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Borehole Logging Application Note 1:

Elimination of the Z-effect in Gamma Logging for Uranium

Summary. This application note reviews the basics of gamma-ray logging for uranium. It seeks to explain the so-called "Z-effect" and how it can be eliminated with proper probe design. For a conventional total gamma logging tool, response is proportional to uranium grade to about 0.5 percent U content. For higher grades, even with proper correction for electronics effects, such as dead time, the response is less than expected for proportionality. This is called the Z-effect and it complicates the calibration of such probes for high U grades, and renders the calibration less accurate than if the response was linear. Here we explain how the proportional range of a total gamma probe can be extended by a factor of 20 or more, to grades as high as 10 percent, by adding a properly designed mechanical filter to the probe's detector. Delta Epsilon Instruments Company and the IFG Corporation are jointly developing such a filtered probe. The design is based on computer simulations done with the Monte Carlo code MCNP. The filtered probe is expected to be available to the logging industry in late 2008.

Gamma logs and the Z-effect. Gamma-ray logging for uranium grade has been in use for many years, since the 1950's. The fundamental principle of this log is that detector response to the gamma rays emitted by U is proportional to the mass fraction of uranium in the earth formation surrounding the borehole. Radiation transport theory shows that this is the case to the extent that the composition of the earth formation is "well-behaved" in a gamma transport sense. For uranium logging, another way of saying this is that probe response will be proportional to U grade as long as the U does not perturb the gamma transport properties of the formation. In particular, to preserve the proportionality between U grade and detector gamma response, the effective atomic number Z_{eff} must be near constant. The deviation from proportionality caused by changes in Z_{eff} is called the "Z-effect" and is due to strong variation in gamma absorption as formation Z changes. The onset and importance of the Z-effect depends on the energy range of detected gamma rays, being most serious at low energies, and also on the atomic number Z of the element or elements responsible for Z_{eff} changes in a formation mixture.

Theory shows that the absorption of gammas at low energies increases approximately as the 4.5 power of Z, a very strong Z dependence indeed. And theory also shows that this Z-effect absorption of gammas varies inversely with gamma energy to the 3rd power, also a very strong dependence.

For most formations Z_{eff} is about 12. The Z of iron is 26. Therefore, for Fe-rich formations Z_{eff} will be much higher than 12 and there will be significant low energy absorption of gamma rays. There are "selective gamma-gamma" probes that exploit this effect at low energies as an iron or other heavy metal indicator. The Z of uranium is 92, so when uranium nears the percent concentration range, Z_{eff} is much higher than 12, and there is an effect similar to iron, but with lower concentrations since Z is so much larger. Z_{eff} is near constant for U concentrations of less than about 0.2%. For higher U grades, effective Z increases due to its high Z value.

Uranium, with a Z of 92, has the largest impact of all chemical elements on Z_{eff}. When logging earth formations having U grade of 0.5 weight percent or higher, the detector response is noticeably less than expected for a linear, or proportional, response. The loss of linearity becomes more serious as grade increases above this 0.5 percent level.

Electron density (Z/A) effect. The proportionality between U grade and detector gamma response is affected to a lesser extent by deviation from a constant relationship between formation mass density and electron density. Electron density is proportional to mass density times the effective ratio of Z/A. Therefore, the proportionality to mass density is preserved when the effective ratio of atomic number to atomic mass $(Z/A)_{eff}$ is constant. Two factors cause changes in the formation $(Z/A)_{eff}$: the water content, and major concentrations of U or other heavy elements such as Pb. The water content affects formation Z/A because H in water has a Z/A of unity, while most other elements encountered in earth formations have a Z/A close to or equal to 0.5 (O, C, Si, Ca). Heavy elements, such as Pb and U, have Z/A values of about 0.4. The effect of changing moisture content on the proportional response to U grade is small, however, and can be neglected in almost all cases (this statement presumes that probe calibration has been performed on the basis of in-situ wet U grade). High U grades will decrease $(Z/A)_{eff}$ only slightly.

Sometimes Mg, Al, K, S, and Fe are major constituents of the formation, depending on mineralogy of the rocks. These elements have Z/A near or equal to 0.5 and so do not significantly affect $(Z/A)_{eff}$.

Relation of gamma attenuation processes to Z- and (Z/A)- effects. There are three basic gamma interactions with matter: 1) the photoelectric absorption by inner shell atomic electrons, 2) Compton scattering from atomic electrons, and 3) pair production in vicinity of atomic nucleus. Mechanism 1 determines the Z-effect; and mechanism 2 depends on (mass density)*$(Z/A)_{eff}$ and is responsible for the linear relation between probe response and U grade. Mechanism 3 has a high energy threshold and is not important to gamma logging. Figure 1 shows the three gamma interaction processes for a typical sandstone formation. Each curve is the fractional contribution of that mechanism to the total gamma attenuation or cross section as a function of gamma energy. The photoelectric absorption is about 10 percent of the total at 0.1 MeV. In the energy range above 0.1 MeV gamma attenuation by compton scattering from atomic electrons is dominant. Pair production is not important for gamma logging because the onset energy is very high, higher than most of the source energies from K, U and Th in earth formations. The Z-effect, due to photoelectric absorption, is not important to total gamma probe response for normal formations for energies greater than about 0.05 MeV.

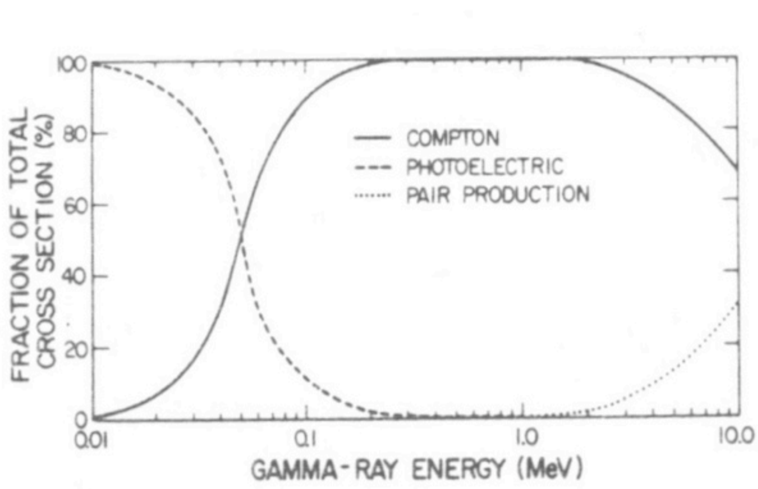

Figure 1. From M. Evans et al, Transport of Gamma Rays, Nucl. Instr. and Meth., p. 590, as taken from Gamma Logging Training Seminar held in Grand Junction, CO, December 2007.

Compton scattering is the dominant attenuation process for gammas reaching the borehole. Figure 1 shows that compton scattering is responsible for 100 % of gamma attenuation for gamma energies from about 0.1 MeV to 3 MeV. Fortunately, $(Z/A)_{eff}$ varies little with formation composition or with U grade, ensuring a linear response of the probe for this energy range. That is, Compton scattering decreases in proportion to mass density so that for a constant amount of U in g/cm^3 there will be a proportional increase in gamma flux at the borehole as U grade, expressed as a mass fraction, increases.

Effect of U grade on probe linearity. The magnitude of the Z-effect on probe linearity at high U grades is highly dependent on the detected gamma energy. For a total gamma probe, utilizing a scintillation detector such as NaI or CsI, about 90 percent of detected gammas have energies less than 0.4 MeV. For a nominal earth formation, with low U concentration, the Z-effect is not important, but because of the low detection energies, at high U grades the Z-effect is significant.

As U grade increases to about the 0.5 % level, the fractional photoelectric effect contribution curve of Figure 1 is modified, and becomes more important at the low energies, such that nonlinearity in the probe response in the energy range below 0.4 MeV becomes significant. This is commonly called the probe Z-effect. Figure 2 illustrates the Z- and Z/A- effects as a function of gamma source energy. The plotted points are the ratio of fluxes (for unit gamma source in the formation) for the stated grade divided by the corresponding flux for the same unit source strength when the formation contains no uranium. At a grade of 6 % the Z-effect from photoelectric absorption is large at low energies (flux ratio decreases sharply from unity). For an energy of 0.4 MeV the ratio is about 0.8. At energies above about 1 MeV compton scattering dominates and the Z/A-effect produces a near constant ratio of about 0.97. For energies below 0.4 MeV, where 90 percent of counts from a normal total gamma probe are obtained, the flux reduction ratio will be much larger. The detectors are much more efficient from 0.1 to 0.2 MeV than at 0.4 MeV, and there are more gammas at these energies in the borehole, so that the Z-effect on total count rate will be very large at high grades. Simulations have shown that the count rates at 5 % U can be less by a factor of 2 than is expected on the basis of a linear or proportional response.

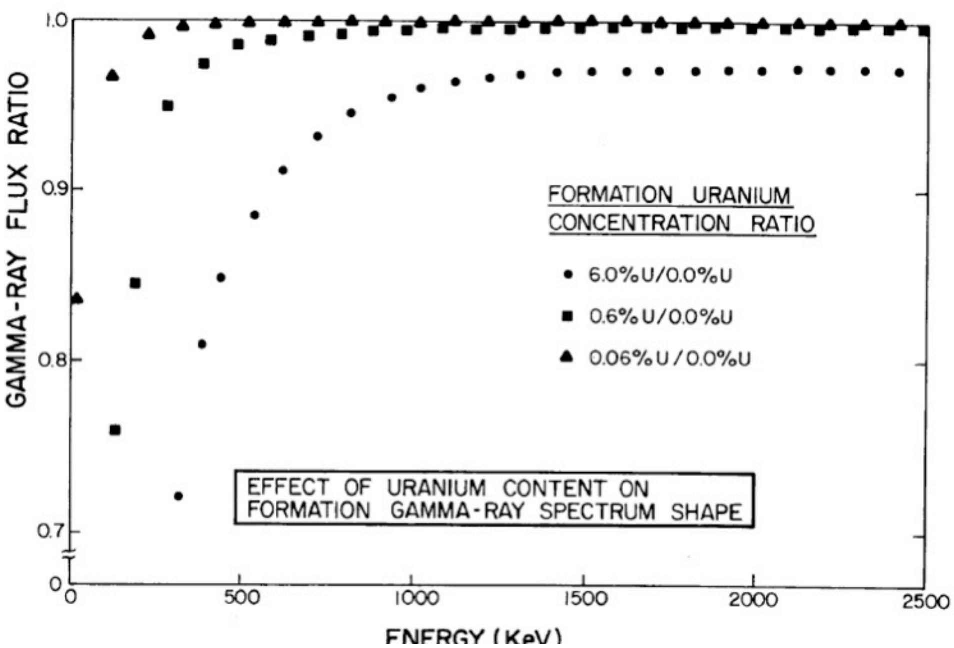

Figure 2. Flux ratio plots based on simulations by Los Alamos National Laboratory showing the so-called Z- and (Z/A)- effects from U concentration in sandstone (from GammaRayWorkshop1981.pdf, technical note 9 of Gamma Ray Logging Studies as taken from Gamma Logging Training Seminar held in Grand Junction, CO, December 2007).

Elimination of Z-effect with mechanical filter. There are two ways to reduce the Z-effect on probe response. One is to electronically discriminate pulses corresponding to energies below some cut-off voltage, and the other is to surround the detector with a gamma absorber that absorbs most of the lower energy gammas before they reach the detector. The electronic method has the serious disadvantage of requiring high electronic gain stability for all count rates and temperatures encountered. It also does not actually absorb low energy gammas and so detector count rates will be very high at high grades, leading to count-rate induced errors. Method two, originally proposed and demonstrated by Dodd and Eschliman (1972) uses what is called a mechanical filter, and is a better way to eliminate the Z-effect. However, it will not absorb all low energy gammas. If properly constructed, and with proper thickness, the filter can eliminate a large fraction of the gammas below about 1-MeV energy. The result is a probe with near proportional response to U grades as high as 10 percent.

IFG Corporation and Delta Epsilon Instruments are together developing a filtered gamma logging probe that provides a near linear response to high uranium grades. The design is based on Monte Carlo simulations with the code MCNP. The simulations produce a detected pulse-height spectrum for a equilibrium U source in the formation surrounding a borehole. The filter design study with MCNP has produced a probe design with total count response that is near proportional to grades up to 10% U. This probe should be available to the uranium logging industry later this year, 2008.

References:

Dodd, P.H. and Eschliman, D.H., *Borehole logging techniques for uranium exploration and evaluation*; in Uranium Prospecting Handbook, S.H.U. Bowie, M. Davis, and D. Ostle, ed., Institute of Mining and Metallurgy, London. 1972.