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Borehole Wall

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Simulations Of A Spectral Gamma-Ray Logging Tool Response To A Surface Source Distribution On The Borehole Wall

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I. ABSTRACT

We have developed Monte Carlo and discrete ordinates simulation models for the large-detector spectral gamma-ray (SGR) logging tool in use at the Nevada Test Site. Application of the simulation models produced spectra for source layers on the borehole wall, either from potassium-bearing mudcakes or from plate-out of radon daughter products. Simulations show that the shape and magnitude of gamma-ray spectra from sources distributed on the borehole wall depend on radial position within the air-filled borehole as well as on hole diameter. No such dependence is observed for sources uniformly distributed in the formation. In addition, sources on the borehole wall produce anisotropic angular fluxes at the higher scattered energies and at the source energy. These differences in borehole effects and in angular flux are important to the process of correcting SGR logs for the presence of potassium mudcakes; they also suggest a technique for distinguishing between spectral contributions from formation sources and sources on the borehole wall. These results imply the existence of a standoff effect not present for spectra measured in air-filled boreholes from formation sources.

II. INTRODUCTION

The spectral gamma-ray (SGR) tool used by the primary logging contractor at the Nevada Test Site typically logs 24.4 cm (9.6-inch) diameter air-filled boreholes. These boreholes are sometimes coated with a thin mudcake that may contain potassium, a natural source of gamma rays. In addition, substantial quantities of radon have been detected in at least one of these large-diameter boreholes. Rn-222, a daughter of U-238, is an inert gas which migrates by diffusion and convective transport [1]. Radon daughters may plate out on the borehole wall and form a surface source containing Bi-214 and Pb-214, both of which are gamma emitters. It is necessary to correct SGR logs for these borehole wall components to the signal when measuring the formation potassium (K), uranium (U) and thorium (Th) content. In addition, measurement of the radon plate out signal may be useful as an indicator of gas migration characteristics of the formation, a parameter of interest to the proper containment of underground nuclear tests. This paper reports the application of simulation models that produce accurate spectral shapes for the various formation and

borehole wall sources. These spectra can be used in analysis and correction procedures.

In this study, simulation models were developed that produce angular flux spectra and scintillation detector pulse-height spectra for several source and borehole conditions. Source conditions include gamma rays from K, U, and Th distributed uniformly in the formation, ~~(K)~~ in the form of thin layers on the borehole wall, radon daughters on the borehole wall, and thin horizontal layers of K, U, and Th in the formation. Borehole diameter, fluid condition, and casing condition were all varied for certain of the source arrangements in order to provide calibration correction data and to properly characterize the spectra. Certain of the simulation models were benchmarked by comparison to experimental data. Results identify some important characteristics of gamma-ray spectra within air-filled boreholes when sources are on the wall.

The simulation models are based on both discrete-ordinates and on Monte Carlo methods. They accurately calculate gamma-ray fluxes at a detection surface for a specified source distribution, formation, borehole, and logging tool. When simulated pulse-height spectra from a detector are desired, the computed energy-, position-, and direction- dependent angular fluxes are enfolded with a detector response function.

Discrete-ordinates simulations were done with the DOT code [2] using multigroup cross sections produced by DINI [3]. Monte Carlo gamma-ray transport was done with the MCNP code [4]. Detector response was simulated with the Monte Carlo code GAMRES [5]. Simulated pulse-height spectra have been compared to experimental data for distributed K, U, and Th sources and were found to produce spectral shapes accurate to 5%. Absolute count rates appear to be about 20% high.

Figure 1 shows the logging geometry for the Nevada Test Site SGR tool in one of the large diameter air-filled boreholes. The sodium iodide detector is 12.7 cm (5 inches) in diameter and 17.8 cm (7 inches) long. The tool diameter is 20 cm and its aluminum housing is 1.27 cm thick. Some of the simulations included these tool materials and others did not, in order to provide spectra without tool perturbations. When tool materials are absent, the simulation models use cylindrical surfaces concentric with the borehole. Direction cosines for the

Fig 1. SGR Tool And Logging Geometry

computed angular flux are measured relative to the outward normal to the detection surface. When tool materials are present the detection surface is coincident with the sodium iodide detector surface. Models were developed for air-filled boreholes ranging from 30.5 cm (12 inches) to 244 cm (96 inches) in diameter.

III. SIMULATED SPECTRA FOR BOREHOLE WALL SOURCES

A. Surface Source Of Potassium.

Initial DOT simulations for small diameter holes were followed by more extensive MCNP simulations for the large 244-cm diameter boreholes typical at the Nevada Test Site. Figure 2 contains MCNP simulated angular flux spectra at the borehole wall when a thin 0.1-cm thick source layer of potassium is present with a strength of one picocurie per cm^2 of surface area.

Fig. 2 Angular Flux Spectra 10 cm From Borehole Wall For 1-mm-Thick Potassium-Heating Source Layer On The Wall With 1 nCi/cm² Activity

The source layer extends for a large distance axially, relative to the 244-cm hole size. There are no tool materials present for this simulation. The negative direction cosine ranges for the angular flux correspond to flux entering the detection surface while the positive values represent outward directions. A major feature of these spectra is the large directional anisotropy for the high energy scattered flux.

The flux entering the detection surface is the sum of all angular fluxes with negative direction cosines in Figure 2. The variation of entrant flux magnitude with position within the borehole is clearly seen for three different energy ranges in Figures 3, 4, and 5. These figures include flux results for several detection surface radii, expressed as a percent of borehole radius. Results for two hole sizes, 30.5 cm and 244 cm, are presented to show the effect of borehole diameter. The source activity for both borehole sizes is the same, one picocurie per cm^2 of surface area.

Fig. 3. Entrant Flux On Detection Surface Versus Radial Position For The Source Energy Of 1.461 MeV Distributed As A Thin Layer On The Borehole Wall. 0% - Detector At Center Of Borehole; 100% - Detector At Borehole Wall.

Fig. 4. Entrant Flux On Detection Surface Versus Radial Position For The Energy Range From 0.8 MeV To 1.46 MeV

Fig 5. Entrant Flux On Detection Surface Versus Radial Position For The Energy Range From 0.0 MeV To 0.2 MeV

When entrant flux is enfolded with SGR tool detector response functions as produced by the GAMRES code, pulse-height response is obtained. Figure 6 shows simulated pulse-height spectra for two locations within the 244-cm diameter borehole with a 0.1-cm thick potassium source layer on the wall.

Fig 6. Detector Response Enfolding With Entrant Flux For Two Positions Within The Borehole For A Thin Potassium Source On The Borehole Wall

B. Surface Source Of Radon Daughters

Dot and MCNP simulations of the borehole spectra from the multiple source energies produced by the radon decay products Bi 214 and Pb 214 exhibit trends with borehole diameter and with position within an filled boreholes similar to those observed with the monoenergetic potassium source layer. However, the multitude of source energies complicates the interpretation of simulated spectra. Figure 7 shows angular flux spectra from the radon daughter source layer for a position near

the borehole wall and for two of the direction cosine bins. Figure 8 results when these entrant flux spectra are enfolded with detector response. Figure 8 also includes for comparison an enfolded spectrum for 1 ppm of uranium uniformly distributed in the formation.

Fig 7. Angular Flux Spectra At Borehole Wall For Radon Daughter Source Gamma Rays Distributed As A Thin Source Layer

Fig 8. Detector Response Enfolding With Entrant Flux For A Formation Uranium Source And A Borehole Wall Radon Daughter Source

IV. DISCUSSION AND CONCLUSIONS

Gamma ray spectra produced within air filled boreholes by uniform formation sources are observed to be independent of flux direction, radial position, and hole size. Figures 9 and 10 illustrate two of these properties, showing angular flux spectra and entrant flux versus radial position, respectively, for a uniform formation K source. These plots are analogous to Figures 2 and 4 for a borehole wall K source. As observed earlier, none of these properties is true for gamma ray sources distributed on the surface of the borehole wall, rather there are

Fig 9. Angular Flux Spectra At Borehole Wall For A Uniform Formation K Source

Fig 10. Entrant Flux On Detection Surface Versus Radial Position For Uniform Formation K Source

large anisotropies in angular flux, especially at the higher scattered energies.

An examination of the flux spectra in Figure 2, for a location near the borehole wall, shows that from 0.7 MeV to just below the source energy at 1.46 MeV, the entrant angular flux varies by approximately two orders of magnitude as a function of direction cosine. Flux at lower energies, where multiple scattering dominates, is near isotropic. The sharp edge in the spectra at 0.24 MeV is the lowest possible energy for singly scattered 1.461 MeV source gamma rays (corresponds to back scattering at 180 degrees); there are no singly scattered gamma rays below this energy. The roll off in the spectra below about 0.1 MeV is due to the formation photoelectric absorption effect. There is also some angular anisotropy in the uncollided source flux at 1.461 MeV.

The lack of dependence on borehole position at the lower energies is illustrated nicely by the near horizontal curves in Figure 5. Yet, this low energy flux does show a dependence on hole size. Figure 3 shows that, while the source energy exhibits a rather large borehole position dependence, especially near the wall, the hole size effect is very small. Intermediate energies exhibit intermediate amounts of hole size dependence (Figure 4). The largest dependence of entrant flux on position within the borehole occurs for the high scattered energies, where the spectrum is dominated by one or two small-angle scatterings (Figure 4). Further, the greatest variation in flux with radial position occurs from about 80% of the borehole radius to the wall. Variations in flux with position at smaller radial positions within the borehole are much smaller (Figures 3 and 4).

Simulations that include the 1.27-cm thick housing of the SGR tool show that the housing has a large effect on the angular flux spectra incident on the detection surface, the effect being largest for flux directions more normal to the tool axis. The effect can be reduced by thinning the housing in the detector region if one desires to maintain sensitivity to the angular anisotropy.

Simulations with the sodium iodide detector material present within the housing show that entrant flux, that which leads to detected pulses, is unaffected by the presence of the sodium iodide, except at very low energies. For example, at 0.1 MeV the flux is depressed by about 25% when the sodium iodide is included in the transport model. Above about 0.3 MeV, there is no significant difference in entrant flux with and without sodium iodide in the model. Sodium iodide was not included in the transport model so that the effect of detector response could be added as a postprocessing step, permitting fluxes to be enfolded with response functions for different detector materials and sizes.

These observations have identified three major differences between spectra produced by borehole wall sources and formation sources:

- 1) there are strong angular anisotropies for particular energy ranges for borehole wall sources, while formation sources produce isotropic angular fluxes at all energies,
- 2) there is a relatively strong radial position dependence of high energy scattered angular flux for borehole wall sources, while formation sources have no such dependence,
- 3) there is a hole size dependence of angular flux at all scattered energies, except the source energy, for borehole wall sources, an effect not observed with formation sources.

In addition, there are shape differences between borehole spectra produced by the two source geometries. Figure 11 compares angular flux spectra simulated for the direction cosine

Fig 11. Angular Flux Spectra Near Normal To Detection Surface For Formation And Borehole Wall Potassium Sources

range most nearly normal to the detection surface for a thin layer potassium source on the borehole wall and for a source distributed uniformly throughout the formation. The diameter of the air-filled borehole is 30.5 cm. No tool housing is present in this simulation model. There is a large difference in spectral shape for these two source distributions for this incident direction. The formation source spectrum is normalized to the borehole wall source spectrum at the 1.46 MeV source peak; the borehole wall spectrum is per source gamma ray. Spectra for other entrant directions on the detection surface show less difference in spectral shape for the two source geometries.

The angular anisotropy of flux from borehole wall sources and the dependence of high energy flux on source location suggests a very sensitive measurement may be made to distinguish between gamma-ray sources on the borehole wall and uniformly distributed formation sources. A collimated detector combined with a spectral analysis method that removes the response to uncollided source gamma rays from the high energy scattered response could provide an extremely sensitive measure of radial source distribution surrounding the logging tool. This measurement would be most sensitive to the radial distribution of the source when the tool housing is thin (ideally absent) and when there is no casing in the air-filled borehole. The measurement should be feasible in water-filled borehole, if the detector is well shielded from flux entering from directions other than those defined by the collimator and if the tool is against the borehole wall. The borehole may also be made thin at the collimator location.

The observation that a dependence of the normal flux on radial position exists at high scattered energies, for the source energy for positions at or within 50% of the borehole radius, implies there is a standoff effect for wall sources. Whenever the wall surface is rugged so that an air gap exists between the tool and the wall, there will be a high energy response for all sources. The sensitivity to this standoff can be improved by collimating the

detector to accept only near-normal incident flux and by running the tool centered or deliberately introducing a standoff of at least 20% of the borehole radius.

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