Material Characterization of Bauxite for Accurate Activity Assessment Using ISOCS

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Abstract

Accurate gamma-ray activity assessment of heterogeneous materials with unknown composition is a persistent challenge in radioanalytical measurements, particularly for low-energy photon emissions where self-attenuation effects significantly impact measurement uncertainty. In this work, a bauxite sample of initially unknown material composition was prepared and characterized as part of Mirion Technologies' participation in the IAEA Proficiency Testing programs for 2024 and 2025. The objective was to determine a material characterization that enabled reliable activity quantification.

This work demonstrates how ISOCS can be used to constrain effective material parameters for complex, unknown samples and improve confidence in modeled detector efficiencies. The resulting activity assessments exhibit stability and agreement with IAEA reference values across multiple gamma emitters, including low-energy Pb-210. These results illustrate the importance of accurate material modeling when analyzing heterogeneous solids and highlight the effectiveness of ISOCS-based methods for quantitative gamma-ray spectroscopy without reliance on source-based efficiency calibration.

Introduction

The International Atomic Energy Agency (IAEA) conducts routine proficiency testing (PT) exercises to evaluate the ability of participating laboratories to correctly identify and quantify radionuclides in unknown samples. These exercises often include a variety of matrices and geometries to assess analytical performance under realistic measurement conditions. Reported results are compared against reference values to evaluate accuracy and precision across participating laboratories.

One of the bulk solid samples included in the proficiency testing program was bauxite, a naturally occurring, multi-component material whose chemical composition can vary significantly depending on origin and processing history. Compared to generic soils or sediments, bauxite is typically enriched in aluminum and iron oxides, resulting in stronger gamma-ray self-attenuation, particularly at low energies. As a result, applying default sediment or soil compositions during efficiency modeling can lead to significant bias in derived activities. Correctly characterizing bauxite therefore requires a dedicated material modeling approach that reflects its distinct attenuation behavior.

ISOCS Methodology

The In Situ Object Counting System (ISOCS) is a physics-based efficiency calibration methodology that replaces traditional source-based efficiency calibration with detector modeling. Rather than relying on traceable calibration sources in fixed geometries, ISOCS calculates detector efficiency by incorporating detector response, measurement geometry, and material-dependent attenuation effects. This approach allows efficiencies to be generated for arbitrary sample geometries and compositions, including cases where standard calibration sources are impractical or unavailable.

Challenges and Objectives

The primary challenge associated with the bauxite sample was its unknown and heterogeneous material composition. Bauxite typically contains varying fractions of aluminum, iron, silicon, oxygen, and lighter elements, resulting in strong attenuation of low-energy gamma rays. This effect can dominate measurement uncertainty and lead to systematic bias at low energies if material assumptions are incorrect, while higher-energy emissions remain relatively insensitive.

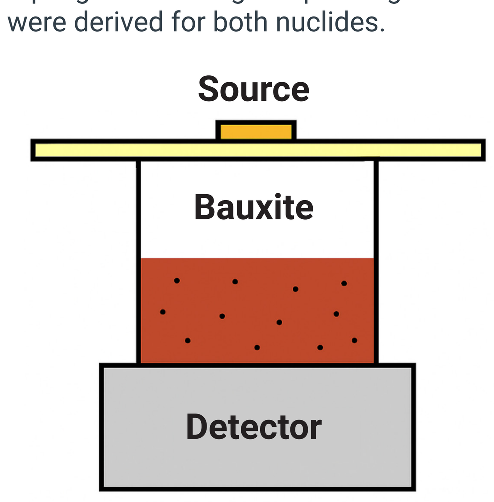
The objective of this work was to derive an effective bauxite material characterization that produced physically consistent efficiency calculations across a broad gamma-ray energy range. Criteria for a successful characterization included: (1) consistent efficiency behavior across multiple energies, (2) agreement between measured and reference activities for attenuation-sensitive nuclides such as Pb-210, and (3) validity of calculated activities without reliance on source-based efficiency calibration.

Methods

Material characterization was performed using an iterative ISOCS modeling approach. The bulk material was represented using combinations of elements including hydrogen, oxygen, silicon, aluminum, and iron. Among these, iron content was found to have the greatest influence on low-energy efficiency due to its high attenuation coefficient.

To experimentally constrain the material model, source attenuation testing was conducted using an external Am-241 / Eu-152 gamma source positioned on top of the open bulk solid container. ISOCS efficiencies were calculated for multiple gamma energies spanning a wide energy range, and corresponding line activities were derived for both nuclides.

The material composition within the ISOCS model was iteratively adjusted until (1) the derived Eu-152 line activities were consistent with each other across all analyzed emissions, and (2) the measured activity ratio between Am-241 and Eu-152 matched the ratio of their reference activities. This tuning process ensured physically consistent attenuation behavior without anchoring the model to a single energy. The volume and mass of the physical bauxite sample was previously measured, and thus every model in the tuning process referenced the same density. Therefore, any differences in the models' attenuation arose from purely from material composition.



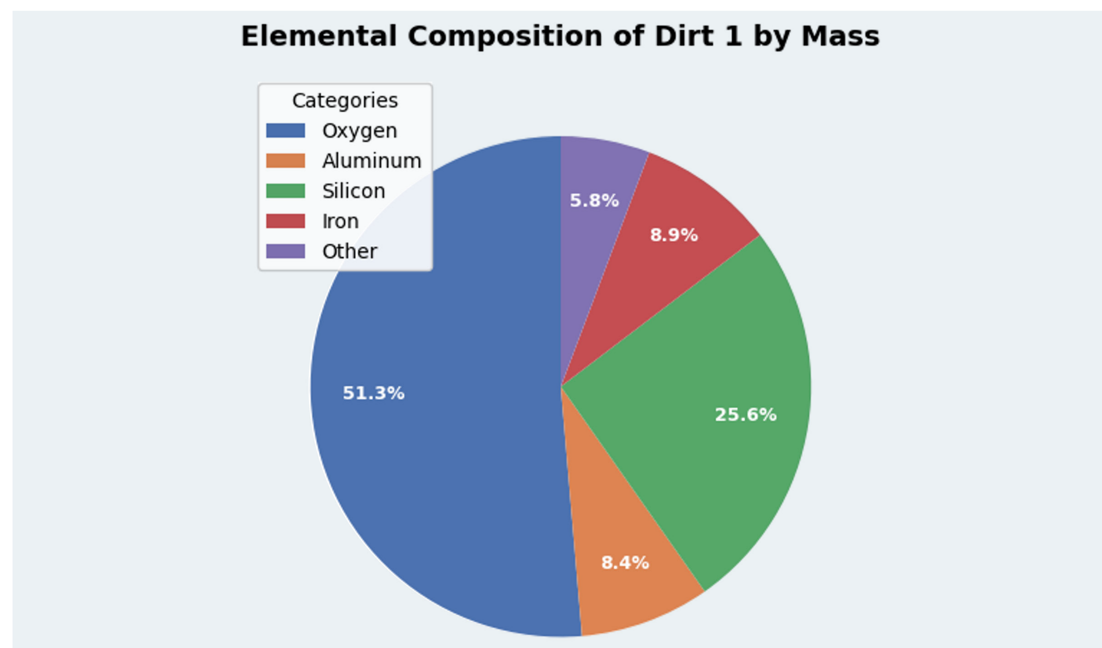
Schematic and photograph of the attenuation test. An Am-241/Eu-152 source is placed above the bauxite container. Gammas from the source must be attenuated by the bauxite, and thus the material properties of the bauxite may be inferred from the resulting spectrum.

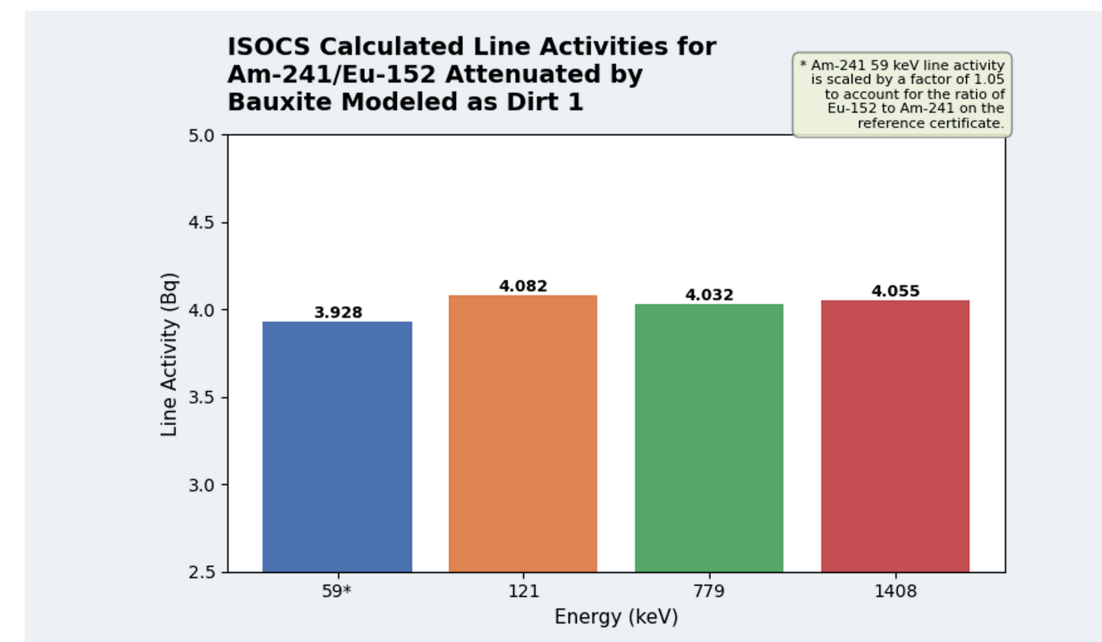
Results

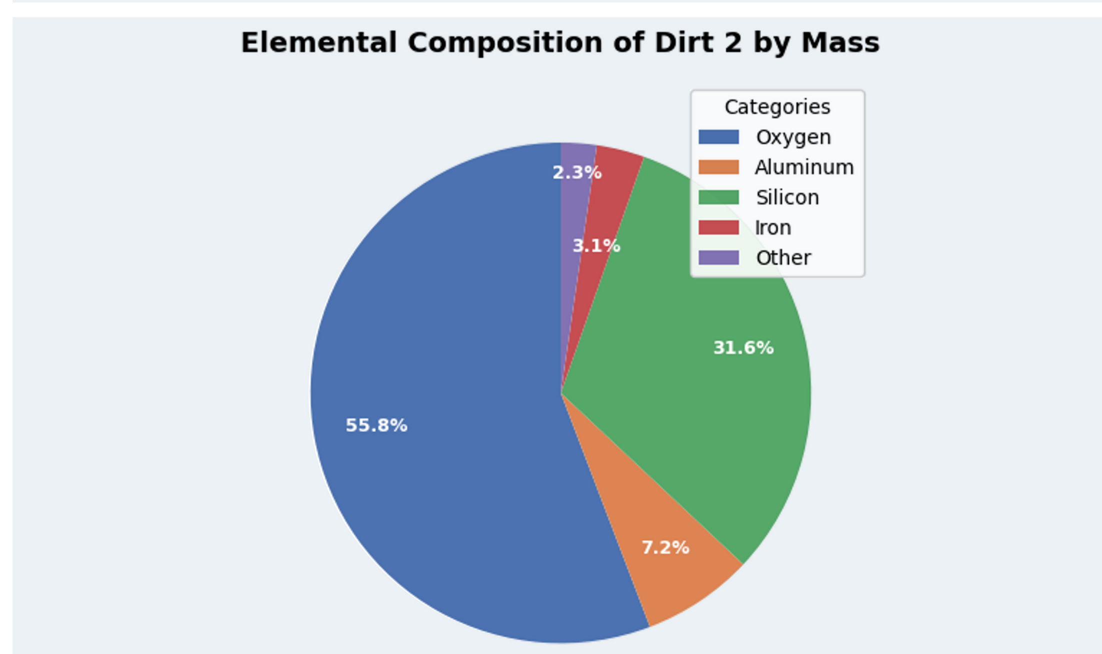
The final tuned material compositions produced strong multi-line consistency for the Am-241 / Eu-152 attenuation measurements, indicating that the modeled efficiencies appropriately captured the energy-dependent self-attenuation behavior of the bauxite sample.

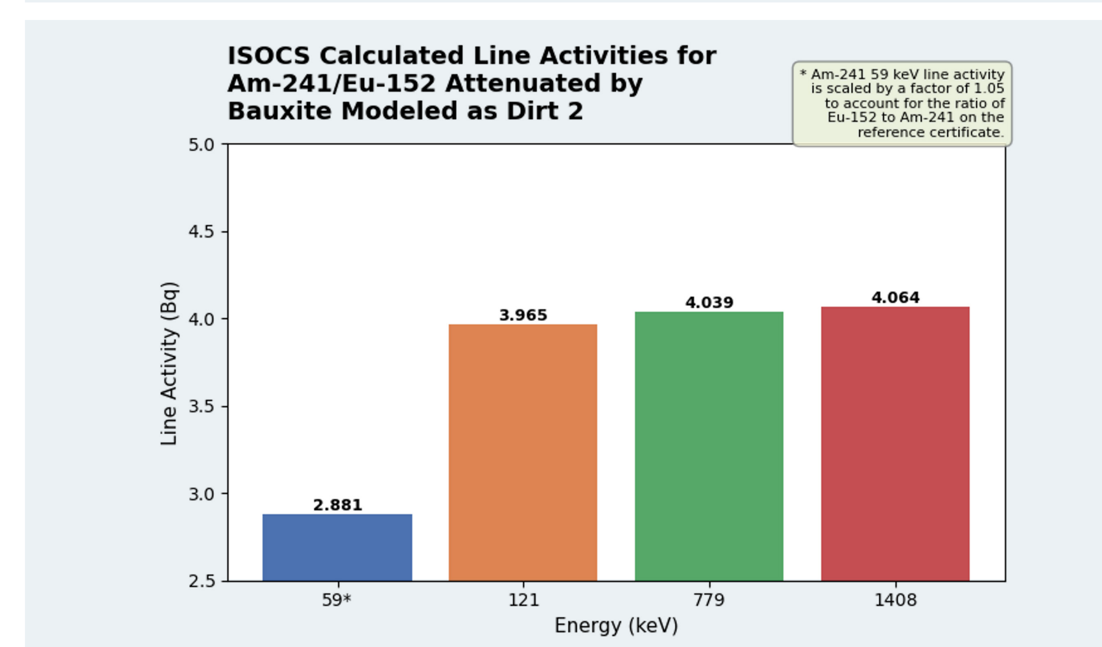
Using this validated material characterization, Pb-210 activities were successfully quantified for the 2024 bauxite proficiency test sample. Despite the strong attenuation associated with Pb-210's 46.5 keV gamma emission, the derived activities showed close agreement with IAEA reference values. Comparable performance was observed for Pb-210 in the 2024 sediment and 2025 soil proficiency test samples, demonstrating the robustness of the characterization approach across multiple bulk solids.

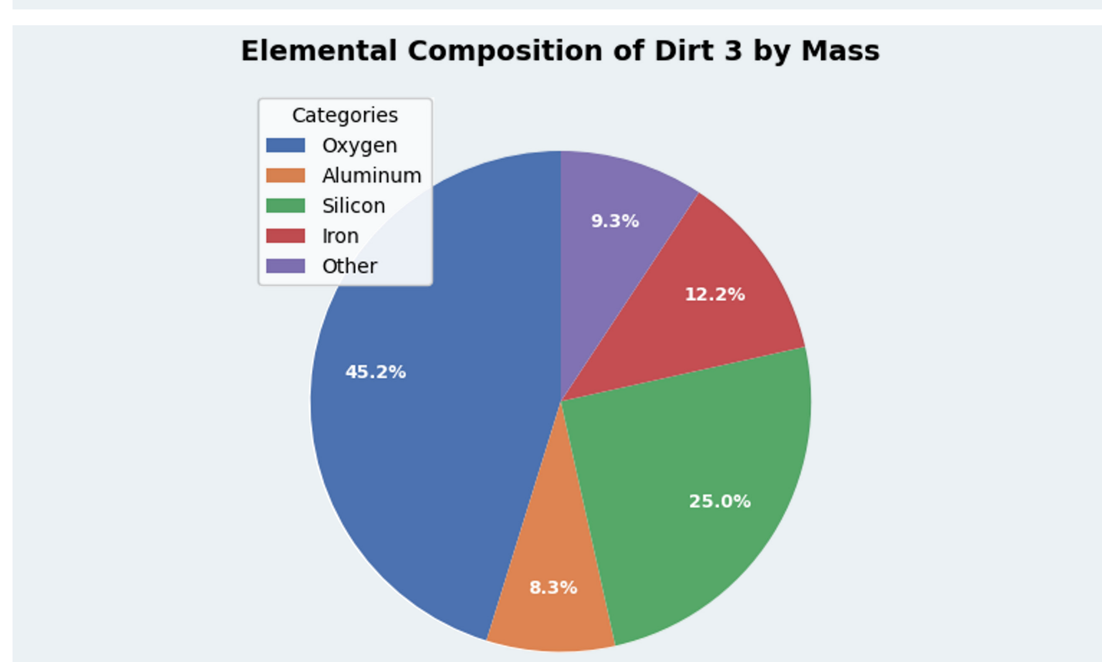
Assumed material compositions are illustrated using pie charts, while corresponding line-by-line activity agreement plots demonstrate the impact of composition on low-energy efficiency behavior. A comparison between derived Pb-210 activities and IAEA reference values further confirms the validity of the modeling approach.

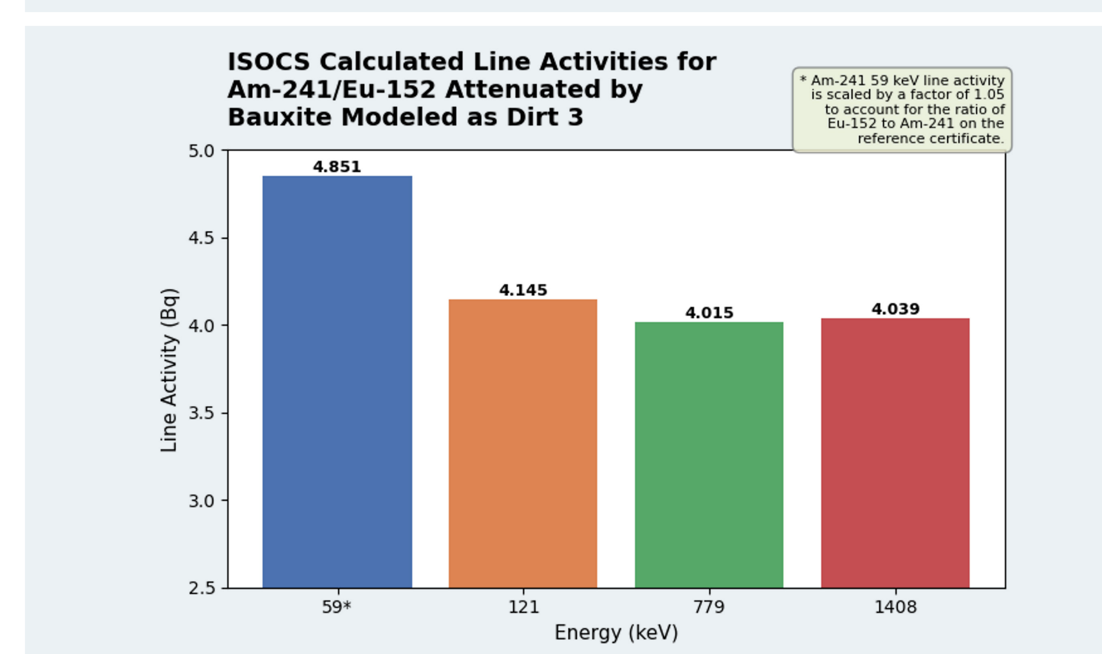








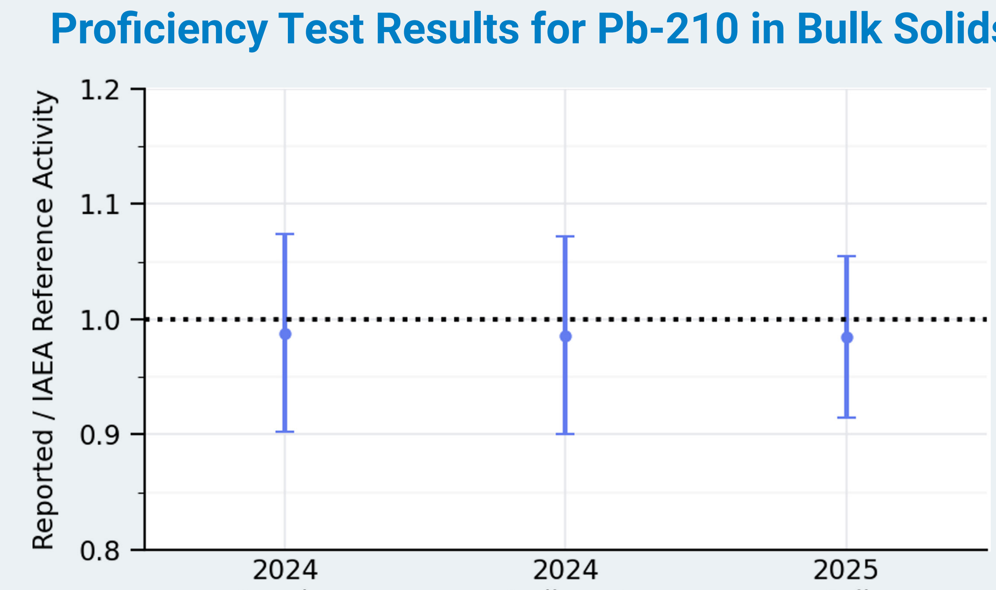




Pie charts demonstrating the different elemental compositions of three material matrices created to model bauxite in ISOCS: Dirt 1, which has an intermediate level of iron, Dirt 2, which has a low level of iron, and Dirt 3, which has a high level of iron.

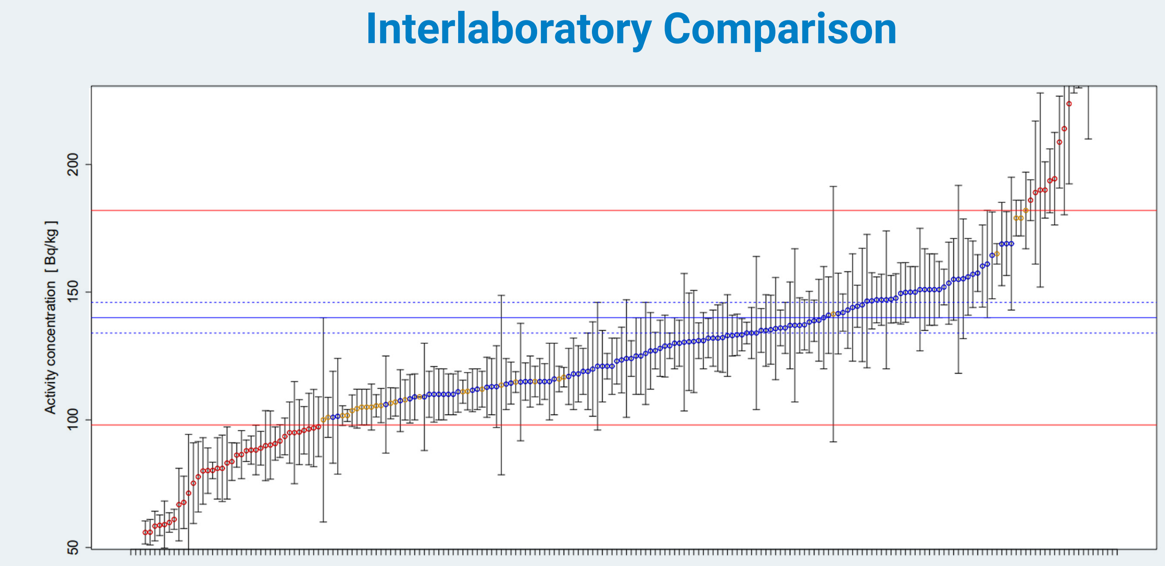
Bar charts demonstrating calculated line activities from an Am-241/Eu-152 source attenuated by bauxite. Results from different ISOCS models applied to the same measurement are depicted in the three charts. Each chart's results were obtained using a different material composition for bauxite as an attenuator, whose constituent elements are depicted in the pie charts.

Proficiency Test Results for Pb-210 in Bulk Solids



Proficiency Test performance for Pb-210 across a range of bulk solids over two years of proficiency testing. Different material compositions were used for each ISOCS analysis to account for the varying chemical compositions of the samples, yet close alignment with the IAEA reference activity was achieved in each case.

Interlaboratory Comparison



Reported results and evaluation parameters for Pb-210 quantification in the 2024 bauxite sample across all participating laboratories. Blue points represent reported activities within the maximum acceptable relative bias (accepted score). A low activity bias in the cumulative results may indicate models that do not account for enough iron in the bulk solid.

Discussion

Multi-line characterization methods succeed where single-line methods often fail because they directly constrain energy-dependent attenuation behavior. Single energy tuning can produce agreement at one gamma energy without enforcing correct energy dependent attenuation behavior, whereas multi line agreement requires a physically realistic material representation across the full energy range. Multi-line material characterization also does not require precise knowledge of the characterization geometry, as opposed to more geometry-sensitive single-line methods. Accurate material characterization relies only on consistent activities across multiple lines, rather than absolute accuracy of one line's activity

Although this work focuses on bauxite, the methodology is broadly applicable to other complex or unknown bulk materials, including industrial byproducts, mineral ores, and environmental samples with variable composition. The same principles may be extended to constrain material parameters for a wide range of challenging matrices.

Future work may include automating the material characterization process by systematically exploring elemental combinations and evaluating multi-line agreement metrics. Such automation would further reduce analyst subjectivity and enable more rapid and reproducible characterization within software frameworks.

Conclusions

Accurate material characterization is essential for reliable gamma-ray activity assessment of heterogeneous bulk solids. By leveraging ISOCS-based efficiency modeling and multi-energy attenuation testing, robust Pb-210 quantification was achieved with agreement to IAEA reference values, despite strong low-energy self-attenuation effects. These results demonstrate the effectiveness of ISOCS-based approaches for quantitative analysis of complex materials without reliance on source-based efficiency calibration.

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