

Dear Editor,

We value the time and effort dedicated to reviewing our manuscript. We have carefully analyzed all comments and addressed them as thoroughly as possible.

However, we noted that several observations address aspects that fall outside the core metrological scope of our study. We gently suggest that the scope of our work’s focus—specifically, the physical characterization of the detector under controlled conditions—could have been more clearly delineated in our original draft.

There appears to be both a terminological and a philosophical gap between the two scientific communities addressed by our article. To address this and prevent any potential misunderstandings for the final readers, we have thoroughly updated the manuscript. All changes have already been made to the version submitted to Reviewer 1 and have been highlighted in red for clarity.

In particular, we have now introduced a completely new section (Section 5.2) to quantitatively demonstrate how validated response functions translate into soil moisture conversion curves. We consider these revisions significantly enhance the practical value of our work for the CRNS community.

Below, we provide a point-by-point response to each comment:

1. Limited Connection to Soil Moisture Applications: The manuscript is motivated by soil moisture monitoring, yet the study remains entirely focused on detector physics and neutron metrology. There is no quantitative demonstration of how the reported calibration factors ($S = 0.79\text{--}1.34$) influence soil moisture retrieval uncertainty, CRNS footprint estimation, or field- scale hydrological applications. The practical implications for CRNS users are therefore unclear.

Authors’ response: The present manuscript indeed focuses on the sensor technology for CRNS and was not the goal to propagate the detector efficiencies or correction factors into general soil-moisture retrieval procedures or footprint estimates.

A direct conversion to soil moisture uncertainty would generally not be possible without specifying a particular retrieval model, site calibration strategy, environmental corrections, etc. Beyond that, in standard CRNS applications, the detector efficiency is often ‘hidden’ in the site-specific calibration parameter. Therefore, the influence of a detector response correction on the final soil moisture measurement cannot be inferred from the detector correction factor alone.

While our primary focus continues firmly at the instrument characterization level, we have embraced this suggestion by showing how these validated response functions can support CRNS calibration methodology. We have revised the manuscript to include an entirely new section, **Section 5.2 (“Volumetric soil moisture retrieval from models”)**, in which we coupled our validated detector models with virtual environmental reference fields generated via URANOS across a soil moisture range of 1% to 50%.

We would like to point out that within CRNS research, many groups (still) rely on using the Desilets/N0 equation for soil moisture evaluations. This equation had been approximated without precise knowledge of the energy sensitivity of the instruments and had been revised by later publications. The current study confirms the assumptions of later publications for the UTS equation, but we intend to limit this study to the instrument level and do not intend to engage within CRNS methodology itself.

2. Calibration Reduced to Empirical Scaling Factors: The methodology relies heavily on applying a single global correction factor (S) to force agreement between simulations and observations. While this improves consistency, it does not identify the physical reasons for the discrepancies. The paper does not determine whether the bias originates from detector geometry simplifications, material properties, cross-section libraries, electronics, or environmental scattering.

Authors’ response: Although it is true that this aspect may have been addressed too briefly in the first version of the manuscript that was submitted, this specific issue was addressed and incorporated into the text during the review phase with Reviewer 1. Since we believe the changes made during that review already address the concerns raised in this comment, we have left the text we incorporated into the manuscript at that time in red in this version (currently in Section 6, Conclusions, lines 366–375).

Specifically, we discuss that the obtained scaling factors ($\bar{S}$) are entirely energy-independent, which strongly indicates that the main discrepancies stem from minor, physically inaccessible manufacturing tolerances inside commercial detectors, such as variations in the actual gas filling pressure of the physical tubes

compared to the nominal values provided by manufacturers or spatial inhomogeneities in the internal electric fields that define the effective "active volume" of the proportional counters.

Because isolating all these geometric and electronic parameters is practically impossible, the metrological consensus is to set a robust, traceable empirical scaling factor ($\bar{S}$) anchored to standard reference fields. This guarantees that the final response function is physically reliable for subsequent applications.

3. Lack of Independent Outdoor Validation: The validation is performed exclusively in laboratory reference fields. Since CRNS detectors operate in complex outdoor neutron environments, the manuscript does not demonstrate whether the corrected response functions remain valid under realistic field conditions involving vegetation, snow, atmospheric humidity, topography, or heterogeneous soils.

Authors' response: It is correct that outdoor measurements assess the performance of the CRNS soil-moisture retrieval, yet with many more variables and assumptions involved than just the response of the devices. The objective of the present study is to validate the detector models and calibration factors with characterized neutron reference fields. An outdoor comparison would not provide a validation of the detector response function alone, as the measured neutron intensity also depends on soil moisture heterogeneity, atmospheric humidity profiles, biomass water-equivalent distribution, partial topography, nearby structures, and usually the accuracy of the independent soil-moisture reference data. Many of these quantities are difficult to characterize with the required accuracy at the CRNS footprint scale. For example, in the literature, values for the said vegetation correction can be found that deviate by nearly 100 %. Under such conditions, discrepancies cannot be attributed to single variables. Ideally, it is necessary to investigate each parameter individually. This work focuses on testing the detector response under controlled conditions. In this way, the laboratory measurements provide an independent basis for validating outdoor CRNS measurements, not vice versa.

To date, there have been only two publications on the response functions of CRNS instruments, and the findings of this work largely align with previous work and now provide more detail. Furthermore, we would like to clarify that the response function is an independent technical feature of the sensor and does not depend on the aforementioned environmental conditions, except potentially on the temperature, which is not named here. For both manufacturers, the temperature drift of the signal energy measurement stays below 100 ppm/K (not shown).

4. Insufficient Description of Detector Models: A significant limitation is the lack of detailed detector geometry and electronics information due to manufacturer confidentiality. This prevents reproducibility and independent verification of the MCNP simulations. Readers cannot assess model completeness or replicate the study.

Authors' response: We agree partially with the reviewer. However, the said limitation does not apply to all detector systems investigated in this study. For the StyX Neutronica detectors, the detector geometry, materials, electronics, and PCB layout are documented in detail in the corresponding publications (The most recent and detailed reference regarding this matter has been included in the corresponding section: Köhli, M. and Weimar, J., Instruments, 10, 31, <https://doi.org/10.3390/instruments10020031>, 2026). For these detectors, the MCNP model can therefore be reconstructed and independently assessed at an unusually high level of detail for a commercial sensor.

For the other detectors, the geometry and materials can be assessed independently, and also the Reuter-Stokes proportional counter tubes used in these systems have documented characteristics. Some internal design details are subject to manufacturer confidentiality, though. Yet, we would also like to distinguish between the study's reproducibility and the independent verification of every proprietary detector detail. The experimental procedure, reference fields, simulation workflow, correction-factor determination, and comparison between measured and simulated responses are reproducible. What is limited for some of the detector systems is the independent verification of the entire detector model. This situation is, however, common when commercial sensors are evaluated, since full access to the design is typically not available to the user community.

5. Weak Validation Energy Range for CRNS Applications: The monoenergetic validation extends only from 24 keV to 5 MeV. However, cosmic-ray neutron spectra span a much broader energy range, extending into tens or hundreds of MeV. The manuscript does not sufficiently justify why validation in this restricted energy interval is adequate for environmental neutron sensing.

Authors’ response: This comment seems to arise from a potential misunderstanding regarding the operational energy range and the overall experimental methodology.

While the ambient cosmic-ray neutron spectrum does extend up to hundreds of MeV, the response function of the detectors is, by design, limited to the range of neutrons sensitive to the soil moisture, which spans roughly from 0.01 eV up to 10 MeV (as is shown in Figs. 2, 4 and 6), so this is the operational energy range needed to characterize the response functions. A detailed explanation of the reason for the characteristic shape of the response functions can be found in the reference Köhli, M., Schrön, M., and Schmidt, U. Nucl. Instrum. Methods Phys. Res. A, 902, 184–189, 2018.

Furthermore, the validation does not rely solely on monoenergetic neutrons. The validation has been performed using radionuclide sources at PTB and CIEMAT, covering the full energy range relevant for CRNS. Section 4 describes how the calibration measurements were performed with the radionuclide sources, and in Section 5, monoenergetic neutrons were used only for benchmarking to verify that the correction factors remain robust when applied to a completely different neutron field and experimental setup.

To preserve clarity for future readers and prevent potential misinterpretation, the relevant paragraph in the Introduction has been updated to remove ambiguity about the scope of these experimental phases and to explicitly clarify the complementary nature of the monoenergetic fields.

In addition, fields from radioactive sources, especially when the scattered component is included, as in this work, are the best candidates for this type of detector. The neutron fields at the irradiation position exhibit a characteristic structure with an evaporation peak, a continuum at low energies, and a thermal peak that covers the full energy range of interest for the CRNS response.

To clarify this point, Section 4 has been expanded to include a dedicated paragraph with the specific characteristics and provides a representative spectrum of these reference fields, alongside the response functions.

6. Large Background Contributions Reduce Confidence: The study reports that room-scattered neutrons contribute:

- 90–99% of counts for bare detectors,
- 50–70% for moderated detectors,
- $\sim 20\%$ for the S1 detector.

These very high background fractions indicate that the measured signal is dominated by scattered neutrons rather than direct beam neutrons, raising concerns about the robustness of the validation results.

Authors’ response: This comment rests on the same potential misunderstanding addressed in the previous comment. It might arise from confusing the two distinct experimental phases of our study, leading to a wrong conclusion about the robustness of our validation.

The high background fractions cited by the reviewer apply strictly to the monoenergetic fields experiments at the PIAF facility, not to the radionuclide reference fields. For radionuclide sources, which form the basis of our primary validation and the determination of $\bar{S}$ factors, the room-scatter component is not an unwanted background, as it is an intrinsic part of the reference field. This scatter component was simulated, characterized, and accounted for using our full-room MCNP models and does not compromise the validity of the calibration factors in any way.

Regarding the monoenergetic field experiments (used just as an independent reference to test the model’s predictive capability under entirely different conditions, as previously explained), the significant background contributions were explicitly addressed. In fact, reporting these high fractions explains precisely why it was not possible to extract useful experimental data for unmoderated detectors in this configuration. For the detectors from which data were successfully obtained, the uncertainties associated with background subtraction via the shadow-cone method were quantified and propagated into the presented error bars (as shown in Fig. 13). Despite these hard conditions, the tuned simulations reproduce the experimental points within those error bars, demonstrating their robustness.

Furthermore, far from undermining credibility, the quantification of these high background fractions represents one of the most significant results of this work. This campaign constitutes the first systematic

attempt to validate commercial CRNS detectors in metrological fields standardized in accordance with ISO norms. Establishing an effective metrological framework requires an assessment of the state-of-the-art and current technological limitations. This finding guides the scientific community toward necessary future steps (specifically, the design of specific reference fields tailored to large-area environmental sensors, as outlined in the conclusions). Consequently, this result is a necessary and valuable outcome of our research, and its inclusion reinforces, rather than diminishes, confidence in the presented work.

7. Uncertainty Analysis is Incomplete: The uncertainty treatment focuses mainly on counting statistics and source strength uncertainties. The manuscript lacks a comprehensive uncertainty budget that includes:

- *detector positioning errors,*
- *geometry simplifications,*
- *nuclear data uncertainties,*
- *room-return corrections,*
- *shadow-cone corrections,*
- *electronics dead-time effects.*

Such uncertainties could significantly affect the reported agreement.

Authors' response: We thank the referee for requesting a more explicit breakdown of the uncertainty budget.

The reported combined standard uncertainty for the scaling factor ($\bar{S}$) is a comprehensive combination of both experimental and simulation components:

- Experimental uncertainties: Including counting statistics, source emission rate, positioning errors (controlled within tight margins, adding $< 1\%$), and electronics/monitoring current stability (0.1% , which was found to be negligible). Dead-time effects were monitored and maintained below 1% due to the controlled flux of the reference fields. When it wasn't possible, the correction factor added a $2\text{-}4\%$ uncertainty.
- Monte Carlo (MC) statistical uncertainties: Kept below 2% across the simulation runs.
- Monte Carlo (MC) systematic uncertainties: Estimated at 5% independently by PTB and CIEMAT, which directly accounts for the level of geometric detail, material compositions, nominal density tolerances, and nuclear data.

However, the dominant uncertainty component for both models is the variation of the Si average, which is considered a systematic uncertainty as well, covering the following effects:

- Influence of the different selection of the irradiation conditions (sources, distances, sensor orientations, etc.) for the model validation
- Influence of the irradiation room description for the MC model

The dominant systematic component in determining $\bar{S}$ is, in fact, the dispersion of the individual S_i values across different irradiation configurations (varying sources, distances, background/room-return descriptions, and sensor orientations). This dispersion naturally envelopes the uncertainties associated with room scattering, shadow cones, and orientation geometries.

The uncertainty analysis was rather complex; there is partial overlap of the different uncertainty sources described above, and our goal was to simplify the description of the uncertainty budget of the ($\bar{S}$) to its main components in order to remain focused on the main goal of the paper.

To make this treatment fully transparent and directly address the referee's concern, we have explicitly expanded the text in lines 248-252 and 315-320 to detail these individual contributions.

8. Limited Scientific Advancement Beyond Calibration: The study mainly demonstrates that measured detector responses can be matched to simulations within 10–12%. While useful from a metrology perspective, the broader scientific advance is modest. The paper does not generate new physical insights into CRNS response mechanisms or improve existing soil moisture retrieval frameworks.

Authors’ response: Although we agree that it would have had a greater impact if our work had found significant deviations, the objective of the study was not to introduce a new soil-moisture retrieval function or CRNS corrections.

The scientific contribution of the work lies at the detector technology and metrology level. CRNS soil-moisture retrievals ultimately rely on neutron count rates from commercial detector systems, yet these detector responses had not previously been benchmarked at all with respect to their actual energy sensitivity. The present work provides such data, tests the detector models in independent neutron reference fields, and quantifies the experimental limitations. Hence, we assess how accurately current detector models can reproduce measured responses under reference conditions.

Nevertheless, while our primary focus is the physical validation of the detectors, we have now fully addressed this comment by adding the already mentioned new section: **Section 5.2 (“Volumetric soil moisture retrieval from models”)**.

In this new section, we coupled our validated MCNP detector models with virtual environmental reference fields generated via URANOS to show how the predicted soil moisture response curves for all three characterized devices agree with the modern Universal Transport Solution (UTS) model and to provide a practical, mathematically simple two-parameter power-law conversion function to directly assist CRNS end-users in retrieving soil moisture from normalized count rates.

We believe this new addition successfully bridges the gap between laboratory metrology and environmental hydrology, providing clear and practical implications for CRNS users.

9. Environmental Sensitivity Not Quantified: The authors repeatedly state that the validated models can be used to study environmental influences such as:

- *buildings,*
- *snow,*
- *water bodies,*
- *vegetation.*

However, no sensitivity experiments are actually presented. Including a few representative simulations would significantly strengthen the manuscript and demonstrate the utility of the validated models.

Authors’ response: We agree with the reviewer’s view that the results will finally translate into improvements in CRNS applications. However, the mentioned experiments address a different level of the CRNS measurement chain than the present work. The objective of this manuscript is to characterize the detector models themselves under controlled neutron reference fields. As mentioned above, effects such as the named buildings, snow, water bodies, vegetation, soil heterogeneity, and topography primarily target environmental neutron transport and require assumptions about site geometry, hydrogen pools, biomass, etc. Hence, including a few selected simulations would not provide a general validation of these effects, but would introduce additional scenario-dependent assumptions and would be out of scope. Yet, we would like to emphasize that the current work is the main step now to go forward and address in more detail the signal response to the said effects once one has a comprehensive picture of the detector response. The newly introduced section **Section 5.2 (“Volumetric soil moisture retrieval from models”)** demonstrates how such studies can be done.

We have clarified the wording to avoid implying that such effects are quantified here.

10. Conclusions Overstate Readiness for Calibration Frameworks: The manuscript concludes that the work is a key step toward SI-traceable calibration frameworks. However, the study itself identifies several unresolved limitations:

- *large room-return contributions,*
- *inability to characterize bare detectors in monoenergetic fields,*
- *dependence on empirical correction factors,*
- *lack of dedicated CRNS calibration facilities.*

Therefore, the conclusions should be more cautious and emphasize that this work is a preliminary validation rather than a complete calibration framework.

Authors' response: We agree that the conclusions should present the objectives and distinguish between the metrological benchmark and a complete calibration framework from the CRNS point of view.

However, we would like to respectfully point out that the manuscript was never intended to claim a fully finalized framework, but rather a foundational first step, as already stated in the conclusions in lines 360-363 and 405-407 (lines 292-294 and 316-318 in the original submitted version).

We consider these original statements already conveyed the exact level of caution requested by the referee. Nevertheless, to prevent potential misinterpretation by future readers, the wording throughout the manuscript was adjusted to further emphasize the preliminary, exploratory nature of this initial benchmark campaign.

That being said, we would like to clarify why some of the specific limitations listed by the referee do not affect the main results in the way implied:

The large room-return contributions were not expected beforehand but resulted from large-area CRNS detectors intentionally designed to be highly sensitive to moderated and low-energy neutrons in relatively small rooms. Although this certainly translates to limitations for CRNS in current calibration facilities and the operationalization of the method used in this work on a large scale, it also opens the perspective for effective calibration strategies.

However, we would like to emphasize that these background fractions are not an indication of a not well-characterized irradiation field. The room contributions are understood, but inconvenient for streamlining calibration measurements for such large devices. Hence, the research should focus on identifying more efficient ways to characterize CRNS devices.

In the case of the bare tubes and the monoenergetic fields, from the response functions we were fully aware that applying narrow, monoenergetic fast-neutron reference fields meant probing a region of very low detector sensitivity. For this reason, as stated earlier, monoenergetic fields were not chosen to calibrate the tubes, but only to benchmark them. Bare tubes were, in fact, successfully calibrated in the radionuclide reference fields alongside the moderated ones, and benchmarking against independent fields was also demonstrated (e.g., the purple data points for CIEMAT irradiations in Fig. 13).

Response characterization of Cosmic-Ray Neutron Sensors in neutron metrology reference fields

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Abstract. Soil moisture is recognized as an Essential Climate Variable (ECV) by the World Meteorological Organization (WMO), as it plays a key role in hydrology, agriculture, and climate by regulating land–atmosphere interactions such as evapotranspiration, groundwater recharge, and surface runoff. Existing monitoring methods operate at different spatial and temporal scales, and despite the importance of soil moisture data, they remain poorly harmonized, leading to inconsistencies among datasets. The SoMMet (Soil Moisture Metrology) project addresses this need by developing robust metrological tools to ensure consistent and comparable soil moisture observations.

Within this framework, the neutron response functions of commercial Cosmic Ray Neutron Sensing (CRNS) detectors (Hydroinnova CRS1000, Hydroinnova CRS2000/B, and StyX Neutronica S1) were characterized in radionuclide-based neutron reference fields (^{252}Cf , moderated ^{252}Cf , and $^{241}\text{Am-Be}$), covering the full energy range relevant to CRNS applications. The experimental campaign was carried out at two neutron metrology laboratories: PTB (Physikalisch-Technische Bundesanstalt, Germany) and CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Spain). Monte Carlo simulations of the detector response were performed using MCNP and adjusted based on experimental data obtained at both facilities.

Independent validations were conducted using experimental data from radionuclide reference sources at both PTB and CIEMAT, complemented by data from monoenergetic neutron fields (from 24 keV to 5 MeV) at PTB. The agreement between the experimental data and the simulations was within 12 % for all validation measurements.

These results provide the first benchmark data for CRNS detector models under reference conditions, representing a **contributing to ongoing efforts toward** establishing robust SI-traceable calibration frameworks and harmonized deployment in soil moisture monitoring applications.

1 Introduction

Soil moisture strongly influences hydrological cycles, agricultural productivity, and land–atmosphere interactions. Its monitoring is therefore critical for climate change impact and adaptation strategies, weather predictions, and applications such as climate-smart agriculture, flood and drought forecasting, or water resources management (Vereecken et al., 2008). Recognizing this importance, the World Meteorological Organization (WMO) includes soil moisture among its Essential Climate Variables (ECVs) (WMO, UNEP, ISC, IOC-UNESCO, 2022).

Due to its important role, different methods have been developed for monitoring and measuring soil moisture at various spatial and temporal scales. Point-scale sensors are commonly used in agriculture and hydrology. These devices, installed at different depths, provide local information of water content that is not representative of large areas and therefore require dense networks or interpolation methods (Famiglietti et al., 2008), limiting their utility in atmospheric and land-surface applications. On the other hand, satellite-based remote sensing can provide spatially extensive data products (Manakos and Lavender, 2014), but only for surface moisture, and are affected by limitations such as coarse resolution in the kilometer range, lack of depth sensitivity, and disturbances due to vegetation, snow cover, or surface roughness (Wang and Qu, 2009).

In this context, intermediate-scale soil moisture measurement methods such as Cosmic-Ray Neutron Sensing (CRNS) (Zreda et al., 2008; Köhli, 2026) provide an observational scale that complements ground-based sensors and satellite missions (Robinson et al., 2008), offering spatial footprints in the hectometer range while retaining sensitivity to subsurface soil moisture (Schrön et al., 2017). It is non-invasive and less sensitive to soil heterogeneity (Köhli et al., 2015), surface roughness, or vegetation (Desilets et al., 2010).

CRNS monitors soil moisture dynamics by detecting variations in the flux of epithermal albedo neutrons (from tens of meV up to about 1 MeV) resulting from the interaction of cosmic-ray-induced neutrons with the soil. These neutrons are moderated by hydrogen atoms in the soil, primarily from water molecules (Desilets et al., 2010), and their intensity is inversely correlated with soil moisture content (Köhli et al., 2021). CRNS detectors are designed to maximize efficiency in this energy range, typically incorporating large active volumes and hydrogenous moderators (Köhli et al., 2018), to increase the neutron detection efficiency for the comparably low neutron fluxes typically encountered in field measurements or in natural settings.

CRNS devices are currently deployed in multiple monitoring networks, such as the COSMOS-UK (Bogena et al., 2022) and ADAPTER (Ney et al., 2021) networks. Despite the growing deployment of CRNS devices, systematic metrological standards and traceable calibration procedures remain underdeveloped. In particular, **while quantifying the impact of site-specific environmental conditions (e.g., soil type, humidity, temperature) is crucial to achieve reliable and comparable soil moisture estimates, this task first requires a precise and traceable characterization of the detector’s fundamental response function (to neutron radiation) under controlled laboratory conditions. This work focuses on establishing this essential metrological foundation, and indispensable prerequisite for reliably simulating or quantifying any subsequent environmental or situational scaling.**

The present work is carried out within the framework of the European project SoMMet (Soil Moisture Metrology) (Zboril et al., 2025), funded under the European Partnership on Metrology of EURAMET. The initiative addresses the current lack of

55 standardized approaches in soil moisture monitoring by providing a coordinated framework where different techniques and methods can be assessed, compared, and linked to metrological standards.

As part of the SoMMet project, a set of state-of-the-art commercial CRNS detectors has been experimentally characterized in neutron reference fields based on radionuclide sources (^{252}Cf , moderated ^{252}Cf , and $^{241}\text{Am-Be}$), covering the full energy range relevant for CRNS. The experimental campaign was carried out at two neutron metrology laboratories: PTB (Physikalisch-
60 Technische Bundesanstalt, Germany), a national metrology institute, and CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Spain), a designated institute for neutron measurements. The response functions of the detectors were obtained using Monte Carlo simulations with the MCNP code and adjusted based on the experimental data acquired at both laboratories. In addition, to verify the performance of the adjusted simulation model and correction methods, an independent benchmarking campaign was performed using monoenergetic neutron reference fields at PTB. These comple-
65 mentary fields, covering neutron energies from 24 keV to 5 MeV, are traceable to primary neutron metrology standards (Nolte and Thomas, 2011a, b), and serve as a cross-check for the calibration factors derived from the radionuclide spectra.

The present work focuses on the characterization of commercial CRNS detectors that utilize gas-based neutron counters (^3He , $^{10}\text{BF}_3$, and ^{10}B -coated proportional counters). Within the broader SoMMet project, a parallel study details the characterization of a CRNS detector employing a scintillation-based detection principle (commercialized as Finapp Model 3) (Vykydal et al.,
70 2025).

2 CRNS devices

CRNS devices used for soil moisture monitoring are based on conventional thermal neutron detectors, typically gaseous proportional counters (Kleinknecht, 1982) filled with ^3He or $^{10}\text{BF}_3$ as the active medium (Knoll, 1979). In this experimental campaign, a boron-lined CRNS detector (Weimar et al., 2020) was also tested.

75 All of the devices investigated in this study are commercially available and incorporate integrated electronics and acquisition systems. Each provides a user interface that outputs the number of neutron counts over a selected time interval, along with relevant environmental parameters such as temperature, atmospheric pressure, and humidity, as well as diagnostic variables.

The list of devices tested during this experimental campaign is detailed below. Due to the commercial nature of these systems, additional details concerning internal geometry, data processing, or design cannot be disclosed:

- 80 – **CRS1000** from Hydroinnova LLC (USA): Contains two ^3He detectors, one bare and one moderated using a high-density polyethylene (HDPE) casing, housed in a weatherproof metallic box that integrates all electronics and support systems. The external dimensions are $33 \times 20 \times 81 \text{ cm}^3$ (Fig. 7 (top)).
- **CRS2000/B** from Hydroinnova LLC (USA): Comprises two $^{10}\text{BF}_3$ detectors, one bare and one moderated with HDPE, each enclosed in separate weatherproof cylindrical housings. The detectors can be mounted together using a dedicated
85 holder or operated independently. Each tube is 122 cm long and 14 cm in diameter (Fig. 3).

- **System S1** from StyX Neutronica GmbH (Germany): Comprises a single gas detector with a ^{10}B -coated conversion layer, moderated by HDPE, which serves as the detector housing. Additionally, it comes with a gadolinium thermal-neutron shield. The unit is 154 cm long and 18 cm in diameter (Fig. 7 (bottom)).

All systems come with their own frontend and readout electronics, which for the StyX Neutronica system is documented (Köhli et al., 2024), for the CRS series see Zreda et al. (2012).

The characterization measurements were performed at the neutron metrology laboratories of PTB and CIEMAT. The devices were distributed between the two facilities to allow for complementary measurements, taking advantage of their respective infrastructure and expertise.

The CRNS devices were irradiated in different orientations depending on the specific geometry of each unit. All measurements were performed using the standard configuration of the device, with the center of the irradiated surface aligned along the source-to-detector axis using laser guides. Acquisition times were adjusted to ensure sufficient statistical significance in the neutron count rates.

Due to the low neutron flux in outdoor environments, CRNS detectors are typically large to maximize sensitivity. However, this high sensitivity also limits the maximum fluence rate that can be processed without pile-up, saturation effects, or electronic instabilities. In the case of the System S1, the original electronics saturated at around 20 counts-per-second (cps) for raw data transmission, an issue that was overcome by using an external multichannel analyzer (MCA). For the CRS1000 detector, where external electronic coupling was not possible, the counting rate was kept below 300 cps, a regime in which no significant loss of linearity was observed. In the case of the CRS2000/B, counting rates exceeding 300 cps were measured, and potential signal losses were compensated for using correction factors.

3 Monte Carlo simulations

The three detectors studied, CRS1000, CRS2000/B and S1 have been simulated with MCNP6 (Version 6.1.0. Pelowitz et al. (2013), for S1 and CRS1000; and version 6.2.0. Werner et al. (2018), for the CRS2000/B). In each case, the neutron response for a specific energy range E_j is defined as:

$$R_{\text{MC}}(E_j)[\text{cm}^2] = \frac{M_{\text{MC}}(E_j)}{\phi_{\text{MC}}(E_j)}, \quad (1)$$

where $M_{\text{MC}}(E_j)$ is the number of simulated neutron reactions in the detector gas and $\phi_{\text{MC}}(E_j)$ is the neutron fluence (in the unit of number of neutrons per cm^2) over the detectors's face of interest.

In all cases, the response function was simulated using a plane-parallel, monoenergetic neutron source incident perpendicularly on each face of interest, with energies ranging from the thermal neutron range up to 100 MeV and the number of reactions produced in each material has been simulated making use of the tally F4 and a multiplier FM to take into account the appropriate

neutron reaction. ENDF/B-VIII.0 cross section library (Brown et al., 2018) and $S(\alpha, \beta)$ treatment of low energy neutrons for polyethylene have been used. Each model is described in the next paragraphs. Due to manufacturer confidentiality, detailed specifications of the detector are not disclosed.

3.1 CRS1000 model

120 The CRS1000 consists of two ^3He proportional counter detectors, each 2 inches (5.08 cm) in diameter and 33.9 cm in length: one moderated by 2.5 cm of high-density polyethylene (HDPE) and one left bare. In the simulations, the device was modeled as a single probe with two readouts.

To characterize the device's intrinsic angular response, the MCNP model was held in a fixed orientation. The response function was then calculated by simulating a planar neutron source irradiating each of the principal faces of its aluminum housing ($33.0 \times 19.7 \times 81.4 \text{ cm}^3$) independently: side 1 (facing the moderated detector), side 2 (facing the bare detector), the front (the largest surface, perpendicular to both detectors), and the top and bottom faces (parallel to both detectors and facing the smaller detector surfaces).

The resulting count rates were calculated for each detector, without separating the contributions from neutrons scattered within the detector assembly (internal scattering). The output of each detector was defined as the number of neutron reactions
130 occurring within the active volume. The geometry used in the simulations and the irradiation directions are shown in Fig. 1. The results are shown in Fig. 2.

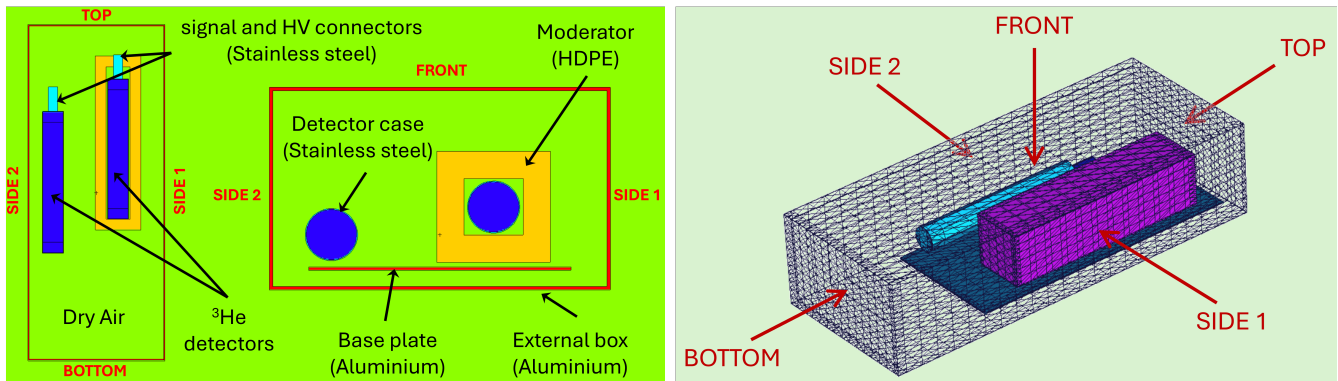


Figure 1. MCNP model of the CRS1000 device. The irradiation directions for the five relevant sides are indicated in the image at the right.

The moderated detector exhibits a nearly flat response across the energy range of interest (1 eV to 1 MeV), whereas the bare detector is primarily sensitive to thermal neutrons. As expected, the detectors exhibit anisotropic behavior, with significant differences in response depending on the direction of irradiation. The shape of the simulated responses is consistent with
135 previous data reported in the literature, as shown in Fig. 2, which includes the response curves published by Köhli et al. (2018) using the URANOS code (Köhli et al., 2023).

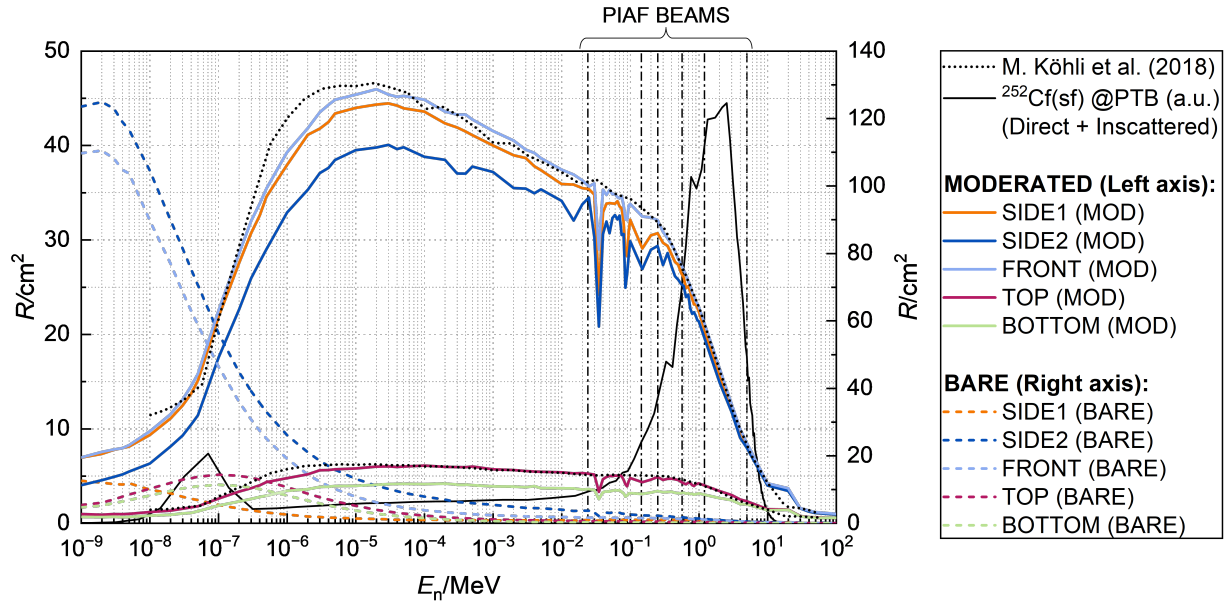


Figure 2. Example of the response functions calculated for the CRS1000 device for both internal detectors (moderated detector shown with solid lines, bare detector with dashed lines) and for all irradiation directions. These responses correspond to the MCNP model. **The solid black line represents the neutron energy spectrum produced by the spontaneous fission (sf) of the $^{252}\text{Cf(sf)}$ source used at PTB as one of the neutron reference fields for validating the response functions. The depicted spectrum includes the in-scattered neutron component covering the low neutron energies relevant for the CRNS methodology. The vertical dashed black lines indicate the monoenergetic energies used for benchmarking.** The dotted black lines represent the response functions reported by Köhli et al. (2018), calculated using the URANOS code and scaled by an arbitrary factor.

3.2 CRS2000/B model

The CRS2000/B system comprises two cylindrical detectors, as shown in Fig. 3, one of which is moderated by HDPE and the other is bare. In the definition of this device, we can distinguish between the tube, with an external length of 122 cm, a diameter of 14 cm; and the internal $^{10}\text{BF}_3$ detector with a length of 85.4 cm and a diameter of 7.6 cm. HDPE surrounds this detector for the moderated tube and by air in the bare tube.

Each tube has been simulated in a vacuum and irradiated only in two geometries, vertical and aligned, considering its cylindrical symmetry. In the vertical geometry, the direction of the incident neutrons is perpendicular to the tube axis, and in the aligned geometry, this direction is aligned with the tube axis. The response functions obtained for both detectors in the two geometries are shown in Fig. 3.

As in the previous model for CRS1000 the moderated detectors exhibit a nearly flat response across the energy range of interest, whereas the bare detectors are primarily sensitive to thermal neutrons for both geometries, vertical and aligned, being much more sensitive for the first one, where a larger cross-sectional area is shown to neutrons, than for the aligned geometry (see Fig. 4).

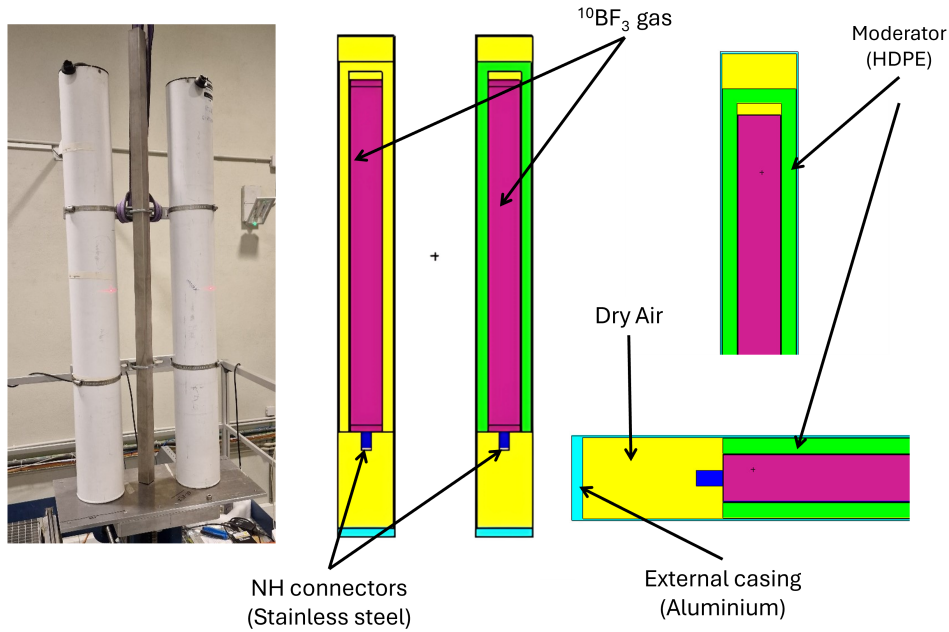


Figure 3. Picture of the CRS2000/B device and MCNP model. For both detectors, bare and moderated, only vertical and aligned directions are considered.

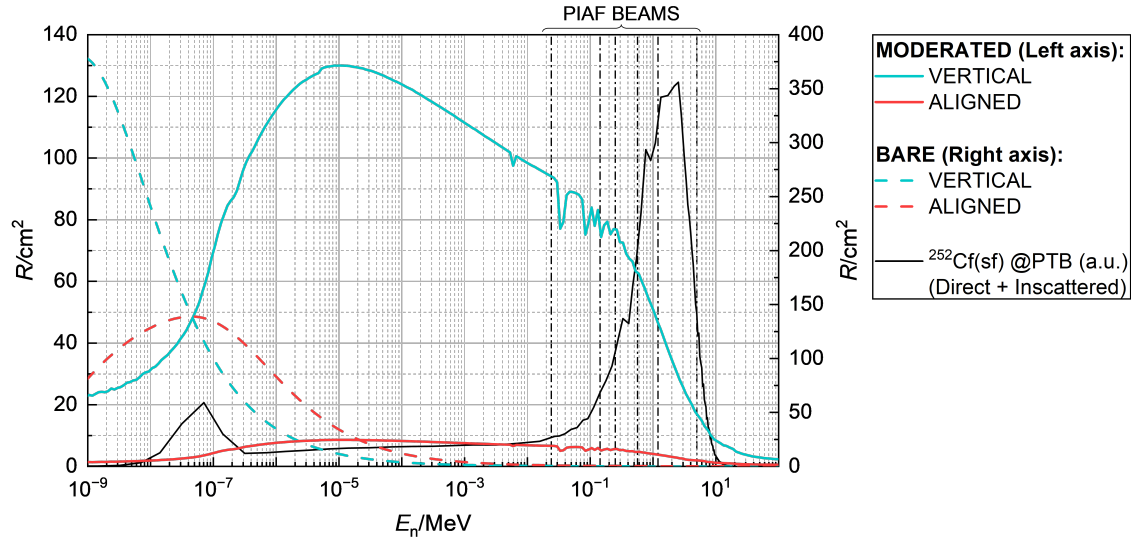


Figure 4. Simulated CRS2000/B bare and moderated detector response functions for both irradiation geometries. As shown in Figure 2, black lines (solid and dashed) represent some of the reference fields used during the experimental campaigns for illustrative purposes.

3.3 System S1 model

The S1 detector is a boron-lined proportional counter of 125 cm long and 5.6 cm diameter embedded in a 2.5 cm thickness high-density polyethylene (HDPE) moderator to thermalize incoming neutrons, [see also Köhli and Weimar \(2026\)](#). Additionally, the inner surface of the detector case is coated with a thin gadolinium oxide layer, which provides further shielding by capturing thermal neutrons and reducing the background from scattered low-energy neutrons. The external dimension of the device, 18 cm diameter and 154 cm length, is mostly due to the external moderator dimensions. The geometry implemented in the simulation is shown in Fig. 5.

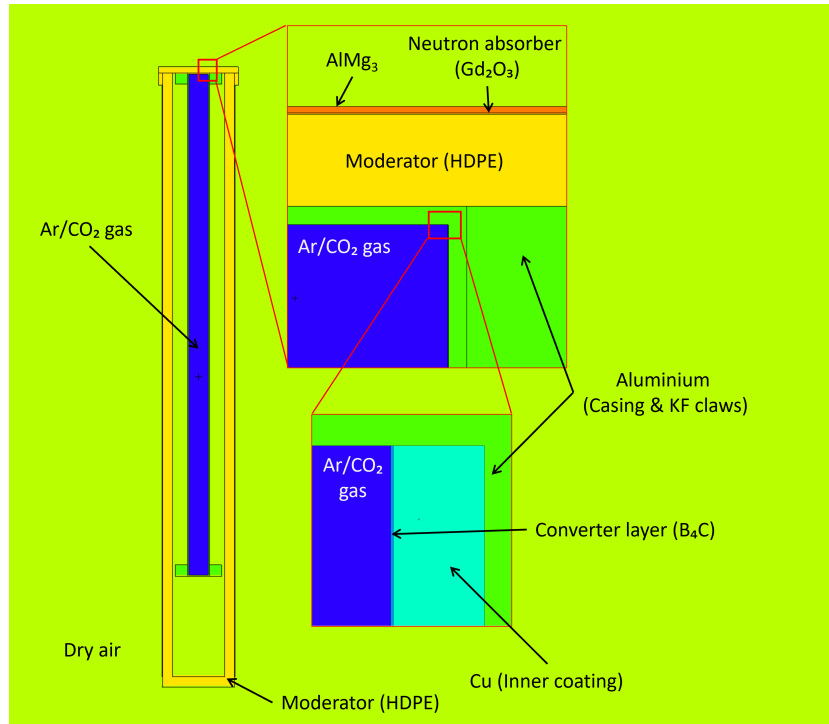


Figure 5. MCNP model of the S1 system detector. The layered structure is illustrative and not to scale.

Two irradiation geometries were considered: with the neutron field perpendicular to the detector's axis (vertical configuration) and parallel to it (aligned configuration), as is shown in Fig. 6. Compared to the CRS1000 and CRS2000/B detectors (see Fig. 2 and 3), the S1 system shows a sharper decrease of the response in the thermal energy region, due to the presence of an additional gadolinium (Gd₂O₃) layer.

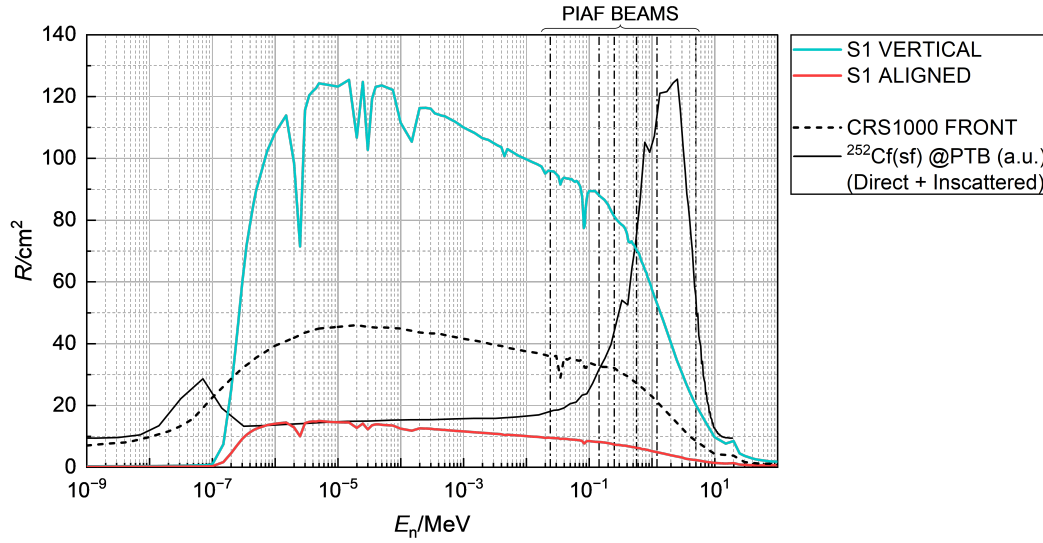


Figure 6. Simulated S1 detector response functions for both irradiation geometries, with the CRS1000 response under FRONT irradiation included for qualitative comparison. The picture also includes an illustrative representation of some of the reference fields used during the experimental campaigns, as shown in Figure 2 (solid and dashed black lines).

4 Irradiations at the radionuclide reference fields: validation of the MC models

Radionuclide-based reference fields were selected as primary experimental validation for the detector models, as the characteristics of their spectra, especially when the scattered component is included, are highly suitable for CRNS applications.

The continuous energy distribution from radionuclides shows an evaporation peak, a low-energy continuum, and a thermal peak, mirroring the main characteristics of the cosmic-ray neutron spectrum encountered above the soil profile in the energy range where the detectors' response functions are relevant. By way of illustration, one of these fields, corresponding to the irradiations at 170 cm with the $^{252}\text{Cf(sf)}$ source at the PTB, is included alongside the response functions in the Figures 2, 4, and 6.

4.1 Experimental setup at the radionuclide reference fields at PTB

At PTB, calibration measurements were performed for the CRS1000 and System S1 devices using well-characterized radionuclide neutron sources: $^{252}\text{Cf(sf)}$, $^{252}\text{Cf(sf)}$ with a D_2O moderator sphere of 15 cm radius and a 1 mm Cd hemispherical filter covering the side of the sphere facing the detector (neutron emission rate $B = (8.49 \pm 0.06) \cdot 10^4 \text{ s}^{-1}$, same source with and without the moderator sphere), and $^{241}\text{Am-Be}(\alpha, n)$ ($B = (2.92 \pm 0.07) \cdot 10^6 \text{ s}^{-1}$). These sources are installed in a dedicated irradiation facility at PTB, with internal dimensions of $7 \text{ m} \times 7 \text{ m} \times 6.5 \text{ m}$ (Kluge, 1998). The walls and ceiling are made of 1 m thick reinforced concrete. The irradiation geometry allows for remote source positioning and automated control of detector distances. During measurements, the sources were suspended near the geometrical center of the room.

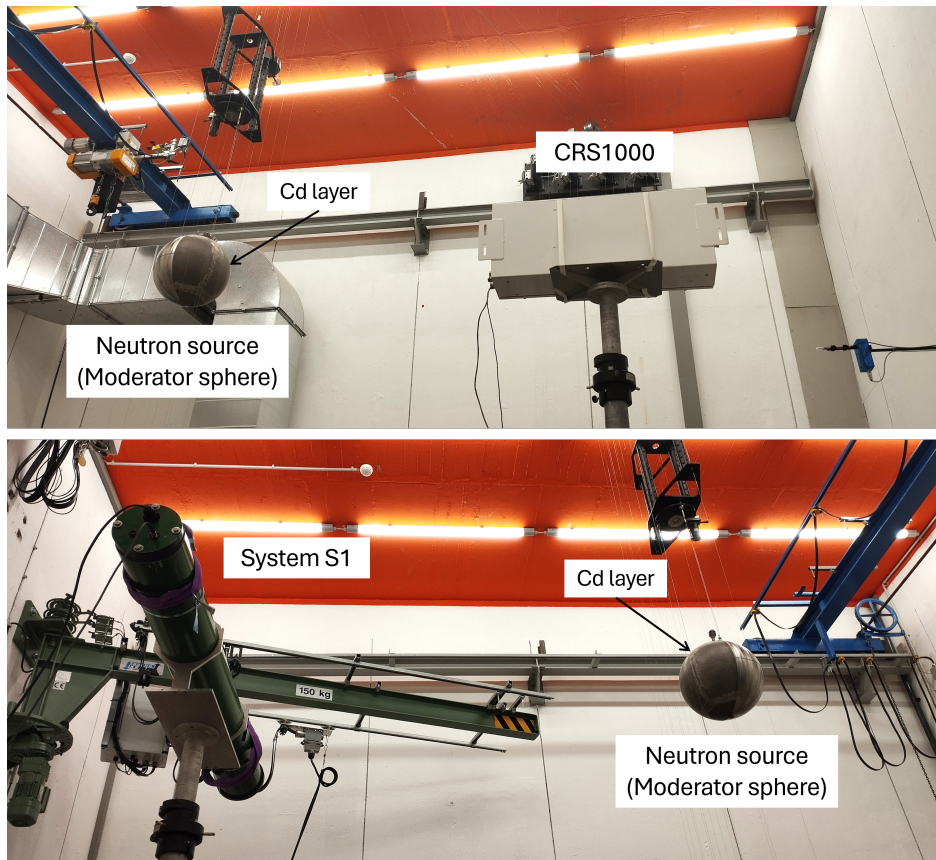


Figure 7. CRS1000 (top) and System S1 (bottom) in the PTB irradiation room during irradiation with the moderated ^{252}Cf source. The moderator sphere, with the Cd foil facing the detector, is also visible in both images.

At the calibration positions, the relative standard uncertainty of the neutron fluence ranges from 1 % to 3 %, depending on the characteristics of the neutron field. It is derived from the calibrated source strengths and evaluated through neutron spectrometry and transport calculations, in accordance with ISO 8529-1 (International Organization for Standardization, 2021).

For the CRS1000, measurements were conducted in five geometrical orientations: front, side 1, side 2, top, and bottom (see Fig. 1). All irradiations were performed at a fixed source-to-detector distance of 170 cm, measured from the center of the neutron source to the center of the detector box.

For the System S1, irradiations were carried out in top and side orientations (with the detector either parallel or perpendicular to the source-to-detector axis, respectively) at three source-to-detector distances: 120 cm, 170 cm, and 220 cm, always referenced to the geometrical centers of the source and the detector.

In similar experimental setups, a shadowing object is typically used to block the detector and separate the in-scattered neutron component from the direct signal (International Organization for Standardization, 2000; Eisenhauer et al., 1985). In the present measurements, no suitable object was available to fully shadow the detector. As a result, both direct and in-scattered neutron

components contributed to the field. To properly characterize this complex neutron field, a detailed MCNP simulation was performed, incorporating the full detector geometry within a comprehensive model of the experimental room.

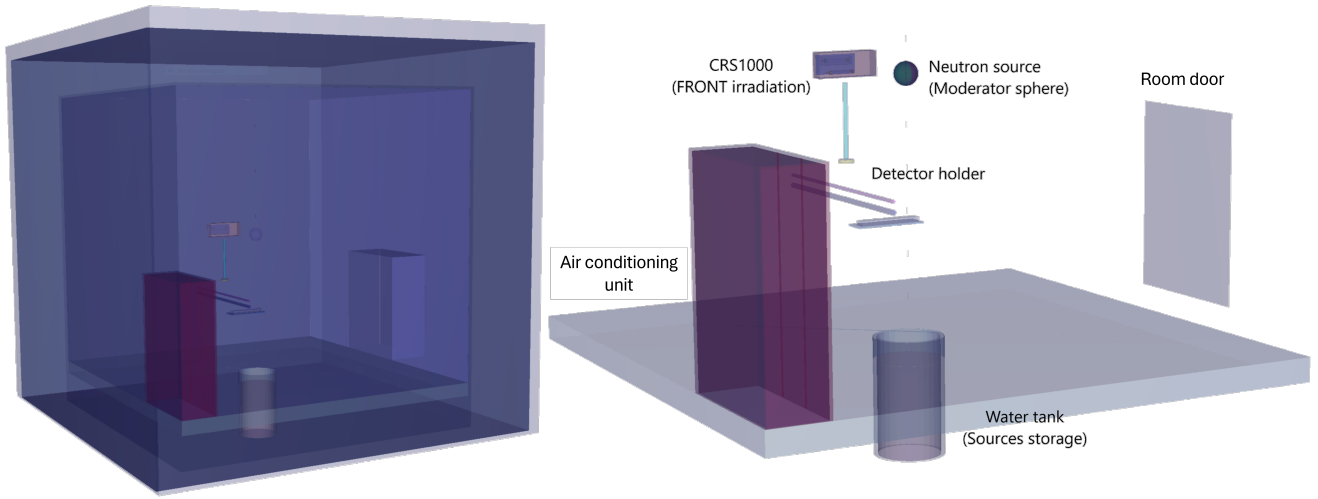


Figure 8. MCNP model of the PTB irradiation room showing the main structural components. Although only the case for the CRS1000 is shown in the picture, both detector geometries (see Fig. 1 and Fig. 5) were included in the simulations to replicate the experimental conditions.

This MCNP room model (Al Qaaod et al., 2024), previously validated at PTB using the NEMUS Bonner sphere spectrometer, includes multiple material layers in the walls, floor, and ceiling, as well as key structural elements such as the water tank beneath the floor (used for source storage), the room door, and detector support structures (Fig. 8).

4.2 Experimental setup at the radionuclide reference fields at CIEMAT

The irradiation room at CIEMAT is a bunker with dimensions of $7.5\text{ m} \times 9\text{ m} \times 8\text{ m}$ and concrete walls of 1.25 m thickness, with a 3 m long bench where the equipment to be calibrated is positioned (Guzman-Garcia et al., 2015). The neutron sources are stored underwater, and an automated system allows their remote manipulation from the control room to position them in the calibration position corresponding to the geometrical center of the room. The laboratory has well-characterized radionuclide neutron sources currently used for calibration purposes: ^{252}Cf , D_2O -moderated ^{252}Cf without Cd, H_2O -moderated ^{252}Cf , and $^{241}\text{Am-Be}$ neutron sources, and other smaller $^{241}\text{Am-Be}$ employed for verification.

In a first approach at the CIEMAT facility, the CRS2000/B system has been measured using this $^{241}\text{Am-Be}$ source (labeled as AmBe (3)) and applying the shadow cone technique to determine the direct contribution. The corrected emission rate on the measurement date is $B = (6.34 \pm 0.09) \cdot 10^5\text{ s}^{-1}$, corresponding to the weakest source in this installation. From this emission rate, the fluence rate at the irradiation position can be determined, and for a distance of 200 cm is $1.35\text{ cm}^{-2}\text{ s}^{-1}$. Two shadow objects have been used, one conventional shadow cone for aligned irradiations, and the other with a pyramidal geometry to be applied for irradiations perpendicular to the detector's longitudinal axis, see Fig. 9.



Figure 9. Irradiation at CIEMAT of one of the CRS2000/B tubes with the shadow object with pyramidal geometry, kindly provided by the Universidad Politécnica de Madrid (UPM).

To complete the model validation a series of simulations to determine the response of the CRS2000/B to this isotopic neutron
 210 source at CIEMAT has been performed. For this simulation, it is not necessary to include the facility, and basically it consists of a convolution of the response function with the ISO spectrum associated with the $^{241}\text{Am-Be}$ neutron source. These results can be compared with those obtained through measurements with and without shadow objects, but, as in the irradiations at PTB with isotopic neutron sources, the results show that the in-scattered component is not properly discriminated with the available shadow objects, and a second approach has to be adopted, considering a detailed model of the laboratory.

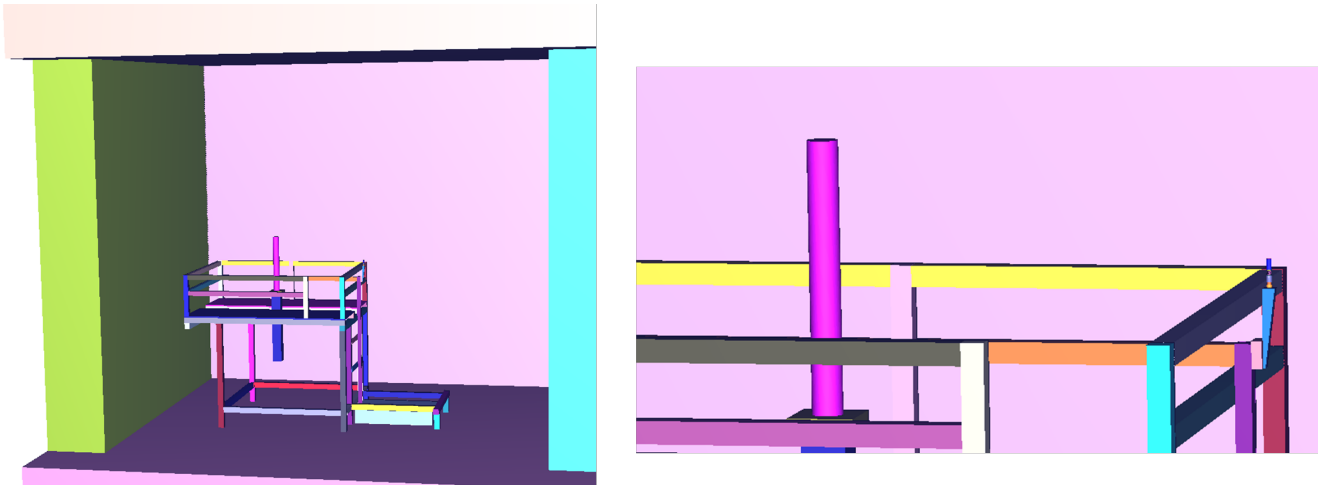


Figure 10. MC model of CIEMAT installation showing details of the bench, calibration table, source support and capsule holder, and sources storage pool.

215 In this case, we can compare the obtained results with the measurements without the shadow cone because the effect of walls, ground, roof, air, and other elements like the irradiation bench are already considered. So, the simulation corresponds to the direct + inscattered case.

In this simulation, the neutron sources are described in detail, and the elements present in the laboratory, like the bench supports, the stairs, or the calibration table, are considered, as can be shown in Fig. 10. For the definition of the neutron source, 220 a detailed model developed to evaluate its anisotropy has been included (Méndez Villafaña et al., 2019).

4.3 Experimental results: adjustment of the MC models

To compare the experimental results with the simulation values, a dimensionless ratio S_i was defined for each irradiation configuration i :

$$S_i = \frac{C_i \cdot B_i}{D_i}. \quad (2)$$

225 Where C_i is the number of simulated neutron reactions in the detector gas per source neutron, $B_i [s^{-1}]$ is the source emission rate of the source used in the corresponding irradiation, and $D_i [s^{-1}]$ is the experimental detection rate. The ratio was defined based on the source strength rather than the fluence over the detector, since the latter showed significant variations along the detector tubes due to the large size of the devices relative to the irradiation room.

230 The mean value $\bar{S}$ of the S_i was determined for each device based on 30 reference irradiations for the CRS1000 (bare and moderated detector), 15 for the System S1, and 15 for the CRS2000/B. The standard deviation was used in all cases to estimate the uncertainty, yielding:

$$\begin{aligned} \bar{S}_{\text{CRS1000}} &= 0.79 \pm 0.07, \\ \bar{S}_{\text{CRS2000/B}} &= 1.34 \pm 0.08, \\ 235 \quad \bar{S}_{\text{S1}} &= 1.26 \pm 0.16. \end{aligned}$$

In the ideal case of full agreement between the experimental data and the simulations, this ratio would be equal to 1. Nevertheless, the average ratio $\bar{S}$ obtained with MCNP across all sources and irradiation configurations shows systematic discrepancies. These are mainly attributed to limitations in the completeness of the model geometries. Furthermore, the magnitude of such deviations fluctuates depending on the neutron field under consideration, as the energy-dependent mismatch between the simulated and the actual detector response impacts each dataset differently. As a result, calibrations performed with multiple sources — despite leading to a larger apparent dispersion — provide a more realistic estimate of the underlying uncertainties than those based on a single source, which underestimate the variability by neglecting energy-range effects.

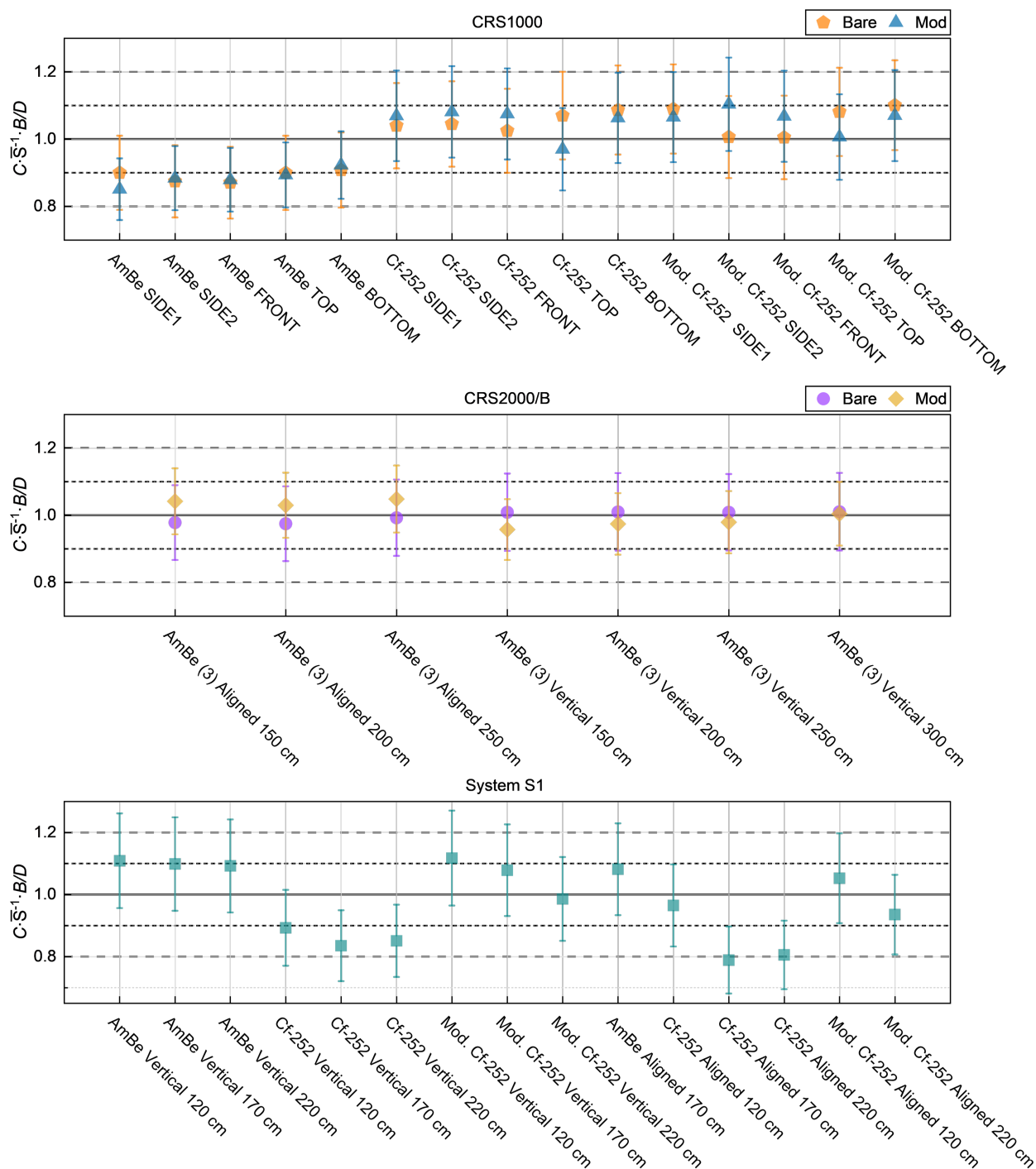


Figure 11. Simulation-to-measurement ratio for all irradiation configurations using the different radionuclide reference fields for the CRS1000 device (top), CRS2000/B (middle), and the System S1 (bottom).

This emphasizes the need to cross-check and validate digital models in well-known, traceable neutron fields before using them to study detector behavior under unknown conditions. The systematic deviation from the experimental data can be corrected by applying the average ratio $\bar{S}$ as a global adjustment factor in the MC simulations. The simulation-to-measurement ratio for the different irradiation setups was redefined as follows:

$$S'_i = \frac{C_i / \bar{S} \cdot B_i}{D_i} \quad (3)$$

The corrected S'_i values are shown in Fig. 11, with error bars representing the absolute combined standard uncertainty (corresponding to a coverage factor $k = 1$). These error bars include experimental uncertainties (less than 3 %, accounting for statistical, source strength components, and 1 % uncertainty in positioning), MC statistical uncertainty (less than 2 %), MC systematic uncertainty (estimated 5 %), and the uncertainty of the scaling factor $\bar{S}$ due to the dispersion of the S_i values. For the bare tubes, the thermal-fraction correction introduces an uncertainty of approximately 6 %.

5 Irradiation at the monoenergetic reference fields at the PTB accelerator facility PIAF

The characterization of the models prepared independently by PTB and CIEMAT was carried out in two steps. First, the MC adjustment coefficient was determined using reference irradiation data, as described in previous sections (see section 4.3). In this second step, these adjusted models of the detectors were used to predict the response of the detectors under totally different irradiation conditions, to ensure that both the adjustment factor and the corrections applied to the experimental data remain valid beyond the specific calibration scenarios.

For this benchmarking purpose, the detectors were irradiated at the PTB Ion Accelerator Facility (PIAF). Monoenergetic neutron reference fields were produced using ion beams delivered by the 2 MV tandetron accelerator operated in continuous (DC) mode, in compliance with ISO 8529 (International Organization for Standardization, 2021).

Fields with nominal peak energies between 24 keV and 5 MeV were produced in a low-scatter experimental hall using the $^7\text{Li}(p,n)$, $^3\text{H}(p,n)$, and $^2\text{H}(d,n)$ reactions (Nolte et al., 2004; Nolte and Thomas, 2011a). These fields are generated in open geometry with well-defined source-detector distances. For this study, six neutron energies were selected, as summarized in Table 1.

A long-term stable ^3He -filled long counter, traceable to the PTB primary standard, was used as a transfer instrument to determine the absolute neutron fluence at the position of the instruments under test (Nolte and Lutz, 2024). The uncertainty in the neutron fluence was below 3 % for all fields except the 5 MeV field, for which it was 7 %.

To minimize background from room-scattered neutrons, the production target was positioned above a gridded floor with an open pit underneath, and surrounded by large distances to all structural surfaces (walls, floor, and ceiling). Nevertheless, given the intrinsic sensitivity of CRNS detectors to low-energy neutrons, the background contribution was determined and corrected using the shadow cone technique (International Organization for Standardization, 2000; Eisenhauer et al., 1985) (see Fig. 12).

$E_{\text{ion}}/\text{MeV}$	Reaction	Angle [°]	E_n/MeV
1.941	${}^7\text{Li}(\text{p},\text{n}){}^7\text{Be}$	80	0.024
1.941	${}^7\text{Li}(\text{p},\text{n}){}^7\text{Be}$	0	0.144
2.021	${}^7\text{Li}(\text{p},\text{n}){}^7\text{Be}$	0	0.250
2.297	${}^7\text{Li}(\text{p},\text{n}){}^7\text{Be}$	0	0.565
2.049	${}^3\text{H}(\text{p},\text{n}){}^3\text{He}$	0	1.2
2.360	${}^2\text{H}(\text{d},\text{n}){}^3\text{He}$	0	5.0

Table 1. Monoenergetic neutron reference fields used in the characterization campaign.

The detectors were placed at 6 meters from the neutron production target at a neutron emission angle of 0° , except for the 24 keV energy, which, dictated by the reaction kinematics, was measured at 80° . In this case, the detector had to be positioned at 4 meters due to geometrical constraints of the experimental setup. Due to the asymmetry in the detector response, irradiations were carried out in the same orientations as those defined in previous sections (see Fig. 1).

According to the simulations (see Fig. 2), the bare detectors are considerably more sensitive — by more than an order of magnitude — to the low-energy background from scattered neutrons in the room than to the direct neutron field. Based on shadow cone measurements, the background contributes on average 90 % of the counting rate in bare detectors for irradiations on the front and side faces, and more than 95 % (up to 99 % depending on the energy) for the top and bottom faces. Combined with the low statistics arising from the low efficiency of the bare detector at these energies, this leads to large uncertainties and discrepancies between measured and expected values. Therefore, for the irradiations in the monoenergetic neutron fields, useful experimental data could only be obtained for the moderated detectors.

For the S1 detector, due to the inherently low detection efficiency observed in the aligned configuration (see Fig. 6), only data from the vertical configuration (neutron field perpendicular to the tube longitudinal axis, i.e., detector in working position) were used for benchmarking. According to the shadow cone method, the inclusion of the Gd neutron absorber layer in this system reduces the background contribution to approximately 20 %, compared to the 50–70 % observed in the other devices.

5.1 Experimental response and validation of the MC models

The experimental results obtained from irradiations with the monoenergetic neutron reference fields at PIAF and the calibration sources at CIEMAT (all reference neutron fields) presented in this section, are used to evaluate the robustness of the calibration of the digital model of each detector. This ensures that the adjustment factors and corrections applied are reliable not only under the specific calibration conditions but also when extrapolated to other scenarios. This decoupled approach ensures that the derived response functions are physically reliable. Although assessing the quantitative impact of site-specific environmental factors (such as buildings, water bodies, or snow cover) remains outside the scope of this work, establishing this robust, validated framework is an essential metrological prerequisite for any such future outdoor simulation studies.

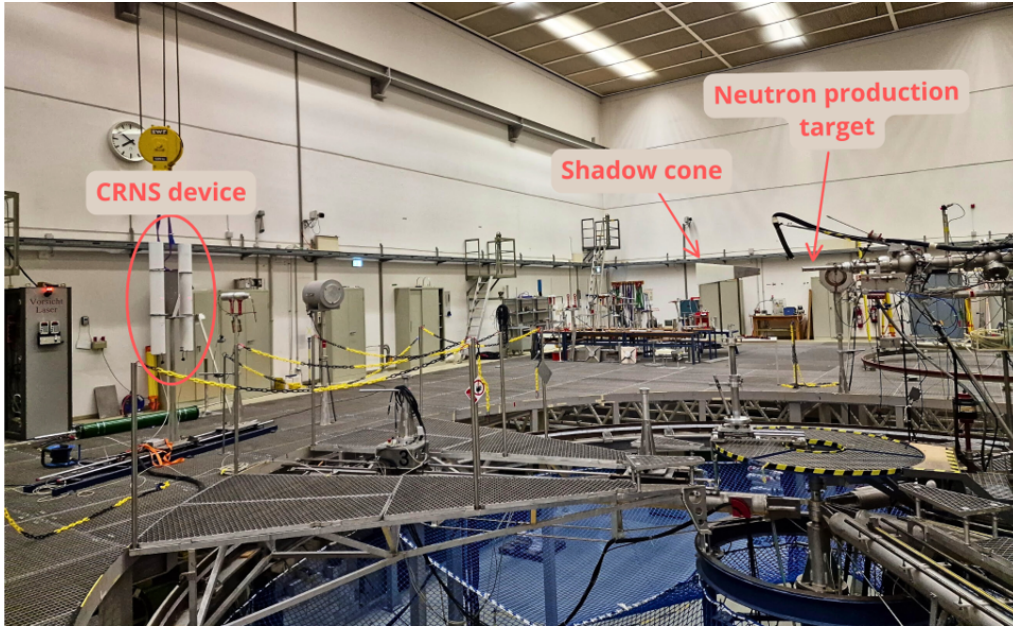


Figure 12. Low-scatter experimental hall of PIAF during one of the irradiations, showing the CRNS device and the shadow cone in a typical experimental configuration. The non-standard pyramidal shadow object was kindly provided by Politecnico di Milano (PoliMi).

Analogously to the definition of the simulated detector response in equation 1, the experimental detector response, R_{exp} , is calculated from the experimental data as:

$$R_{\text{exp}}[\text{cm}^2] = \frac{M_i}{\phi_i}, \quad (4)$$

where M_i is the instrument output (counts) and ϕ_i is the neutron fluence over the detector [cm^{-2}] for an specific configuration.

300 To compare experimental results with the adjusted simulations, a dimensionless ratio $\bar{T}$ between simulated and experimental responses is defined:

$$\bar{T} = \frac{R_{\text{MC}}/\bar{S}}{R_{\text{exp}}}. \quad (5)$$

Obtaining, for each device:

$$\begin{aligned} \bar{T}_{CRS1000} &= 1.01 \pm 0.11, \\ 305 \quad \bar{T}_{CRS2000/B} &= 1.00 \pm 0.07, \\ \bar{T}_{S1} &= 1.01 \pm 0.06. \end{aligned}$$

The average ratios for each device are consistent with unity across all energies and irradiation configurations, within experimental uncertainties, indicating that the model adjustment is accurate and that the calibration procedure is validated under the tested conditions.

Fig. 13 shows the ratio $\bar{T}$ for all the irradiation configurations performed on the detectors, with an average agreement within 8 %. The largest fluctuations and uncertainties are observed at the top and bottom faces, where detector efficiency is lower, and the fraction of counts from the direct neutron field is reduced, leading to larger statistical variations. In these orientations, the MCNP model is also less complete because it does not account for contributions from internal components, such as the device electronics present in the irradiation line.

The error bars in Fig. 13 represent the absolute combined standard uncertainty ($k = 1$) for each ratio $\bar{T}$. These uncertainties include the fluence uncertainty, which is approximately 3 % for most neutron fields, except for the 5 MeV configuration, where it ranges from 7 % to 16 %. They also include the experimental statistical uncertainty after background subtraction, the MC statistical uncertainty (less than 1 %) and systematic uncertainty (5 %), and the uncertainty propagated from the scaling factor $\bar{S}$. For the CRS2000/B, a loss-of-linearity correction factor was required to compensate for saturation-induced losses. This factor introduced an extra uncertainty factor of 2-4 % depending on the source.

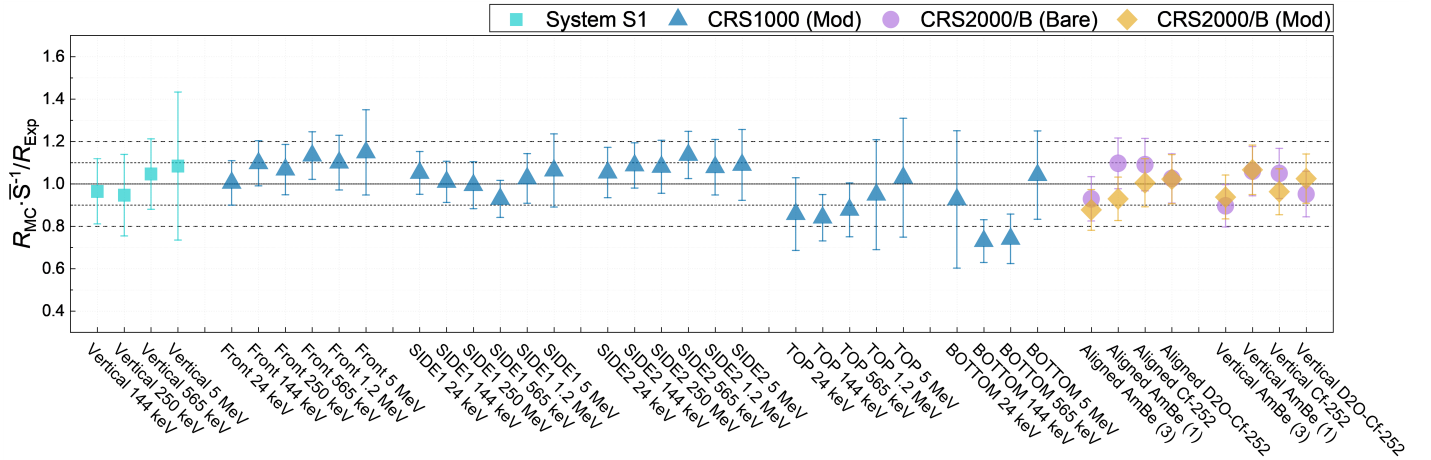


Figure 13. Benchmarking measurements for the different detectors and irradiation configurations: System S1 and CRS1000 in the monoenergetic neutron fields at PIAF, and CRS2000/B in the calibration sources at CIEMAT. Ratios are shown between the responses obtained from the calibrated MC model (corrected by the corresponding scaling factor $\bar{S}$) and the experimental data.

5.2 Volumetric soil moisture retrieval from models

Once validated, the digital models of the probes can be used to predict device behavior under realistic outdoor conditions. Following the same procedure presented in Vykydal et al. (2025), URANOS (Ultra Rapid Adaptable Neutron-Only Simulation, Köhli et al. (2023)) simulations were used to generate a set of virtual reference fields in which the volumetric soil moisture levels (θ) was systematically varied between 1 % and 50 %. A virtual sphere of 2 m around the ideal working position of the

CRNS probes (1 m above the soil level) was used as a scorer to record the energy, intersection point with the sphere, direction, origin, and last interaction point of each neutron crossing the sphere. All the specific details for the URANOS simulations can be found in Vykydal et al. (2025).

These reference fields are then introduced as source definitions for the validated models presented in this work, which were placed at the center of the virtual sphere and irradiated under different soil moisture conditions. For each detector and soil moisture level, Table 2 presents both the absolute neutron counts N registered in the detector body (per primary neutron in the URANOS simulation) and the corresponding relative neutron response (N/N_{cal}), where a volumetric soil moisture of 10% has been selected as the baseline reference condition (θ_{cal}). These predictions can be compared with two common models in the literature for the retrieval of soil moisture: the N0 equation from Desilets et al. (2010) and the Universal Transport Solution (UTS) from Köhli et al. (2021).

θ [%]	CRS1000		CRS2000/B		System S1	
	$N / 10^{-9}$	N/N_{cal}	$N / 10^{-9}$	N/N_{cal}	$N / 10^{-9}$	N/N_{cal}
1	40 ± 4.0	2.02	58 ± 2.6	1.99	29 ± 8.1	2.01
3	29 ± 3.0	1.50	45 ± 2.0	1.54	22 ± 6.2	1.53
6	24 ± 2.5	1.24	36 ± 1.6	1.25	17 ± 4.8	1.18
10	20 ± 2.0	1.00	29 ± 1.3	1.00	14 ± 4.0	1.00
20	16 ± 1.7	0.84	23 ± 1.0	0.80	11 ± 3.2	0.78
30	14 ± 1.4	0.71	21 ± 0.9	0.72	9.7 ± 2.7	0.68
40	12 ± 1.2	0.62	18 ± 0.8	0.63	8.6 ± 2.4	0.60
50	12 ± 1.2	0.61	19 ± 0.8	0.65	8.1 ± 2.3	0.57

Table 2. Model-predicted neutron counts (per primary neutron) and normalized scaling factors relative to a 10 % soil moisture reference condition for each characterized CRNS device across the 1 %–50 % volumetric soil moisture range.

To reflect how the devices are operated in practical applications—where measured neutron counts are used to retrieve soil moisture—the conversion curves are presented in Figure 14 with the relative detector response as the independent variable (X-axis). As observed in the figure, the simulated data points for all characterized devices align remarkably well with the Universal Transport Solution (UTS), showing a significantly better agreement than with the standard N0 equation.

Alternatively, to provide a more practical and mathematically straightforward approach for end users, the simulated data can be parameterized using a simplified two-parameter power-law model. Developed as a key outcome of the 21GRD08 SoMMet project and thoroughly evaluated in recent literature Vykydal et al. (2025), this function describes the inverse relationship for directly obtaining soil volumetric moisture from the relative neutron response (N/N_{cal}):

$$\theta = \theta_{\text{cal}} \times \left(\frac{N}{N_{\text{cal}}} \right)^p \quad (6)$$

345 where θ_{cal} represents the volumetric soil moisture under reference calibration conditions, and p is a device and site specific empirical fitting parameter that accounts for the intrinsic geometry of the equipment and the nominal characteristics of the soil. For the reference environmental field used in this work, the parameters fitted for the characterized instruments are:

$$p_{\text{CRS1000}} = -3.16 \pm 0.08,$$

$$p_{\text{CRS2000/B}} = -3.22 \pm 0.12,$$

350 $p_{\text{S1}} = -2.99 \pm 0.08.$

This power-law formulation avoids the analytical inversion challenges associated with the multiparameter UTS equation while maintaining an excellent fit across the entire operational range of soil moisture, providing an efficient tool for harmonized field-scale calibrations.

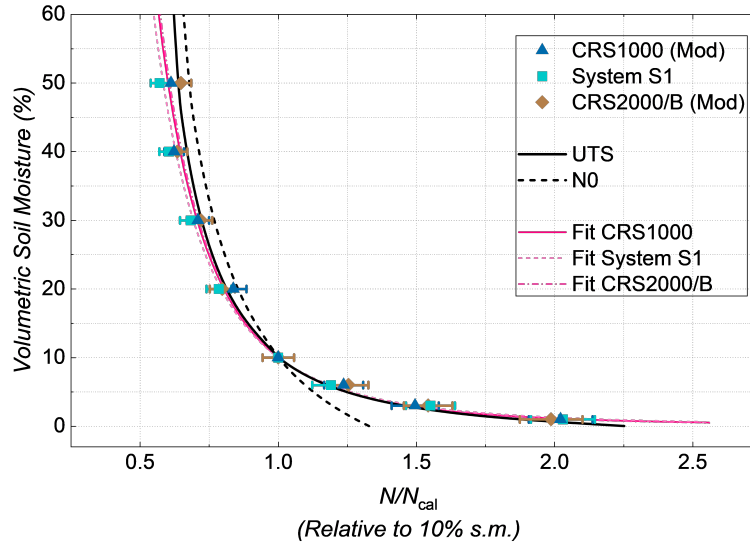


Figure 14. Volumetric soil moisture retrieval as a function of the relative detector response (normalized to 10 % soil moisture) for the three commercial CRNS devices characterized in this work. The simulated data points (symbols) are compared against the Universal Transport Solution (UTS, black solid line) and the standard $N0$ equation (black dashed line), showing a better agreement with the UTS model across the entire moisture range. The two-parameter power-law fitting for the different devices is represented with the magenta lines.

6 Conclusions

355 In this work, we conducted an experimental campaign to characterize commercial cosmic-ray neutron sensors (CRNS) using reference neutron fields based on radioactive sources such as ^{252}Cf , $^{241}\text{Am-Be}$, and ^{252}Cf moderated with heavy water. These experiments were performed at two metrology institutes: PTB and CIEMAT.

The source-based reference fields provide a broad energy spectrum, enabling calibrations across the entire range relevant for CRNS applications. This campaign represents a first step toward the development of a metrological framework for CRNS calibration under controlled laboratory conditions. It also highlights current limitations, key requirements, and future steps necessary for establishing a robust calibration protocol.

The experimental detector responses were employed to validate the Monte Carlo (MCNP) models, providing insight into the detectors' behavior. The results show agreement between simulations and experimental data within a relative uncertainty of approximately 10 %, which is consistent with the estimated experimental uncertainties. A summary of the devices, simulation tools, and the obtained calibration factors is presented in Table 3.

Manufacturer	Device model	Simulation/Validation	Simulation code	Nuclear data	MC adjustment factor $\bar{S}$	$u_{\text{rel}}(\bar{S})$
Hydroinnova	CRS1000	PTB	MCNP6.1	ENDF/B-VIII.0	0.79 ± 0.07	9 %
Hydroinnova	CRS2000/B	CIEMAT	MCNP6.2	ENDF/B-VIII.0	1.34 ± 0.08	6 %
StyX Neutronica	System S1	PTB	MCNP6.1	ENDF/B-VIII.0	1.26 ± 0.16	12 %

Table 3. Summary of the characterized detectors, including the simulation code and version used, the institution responsible for the simulation and validation, and the calibration factors obtained from the experimental data.

The calibration factors $\bar{S}$ presented in Table 3 are energy-independent, systematic scaling factors. This indicates that the discrepancy is not due to a flawed modeling or specific nuclear interactions, but rather to a global over or underestimation of the detector's absolute efficiency by the Monte Carlo model. Such offsets are well established in neutron transport simulations, where predicted count rates are highly sensitive to minor, often inaccessible uncertainties in the exact material composition, density, or geometry of complex commercial detectors. For instance, while a nominal gas pressure is used in the model, the actual pressure in each physical tube can vary within its tolerance margin, leading to efficiency differences of a few percent. Similarly, the internal electrical field—which defines the effective "active volume"—has inhomogeneities that are not precisely known. Achieving a perfect, first-principles simulation (where $\bar{S} = 1$) is therefore not only computationally demanding but also practically unattainable.

Consequently, the core outcome of this validation is not the pursuit of an idealized model, but the establishment of a robust, traceable, and efficient correction protocol. By anchoring the simulation to experimental data from reference fields, a calibrated and reliable detector response function is obtained. This empirically corrected model provides the essential metrological foundation for reliable detector performance, which is the main objective of this characterization campaign.

As a further validation, the already corrected MCNP models were applied to simulate detector responses in PTB's monoenergetic neutron fields, with energies ranging from 24 keV to 5 MeV. While irradiations with isotopic sources provide a basis for deriving calibration factors, the monoenergetic fields allow pointwise verification of the simulated response function and assessment of the applied corrections.

Building upon this metrological foundation, the validated digital twins were integrated into virtual environmental reference fields generated with URANOS as part of the 21GRD08 SoMMet project. This coupled simulation approach allowed us to

385 predict the relative detector response across a realistic range of volumetric soil moisture from 1 % to 50 %, demonstrating that
the simulated responses for all characterized devices align remarkably well with the theoretical Universal Transport Solution
(UTS). Furthermore, to facilitate practical field applications for end users, a simplified two-parameter power-law conversion
function was evaluated. The resulting device and site specific fit parameters (p) provide a straightforward, physics-based tool
for retrieving soil moisture directly from normalized neutron count rates, successfully bridging the gap between fundamental
390 metrology in the laboratory and environmental applications.

It should be noted that these detectors, designed for outdoor deployment in environmental neutron fields, are optimized
for epithermal and low-energy neutrons (<1 MeV) at fluxes below $1\text{ cm}^{-2}\text{ s}^{-1}$. This results in limitations when applied to
monoenergetic fields, which primarily probe the high-energy end of the response function. In this region, detector efficiency is
low. For the moderated detectors, less than 20 % of the detected events originated from the direct neutron field, dropping to about
395 10 % at higher energies and for smaller detector faces. The situation was even worse for the bare detectors, where measurements
could not be performed in the monoenergetic fields because their response was entirely dominated by background.

Additionally, the large physical size of the detectors introduces spatial inhomogeneities in the neutron field profile, affecting
both fluence and energy uncertainty. Due to their size and non-standard shapes, the shadow object method was not always
applicable for accounting the background contribution.

400 Considering these factors, there is a clear need for a dedicated reference neutron field specifically designed for CRNS
calibration. Such a field should provide a broad energy spectrum, an appropriate counting rate, and homogeneity over large
areas to accommodate the typical dimensions of these devices. Furthermore, given the detectors' sensitivity to scattered neutrons,
suitable shadow cones or a well-characterized room-return component are required.

While the present measurements are subject to significant uncertainties, this campaign constitutes the first systematic val-
405 idation of commercial CRNS detectors in laboratory-based neutron reference fields, marking an important step toward the
development of dedicated calibration facilities that will allow higher precision in the future.

Data availability. The datasets that support the findings of this study are available from the corresponding author upon reasonable request.

Author contributions. MZ, RMV, PB, MK, MR, ZV, JW contributed to the conceptual design and development of the research project.
MAMC, RMV, PB, ADC, MD, MK, BL, ZV, and MZ contributed to the preparation and execution of the experimental campaign, including
410 data collection. MAMC and RMV carried out the analysis, evaluation, and interpretation of the data, with additional support and supervision
from MR, BL, and MZ. Simulations were prepared by MAMC and RMV, with support from MK, JW, MR, BASA, PB, JS and ZV. MAMC
wrote the original draft of the manuscript, while RMV, MK, BL, MD, MZ, and MR contributed to its revision. All authors took part in
discussions and interpretation of the results.

Competing interests. The authors declare that they have no conflict of interest.

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