MSND rem counter.

Figure 1. Picture of the MSND based rem counter.

A similar implementation of the moderator was adopted for the development of other rem counters found in the literature [12]. It consists of two polyethylene shells separated by a lead shell, with strategically placed cadmium insertions.

The detector's sensitive area comprises a 1 cm² square diode with a thickness of 5 mm, which is composed of four MSNDs, totaling a sensitive area of 4 cm². Its onboard electronics encompass a pre-amplifier, shaping-amplifier, discriminator, analog-to-digital converter, temperature sensor, and voltage regulator, producing an output signal. For detailed specifications, users can refer to the characteristics outlined in the official datasheet by Radiation Detection Technologies [13]. The reported efficiency is 30% for thermal neutrons at 20°C. The generated output takes the form of a square wave with a pulse width ranging between 5 and 50 µs. The diode interfaces directly with the General Purpose Input-Output (GPIO) pins of a Raspberry Pi, providing the necessary low-voltage power supply (5V) for the detector's operation. This connection enables the implementation of counting software on the Raspberry Pi to manage the rem counter. GPIO pins operate in high/low states. Upon detecting a thermal neutron, a 5V signal triggers the Raspberry Pi pin, changing its state to high. The software monitors this pin's status, registering a count each time the state shifts from low to high. Tests conducted with an external square wave generator show that the Raspberry Pi is capable of detecting signals up to 90 kHz, beyond the pile-up limit of the detector of 33 kcps and a 150 µs dead time.

The detector's software comprises a visualization code scripted in Python and a counting code developed in C. The code enables users to input measurement parameters, displays cumulative counts upon request, and plots the counts against measurement time. The C code continuously monitors the GPIO state; upon detecting a change from off to on, it increments the counter by one unit. Additionally, every second, a text file is updated with the date, time, and the counter's value.

In the next section, the model of the rem counter implemented with the Monte Carlo FLUKA is presented.

2.1. Monte Carlo model of the Rem Counter

The rem counter has been implemented in the FLUKA Monte Carlo code to assess the detector's response to the incident mono-energetic neutron beam. The characterization process involved testing at 55 neutron energies ranging from 1 meV to 1 GeV using a 25 x 25 cm² neutron beam. The same geometry has also been utilized to evaluate the detector's response to Am-Be source and neutron fields at the CERF facility. Figure 2 depicts the detector's geometry implemented in FLUKA. In particular, Figures 2a and 2b show the models of the moderator and the MSND detector, respectively.

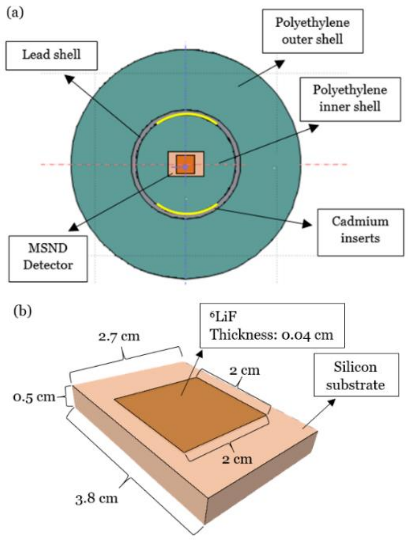

Figure 2. Geometry of the rem counter implemented in FLUKA. (a) Model of the moderator. (b) Model of the MSND detector including the silicon substrate.

The MSND features a 0.16 cm^3 ^6LiF active material surrounded by a silicon substrate. The entire system is centrally positioned within the moderator. In simulations, the active area is aligned to intercept the incoming neutron beam. However, it is almost impossible to perfectly model the exact structure of the diode; nevertheless, the volume of the active area is preserved.

The moderator setup consists of an outer sphere with a diameter of 25 cm and an inner sphere with a diameter of 11.2 cm. Between these polyethylene spheres, a 6 mm lead circular layer with 11 cadmium inserts, each 1 mm thick, is placed.

FLUKA enables users to track energy deposition on an event-by-event basis. A plot of this scoring is presented in Figure 3, displaying a prominent peak at 4.78 MeV. This peak aligns with the Q-value associated with the thermal neutron reaction with ^6Li. In this work, the counts under the peak are considered as detector's counts.

However, in the simulations performed in this paper, neutrons are transported using groups. The pointwise capture reaction on ^6Li for thermal neutrons is activated using the JENDL 3.3 cross-section library.

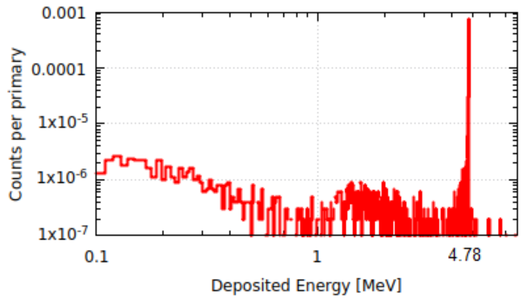

Figure 3. Plot of the deposited energy inside the ^6LiF performed with a 5 MeV neutron beam.

Once this procedure is established, the response of the detector as a function of neutron energy is determined, typically expressed as counts per unit of fluence, C_ϕ. Then, response curve in units of Sv·cm², R, is calculated using the following formula:

$$R = C_\phi \cdot k \qquad (1)$$

where k is the computational calibration factor. This coefficient is evaluated using the Monte Carlo model of the detector by dividing the ambient dose equivalent from an Am-Be source by the counts provided by the detector, considering one hour of irradiation. Furthermore, the model of the detector can also be adopted to simulate the detector's counts when the neutron spectrum is available.

2.2. Measurements performed at CMI

The Czech Metrology Institute, situated in Prague, specializes in instrument calibration using diverse measurement standards. At CMI's Unit of Primary Metrology of Ionizing Radiation, radioactive sources are employed for calibration, including those designed for measuring environmental neutron dose equivalents. CMI upholds the primary standard (ECM 440-2/97-003) for the spectral response of neutron fluxes using Am-Be and ^{252}Cf sources. These measurements cover dose rates ranging from 30 μSv/h to 20 mSv/h, certified for various neutron field locations.

The results of the measurements enable the calculation of the rem counter calibration factor by dividing the reference dose expressed in nSv by the detector's counts. This calibration factor is then used to perform the linearity test of the instrument and to assess the ambient dose equivalent response as a function of neutron energy.

This evaluation enables the comparison of the curve with ambient dose equivalent coefficients provided by ICRP and Pelliccioni [14] as a function of energy.

Additionally, the linearity test of the detector has been performed with dose rates ranging from 30 μSv/h to 20 mSv/h.

2.3. Measurements performed at CERN's Calibration Facility

The CERN radiation protection group conducts annual calibrations for approximately 8000 dosimeters and hundreds of both portable and fixed instruments [10]. Their calibration facility spans 13x13x13 m³ and houses Am-Be sources ranging from 100 MBq to 888 GBq, ensuring a dose rate range from μSv/h to mSv/h. These sources are securely stored in borated polyethylene containers shielded by steel and surrounded by 80 cm of concrete blocks. To handle the sources, a pneumatic system is used for remote extraction.

Measurements were conducted using 100 GBq Am-Be sources, yielding dose rates of 80 μSv/h and 200 μSv/h. The aim was to validate the calibration factor previously determined at CMI with a different setup.

2.4. Measurements performed at CERF Facility

The CERF facility is located in the North Experimental Area of CERN. In this facility, protons up to 120 GeV/c, provided by the Super Proton Synchrotron, collide with a 50 cm thick copper target, as illustrated in Figure 4.

Secondary neutrons are subsequently attenuated by concrete or iron before reaching the scoring positions. The facility provides reference positions for H*(10) measurements on the Concrete Top, Concrete Side, and Iron Top. Examples of neutron spectra in each scoring region (Concrete Top, Concrete Side, and Iron Top) are shown in Figure 5.

The dose rates in reference positions range from 5 to 250 μSv/h on the concrete top and the concrete side, and from 1 to 360 μSv/h on the iron top. Measurements were conducted at the CERF facility to validate the calibration factor of the rem counter in complex mixed fields up to a few GeVs.

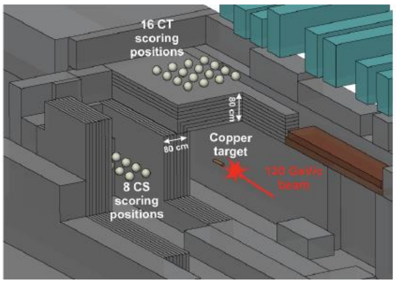

Figure 4. Description of CERF's facility with the indication of scoring positions [11].

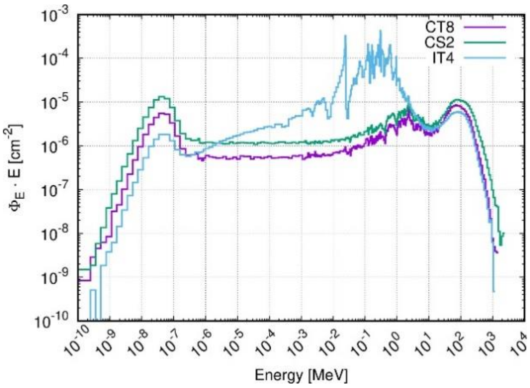

Figure 5. Neutron spectrum in CERF's reference positions on the Concrete Top (CT8), Concrete Side (CS2) and Iron Top (IT4) [11].

3. Results

In this section, the results of the measurements performed at the CMI's and CERN's calibration facilities, as well as at CERF's facility, are reported.

The calibration factor was evaluated at CMI and confirmed at CERN's calibration facility under different beam conditions. This calibration factor was then used to calculate the response function using the Monte Carlo model implemented in FLUKA. Furthermore, the results of the linearity test conducted at CMI are presented.

Finally, data obtained at CERF's facility are included to evaluate the rem counter's response in a mixed field with a significant component of high-energy neutrons.

3.1. Calibration Factor Assessment

The instrument was positioned 50 cm from the Am-Be source, with a neutron dose rate of 36 ± 1.6 μSv/h. The rem counter was irradiated in the reference position for 10 minutes, resulting in a total dose of 6 ± 0.3 μSv. The counts of the 9 measurements performed under these conditions are reported in Table 1. A calibration factor of 1.25 ± 0.06 nSv/count has been evaluated.

Table 1. Results of the measurements performed to assess the calibration factor of the rem counter. The ratio has been calculated dividing the reference dose by the counts provided by the detector.

Counts	Ratio [nSv/count]
4896 ± 70	1.23 ± 0.07
4420 ± 66	1.36 ± 0.08
4773 ± 69	1.26 ± 0.08
4912 ± 70	1.22 ± 0.07
4907 ± 70	1.16 ± 0.07
5148 ± 72	1.17 ± 0.07
4715 ± 69	1.27 ± 0.08
4727 ± 69	1.27 ± 0.08
4567 ± 68	1.31 ± 0.08

3.2. Response function

In Figure 6, the computational response of the MSND-based rem counter as a function of neutron energy, ranging from 1 meV to 1 GeV, is shown. Additionally, the results are compared to the fluence-to-ambient dose equivalent coefficients calculated by ICRP and Pelliccioni [14], as well as the LINUS and WENDI response functions.

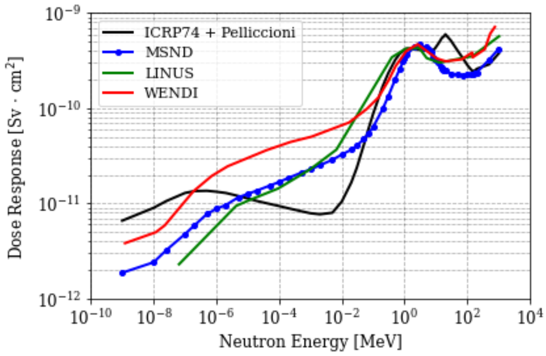

Figure 6. Response function of the detector, expressed in Sv·cm², as function of the incident neutron energy. The black line indicates the fluence to ambient dose equivalent coefficients calculated by ICRP and Pelliccioni [14], the blue line indicates the MSND rem counter results, the green line and the red line indicate respectively the LINUS and WENDI dose response.

Data are expressed in Sv·cm² and the MSND detector curve has been evaluated multiplying the counts·cm² of the detector as function of neutron energy by the computational calibration factor, following the methodologies described in Section 2.1.

The response of the detector is in agreement with typical rem counter responses found in literature [3], [15], as shown in Figure 6.

3.3. Linearity Test

In Table 2 and in Figure 7 the results of the measurements conducted at CMI for the linearity test of the rem counter are shown. In Figure 10 the ideal response is the expected value of the measure without count losses.

Dose rates were provided by the institute and the irradiation occurs in reference positions.

Table 2. Results of the measurements conducted for the linearity test of the rem counter.

Dose Rate [mSv/h]	Counts/h
0.04	$2.94 \cdot 10^4 \pm 6\%$
0.14	$1.04 \cdot 10^5 \pm 6\%$
0.28	$2.21 \cdot 10^5 \pm 6\%$
0.49	$3.69 \cdot 10^5 \pm 6\%$
1.09	$7.89 \cdot 10^5 \pm 6\%$
2.05	$1.54 \cdot 10^6 \pm 6\%$
4.03	$2.75 \cdot 10^6 \pm 6\%$
6.30	$3.92 \cdot 10^6 \pm 6\%$
11.21	$5.94 \cdot 10^6 \pm 6\%$

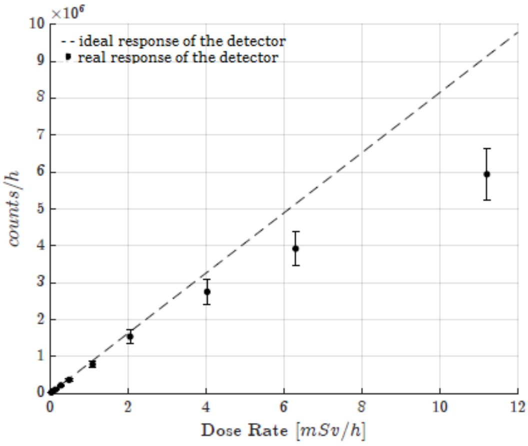

Figure 7. Plot of the linearity test performed at CMI. The dashed lines represent the ideal response of the detector without count losses.

Data show a linear behaviour up to 2 mSv/h considering a 2 sigma error. This response is mainly due to the MSND dead time of 150 µs [13]. Other commercial rem counters [2]-[5] are reliable in even higher neutron fields up to 100 mSv/h.

3.4. CERF's measurements

Measurements at CERF were performed in reference positions on the Concrete Side, the Concrete Top and Iron Top. In total, more than 70 measurements were evaluated. In Table 3 a summary of the results are reported.

Data show a mean underestimation of 15% for the Concrete Side and Top and of 30% for the Iron Top. These results are considered acceptable for this kind of detector for neutron dose evaluations. In order to investigate this underestimation, the Monte Carlo model of the rem counter is adopted. In particular, simulation irradiating the detector with Am-Be and CERF's neutron spectra in reference position are performed.

Table 3. Summary of the measurements conducted at CERF's facility with reference dose (Ref Dose) in the indicated position (CS, CT, IT) and the rem counter underestimation.

Position	Ref Dose [µSv]	RC Dose [µSv]	Rem Counter Underestimation
CS1	19.14	16.12	16%
CS1	18.05	15.38	15%
CS1	37.15	32.08	14%
CT10	23.60	20.31	14%
CT3	13.98	11.69	16%
CT3	7.20	6.22	14%
CT5	34.04	29.04	15%
IT1	16.19	11.06	32%
IT16	18.59	13.02	30%
IT9	20.04	14.44	28%

4. Discussion

A series of simulations were performed using FLUKA to investigate the underestimation of the detector in reference positions. The detector was irradiated with the Am-Be and CERF's spectra in reference positions, as respectively shown in Figures 8 and 5. The same methodologies exposed in section 2.1 were adopted in the simulations.

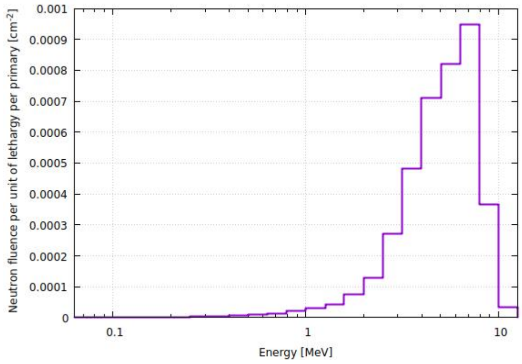

Figure 8. Lethargy plot of Am-Be spectrum adopted in the simulation.

The ratio between the results obtained with Am-Be and CERF's spectra is compared and data are shown in Table 4.

Table 4. Comparison between the rem counter response modelled in FLUKA with different spectra (Am-Be or CERF's reference positions).

Spectrum	Counts/primary	FLUKA Underestimation
Am-Be	$1.77 \cdot 10^{-3}$	-
CS-CT	$1.61 \cdot 10^{-3}$	10%
IT	$1.32 \cdot 10^{-3}$	25%

The outcomes obtained with the rem counter model are in great agreement with experimental measurements performed at CERF's facility, demonstrating excellent consistency despite the inevitable geometry approximations introduced by the Monte Carlo model of the detector.

5. Conclusion

In this study, the characterization of an extended-range rem counter was conducted. The assessment of the calibration factor and the detector's saturation limit was performed using experimental methods, while the evaluation of the response function utilized a Monte Carlo model implemented in FLUKA. Additionally, testing was conducted with intense mixed fields, exposing the detector to neutrons up to several GeVs.

At CMI, the detector's calibration factor was assessed at 1.25 ± 0.06 nSv/count, and a linearity test indicated a saturation limit of 2 mSv/h using an Am-Be source. Following this evaluation, the calibration factor was subsequently validated through irradiation conducted at CERN's calibration facility.

The experimental campaign carried out at CERF's facility indicated an underestimation of the detector's readings in complex neutron fields. This same discrepancy was confirmed through evaluation using the Monte Carlo model of the rem counter. These findings suggest that the detector, calibrated with an Am-Be source, underestimates the dose in the specified fields due to its response function.

The data assessed in this paper suggest that the rem counter is applicable for scenarios with both low neutron dose rates, such as ambient dose monitoring, and higher neutron dose rates, such as in beam loss monitoring.

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