




Effects of soil moisture variations on the neutron spectra measured above ground: feasibility of a soil moisture monitor system based on neutron moderating cylinders

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Abstract Mapping the soil moisture is a key activity in water management and sustainable agriculture, especially in regions characterised by fragile agri-food systems and water scarcity. Cosmic Ray Neutron Sensors (CRNS) is a contactless nuclear technology used for estimating soil moisture (SM) content on a 20–30 m scale at the landscape level. Very interestingly, this corresponds to the so-called intermediate scale gap between the local probes, operating on the meter scale, and the satellite-based technologies, working on the kilometre scale and above. In state-of-art CRNS, the cosmic neutrons degraded by the soil are simply counted by a slightly moderated thermal neutron counter. After a calibration procedure, the SM is inferred by combining this count rate with environmental parameters: the atmospheric pressure, temperature and the air humidity. As the SM affects not only the environmental neutron fluence rate but also its energy distribution, this study was organised in such a way to understand if a CRNS with spectrometric capabilities could provide improved information on the SM distribution. To this aim, an environmental neutron spectrometer was designed by extending the Bonner Spheres to a more sensitive system made of moderating cylinders embedding long BF₃ proportional counters, the Moderating Cylinders Spectrometer (MCS). Relying on literature environmental neutron spectra, corresponding to different SM values in a standardised soil, the count rates in the MCS were calculated for different values of SM. To simulate various counting scenarios, these count rates were associated to different levels of “realistic” uncertainties and unfolded by means of the FRUIT code. The resulting neutron spectra are compared to the literature ones, allowing at estimating the resolving power of the spectrometer in terms of SM.

1 Introduction

Established methods to determine the soil moisture are known to operate over very different distance scales [1, 2]: local probes work on the meter scale, whilst satellite-based technologies work on the kilometre and above. The so-called intermediate scale gap is, to date, only covered by the CRNS. The CRNS technique is recommended by IAEA as a crucial tool for sustainable agriculture as it is contactless, it allows a continuous monitoring, and its exploration radius is as large as 200–300 m [2]. The technique can be briefly described as follows. After reaching the earth ground, high-energy neutrons of cosmic origin lose their energy by interacting with the soil constituents, mainly carbon, oxygen and hydrogen. Particularly they are moderated by the hydrogen nuclei of the soil moisture. A fraction of these neutrons emerges to the air, scatters off the air nuclei and travels up to hundreds of metres before being absorbed. Thus, a localized neutron spectrum measurement at a point above ground is influenced by the soil moisture within a radius of influence of 200–300 m. As shown in the following, the 100 eV to 100 keV energy domain is the most affected by soil moisture. An epithermal detector, usually a single, slightly moderated, boron tri-fluoride (BF₃) or helium-3 (³He) proportional counter, is used to measure this component of the neutron spectrum. In principle, a whole neutron spectrometer could provide more accurate information than a single counter with no energy resolution.

To this aim, an environmental neutron spectrometer was designed by extending the Bonner Spheres concept [3] to a set of five moderating cylinders embedding long BF₃ proportional counters, the Moderating Cylinders Spectrometer (MCS). Its response matrix was calculated using MCNP6 [4] and applied to literature environmental neutron spectra calculated with different levels of soil moisture. This produced the “expected” MCS count rates corresponding to different levels of SM. Different levels of acquisition time were assumed to affect the expected MCS count rates and the following uncertainty ranges, namely: ± 1%, ± 3% and ± 5%. These ranges of uncertainty correspond to different counting times: roughly 70 h, 8 h and 3 h. These times are calculated considering a

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realistic total fluence rate of $2 \times 10^{-3} \text{ cm}^{-2} \cdot \text{s}^{-1}$ and a typical response value of $\sim 20 \text{ cm}^2$. These count rates and their uncertainties were unfolded by means of the FRUIT code [5–7] and the resulting spectra were compared to the reference ones, allowing to estimate the SM resolving power of the MCS in different workplace conditions. Other systematic effects existing in workplace would contribute to the total uncertainty budget, such as: day/night variations, presence of vegetation, air humidity and calibration procedure [8, 9]. Clearly, prior to applying this technique in a specific place, simulations will be needed to evaluate how variations of these parameters could affect the measured neutron spectra. As the purpose of this work is only to demonstrate the potentiality of neutron spectrometry in SM estimation, none of these environmental factors are here considered. In addition, the site where the MCS technique will be applied (Tabuk region, KSA) is arid, so it is expected that the impact of air humidity and vegetation will be limited.

2 Environmental neutron spectrum and soil moisture

The current CNRS method relies on a large thermal neutron counter surrounded by about 2.5 cm of polyethylene, providing a significant response from about 1 eV to about 100 keV. By contrast, environmental neutrons span in energy from thermal up to hundreds MeV. Relying on a semi-empirical approach and a complex calibration procedure [2], the volumetric soil moisture SM (%Vol) is derived from:

- The measured count rate;
- The count rate expected over entirely dry soil;
- Relevant factors of influence such as: the level of cosmic radiation impinging the upper atmosphere, the atmospheric pressure, temperature and the air humidity.

Elaborated from Ref. [1], Fig. 1 shows the simulated neutron spectrum at 2 m above the ground for different volumetric soil moisture conditions from 0% (entirely dry soil) to 100% (water body). Thermal neutrons are not transported, as they are not of interest for the soil moisture. The soil is assumed to be composed of silica and alumina in fixed proportions (3:1) plus a variable amount of water [1]. For a better readability, the total fluence rate in the entirely dry soil condition was fixed to $1 \text{ cm}^{-2} \cdot \text{s}^{-1}$. As expected, the presence of hydrogen from the soil humidity causes a decrease in total neutron fluence, so that the minimum in the fluence rate is obtained at $\text{SM} = 100\%$. It is also evident from literature [2], that the energy region from 1 eV to about 100 keV is the most indicated to infer the soil moisture from the neutron spectrum. Also, it appears to be easier to discriminate from different SM values when the soil is dry, as compared to a more humid scenario. As a relevant example, because of the spectra of Fig. 1, it seems easier to distinguishing the $\text{SM} = 0\%$ curve respect to the $\text{SM} = 0.8\%$ one, rather than the two $\text{SM} = 30\%$ and $\text{SM} = 38\%$ ones. Clearly, the neutron field is intricately linked to soil humidity, impacting not only the overall neutron flux but also influencing the energy distribution. Therefore, a spectrometric instrument is likely to exhibit larger descriptive capability compared with a single counter with no spectrometric capabilities. In Fig. 1 it can be noticed a high-energy structure in the hundred MeV region, due to the hadron cascade in atmosphere. This energy interval is of no interest for this work as it is not sensitive to soil moisture.

3 The moderating cylinders spectrometer (MCS)

The MCS environmental neutron spectrometer was designed as follows. The concept of Bonner Spheres [3] was extended [10] to a set of moderating cylinders embedding a commercially available cylindrical thermal neutron counter; the LND Model 20361 BF_3 proportional counter was chosen for this purpose. Its effective volume is 1581 cm^3 , the length about 80 cm and the diameter about 5 cm (<https://www.lndinc.com/products/neutron-detectors/25384/>). Figure 2 shows the MCNP geometry of the system, where the counter is surrounded in all directions by the same moderating thickness t of high-density polyethylene (density $\sim 0.94 \text{ g} \cdot \text{cm}^{-3}$). The neutron source was modelled as a disc of radius $R_{\text{Source}} = 50 \text{ cm}$ located at 15 cm from the detector.

As explained elsewhere [11], for moderation-based spectrometers such as the Bonner spheres there is no simple way to define the “energy resolution”, as every detector-moderator configuration responds to all neutron energies. In addition, the energy-dependent responses of different configurations show overlapping and similarities. The resolving power tends to improve in energy regions where the response functions shows larger different behaviour between each others [12]. In order to emphasise the resolving power of the spectrometer in the energy region from 1 eV to 100 keV, known to be the most sensitive to soil moisture, five values of t from 1 to 5 cm, in steps of 1 cm, were chosen. The resulting system was fully simulated using MCNP6 code from 1 meV to 100 MeV. The detector data-sheet was used as a reference for dimensions and materials. A total of 130 logarithmic equidistant energy bins were chosen for each configuration. The neutron source was modelled as a disc with the same diameter as the total length of the cylinder being irradiated, emitting a parallel neutron beam toward the detector. The ENDF/B VIII.0 nuclear data libraries [13] and its thermal neutron scattering kernel $S(\alpha, \beta)$ were also employed in all the calculations. The number of counts was assumed to coincide with the number of (n, α) capture reactions in the BF_3 . According to nominal detector data, the BF_3 density in the active volume was preliminarily fixed to $7.6 \times 10^{-3} \text{ g} \cdot \text{cm}^{-3}$. The simulated response matrix of the MCS (units: cm^2) is defined as the number of $(n,$

Fig. 1 Simulated neutron spectrum at 2 m above the ground for different volumetric soil moisture conditions from 0% (entirely dry soil) to 100% (water body) (data elaborated from Ref. [1])

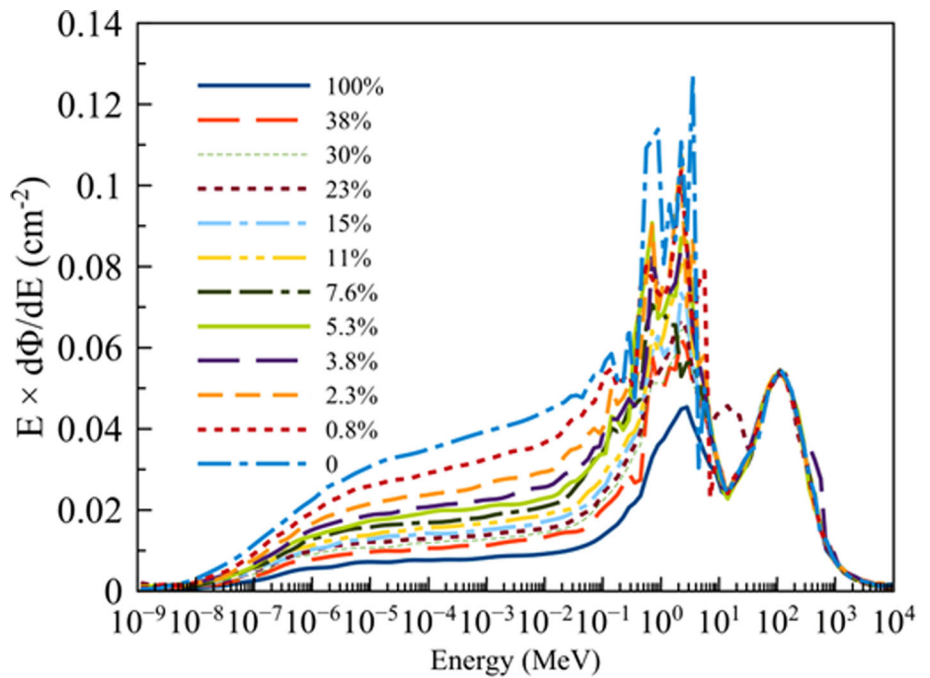
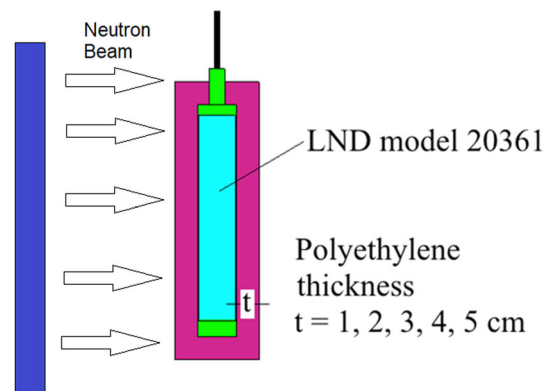


Fig. 2 Geometric model of the MCS in MCNP with the neutron source



α) reactions in the BF_3 counter per unit incident neutron fluence as a function of monoenergetic energy and moderating thickness t , see Fig. 3. The matrix is very similar to those of Bonner Spheres found in the literature [3, 10, 11].

Starting from the literature spectra presented in Fig. 1, the expected MCS count rates were obtained as follows:

$$C_i(SM) = \Phi \times \int_E R_i(E) \cdot \frac{d\varphi}{dE}(E, SM) dE. \tag{1}$$

Where:

- $C_i(SM)$ is the count rate in the i -th moderating cylinder as a function of the soil moisture;
- Φ is the total neutron fluence rate expected at the measurements place;
- $R_i(E)$ is the response matrix for the i -th moderating cylinder as a function of the energy.

As an example, the typical value $2 \times 10^{-3} \text{ cm}^{-2} \cdot \text{s}^{-1}$, derived for the Tabuk location using the EXPACS code [14], was assumed. $\frac{d\varphi(E, SM)}{dE}$ is the soil moisture dependent neutron spectrum shown in Fig. 1. The hydrogen from the soil humidity causes a decrease in total neutron fluence, a decrease is also observed in the MCS count rates. Different values of SM clearly produce different profiles in the count rates, see Fig. 4, but it appears easier to discriminate from different moisture values when the soil is dry.

Fig. 3 Simulated response matrix of the MCS, defined as the number of (n,α) reactions in the BF_3 counter per unit incident neutron fluence as a function of the monoenergetic energy and moderating thickness t

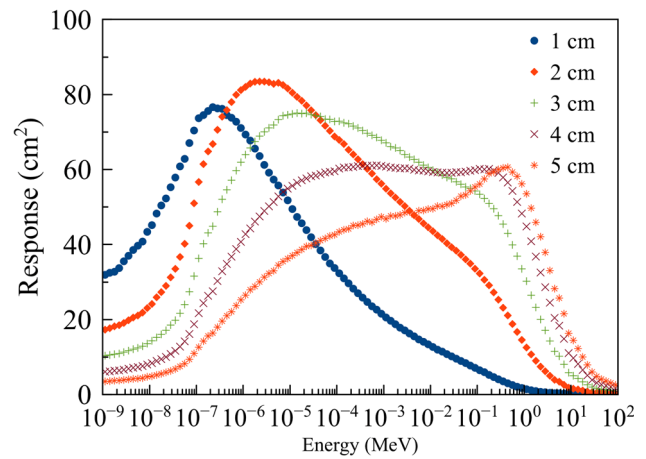
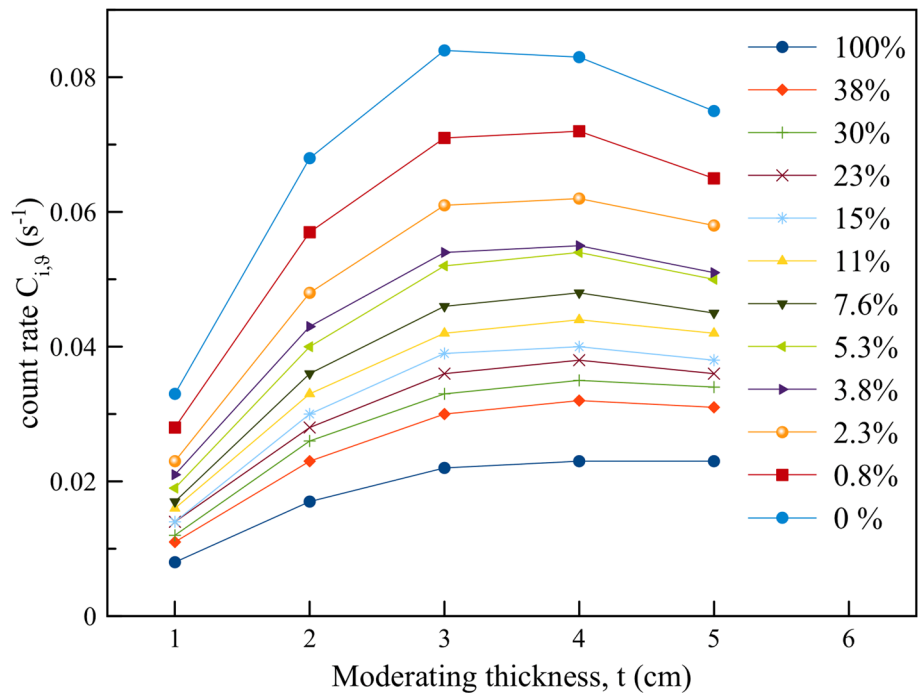


Fig. 4 Simulated count rates of the MCS as a function of the moderation thickness, t and the soil moisture, SM. A realistic total neutron fluence rate of $2 \times 10^{-3} \text{ cm}^{-2} \cdot \text{s}^{-1}$ was assumed



4 Unfolding analysis

MCS data derived for various SM values, together with realistic acquisition times, were unfolded using the FRUIT code [5–7]. As the soil moisture information is found in the energy interval from 1 eV to 0.1 MeV, the energy scale in the unfolding process was limited to 10 MeV. The unfolded spectra are compared to the reference ones from Fig. 1.

Three different levels of uncertainties in the counting rates were assumed, corresponding to different counting time: $\pm 1\%$ (counting time ≈ 3 days), $\pm 3\%$ (counting time ≈ 8 h) and $\pm 5\%$ (counting time ≈ 3 h). As it is assumed that the calibration of the MCS will take place directly “in the field” by recording spectral data under known conditions of SM, no other sources of uncertainty were considered.

For a better readability, the results of the unfolding sessions are organised in various different figures according to the scheme of Tables 1, 2, and 3 explained in the following:

- Column 1 indicates the reference SM value (Ref. SM). The spectrum corresponding to this SM value was applied to the MCS response matrix, see Eq. (1), to obtain the MCS counts;
- Column 2 (Guess SM) specifies the guess spectrum used for the unfolding session. Intentionally, the spectrum at a SM value very different from the reference one was used to initiate the unfolding. Using a “potentially misleading” guess spectrum is a way to check the robustness of the unfolding process;

Table 1 Results reporting for the uncertainty level $\pm 5\%$

Ref. SM (%)	Guess SM (%)	UI (%)
0	38	0–0.8
0.8	38	0–2.3
5.3	38	3.8–11
7.6	38	3.8–11
15	38	11–30
30	15	11–30

Table 2 Results reporting for the uncertainty level $\pm 3\%$

Ref. SM (%)	Guess SM (%)	UI (%)
0	38	0–0.8
0.8	38	0–0.8
5.3	38	5.3–11
7.6	38	5.3–11
15	38	15–30
30	38	15–30

Table 3 Results reporting for the uncertainty level $\pm 1\%$

Ref. SM (%)	Guess SM (%)	UI (%)
0	38	$\ll 0.8$
0.8	38	0.8
5.3	38	5.3–7.6
7.6	38	5.3–7.6
15	38	15–23
30	15	23–30

- For a given scenario, the unfolded spectrum is provided with uncertainty bars specified on a bin-per-bin basis. These bars visually identify a range of reference spectra, corresponding to a range of SM. This SM range is called “undetermined interval” UI (column 3). UI quantifies the resolving power of the system in terms of SM.

According to the reported results, distinguishing among different values of SM is much easier when the soil is very dry. This is true at any level of uncertainty/measurement time and the width of the UI is limited to few percent.

When the SM increases to 5.3% and 7.6%, the reference spectra tend to be similar in value and flat in shape. Consequently, low uncertainties ($\pm 1\%$ and $\pm 3\%$) are needed to keep the width of the UI lower than 5–6%.

For SM = 15% and SM = 30% the reference spectra are so similar and flattened that the resolving power of the MCS is minimal, and even with low uncertainties ($\pm 1\%$) the width of the UI is in the order of 10%.

Figures 5, 6, and 7 show the results for SM = 0.8%, while Figs. 8, 9, and 10 show for SM = 15%.

5 Conclusions

A computational study was performed to evaluate the convenience of extending the CRNS technique to an environmental neutron spectrometer composed of multiple moderating cylinders embedding a long BF_3 thermal neutron counter (MCS). An MCS was designed to describe the neutron energy distribution from thermal up to 10 MeV, covering the moisture-sensitive domain from 100 eV and 100 keV. The MCS response matrix was applied to literature simulated neutron spectra corresponding to different levels of SM, obtaining the “expected” MCS count rates. The effect of the counting time was included by assuming three levels of counting uncertainty: $\pm 1\%$, $\pm 3\%$ and $\pm 5\%$. These count rates, together with the response matrix and the uncertainties, were processed by the FRUIT unfolding code using non-specific pre-information. By comparing the unfolded spectra and associated uncertainties to the reference spectra, the capability of the MCS to distinguish among different levels of SM was studied (SM resolving power). As expected, distinguishing among different values of SM is much easier when the soil is very dry. This is true at any level of uncertainty/measurement time. When the SM increases the reference spectra tend to be similar in value and flat in shape. Consequently, low counting uncertainties ($\pm 1\%$ and $\pm 3\%$) are needed to achieve a good resolving power. For humid soils (SM = 30% and higher) the resolving power of the MCS is minimal, and even with very low counting uncertainties is difficult to discriminate among scenarios differing by less than 10% in terms of SM.

Fig. 5 The 0.8% SM unfolded cosmic neutron spectra compared to various reference one with an uncertainty of $\pm 5\%$

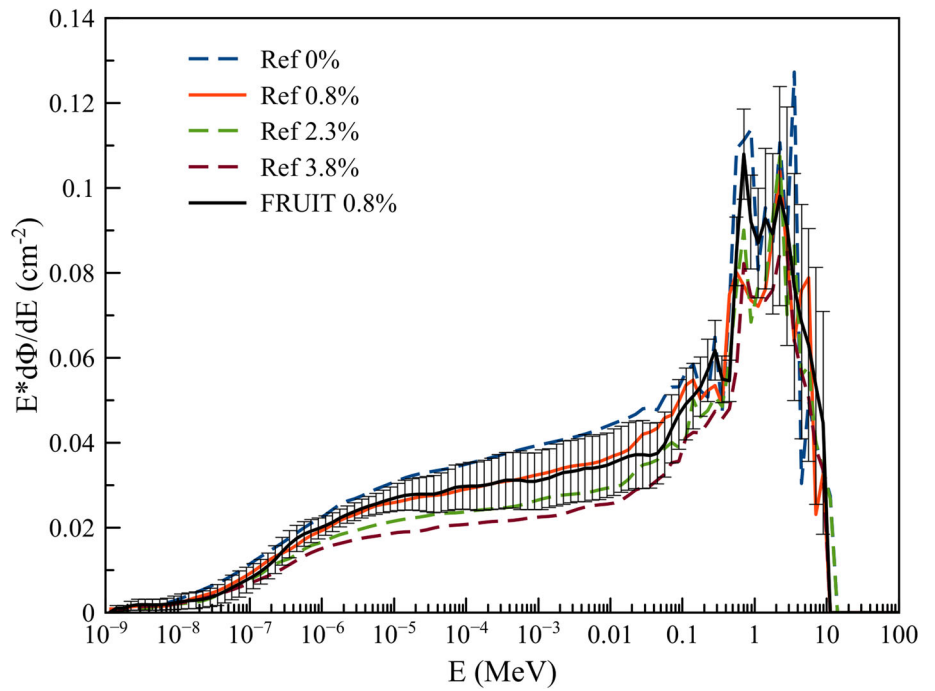
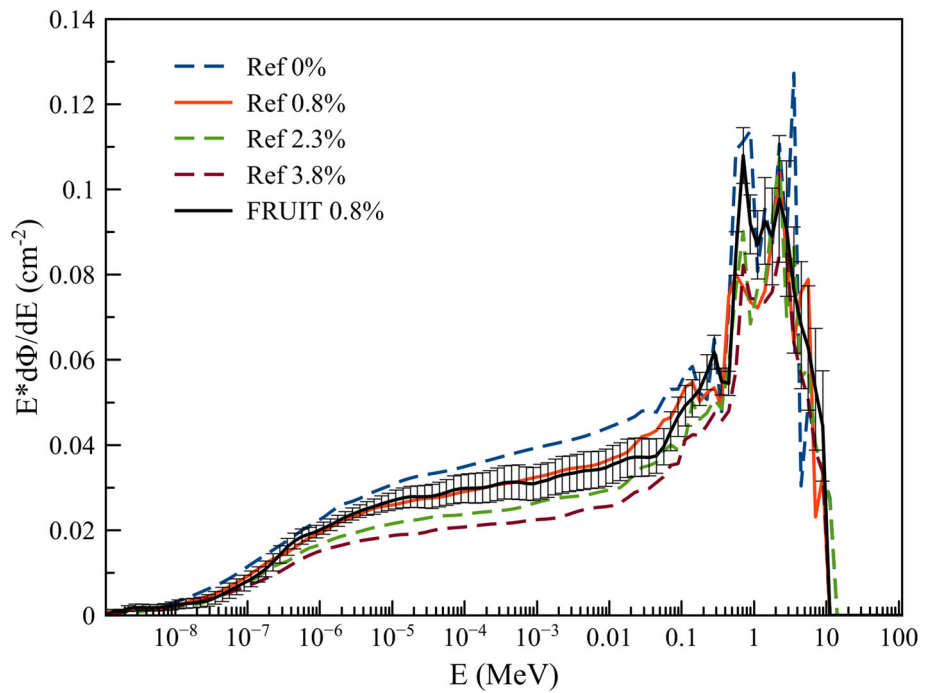


Fig. 6 The 0.8% SM unfolded cosmic neutron spectra compared to various reference one with an uncertainty of $\pm 3\%$



The method based on the MCS seems very promising especially for measuring in dry soils. In fact, a major application of this technique for the SM measurement, would be the SM determination in the Kingdom of Saudi Arabia (KSA). Soils in KSA are known to be very arid, with SM values usually below 1% [15].

Fig. 7 The 0.8% SM unfolded cosmic neutron spectra compared to various reference one with an uncertainty of $\pm 1\%$

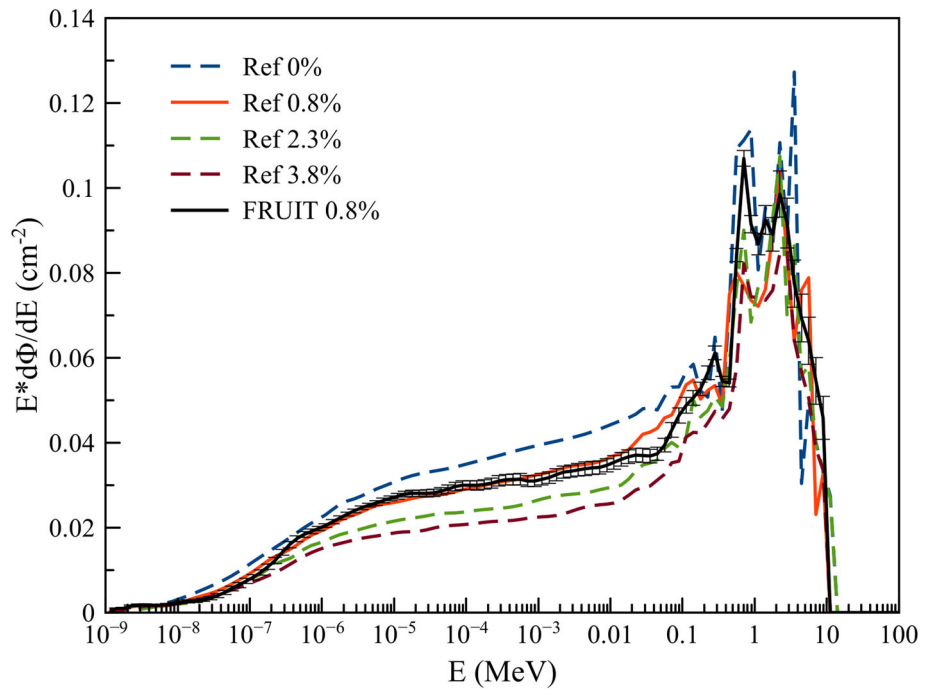


Fig. 8 The 15% SM unfolded cosmic neutron spectra compared to various reference one with an uncertainty of $\pm 5\%$

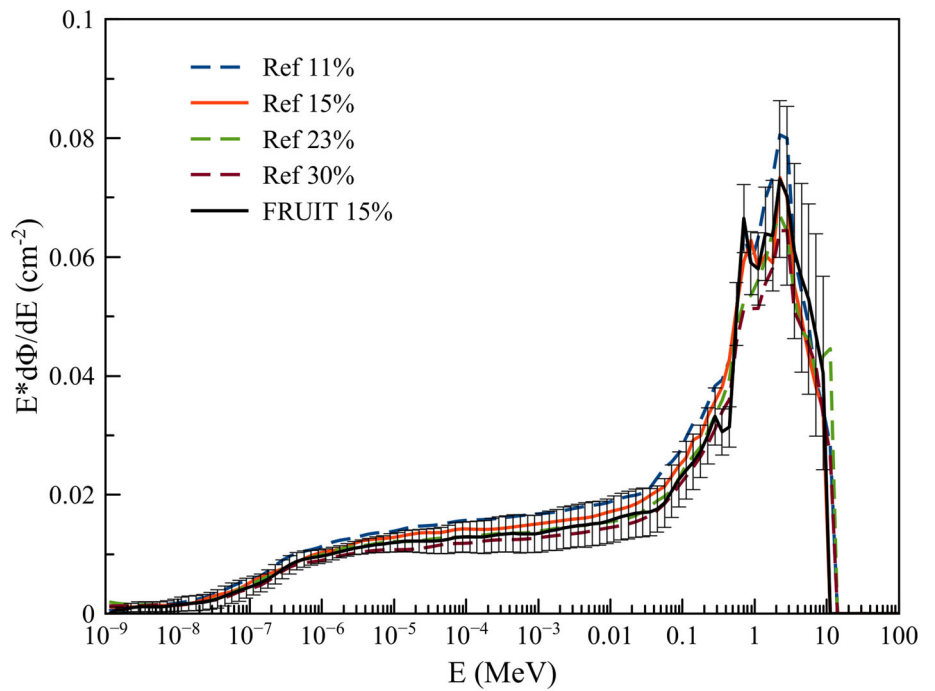


Fig. 9 The 15% SM unfolded cosmic neutron spectra compared to various reference one with an uncertainty of $\pm 3\%$

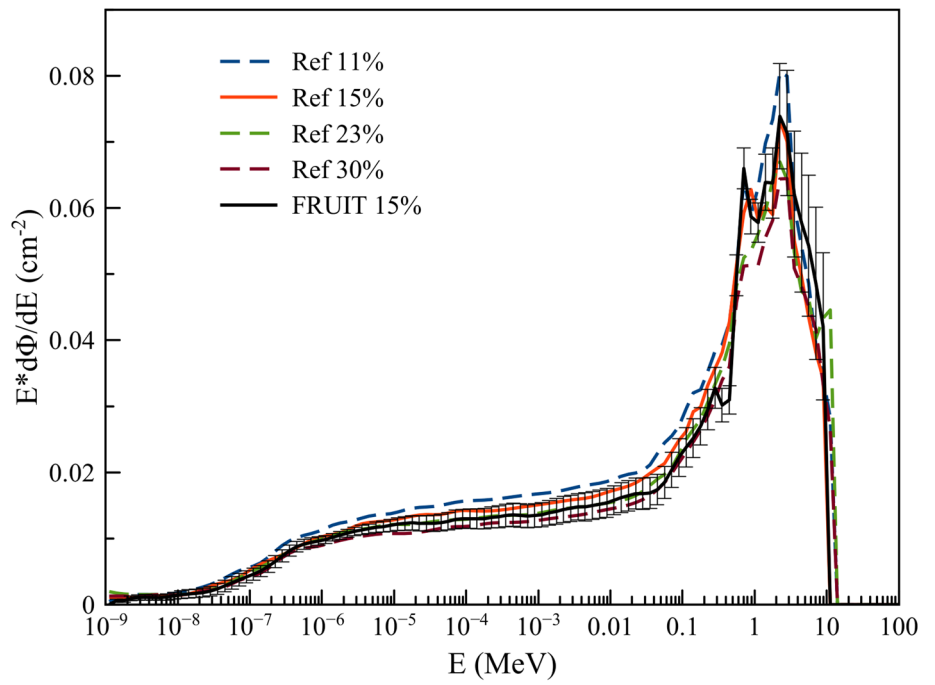
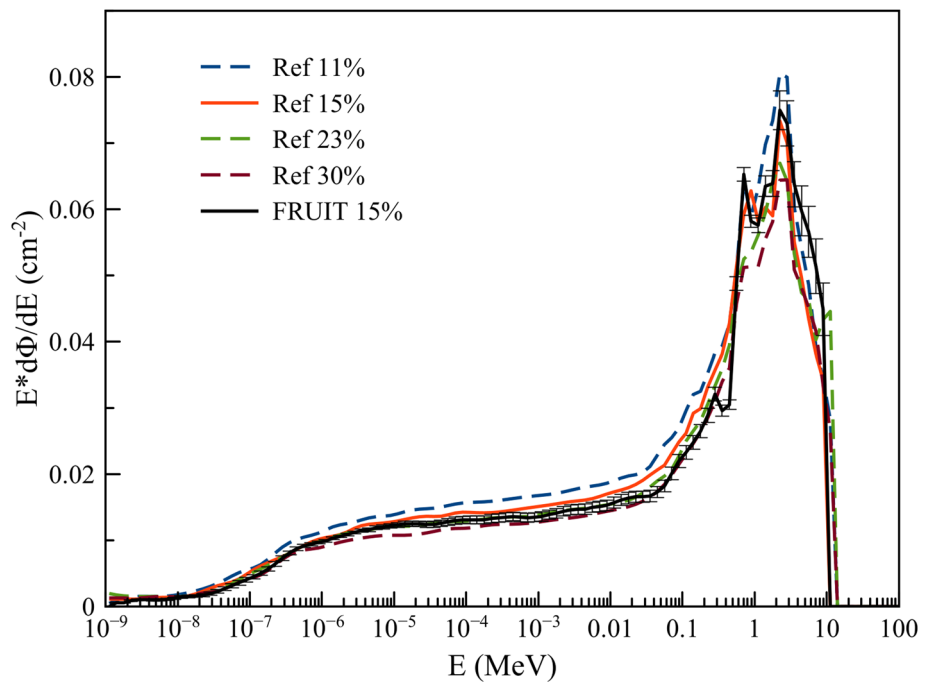


Fig. 10 The 15% SM unfolded cosmic neutron spectra compared to various reference one with an uncertainty of $\pm 1\%$



However, prior to its use in field, the system will need an in-situ calibration, where spectrometric data will be acquired under known conditions of SM. This experiment will also allow including aspects that were not treated here, such as the impact of the direction distribution of the environmental neutron field.

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Data Availability Statement The data sets generated during and/or analysed during the current study are available from the corresponding author on reasonable request. The manuscript has associated data in a data repository.

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