

# Fast Simulation of Gamma-Ray Logs for Uranium Exploration in Roll-Front Deposits

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**Abstract**—Orano Mining is evaluating the potential of the CeBr<sub>3</sub> spectrometric gamma-ray logging probe developed by Advanced Logic Technology (ALT) for estimating uranium concentration in roll-front deposits, where decay chain disequilibrium disrupts its relationship with total gamma count rate. The Nuclear Measurement Laboratory of CEA IRESNE, in Cadarache, France, is working on predictive algorithms capable of fully exploiting the shape of the recorded gamma spectra. However, the current number of logged wells is insufficient to properly train such algorithms. This calls for the creation of a diverse database of simulated gamma-ray logs, using the Monte Carlo N-Particle (MCNP) transport code. Conventional analog simulations based on MCNP pulse-height (F8) tally provide accurate estimates but are too computationally expensive for this task. Achieving low statistical uncertainty in every energy bin necessitates simulating a large number of particle histories. Moreover, modeling borehole measurements involves simulating numerous probe locations. Designing a more efficient yet sufficiently accurate simulation procedure is therefore crucial. We propose a 2-step method, where the flux reaching the probe surface and the detector response to this flux are simulated separately. The bulk of runtime reduction is achieved in the first step, through the use of MCNP point detector (F5) tally, which acts as a variance reduction technique. However, treating the detector as a point may lead to significant bias. We conducted an experimental validation on Orano CIME calibration blocks (Bessines, France) and observed good agreement between measured and simulated spectra. These findings support the 2-step approach as a viable option for building our database.

**Keywords** —Uranium mining, gamma logging, CeBr<sub>3</sub> probe, fast simulation.

## I. INTRODUCTION

ORANO Mining is partnering with the Nuclear Measurement Laboratory of CEA IRESNE to develop new techniques for reconstructing uranium grade vertical profiles in roll-front deposits from gamma-ray logs, which correspond to series of gamma measurements performed at near-adjacent depths. Since uranium ore bodies can be as thin as a few decimeters (see Fig. 1), Orano Mining acquires gamma-ray spectra at 10-cm intervals to enable fine-grained spatial estimations.

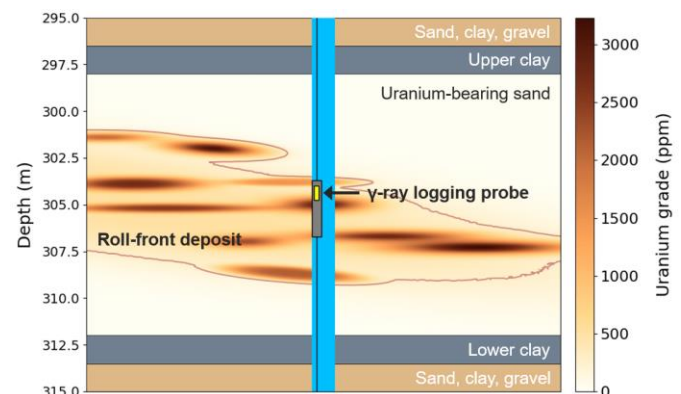


Fig. 1. Simplified 2D schematic of gamma borehole logging in a uranium roll-front deposit.

Until recently, gamma logging has been confined to profiling total count rates. At secular equilibrium, the total gamma count rate is directly proportional to uranium content. In this case, computing a detector-specific calibration coefficient is sufficient to provide an accurate estimate. Calibration coefficients accounting for borehole geometry, tubing effects, and uranium self-absorption have been determined experimentally for NaI detectors using calibration blocks [1]. However, the linear relationship between total count rate and uranium grade is disrupted in roll-front deposits due to the presence of radioactive disequilibrium in the <sup>238</sup>U decay chain (see Fig. 2). The imbalance between the activities of <sup>238</sup>U and those of its daughter nuclides stems first from the differential leaching of uranium and radium. Although uranium solubility in groundwater is influenced by the redox potential of the medium, the same does not apply to radium, one of its decay products. This results in the formation of radium-depleted and radium-enriched regions. Secular equilibrium may also be disrupted by radon evaporation during borehole drilling, radon being a volatile noble gas that tends to escape from the host rock through pores and fractures. Emissions from decay products of <sup>222</sup>Rn, <sup>214</sup>Pb, and <sup>214</sup>Bi are responsible for the majority of the recorded gamma signal. Relying solely on total count rate might therefore lead to inaccurate estimates.

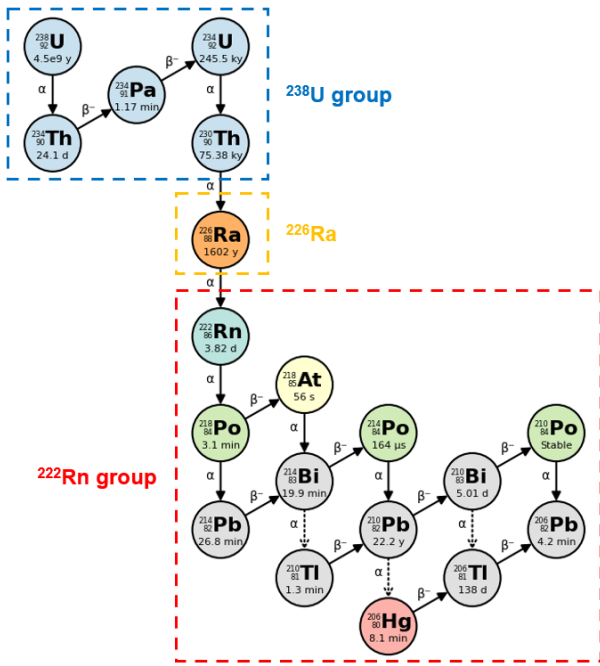


Fig. 2.  $^{238}\text{U}$  decay chain, with radionuclide groups involved in radioactive disequilibrium identified by dotted rectangles. The  $^{222}\text{Rn}$  group accounts for 95% of the total gamma count rate at secular equilibrium.

This has prompted a shift toward exploiting spectral information. The characterization of uranium content based on spectrometric measurements with high-purity germanium detectors (HPGe) has been carried out on ore samples [2, 3]. These high-resolution detectors are unfortunately ill-suited to *in situ* measurements because of their cost, their volume, and the need to cool the germanium crystal. Orano Mining has therefore turned to scintillator-based spectrometric probes for borehole logging. For example, the performance of a  $\text{LaBr}_3(\text{Ce})$  gamma probe in quantifying uranium content in ore samples despite U/Rn disequilibrium has been evaluated [4]. Orano Mining is now appraising the capabilities of the  $\text{CeBr}_3$  probe developed by the Advanced Logic Technology (ALT) company [5, 6].

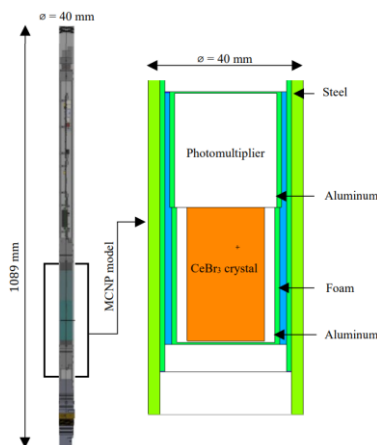


Fig. 3. ALT QL40-SGR-2G logging probe equipped with a  $\text{CeBr}_3$  crystal, and its MCNP model [6].

Measurement conditions inside boreholes are particularly demanding. The low energy resolution of the  $\text{CeBr}_3$  detector and the short acquisition times imposed by the high probe speed inside the borehole, the latter leading to increased measurement

uncertainty, make usual estimation techniques, such as net peak area analysis [7], fail. This motivates the adoption of automated predictive algorithms. However, their performance hinges on the quality and the quantity of data they are trained on. Supervised methods need to be trained on a labeled dataset that comprises pairs of observations and corresponding target values. Acquiring accurate underground uranium profiles requires numerous core extractions, a process which is both expensive and time-consuming. To date, the number of logged boreholes for which laboratory-analyzed core samples are available remains scarce, which hinders the training of supervised algorithms. A suggested workaround involves building a synthetic dataset of gamma-ray logs using MCNP6.3 (Monte Carlo N-Particle) simulations [8].

So far, methods for estimating uranium grade from gamma-ray logs have been designed without taking geological stratification into account [9, 10]. This assumption needs to be revised when the goal is to reconstruct precise uranium depth profiles. This implies modeling fine-scale vertical fluctuations of uranium content (see Fig. 4a). Variations in other geological (bulk density) and drilling parameters (borehole diameter) also need to be introduced into the simulations to enhance realism. The number of simulations needed to cover the full range of geological configurations then becomes intractable.

## II. 2-STEP (F5+F8) SIMULATION METHOD

Due to the low probability of gamma particles reaching the detector, the conventional analog simulation method relying on MCNP pulse-height (F8) tally requires sampling a significant number of particles ( $10^{10}$  per radionuclide group) to sufficiently reduce statistical uncertainty in each of the 292 energy channels of the gamma spectrum. As a result, the average runtime per simulation amounts to 580 h.

We propose an alternative approach which consists in dividing the simulation into two distinct parts. The first step involves computing the gamma flux incident on the probe surface with the efficient, semi-deterministic MCNP point detector tally (F5), as described below. In the second step, the simulated flux is projected onto the probe to estimate the energy deposition spectrum in the  $\text{CeBr}_3$  crystal using the more time-consuming analog F8 tally (see Fig. 4c). This step requires only a small number of source particles.

The flux on the probe surface can be approximated very efficiently thanks to MCNP point detector (F5) tally (see Fig. 4b). The F5 tally is referred to as a next-event estimator, meaning that it evaluates during each particle history a contribution to the detector at every source emission or collision site. Each of these contributions is weighted by the probability of scattering towards the point detector along a direct path, accounting for geometric and attenuation effects. The number of contributions per particle is thus drastically increased. Acting as a variance reduction technique, the F5 tally achieves high statistical precision with far fewer particle histories. On average, F5 simulations complete in only 15 h. Moreover, vertically stacking F5 tallies (see Fig. 4b) enables flux estimation at multiple probe locations simultaneously, further decreasing simulation time.

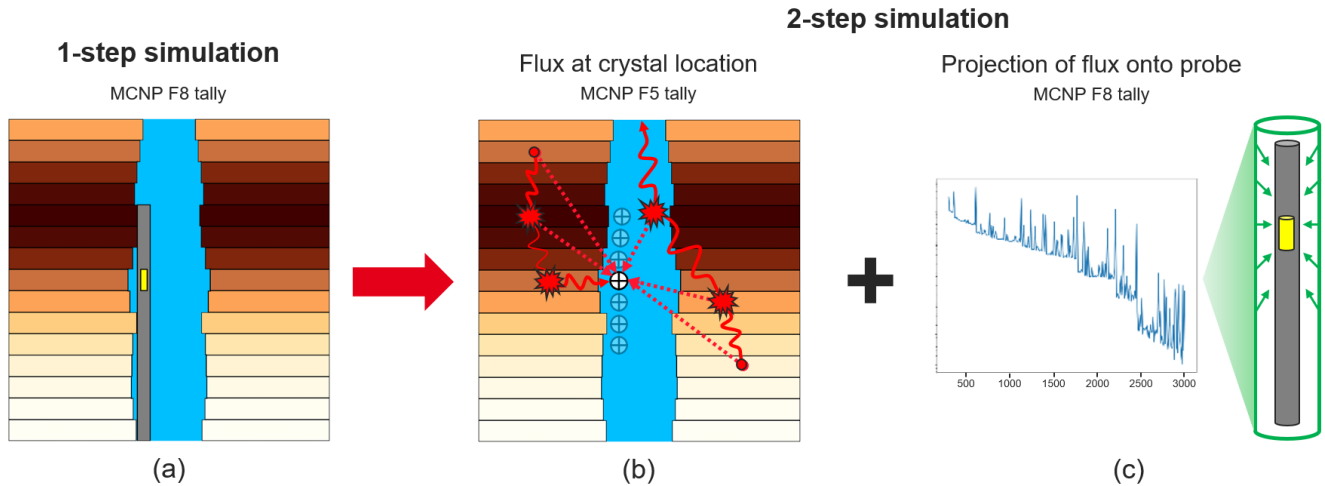


Fig. 4. Simulation of a gamma-ray spectrum acquired within a vertically stratified formation. (a) Conventional 1-step (F8) simulation including the probe geometry. (b) Estimation of the probe flux by MCNP point detector (F5) tally. Straight dotted arrows represent direct contributions computed at source and collision sites. (c) Projection of the simulated flux onto the probe to compute the energy deposition in the crystal using MCNP F8 tally.

Given the pointwise nature of the F5 tally, runtime reduction comes at the price of physical simplification. The tally only captures the energy distribution of the flux at a single point. Information about particle positions and angles of incidence is inevitably lost. This may introduce a bias when projecting the flux onto the probe. Automated algorithms designed to predict uranium grade profiles are likely to exploit not only total count rates, but also subtle shape-related features. If these characteristics were to be altered, prediction accuracy could be undermined. We therefore evaluate the extent of a potential bias by comparing 2-step simulated spectra with measurements taken in calibration blocks designed to replicate actual borehole conditions as closely as possible.

### III. EXPERIMENTAL VALIDATION ON BESSINES STANDARD BLOCKS

The Orano CIME (Innovation Center for Extractive Metallurgy) calibration station in Bessines, France, includes seven cubic concrete blocks with 70-cm edges (see Fig. 5). Each block is built from a carefully controlled homogeneous mixture of fine sand, cement, and crushed uranium ores. A central air-filled hole of 8 cm diameter allows the insertion of the radiometric probes. Their uranium content, as well as their elemental composition, has been estimated through chemical analysis. Uranium concentrations range from 0 to 9700 ppm<sub>U</sub> (milligrams of uranium per kilogram of ore). A gamma-ray spectrometry measurement campaign using an HPGe detector has also been carried out [2]. The estimated concentrations, reported in Table I, agree with those obtained from chemical analysis. Orano Mining has determined thorium and potassium mass fractions of 20 ppm and 3.7%, respectively. However, the absence of the 2 615 keV photopeak, characteristic of <sup>208</sup>Tl, a daughter nuclide of <sup>232</sup>Th, in the recorded gamma-ray spectra (see Fig. 6), indicates that no thorium is present in the concrete matrix. Emissions from the <sup>232</sup>Th decay chain are therefore not modeled in the simulations. All blocks are at secular equilibrium. The B1 block contains no uranium and is therefore not considered in the remainder of the study.

TABLE I. URANIUM MASS CONCENTRATIONS (IN PPM<sub>U</sub>) OF ORANO CIME CALIBRATION BLOCKS ESTIMATED BY CHEMICAL ANALYSIS AND HPGe GAMMA-RAY SPECTROSCOPY

Block ID	Chemical analysis (in ppm <sub>U</sub> )	HPGe gamma-ray spectroscopy (in ppm <sub>U</sub> )	Bulk density (g/cm <sup>3</sup> )
B2	500	459 (± 3.7%)	1.92
B3	1000	958 (± 1.9%)	1.89
B4	1900	1960 (± 2.3%)	1.91
B5	2900	2800 (± 3.7%)	1.92
B6	4800	4550 (± 3.3%)	1.93
B7	9700	9530 (± 2.0%)	1.92

In prior work, MCNP 1-step (F8) simulations of CeBr<sub>3</sub> probe measurements inside each standard block were carried out using uranium concentrations determined by chemical analysis [6]. In the present study, the simulated uranium concentrations correspond to those derived from HPGe measurements. Fig. 5 shows the block geometry as implemented in MCNP. Acquisition times for the experimental spectra range from 612 s to 1170 s.

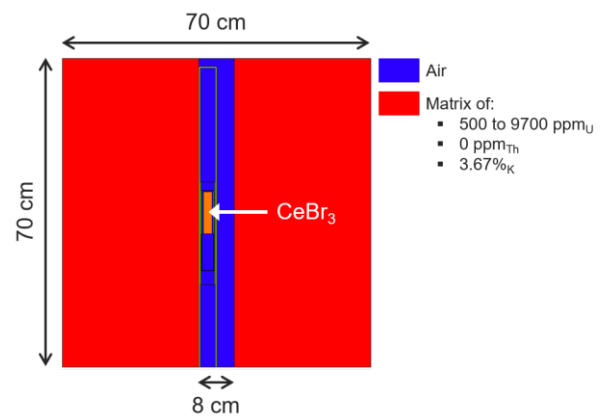


Fig. 5. MCNP simulation of ALT CeBr<sub>3</sub> logging probe positioned inside a Bessines standard block.

Table II reports the relative differences between the total count rate  $C_{TOT}$  measured above the electronic cutoff, set at an

equivalent energy of 80 keV, and the 1-step (F8) or 2-step (F5+F8) simulations, for the six calibration blocks. We observe satisfactory experimental agreement for both approaches. The 2-step method tends to yield slightly higher count rates than the 1-step method. Relative to experimental values, the 2-step method more frequently overestimates the  $C_{TOT}$ .

TABLE II. RELATIVE DIFFERENCES IN TOTAL COUNT RATES ABOVE THE 80-KEV THRESHOLD BETWEEN MEASUREMENTS AND 1-STEP (F8) AND 2-STEP (F5+F8) SIMULATIONS

Block ID	$\frac{1\text{-step} - \text{EXP}}{\text{EXP}}$	$\frac{2\text{-step} - \text{EXP}}{\text{EXP}}$
B2	-2.6%	-0.8%
B3	0.9%	2.7%
B4	1.7%	3.6%
B5	0.7%	2.6%
B6	-1.3%	0.5%
B7	5.3%	7.2%

Next, we evaluated the accuracy of both methods in reconstructing the spectral shape. The experimental gamma spectrum recorded in block B3 (958 ppm<sub>U</sub>), along with the simulated spectra, is displayed in Fig. 6. For this uranium concentration, which is typical of roll-front deposits, the overall shape of the experimental spectrum is well reproduced by both simulation methods. However, we observe a slight overestimation of the low-energy bump in both simulations, which is a bit larger with the 2-step approach.

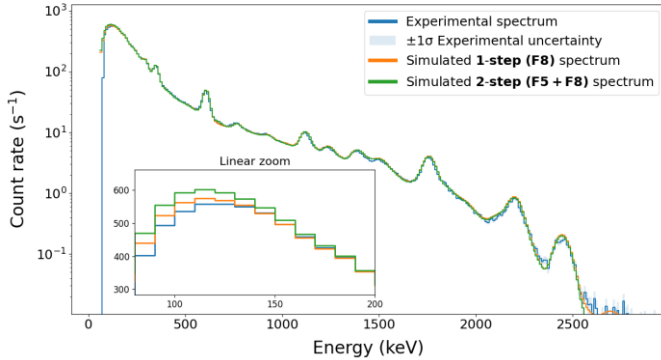


Fig. 6. Gamma-ray spectra measured with the CeBr<sub>3</sub> probe inserted in the B3 block (958 ppm<sub>U</sub>), and corresponding 1-step and 2-step simulations

We then performed a comparison between the count rates in the two energy windows (120-170 and 960-1040 keV) specified by the  $K_{APC}$  (Peak-to-Compton) indicator, developed in earlier work for uranium grade estimation [4], for all calibration blocks. The count rate in the low-energy region is overestimated by MCNP 1-step simulation for all blocks, except B2 (see Fig. 7). Conversely, mid-energy count rates are all underestimated. This distortion of the spectrum becomes more pronounced as uranium grade increases. The same pattern is observed with the 2-step approach, and is slightly amplified.

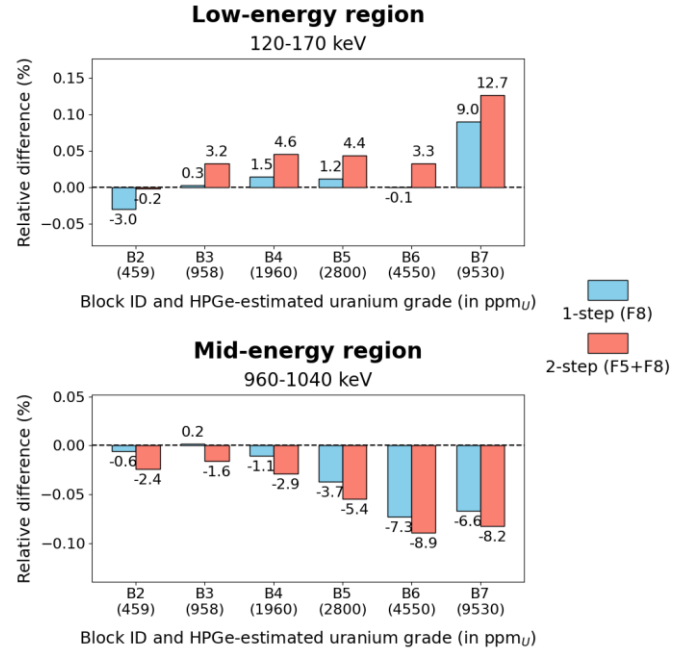


Fig. 7. Relative differences between experimental count rates and those simulated with 1-step and 2-step methods in low- and mid-energy regions (120-170 and 960-1040 keV, respectively), computed for the six standard blocks of Orano CIME calibration station (Bessines, France).

#### IV. CONCLUSIONS

We designed a 2-step MCNP simulation approach for fast gamma-ray log generation. By employing MCNP point-detector (F5) tally as a variance reduction technique, we achieved a substantial reduction in computation time. Experimental validation using Orano CIME calibration blocks at Bessines (France) shows satisfactory agreement between simulations and measurements, both in terms of total count rate and overall spectral shape. The physical simplification involved in the nonanalog flux estimation phase leads, however, to greater spectral distortion than the conventional 1-step method. Given the small magnitude of this bias, the 2-step approach proves to be a well-suited candidate for building a comprehensive database of gamma-ray logs to train predictive algorithms.

The calibration blocks, however, reproduce borehole geometry only imperfectly. In particular, logging operations in roll-front deposits take place within water-filled boreholes. This difference in the surrounding medium may affect the accuracy of the 2-step approach. Moreover, the potential impact of geological vertical heterogeneities on the experiment-simulation bias remains to be assessed, as the calibration blocks are homogeneous.

Another promising strategy for efficiently generating gamma-ray logs is to bypass MCNP altogether, instead of trying to accelerate the simulations. This could be achieved by developing a surrogate model, *i.e.*, an emulator based on a machine learning algorithm trained to predict gamma-ray spectra directly from geological and drilling input parameters. The surrogate model is trained on an experimental design built from MCNP 1-step simulations spanning various geological configurations. This design must be carefully constructed to

ensure that the trained emulator can replicate MCNP outputs as faithfully as possible. We are currently exploring this approach and plan to validate it against both 1-step reference simulations and actual borehole logging data to assess its reliability.

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