Improving Gross Count Gamma-Ray Logging in Uranium Mining With the NGRS Probe

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***Abstract*— AREVA Mines and the Nuclear Measurement Laboratory of CEA Cadarache are collaborating to improve the sensitivity and precision of uranium concentration measurement by means of gamma-ray logging. The determination of uranium concentration in boreholes is performed with the Natural Gamma Ray Sonde (NGRS) based on a NaI(Tl) scintillation detector. The total gamma count rate is converted into uranium concentration using a calibration coefficient measured in concrete blocks with known uranium concentration in the AREVA Mines calibration facility located in Bessines, France. Until now, to take into account gamma attenuation in a variety of boreholes diameters, tubing materials, diameters and thicknesses, filling fluid densities, and compositions, a semiempirical formula was used to correct the calibration coefficient measured in Bessines facility. In this paper, we propose to use Monte Carlo simulations to improve gamma attenuation corrections. To this purpose, the NGRS probe and the calibration measurements in the standard concrete blocks have been modeled with Monte Carlo N-Particles (MCNP) computer code. The calibration coefficient determined by simulation $5.3\ \mathrm{s}^{-1} \cdot \mathrm{ppm}_U^{-1}$ with 10% accuracy is in good agreement with the one measured in Bessines (and for which no uncertainty was provided), $5.2\ \mathrm{s}^{-1} \cdot \mathrm{ppm}_U^{-1}$. The calculations indicate that the concrete blocks used for measuring the calibration coefficients measured in Bessines are underestimated by about 10%. Based on the validated MCNP model, several parametric studies have been performed. For instance, the rock density and chemical composition proved to have a limited impact on the calibration coefficient. However, gamma self-absorption in uranium leads to a nonlinear relationship between count rate and uranium concentration beyond approximately 1% of uranium weight fraction, the underestimation of the uranium content reaching more than a factor 2.5 for a 50% uranium weight fraction. Parametric studies have also been performed with different tubing materials, diameters, and thicknesses, as well as different borehole filling fluid representative of real measurement conditions, in view to validate gamma attenuation corrections based on the semiempirical formula. In addition, a multilinear analysis approach has been tested to further improve accuracy on uranium concentration determination, leading to only a few percent uncertainties on a large range of configurations.**

***Index Terms*— Monte Carlo N-Particles (MCNP), NaI(Tl) scintillators, uranium mining.**

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I. Introduction

THE detection of gamma rays emitted by ^{238}U and its daughter nuclei is one of the reference methods for detecting uranium in borehole. One approach consists in inferring the uranium concentration in boreholes from the total count rate provided by scintillation counters such as NaI(Tl) detectors. This approach, known as gross count gamma-ray logging [1], [2], requires a calibration coefficient which is usually measured in the concrete blocks of well-defined composition with known uranium concentration. However, the measurement conditions of the calibration coefficient are not always representative of field conditions and corrections of the measured calibration coefficient are needed [1]. This paper reports numerical simulations performed with the Monte Carlo N-Particles (MCNP) code in view to improve the accuracy of uranium concentration determination in gross count gamma-ray logging.

II. Validation of the MCNP Numerical Model

To assess uranium concentration in boreholes, a GEOVISTA Natural Gamma Ray Sonde (NGRS) [3] equipped with a 2.4 cm (diameter) × 3.9 cm (height) cylindrical NaI(Tl) scintillation crystal is used. The uranium concentration is linearly related to the NGRS count rate via a calibration coefficient K [2]. Following standard procedures [4], [5], K is measured using concrete blocks of known uranium concentration. In the AREVA Mines calibration facility in Bessines, France, the calibration block's size is 70 cm × 70 cm × 70 cm.

The calibration measurement geometry presented in Fig. 1 has been modeled with the MCNP Monte Carlo code. Being a reliable and renown photon–neutron transport code, MCNP is already used in the field of uranium logging to model measurement methods involving neutron sources [6] or measurements based on gamma-ray detection [7], this last approach being also manageable with free available codes like GEANT 4 [8]. The modeled concrete blocks have a $1.9\ \mathrm{g} \cdot \mathrm{cm}^{-3}$ density and an isotropic, homogeneously distributed gamma-ray source corresponding to 2906 ppm of uranium, 15.6 ppm of thorium, and 3.7% of potassium. With a 65-keV energy threshold, the calculated reference calibration coefficient is $K_{\mathrm{air}}^{\mathrm{MCNP}} = 5.3\ \mathrm{s}^{-1} \cdot \mathrm{ppm}_U^{-1} \pm 10\%$ for a tubeless NGRS probe in the calibration block, with only air filling the borehole (no fluid), which is compatible with the measured reference calibration coefficient (for which the uncertainty has not been provided to the authors): $K_{\mathrm{air}}^{\mathrm{meas}} = 5.2\ \mathrm{s}^{-1} \cdot \mathrm{ppm}_U^{-1}$. The 10% uncertainty on the simulation is caused not only by

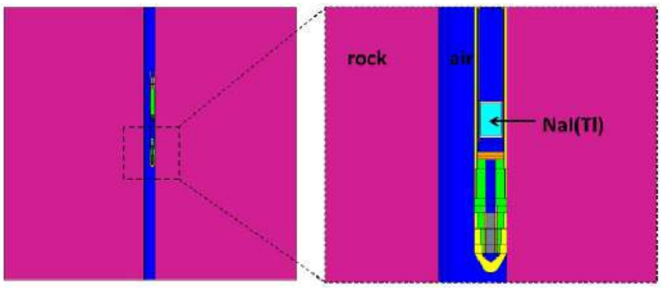

Fig. 1. MCNP model of a count rate measurement performed with an NGRS probe positioned inside an air-f lled borehole drilled in a 70 cm × 70 cm × 70 cm calibration concrete block.

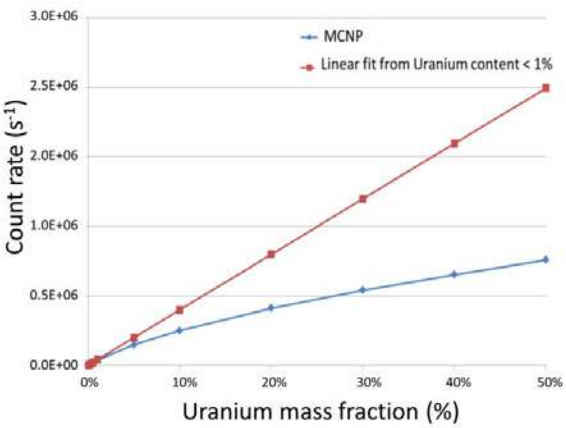

Fig. 2. Gamma count rate as a function of uranium mass fraction in a 70 cm × 70 cm × 70 cm calibration concrete rock.

uncertainties associated with the numerical model precision (crystal dimensions and cement composition) but also by the precision on the detection energy threshold and the accuracy of the chemical analyzes performed to determine the uranium concentration in the cement blocks. Measurements with the NGRS probe inside tubes of different thicknesses and nature have also been modeled with MCNP. Table I shows that the calculated tube attenuation corrections match the measurements.

III. Sensitivity Parametric Studies

A. Influenc of Rock Composition

The impact of the rock mineralogy on the calibration factor has been studied, replacing SiO_2 with $CaCO_3$, $CaSO_4$-$2H_2O$, or Na_2CO_3. As shown in Table II, rock composition has a small impact on the calibration factor. This lack of sensitivity is caused by the lesser atoms sensitivity of the mass attenuation coeff cients when photons have energy larger than 100 keV.

B. Gamma Self-Absorption in Uranium

Fig. 2 shows the calculation results on a wide range of uranium mass fractions, for an NGRS probe inside an iron tube fille with water, located in a 70-cm edge concrete cube similar to Bessines calibration block. As already observed in [9], the deviation from the linear fi due to self-attenuation, obtained for uranium mass fractions lower than 1%, begins above uranium 1%, and the self-attenuation effect reaches a factor of 2.6 for 50% of uranium.

TABLE I

Calculated and Measured Calibration Coefficients K^{MCNP} for Different Tubes (Nature and Thickness) and Attenuation Corrections Relative to the Tubeless Configuration

	No tube	2 mm thick Al tube	5 mm thick Al tube	5 mm thick steel tube
K_x^{MCNP} (s^{-1} $ppmU^{-1}$)	5.33	5.23	5.09	3.94
$\frac{K_{air}^{MCNP}}{K_x^{MCNP}}$	1	1.02	1.05	1.35
$\frac{K_{air}^{meas}}{K_x^{meas}}$	1	1.02	1.06	1.37

TABLE II

Calculated Calibration Coefficients for Different Rock Mineralogies and a Density of 1.6 $g \cdot cm^{-3}$ Relative to the Calculated Calibration Coefficients Associated With Concrete

	$CaCO_3$	$CaSO_4$-$2H_2O$	Na_2CO_3
65 keV threshold	0.94	0.94	1.03
100 keV threshold	0.96	0.96	1.02

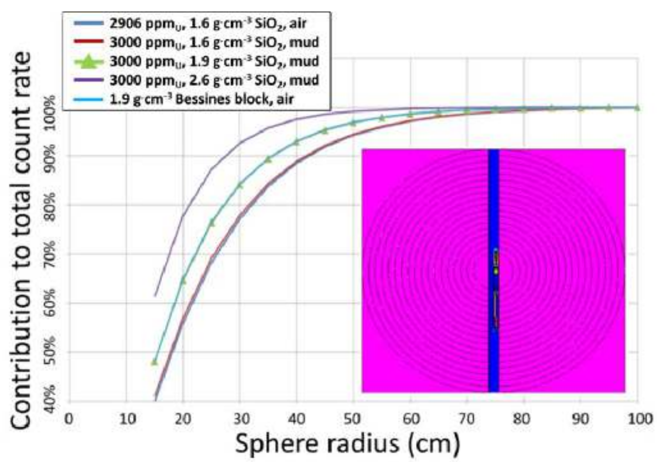

Fig. 3. MCNP model and cumulated signal due to uranium present in spheres with an increasing radius for different rocks' density and borehole f llings.

C. Gamma Range Seen by the NGRS Probe

Monte Carlo calculations have been performed to study the range of the gamma rays detected by the NGRS probe using the model shown in Fig. 3. The saturation of the signal is reached for a sphere with a radius of about 100 cm. Therefore, we have calculated the calibration coeff cient in a concrete block with an edge of 200 cm, instead of 70 cm for Bessines blocks. The result is $K_{\infty}^{\mathrm{MCNP}} = 5.8\ \mathrm{s}^{-1} \cdot \mathrm{ppm}_U^{-1}$ instead of $5.3\ \mathrm{s}^{-1} \cdot \mathrm{ppm}_U^{-1}$, indicating that calibration coeff cients measured in Bessines are underestimated by about 10%. Our calculations are in agreement with the 60-cm minimum radius recommended in [9] for calibration boreholes with $2\ \mathrm{g} \cdot \mathrm{cm}^{-3}$ material.

D. Influenc of Rock Density

Calculations with 2906 ppm_U have been performed with a 200-cm edge SiO_2 block, the reference gamma-ray source, and a tubeless borehole f lled with mud. Given the lesser sensitivity of the mass attenuation coeff cients to mineralogy, mud has been simulated by water with a density of $1.2\ g \cdot cm^{-3}$. Table II indicates that the maximum effect of this approximation would be of the order of 6%. The calculations show that the calibration coeff cient slightly decreases from 5.44 to 5.36 $s^{-1} \cdot ppm_U^{-1}$ when the density varies from 1.2 to 2.6 $g \cdot cm^{-3}$. Since calculations keep the uranium concentration to 2906 ppm_U, increasing rock density increases the amount of uranium. Being modif ed only by about 1.5% when increasing the density by 1.4 $g \cdot cm^{-3}$, the calibration coeff cient is therefore poorly sensitive to rock density. With the mineralogies shown in Table II, the increase of gamma attenuation is indeed compensated by a larger amount of uranium when density rises.

E. Influenc of Borehole Diameter and Filling Fluids

The correction of the calibration factor to take into account the attenuation by the filli g f uids, the borehole dimension and tube casing can be obtained by measurement at the cost of a dedicated facility that can cover a suff cient set of conf gurations [2], [10]. Up to now, to take into account the attenuation by the borehole and tube filli g f uids, the borehole dimension, and tube thickness, AREVA corrected the reference calibration coeff cient K_{air}^{meas} by a semiempirical factor A define as

$$A^{-1} = \left[1 + C_1 \frac{(\O_b - \O_s - 2d)}{2}\right][1 + C_2 d] \qquad (1)$$

where $\O_b$ is the borehole diameter, $\O_s$ is the NGRS probe diameter, d is the tube thickness, $C_1 = 0.0047\rho_f$ (mm^{-1}) is an empiric gamma-ray linear attenuation coeff cient in the f uid of density ρ_f (dimensionless parameter), and $C_2 = 0.043$ (mm^{-1}) is an empiric gamma-ray attenuation coeff cient of steel. Note that this correction considers the same f uid in the tube and in the borehole, with a common C_1 attenuation factor and ρ_f density, which is not always the case in the field

To check the accuracy of this empirical correction, MCNP calculations have been performed with water, mud, or cement f llings. The detector response is modeled using a type-8 tally which allows obtaining the gamma-ray energy deposit spectrum in the NGRS probe. The mud is simulated by water with a density of $1.2\ g \cdot cm^{-3}$, and bentonite cement is simulated with a density of $1.8\ g \cdot cm^{-3}$. From the MCNP calculations with material m filli g the borehole and the tube, a correction B is define as

$$B^{-1} = \frac{K_{air}^{MCNP}}{K_m^{MCNP}}. \qquad (2)$$

Table III shows a signif cant inf uence of borehole diameter and f lling f uid. On the other hand, the maximum discrepancy between the semiempiric correction A and the correction B calculated with MCNP is about 26%.

TABLE III

CALIBRATION COEFFICIENT K^{MCNP} ($s^{-1} \cdot ppm_U^{-1}$) CALCULATED WITH MCNP FOR DIFFERENT BOREHOLES DIAMETERS FILLED WITH AIR AND CORRECTION FACTORS A^{-1} AND B^{-1} FOR DIFFERENT FILLING FLUIDS (WATER, MUD, AND CEMENT)

Borehole diameter (mm)		80	101	132	160	216	300
K_{tube}^{MCNP} ($s^{-1} \cdot ppm_U^{-1}$) in air		5.86	5.86	5.85	5.83	5.75	5.57
Water correction factors	A^{-1}	1.10	1.15	1.22	1.29	1.42	1.62
	B^{-1}	1.07	1.10	1.15	1.19	1.27	1.38
	$\frac{A^{-1} - B^{-1}}{B^{-1}}$ (%)	2.6	3.9	6.1	7.9	11.4	17.0
Mud correction factors	A^{-1}	1.12	1.18	1.27	1.34	1.50	1.74
	B^{-1}	1.09	1.13	1.19	1.24	1.33	1.47
	$\frac{A^{-1} - B^{-1}}{B^{-1}}$ (%)	2.8	4.3	6.6	8.7	12.7	18.5
Cement correction factors	A^{-1}	1.18	1.27	1.40	1.52	1.75	2.11
	B^{-1}	1.14	1.21	1.30	1.38	1.51	1.68
	$\frac{A^{-1} - B^{-1}}{B^{-1}}$ (%)	3.1	4.8	7.8	10.3	15.8	25.6

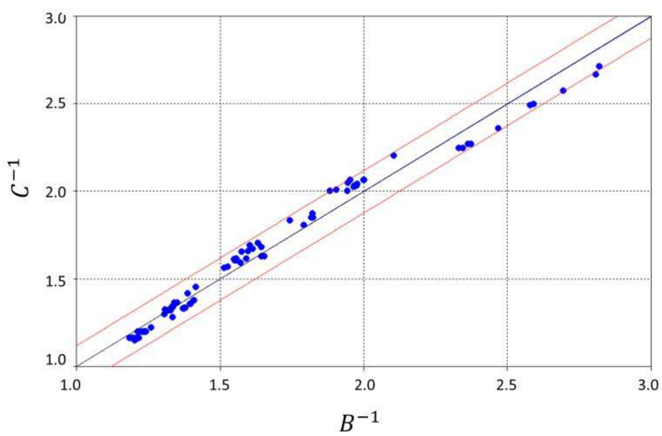

Fig. 4. Correction $\boldsymbol{C^{-1}}$ calculated using (4) versus the correction $\boldsymbol{B^{-1}}$ calculated using MCNP for PVC and aluminum tubes.

F. Influenc of the Tube Thickness

The effect of the tube thickness on the calibration factor has been studied performing simulations for thicknesses of 2, 4, 6, and 8 mm, for a 100-mm-diameter steel tube in a 300-mm-diameter hole when f lling the tube with water, mud, or cement. These simulated conf gurations have also been used to propose new values of the C_1 and C_2 parameters: $C_1 = 0.0030\rho_f \cdot mm^{-1}$ and $C_2 = 0.063, 0.012$, and 0.007 mm^{-1} for steel, aluminum, and PVC, respectively.

The results shown in Table IV indicate that the semiempirical correction given by (1) can overestimate the correction calculated with MCNP by 19% with the original C_1 and C_2 parameters and by 7% with the new proposed parameters.

TABLE IV

CALIBRATION COEFFICIENT K^{MCNP} ($s^{-1} \cdot ppm_U^{-1}$) CALCULATED WITH MCNP FOR A 300-mm BOREHOLE DIAMETER AND VARIOUS FILLING FLUIDS AND STEEL TUBE THICKNESS. THE VALUES INDICATED IN BOLD USE (1) WITH THE NEW PROPOSED C_1 AND C_2 PARAMETER VALUES

Tube thickness (mm)		2	4	6	8
K_{tube}^{MCNP} ($s^{-1} \cdot ppm_U^{-1}$)		4.88	4.32	3.89	3.54
Water correction factors	A^{-1}	1.74	1.87	2.00	2.12
	B^{-1}	1.59	1.79	2.00	2.20
	$\frac{A^{-1}-B^{-1}}{B^{-1}}$ (%)	9.5 **2.6**	4.3 **4.3**	0.1 **5.8**	3.7 **7.2**
Mud correction factors	A^{-1}	1.88	2.01	2.14	2.28
	B^{-1}	1.68	1.90	2.11	2.30
	$\frac{A^{-1}-B^{-1}}{B^{-1}}$ (%)	11.7 **2.6**	6.0 **4.7**	1.4 **6.3**	1.2 **6.7**
Cement correction factors	A^{-1}	2.27	2.43	2.59	2.74
	B^{-1}	1.91	2.14	2.38	2.62
	$\frac{A^{-1}-B^{-1}}{B^{-1}}$ (%)	18.8 **1.1**	13.5 **2.5**	8.7 **4.1**	4.7 **5.4**

IV. MULTIPARAMETRIC STUDY

In an attempt to take into account the possibility that different fuids might be present in the borehole and in the tube and to improve the accuracy of the correction to be applied on $K_{\text{air}}^{\text{meas}}$ and MCNP calculations have been performed for different fuids (air, water, mud, and cement) inside different tubes made of iron, PVC, or aluminum, with a 100-mm diameter and thicknesses of 2, 4, 6 or 8 mm, and inside different boreholes of diameters of 132, 160, 216, or 300 mm.

A multiparametric study has been performed to study correlations between the calibration factor correction and different parameters, including a reduced parameter t define as

$$t = \rho_{\text{ft}}\left(Ø_t^{\text{int}} - Ø_s\right) + \rho_t\left(Ø_t^{\text{ext}} - Ø_t^{\text{int}}\right) + \rho_{\text{fb}}\left(Ø_b - Ø_t^{\text{ext}}\right) \quad (3)$$

where $Ø_t^{\text{int}}$ and $Ø_t^{\text{ext}}$ are the inner and outer diameters of the tube, respectively, ρ_{ft} is the density of the fuid inside the tube, ρ_t is the density of the tube, and ρ_{fb} is the density of the fuid between the borehole and the tube. Parameter t, in units of $g \cdot cm^{-2}$, represents the mass per unit area that photons have to cross from the borehole border before reaching the NGRS probe. For PVC or aluminum tubes, the correction C to be applied on $K_{\text{air}}^{\text{meas}}$ is expressed as

$$C^{-1} = a_0 + a_t t. \quad (4)$$

Fig. 4 shows that this linear correlation gives a good estimation of the "true correction" calculated with MCNP. The residual standard deviation is 0.04 for a range of correction factors extending from 1.2 to 2.8.

In the case of a 100-mm tube, borehole diameters do not exceed 132 mm in the feld and the coeffcients of (4) are $a_0 = 8.9326\text{E-}01$ and $a_t = 2.8889\text{E-}02$ ($g^{-1} \cdot cm^2$), with a residual standard deviation of 0.01 on a range of correction factors between 1.20 and 1.35, which represents an accuracy of about 1%.

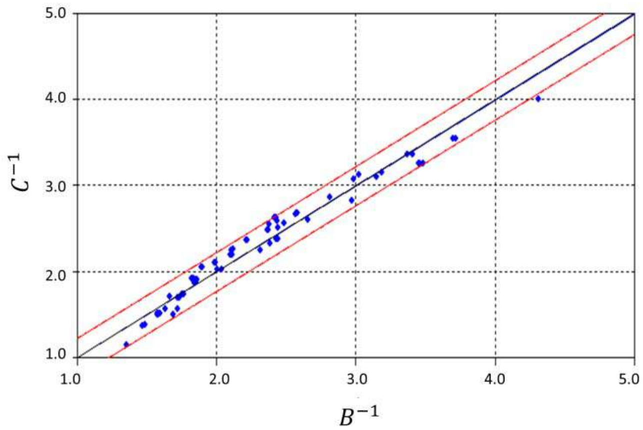

Fig. 5. Correction $\boldsymbol{C^{-1}}$ calculated using (4) versus correction $\boldsymbol{B^{-1}}$ calculated using MCNP for an iron tube.

For steel tubes, photon attenuation is larger and the tube thickness d must also be taken into account to obtain a good linear regression, although it already appears in t. The correction for a steel tube is therefore

$$C^{-1} = a_0 + a_t t + a_d d. \quad (5)$$

Fig. 5 shows that this correlation also gives a good estimation of the correction calculated with MCNP. The residual standard deviation is 0.11 for a large range of correction factors extending from 1.2 to 4.2.

Limiting again the correlation (up) to borehole diameters of 132 mm in the case of 100-mm tubes, the coeffcients of (5) are $a_0 = 8.8122\text{E-}01$, $a_t = 2.6087\text{E-}02$ ($g^{-1} \cdot cm^2$), $a_d = 4.9486\text{E-}01$ (cm^{-1}), with a residual standard deviation of 0.03 on a range of correction factors extending from 1.35 to 2.10, which represents an accuracy of less than 2.2%.

V. CORRECTION FORMULAS APPLIED TO GEIGER COUNTERS

Since Geiger counters are widely used for gross gamma-ray counting due to their robustness and simplicity to use, it is of interest to apply the above-presented corrections on gross gamma-ray counting performed with Geiger counter. To this aim, MCNP calculations have been performed replacing the NGRS probe by a 28-mm diameter Geiger Muller probe. Because of prohibitively long calculation time needed to calculate the Geiger detector response, the type-5 point detector tally has been used to get the gamma-ray fux inside the Geiger Muller tube, instead of using the type-8 energy deposition tally as in the case of the NGRS probe based on a solid-state NaI scintillator. Three bore hole diameters that are commonly used with this kind of probes have been considered, tubing the probe with steel or PVC or using no tubing. The steel tube is 5.5 mm thick and 89-mm diameter, with a density of 7.35 $g \cdot cm^{-3}$, whereas the PVC tube is 1.5 mm thick and 32.9-mm diameter, with a density of 1.38 $g \cdot cm^{-3}$. Comparisons between the corrections calculated with MCNP and obtained using (1), (4), or (5) are presented in Table V, showing that the corrections calculated with the same formula

TABLE V

CALIBRATION COEFFICIENT K^{MCNP} ($\mathrm{s}^{-1} \cdot \mathrm{ppm}_U^{-1}$) FOR GROSS GAMMA-RAY COUNTING EMPLOYING A GEIGER MULLER COUNTER CALCULATED WITH MCNP FOR DIFFERENT BOREHOLES DIAMETERS, FILLING FLUIDS, AND TUBING

$Ø_b$ (mm)		100	100	100	120	120	130	130
Tube		-	steel	PVC	-	steel	-	steel
Water	B^{-1}	1.15	1.49	1.15	1.18	1.56	1.24	1.59
	A^{-1}	1.17	1.41	1.24	1.22	1.47	1.24	1.50
	$\frac{A^{-1}-B^{-1}}{B^{-1}}$ (%)	2.07	-5.19	8.00	2.80	-5.38	0.36	-5.89
	C^{-1}	1.10	1.52	1.10	1.16	1.58	1.19	1.60
	$\frac{C^{-1}-B^{-1}}{B^{-1}}$ (%)	-3.86	2.17	-3.57	-2.03	1.29	-3.83	0.42
Mud	B	1.17	1.52	1.18	1.24	1.61	1.27	1.66
	A	1.20	1.45	1.27	1.26	1.52	1.29	1.55
	$\frac{A^{-1}-B^{-1}}{B^{-1}}$ (%)	2.64	-4.54	7.99	1.95	-5.37	1.68	-6.28
	C	1.14	1.56	1.14	1.21	1.62	1.25	1.65
	$\frac{C^{-1}-B^{-1}}{B^{-1}}$ (%)	-2.49	2.45	-2.82	-1.87	0.80	-1.54	-0.53
Cement	B	1.30	1.64	1.32	1.41	1.77	1.48	1.85
	A	1.30	1.56	1.38	1.39	1.66	1.43	1.71
	$\frac{A^{-1}-B^{-1}}{B^{-1}}$ (%)	0.12	-4.96	3.97	-1.76	-6.43	-3.36	-7.53
	C	1.27	1.65	1.26	1.37	1.74	1.42	1.79
	$\frac{C^{-1}-B^{-1}}{B^{-1}}$ (%)	-2.71	0.86	-4.43	-2.99	-1.67	-3.89	-3.26

parameters as for the NGRS probe are also valid for the Geiger Muller probe. As for NGRS, the multiparametric approach leads to more precise corrections than those of the empirical formula.

VI. CONCLUSION

The MCNP Monte Carlo simulation code has been extensively used to model uranium gamma logging with an NGRS probe. MCNP reproduces with a good accuracy the gross gamma counting measurements performed with the NaI(Tl) gamma scintillator of the probe, such as the calibration coefficie t K ($\mathrm{s}^{-1} \cdot \mathrm{ppm}_U^{-1}$) measured in the calibration facility of Bessines, France, which is used to convert the signal (s^{-1}) in terms of uranium weight fraction (ppm_U): the calibration coefficie t determined by simulation 5.3 $\mathrm{s}^{-1} \cdot \mathrm{ppm}_U^{-1}$ with 10% accuracy is in good agreement with the one measured in Bessines (and for which no uncertainty was provided), 5.2 $\mathrm{s}^{-1} \cdot \mathrm{ppm}_U^{-1}$. The calculations also indicate that the concrete blocks used for measuring the calibration coeff cients measured in Bessines are underestimated by about 10%.

Sensitivity studies have been performed with MCNP, showing that the rock density and mineralogy have a limited influenc on K coeff cient. The uranium concentration induces a signif cant self-absorption effect above a uranium mass fraction of 1%, which leads to an underestimation of the real uranium content up to a factor of 2.6 for 50% of uranium.

The simulation tool has also been used to check the validity of a semiempirical formula used to correct the reference calibration coeff cient measured in Bessines in a tubeless borehole fille with air, for *in situ* gamma-ray attenuation with different fl ids f lling the borehole and the tube, and with different tubes housing the NGRS probe. The discrepancy between the correction calculated with the semiempirical formula and the one calculated with MCNP can reach up to 26%. In order to improve the accuracy of this correction, a multiparametric analysis has been performed with a large series of simulated data, evidencing linear correlations between the correction and different parameters including information on the borehole diameter, density of filli g f uids, tube material, and thickness. This alternative approach leads to an estimation of the calibration coeff cient correction with a precision better than 3%. This approach has also been tested in the case of a Geiger Muller probe, showing that the same formulas can be used for both NGRS and Geiger probes in view to correct for gamma attenuation.

These simulations are the f rst step of a larger study on uranium gamma logging techniques by CEA and AREVA Mines. Gross count gamma-ray measurement indeed may underestimate the quantity of uranium in the case of disequilibrium in the uranium chain due to *in situ* leaching techniques (roll front deposits). For a better assessment of the uranium content, next studies will focus on the use of high energy resolution gamma-ray spectroscopy [11].

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