Towards better borehole logs

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SUMMARY

Borehole properties such as diameter, fluid, casing and probe diameter strongly influence the outcome of gamma ray borehole logging. To properly interrelate gammaray data from different boreholes, one should carefully correct the data for these properties. In this article, we present computersimulation-based correction models that allow for a quantitative full-scale correction of borehole data, taken with probes of different sizes and make.

We show for instance that formation density virtually does not affect the activity concentrations found in gammaray borehole logs.. Borehole diameter does not affect the data for an air filled borehole. However, the presence of borehole fluid does have a significant effect which depends on the density of the borehole fluid and the diameters of both the borehole and the probe. Correction formulae have been retrieved for three radio nuclides (^{40}K, ^{238}U and ^{232}Th) both for the probe in the centre and against the wall of the borehole.

Casing between the borehole and the formation has an effect similar to that of borehole fluid. It is shown that it is possible to correct for the effects of casing using the same formulae that can be used to correct for the presence of borehole fluid.

We have tested the models found on measurements with both a BGO and a NaWEprobe in the Grand Junction and AMDEL (Adelaide) calibration pits, and find excellent agreement between listed and measured activities. This allows for “local” calibration to be applied “globally”.

INTRODUCTION

Various types of scintillator-based spectral gamma probes are being used now-a-days to measure ^{40}K, ^{238}U and ^{232}Th concentrations in boreholes. To get a quantified measurement of the activity concentrations, a probe needs to be calibrated carefully. Typically, this is done by placing the probe in pit with well-known activity concentrations and geometry. This evidently yields a tool ready for use in borehole of similar geometry. However, without proper correction, However, for borehole environments that do not match the calibration borehole, the measured nuclide activity concentrations need to be corrected.

The Schlumberger work (2009) includes charts that provide correction factors for variations in borehole diameter, fluid density and casing thickness, which have been determined by experiment for borehole probes with two different diameters. As a result, these charts are only useable for a limited number of situations.

Hendriks (2003) provides correction formulae based on a large set of Monte Carlo simulations, but due to limited computer resources at that time, the authors were forced to restrict their simulations to a relatively small set of parameters while only changing one borehole parameter at a time.

Van der Graaf et al (2011) describe the mechanism how to translate the calibration of a scintillation detector from one environment to another environment by comparing the results from Monte Carlo simulations for both environments. The same method can also be applied for a whole range of different environments. Our article here summarizes over 500 full spectrum simulations that we have run using the MCNPX code (Pelowitz, 2005) in an effort to get a better understanding of the various parameters involved in borehole logging. The involved parameters include:

- Probe diameter from 0.5” to 3.4”;
- Borehole diameter from 1” to 12”;
- Casing thickness up to 25 mm steel or 100 mm PVC;
- Formation density from 1 to 2.65 kg/l;
- Borehole filled with air or 1 kg/l to 2 kg/l bentonite ‘mud’.

All simulations ran for at least 3 hours on a desktop computer and produced an spectrum in the range between 0 and 3 MeV in bins of 10 keV for each of the three radio nuclides (^{40}K, ^{238}U and ^{232}Th). In most cases, changing one of the borehole parameters has an almost linear effect over all the energy bins above 300 keV. Therefore, in most cases only the sum of the bins above 300 keV is being discussed.

EFFECTS OF FORMATION DENSITY

Hendriks (2003) finds that the formation density has a significant effect on the count rate, where an increase in the density would result in an increasing probability for a gamma particle to be registered by the detector. Hendriks attributes this to a combination of the change in geometry and the effects of changing water content.

To verify these results, a series of Monte Carlo models were run assuming a cylindrical BGO detector 50x150mm, located in an ‘infinite’ (1m radius) source. The borehole in the model has a diameter of 70mm and is filled with water. The borehole and the probe are identical to the model used by Hendriks. The formation is modelled with various densities, either as either pure SiO_2, or as a mixture of SiO_2 and water. For the latter set, the SiO_2 is considered to have a density 2.65 kg/l, and water 1.00 kg/l. The ratio between SiO_2 and water is such as to get the desired average density. Results for both sets are shown in figure 1 below.

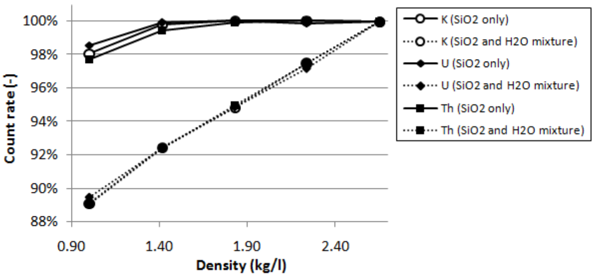

Figure 1. Count rate as a function of density for K, U and Th in both a pure SiO2 and a SiO2/water mixture matrix. Count rates are normalized to the situation with 2.65 kg/l density.

Contrary to the results from the simulations run by Hendriks, we only found a limited decrease in the count rate for decreasing formation densities for the "dry" situation (pore space empty), solid lines in figure 1. We attribute the small drop in count rate below 1.4 to a too-small source model of 100cm radius. Low formation density results in less absorption of radiation. The detector might "see" outside the 100cm – in other words, the simulated source in this case is not an infinite one. Since Hendriks uses only a 50 cm radius model as "infinite" source in his simulations, his results are deviating even stronger than ours. His conclusion of density affecting count rate is therefore wrong.

The second set of Monte Carlo simulations with changing density assumes the pore space in the SiO_2 matrix to be filled with water. The result is not only a change in density, but also in composition of the formation. Most notable is an increase in the average number of electrons per nucleon due to the introduction of hydrogen. As a result, the cross section for photon attenuation will increase when the formation density decreases (Storm and Israel, 1970), which leads to a higher probability for gamma radiation to be absorbed. This effect is visible in Figure 1 as the dotted lines. For all three radio nuclides, the drop in count rate is more than 10% when the formation is changed from 1 kg/l SiO_2 to pure water.

EFFECTS OF BOREHOLE DIAMETER

To estimate the effects of the borehole diameter on the count rate of a borehole probe, we created a set of Monte Carlo models with again a 50x150 mm BGO crystal placed in the centre of boreholes with various diameters. The borehole is empty, so no absorption occurs inside the borehole, and effects, if any are solely coming from the change in geometry. The formation is basically infinite, but was limited in the models to a 400 cm long cylinder with a 80 cm radius.

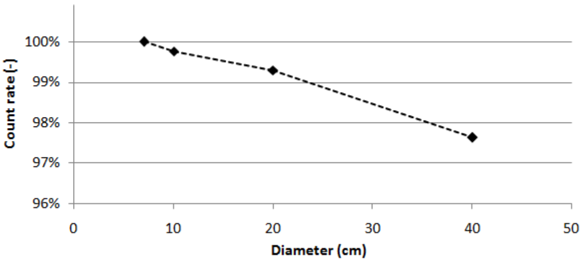

Figure 2: Count rate in the ^{232}Th spectrum above 300 keV as a function of borehole diameter. Count rates are normalized to the count rate for a borehole diameter of 7 cm.

Similar to Hendriks (2003), we find a slightly decreasing count rate as the borehole diameter increases (figure 2) However, to much less extent than Hendriks who finds a drop in the count rate of around 30% for a borehole diameter of 40 cm. We attribute the observed decrease in count rate again to be a result of the Monte Carlo model not fully representing an infinite formation.

The diameter not having an influence on the count rate also implies that the gamma-ray flux at any point inside the borehole is unaffected by the borehole diameter. For an infinite formation without a borehole, particle production and absorption is in equilibrium everywhere, and the flux is constant over the complete volume. For an empty (vacuum filled) borehole, there is no absorption inside the borehole, and the flux at any point inside the borehole should be identical to that on the wall of the borehole. At each point on the wall, the flux going out of the formation into the borehole is therefore equal to the flux going from the borehole into the formation. In other words, flux is not affected by the borehole, which is in agreement with the results from the Monte Carlo simulations.

ATTENUATION BY BOREHOLE FLUID

Although the borehole diameter of an empty (vacuum) borehole does not affect the count rate, it is expected that filling it with borehole fluid will cause a drop in the count rate. The fluid will remove gamma particles through absorption, while not introducing new particles.

In order to estimate the effects of absorption, we designed many Monte Carlo models to simulate the effect of several parameters. Parameters varied include fluid density, borehole diameter and also the diameter of the probe. Schlumberger (2009) combine these parameters into a variable t:

$$\boldsymbol{t = W \cdot \frac{d_h - d_t}{2}}, \qquad (1)$$

where W is the density of the borehole fluid in g/cm^3 and d_h and d_t are the borehole and probe diameter in cm.

Schlumberger presents charts with correction curves for probes with two different diameters both for the probe centred in the borehole and for the probe positioned against the wall.

For the Monte Carlo simulations, we made models with six different values of d_t (up to 3.4” diameter), seven values of d_h (op to 12”), and four values of W. Each possible combination where the $d_t \leq d_h$ was run six times, for each nuclide ^{40}K, ^{238}U and ^{232}Th with the probe both centred and against the wall. The borehole fluid modelled is either air ($W = 1.29 \cdot 10^{-3}$ g/cm^3) or a water / bentonite mixture, where bentonite was modelled as pure SiO_2 with a matrix density of 2.65 g/cm^3. With water modelled as H_2O with density 1.00 g/cm^3, the resulting mixture has values of W ranging from 1.0 (pure water) to 1.4 g/cm^3.

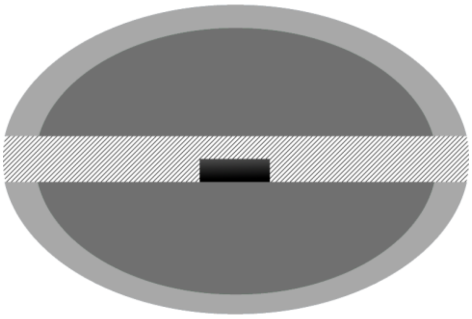

Figure 3: Cross section of the Monte Carlo model (not to scale) with the detector (black) against the wall of the borehole (hatched). The formation (grey) is only partially modelled as a source of gamma radiation (dark grey).

The modelled detector is a simple NaI crystal with variable diameter and a length of 4". The modelled volume is restricted by an ellipsoid of 120x120x180 cm. Surrounding this ellipsoid is another ellipsoid of 140x140x210 cm (see figure 3), which has the same material properties, but is not a source of gamma particles. The longest axis of the ellipsoids is also the centre of the borehole.

The result of each simulation is a spectrum which the detector would collect for a 1 Bq/kg activity in the formation. From this spectrum, we have determined a count rate for the 0.3 to 3.0 MeV range. As expected, the collected count rate decreases for increasing values of t. Similar to the approach by Schlumberger (2009), we have determined a correction factor F for each situation, which is defined as the count rate in the $t = 0$ situation divided over the count rate in this specific situation. Figure 4 shows F as a function of t for different probe diameters where the count rate was calculated over the 300 keV to 3 MeV range in the ^{238}U spectrum in the case of the probe being positioned in the centre of the borehole. The dotted lines show a least-squares best fit according to the equation

$$\boldsymbol{F = (c_0 + c_1 d_t t) \cdot e^{c_2 t}}, \tag{2}$$

where c_i are constants determined in the best fit process. The curves for ^{40}K and ^{232}Th show comparable results although with a slightly different slope.

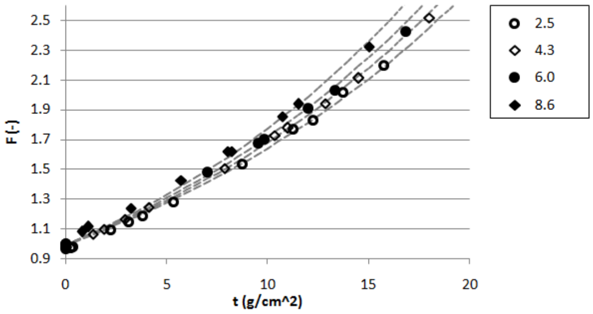

Figure 4: Correction values *F* required to convert the observed count rate back to the count rate at *t* = 0 (i.e. a borehole without fluid) for count rates in the 0.3 tot 3.0 MeV energy range of the ^{238}U spectrum when the probe is centred in the borehole. Dotted lines indicate the best fit.

From figure 4, it is obvious that larger probe diameters require larger correction values for increasing values of t, but it should be noted that a larger probe inside a specific borehole yields a smaller value of t (equation 1). For the two probe diameters in the correction charts by Schlumberger (2009), the largest probe diameter also has the largest correction factor F.

When the detector is positioned against the wall of the borehole, it is expected that the attenuation by the borehole fluid is less than when the detector is positioned in the centre of the borehole, since the fluid barely attenuates radiation coming from the side where the detector touches the wall.

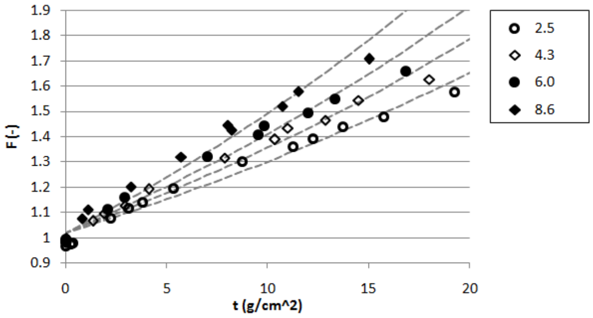

Figure 5: Correction values *F* required to convert the observed count rate back to the count rate at *t* = 0 (i.e. a vacuum filled borehole) for count rates in the 0.3 tot 3.0 MeV energy range of the ^{238}U spectrum when the probe is located against the wall of the borehole. Dotted lines indicate a best fit.

Figure 5 shows the relationship between the required correction factor F and the variable t for different probe diameters when the probe is positioned against the wall of the borehole. As expected, larger values of t require larger correction values, but F is always smaller than with the detector positioned in the centre of the borehole. As before, a combination of probe diameter d_t and t appear to a good indication for the required correction factor, but the correlation is less a fluid line. Nevertheless, a best fit following equation (2) yields a good approximation of the required correction value.

The Monte Carlo simulations returned full spectrum data. When applying F to each 10 keV bin in these simulated spectra, the corrected contents for the bins fall within the uncertainty of the simulation. The correction factor F therefore not only applies to the count rate but also to the complete spectrum. Figure 6 illustrates this by showing the uncorrected and corrected ^{232}Th spectra for two different boreholes for a probe with 1” diameter. After correction, there is not much difference between the spectra.

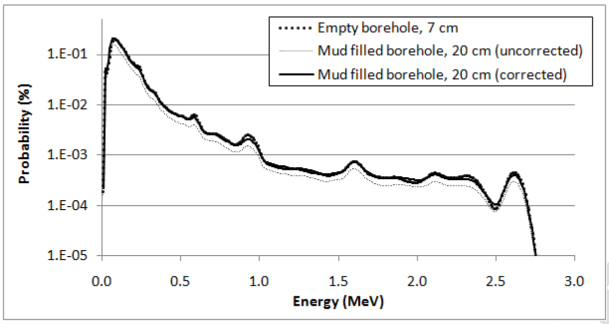

Figure 6: ^{232}Th spectra from simulations for a 1” diameter probe positioned against the wall of the borehole. One spectrum is for an empty (vacuum) borehole of 7 cm diameter, which does not need correction (F = 1). The other spectra are for the same probe, but in a 20 cm diameter borehole filled with bentonite mud with a density of 1.4 kg/l. After correction (F = 1.43), this spectrum is almost identical to the spectrum for the empty borehole.

ATTENUATION BY CASING

Steel or PVC casing between the formation and the borehole will absorb some of the radiation from the formation which causes a reduction of the measured count rate. A set of Monte Carlo models has been run to estimate the effect of casing thickness on the collected count rate. As before, the count rate is determined from spectra in the 0.3 to 3.0 MeV range.

In this approach a steel casing was modelled with a fixed thickness of 0.1 mm and a fictional density ranging from 80 to 640 kg/l, corresponding to steel casings with density 8 kg/l and ranging in thickness from 1 to 8 mm. Using this approach, we made sure any effects on the collected spectrum are caused by absorption in the casing, and not by a change in the geometry.

Figure 7 shows the relative count rate as a function of the apparent casing thickness.

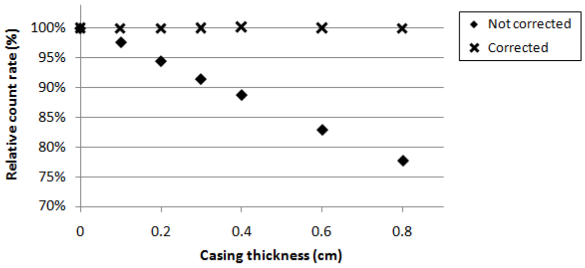

Figure 7: Count rate in the ^{40}K spectrum as a function of casing thickness before correction (squares) and after correction (crosses). The count rate is relative to the count rate observed when no casing is present.

Since a steel casing and borehole fluid are comparable in a sense that both can be regarded as a hollow cylinder of absorbing material between the formation and the detector, the correction equations determined to correct for the absorption by borehole fluid can be applied to correct for the steel casing as well. The variable t in equation (2) can now be determined as

$$\boldsymbol{t = W \cdot d_c}, \qquad (3)$$

where W is the density of the casing in kg/l and d_c is the thickness of the casing in cm.

When applying the correction equations with the parameters c_i as determined before, the result is remarkably good, as shown in figure 6. For all three radio nuclides, and for all modelled casing thicknesses, the corrected count rate is within 2% of the count rate found for the simulation where no casing is modelled.

CALIBRATION PITS COMPARED

By applying borehole corrections it is possible to compensate for differences in boreholes, which makes it possible to compare measurements from different boreholes, including different calibration pits. We have calibrated many borehole probes using the Medusa Stonehenge calibration set-up, and one of these probes, containing a 1” diameter, 4” long BGO crystal, has also recorded spectra in the calibration facilities in Grand Junction, USA (Leino et al, 1994) and at the AMDEL AM-6 calibration pits in Adelaide, Australia.

The borehole probe has been calibrated using the method described by Van der Graaf et al (2011). During the calibration, a measurement was performed at the Medusa Stonehenge set-up, which is a large semi-infinite brick castle with known activity concentrations. A Monte Carlo model was made of the probe inside this set-up, including the housing and all major components of the probe. The result of the Monte Carlo simulations are theoretical histograms which an ideal detector with perfect resolution would record. During the calibration process, the histograms are Gaussian broadened and corrected for efficiency, offset and a-linearity of the probe. The result is a set of so called ‘standard spectra’, spectra that the calibrated probe would record in a Stonehenge like environment with 1 Bq/kg of ^{40}K, ^{238}U or ^{232}Th.

The spectra recorded by the probe in Grand Junction and Adelaide have been analyzed using Full Spectrum Analysis using the standard spectra obtained during the Stonehenge calibration. When borehole corrections for casing and borehole fluid have been applied, absolute activity concentrations for the calibration pits can be obtained. The results of these measurements are shown in tables 2 and 3, along with the activity concentrations listed for these pits.

Pit	**Listed**	**Before correction**	**After correction**
^{40}K	5.34 %	4.14 %	5.14 %
^{238}U	421 ppm	321 ppm	441 ppm
^{232}Th	413 ppm	316 ppm	422 ppm

Table 2: Activity concentrations in % or ppm for three Grand Junction pits.

Zone	**Listed**	**Before correction**	**After correction**
^{40}K	4.52 %	3.70 %	4.04 %
^{238}U	31.8 ppm	28.3 ppm	32.9 ppm
^{232}Th	60.9 ppm	50.2 ppm	57.6 ppm

Table 3: Activity concentrations in % or ppm for three zones in the AMDEL AM-6.

From the activity concentrations in tables 2 and 3, it is apparent that uncorrected measurements do not correspond to the listed values. After correction, the activity concentrations correspond much better. The differences between listed and corrected values can be attributed to uncertainties in both listed and measured values, but effects of possible changes to the hardware between calibration and measurement cannot be excluded.

CONCLUSIONS

Based on the results of the Monte Carlo simulations, it appears that borehole diameter, probe diameter, borehole fluid and casing thickness have a significant effect on the observed gamma spectrum. The effects are mostly evenly distributed in the energy range above 300 keV, in a sense that each channel has the same relative reduction in the count rate. Therefore it is possible to express the effects of absorption by the reduction in the count rate in the range above 300 keV.

It appears that the formation density and the diameter of an empty (vacuum) borehole do not significantly affect the count rate. A borehole filled with water or borehole fluid reduces the collected count rate, but can be corrected for. The amount of material between the probe and the wall of the borehole can be expressed as a variable *t*, which together with the diameter of the probe provides a solid relationship with the observed reduction in count rate.

With a set of six correction formulae, one for each of the three radio nuclides and two probe position combinations, it is possible to correct for the absorption of radiation by borehole fluid.

The same set of formulae used for borehole fluid correction can also be applied to correct for absorption by casing between the formation and the borehole.

By combining the correction factors for borehole fluid and casing with a calibration as described by Van der Graaf et al (2011), it is possible to determine absolute activity concentrations for ^{40}K, ^{238}U and ^{232}Th in any borehole which has parameters within the boundaries for which the correction formulae apply.

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