CALCULATION OF BOREHOLE CORRECTION FACTORS FOR NATURAL g-RAY SPECTRA†

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1. INTRODUCTION

Borehole measurements provide information on subsurface geology. The relative abundances of the natural radionuclides ^{40}K, ^{232}Th and ^{238}U are used to determine formation types (such as sand or clay). Activity concentrations derived from spectral γ-ray measurements even allow for the distinction between several classes of a type (e.g., kaoline or illite). However, borehole characteristics such as the borehole diameter and the presence of casing material will influence the shape and intensity of the recorded γ-ray spectra. For novel tools using large, high-efficiency BGO detectors and full spectrum analysis (Hendriks, 2001), it is not yet known how variations in these characteristics influence the γ-ray spectra. In a joint project of Medusa Explorations B.V., NGD/KVI and TNO-NITG, the effects of various measuring parameters are investigated by means of Monte Carlo simulations. The results show that it is possible to obtain *quantitative* correct results from spectral γ-ray measurements. This is a requirement for the determination of geotechnical parameters such as grain-size and geological parameters such as sediment provenance. The results indicate that one cannot always ignore the change of shape of the γ-ray spectra measured in a borehole as a result of the presence of perturbing effects like casing material and diameter. It is therefore recommended to include these shape- and intensity-variations in the analysis of the gamma spectra. This way, proper account can be taken of the factors perturbing the measurement, thereby improving the quality of the natural γ-ray data.

2. BOREHOLE CONFIGURATIONS

Monte Carlo simulations are a well-established method to calculate the transport of radiation through matter as well as detector responses. The general Monte Carlo code MCNP, version 4C, Briesmeister (2000), is used to model an *in-situ* γ-ray detector. All simulations concern the TNO-NITG detector (serial no. 51AR150/2/HV/E3/BGO/T/X), which has a 5x15cm cylindrical BGO scintillation crystal and a total outer diameter of 7cm. In the calculations an unconsolidated homogenous formation is assumed, consisting of quartz sand and water-filled pores, with a density of 2.15g/cm^3. The γ-radiation is only emitted by the formation, and not by the borehole fluid, casings or the detector. A listing of simulated borehole configurations can be found in Table 1, and the various casing configurations are shown schematically in Figure 1. The counterflush configuration is shown in Figure 6. The borehole diameter is determined by the outer diameter of the casings that are used. For each configuration, the detector response to a pure ^{40}K, ^{232}Th and ^{238}U source were simulated, assuming that the detector is located against the borehole wall or casing. The borehole is filled with pure water.

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Table 1: Simulated configurations for various borehole diameters. Calculated geometries are indicated with an **X**.

borehole diameter (cm)	open hole	Single casing	double casing	Triple casing	Counter flush
15.24	X				X
17.8	X	X			
21.9	X	X	X		
26.7	X	X	X	X	
32.4	X	X	X	X	
50.0	X				
100.0	X				

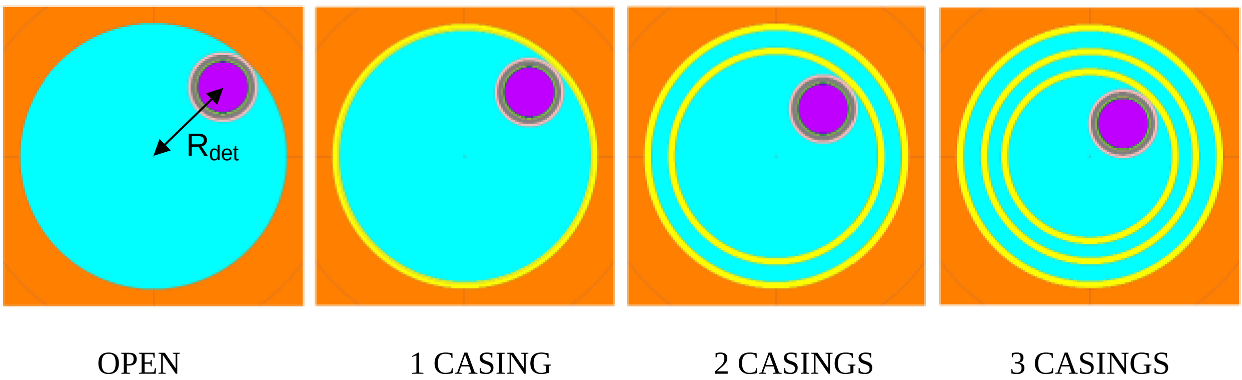

Figure 1: Borehole configurations. All casings (light) are steel, and have a thickness of 7.1mm. The detector is the small dark circle in the upper right-hand corner of the borehole. The outer diameters of the casings correspond to the borehole diameters given in Table 1.

3. RESULTS

A. BOREHOLE CASING

As additional casings are inserted in the borehole, the detector is located at a larger distance to a nearby formation and hence shielded from the sediment by heavy – and thus γ-ray absorbent – steel and additional water between detector and formation. Comparing the intensity of the γ-ray spectrum measured in a cased hole to that of an uncased hole, a reduction is observed that is dependent of the γ-ray energy. An example of this is given in Figure 2 for a ^{40}K spectrum simulated in a 26.7cm borehole for a number of casings. A strong decrease in photopeak intensity (E_{γ} = 1.46MeV) is observed as more γ-rays interact with the medium before reaching the detector, are

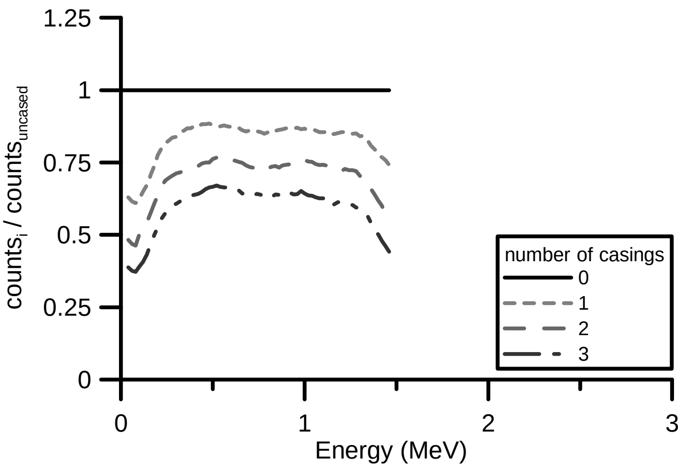

Figure 2: The relative intensity of simulated ^{40}K spectra for a borehole with one, two and three steel casings is given, compared to a configuration without casings. The borehole diameter is 26.7cm.

either absorbed or Compton scattered. This results in a stronger reduction of the photopeak compared to the Compton continuum. At E_γ < 0.5MeV, the spectrum is reduced due the heavy casings which absorb low-energy γ-radiation more effectively. The reduction through increased absorption extends, as expected, to higher energies when more casings are inserted. The spectral intensity for 0.5MeV < E_γ < 1.46MeV is also reduced compared to the uncased configuration but this effect is partly diminished by the difference in the *Z* dependence of Compton scattering and photopeak absorption. The same effects occur for Th and U, but due to the large number of γ-rays emitted, the overall effect is less transparent.

When measurements from cased boreholes are quantitatively analyzed with standard spectra that are determined in an uncased geometry, the standard spectra have to be modified in shape and magnitude to compensate for the presence of casings. The curves in Figure 2 can be approximated by a straight line, resulting in the scaling factors as given in Table 2 for a borehole diameter of 26.7cm. The standard spectra have to multiplied by these factors, or the activity concentrations can be divided by these numbers. As can been seen in Table 2, the effect of adding casings is exponential, for instance, if the effect of one casing is a reduction to 0.86, then two casings reduce the intensity to $(0.86)^2 = 0.74$, and three casings reduce the intensity to $(0.86)^3$=0.63. This can be understood from the transmission of γ-radiation through an absorber, which scales with e^{-t}, with *t* the thickness of the absorber, in this case the distance from borehole wall to detector.

Table 2: Linear scaling factors to compensate for the effects of casing in a 26.7cm borehole. The ^{40}K, ^{232}Th and ^{238}U curves were fitted in the energy range where the functions can be approximated by a constant : 340keV-1.32MeV, 1.06MeV-2.50MeV and 320keV-2.42MeV, respectively.

casings	$\mathbf{R_{det}}$	$\mathbf{^{40}K}$	$\mathbf{^{232}Th}$	$\mathbf{^{238}U}$
0	9.7	1	1	1
1	7.45	0.86	0.85	0.81
2	5.4	0.74	0.70	0.65
3	4.12	0.63	0.61	0.52

In Figure 3, the reduction factors are shown for the most-frequent used borehole diameters.

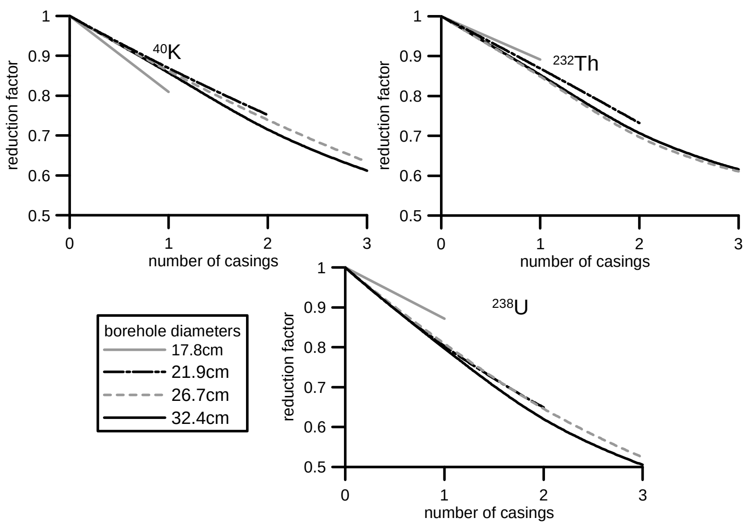

Figure 3: Casing reduction factors per nuclide for various borehole diameters.

The correction factors do not only depend on the number of casings but also on the borehole diameter. As the diameter increases, the diameter of the casings increases in larger steps, thus a detector will be separated from the formation by thicker layers of water (Table 1 lists the outer diameters of the casings). This not only increases the absorption and attenuation of γ-radiation before reaching a detector and therefore higher correction factors are needed for larger borehole diameters. Moreover, the absorption of γ-radiation is energy-dependent and since each nuclide emits γ-ray of specific energies, the casing-correction factors are nuclide specific. For instance as shown in Table 2, the correction for ^{40}K is smaller than those for ^{232}Th and ^{238}U. Since ^{40}K emits radiation with the highest *average* energy it is generally less absorbed by the casing(s). However, the statistical uncertainty in the calculated activity concentrations is reduced if the count-rich low-energy part of the spectrum is included in the data analysis. In that case, a simple linear approximation will not suffice and energy- and nuclide-dependent corrections must be applied.

B. BOREHOLE DIAMETER

Figure 4 shows the intensity of ^{40}K spectra relative to a borehole diameter of 15.24cm for several borehole diameters. The data are smoothed using an 9pt running average to reduce the statistical scatter. The changes in detector response are caused by the radiation ‘seen’ by the detector from the opposite side of the borehole. As the diameter increases, the water thickness between detector and opposite side of the borehole is increased. Two effects play a role: 1) low-energy radiation from the matrix on the opposite side of the hole is increasingly absorbed by water before it reaches the detector reducing the intensity of the low-energy part and 2) radiation with higher energies is scattered and reaches detector with a lower energy. This second effect reduces the intensity in the high-energy part of the spectrum but leads to an increased intensity at lower energies. For small diameters the high-energy attenuation is not very strong yet; for large diameters it is not strong anymore. For intermediate diameters, the intensity at high-energy part is reduced relatively stronger than for lower energies because the second effect effectively causes a shift from high energies to lower energies.

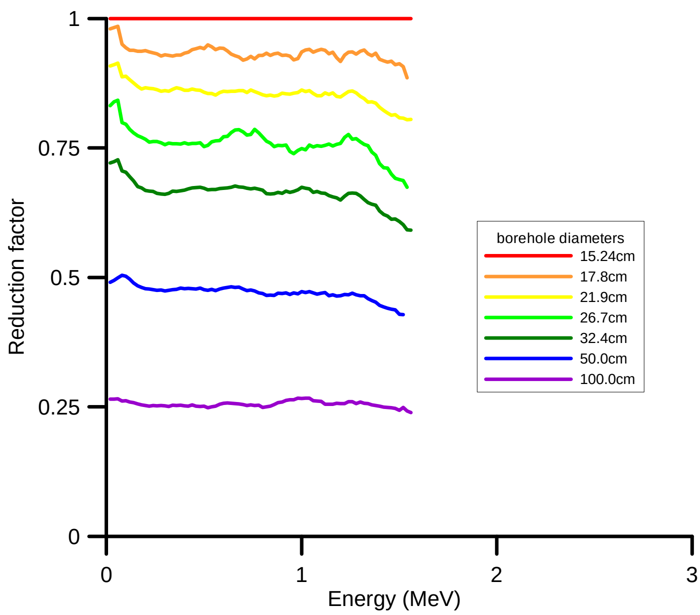

Figure 4: Relative ^{40}K spectral intensities for various borehole diameters with respect to a 15.24cm diameter.

Similar to the assessment of reduction factors for borehole casings the spectral correction for borehole diameter can be approximated by a constant. Fitting the data in Figure 4 in the same energy windows as for the casing correction, the reduction factors to correct the standard spectra for borehole diameter are found. The results are graphically shown in Figure 5. The drawn line is a smooth spline through the data points. The deviations from a smooth curve at smaller diameters are caused by the approximation of the reduction function by a constant.

For very large diameters the reduction factor will asymptotically reach a value of 0.2. This asymptotic value corresponds to a underwater flat-bed geometry. For small diameters, the slope of the correction is steep, indicating the need for accurate caliper measurements.

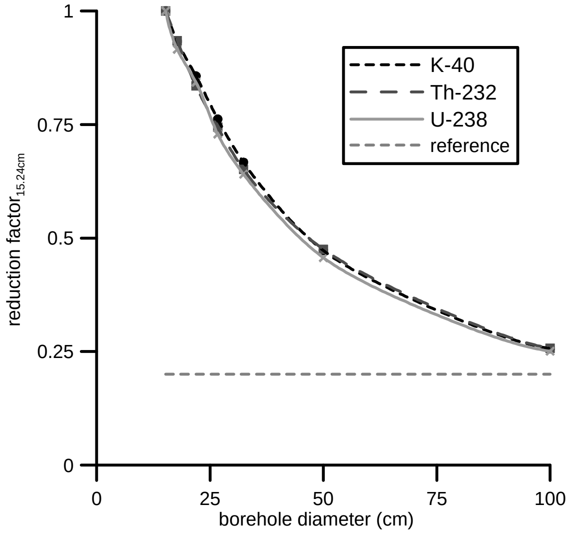

Figure 5: Spectra intensity reduction coefficients to compensate for borehole diameters compared to a 15.24cm borehole.

4. EXPERIMENTAL VALIDATION

In a case study, natural gamma ray spectra were collected in a borehole in Vollenhove, the Netherlands. The first measurements were done by TNO-NITG in a double-cased counterflush system (see Figure 6) still present in the borehole, and a second run was conducted in the open borehole after removal of the counterflush system.

The acquired γ-ray spectra are analyzed in the following ways:

1. Using the TNO-NITG standard spectra. These spectra are determined in the KVI calibration drums for uncased boreholes with a diameter of 10cm. These are the spectra routinely used for analyzing natural γ-ray spectra at TNO-NITG.
2. Using Monte Carlo-simulated standard spectra containing energy-dependent corrections for borehole diameter and casing.

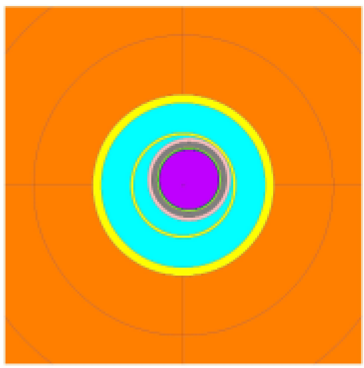

Figure 6 : Counterflush geometry. The borehole diameter is 15.24cm. The outer steel casing is 0.71cm thick, the inner is 0.25cm.

As an example the calculated ^{40}K concentration-profiles are given in Figure 7, for both cased and open borehole. The data represent a running average over 10s at a logging speed of 2 minutes/meter. The depth information from both runs is not synchronized causing small mismatches in locations, towards both higher and lower positions. The top panel shows the results for analysis using the TNO-NITG standard-spectra for the open and the cased boreholes. These figures represent the current “state of the art” data analysis: one set of standard spectra is used for all borehole configurations. The results show that for the open and cased boreholes different radionuclide concentrations in the geological matrix are obtained. Such a result is physically unrealistic and indicates that borehole configurations have to be included in the analysis.

The concentrations in the bottom panel are calculated using two sets of simulated standard spectra, one set for uncased boreholes, another for cased boreholes. Since these spectra take the spectral changes induced by the stainless steel tubing of the counterflush system into account, quantitative results are obtained, and the results should be the same. As one notices the two curves are within the statistical and experimental uncertainties identical.

Moreover, a strong difference in absolute concentrations between is observed between analysis with the TNO-NITG standard spectra and simulated spectra. The TNO-NITG spectra are determined in a dry borehole with a 11cm diameter, but the actual measurements were conducted in a wet borehole with a 15.24cm diameter. The standard spectra lack self-absorption and have therefore its amplitudes are too large. Applying such standard spectra results an *underestimate* of the activity concentrations.

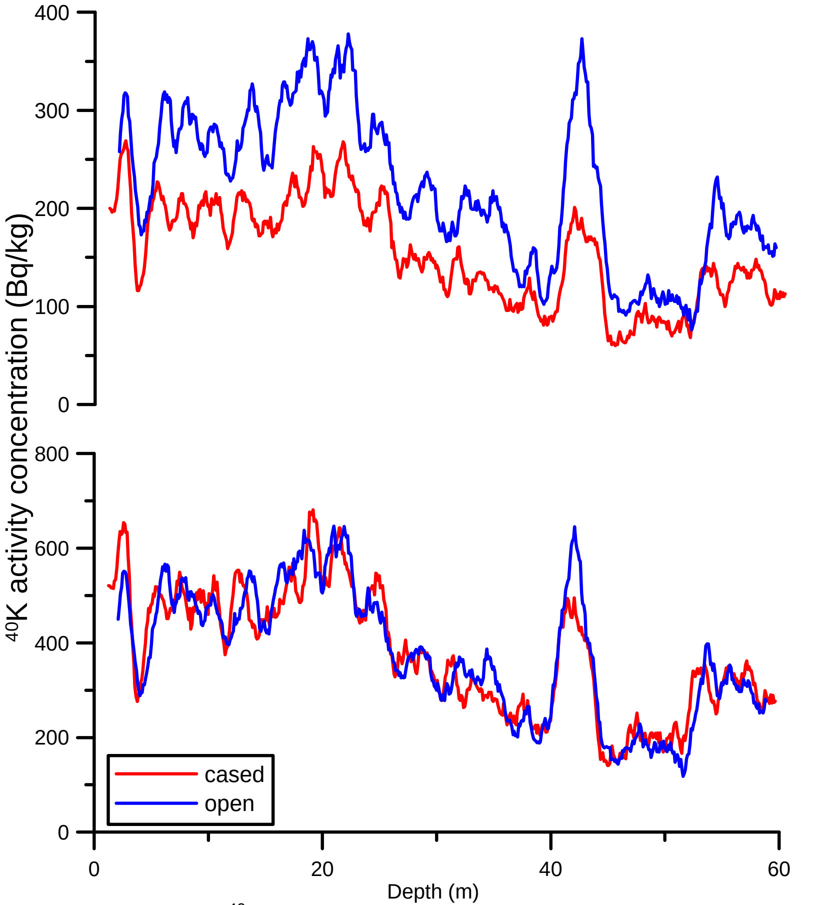

Figure 7: Calculated ^{40}K of the borehole in Vollenhove, the Netherlands. The concentrations in the top panel are based on analysis using the routinely used TNO-NITG standard spectra, the data in the bottom panel is based on simulated standard spectra.

5. SUMMARY

To get correct quantitative results from borehole γ-ray measurements, the proper borehole configuration of the measurements has to be included in the data analysis. The results presented in this paper for measurements in a borehole with and without steel casing underlined this need again. For large, high-efficiency γ-ray detectors, these factors were unknown until now. Employing simulated standard-spectra for data analysis gives reliable *quantitative* activity concentrations, regardless of the configuration, which is a requirement for absolute comparisons of data collected in different borehole configurations and for the determination of geotechnical- and geological parameters from natural γ-ray measurements.

We like to thank TNO-NITG for making the borehole data available to us.

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