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Gamma Ray Scattering and Absorption Measurements

12.1 INTRODUCTION

As noted in Chapter 10, the transmission of gamma rays through matter can be related to the electron density if the predominant interaction is Compton scattering. In the borehole environment, a transmission measurement is not possible. However, a gamma ray transport measurement through a formation can be used to determine its density. With some information on the material composition (lithology and pore fluids), the porosity can be determined.

The motivation for the measurement of formation bulk density comes from its direct relationship with the formation porosity and from geophysical applications. As seen earlier, porosity is an essential petrophysical descriptor and an important ingredient in the interpretation of resistivity measurements in terms of water saturation, $S_w$. Bulk density is used to compute the acoustic impedances of adjacent layers for seismic interpretation and for estimating overburden pressure.

The basic equation which relates the bulk density of the formation, $\rho_b$, to the porosity $\phi$ is:

$$\rho_b = \phi \rho_f + (1 - \phi)\rho_{ma},$$

(12.1)

where $\rho_f$ is the density of the fluid filling the pores and $\rho_{ma}$ is the density of the rock matrix. Although this equation is exact, it presents several problems for the determination of porosity. What value is to be used for the matrix density? For normally encountered formations, it is generally between 2.65 and 2.87 g/cm$^3$, depending on the lithology. For values of fluid density, it is necessary to know the type of fluid in the pores. The fluid density for hydrocarbon ranges from 0.2 to 0.8 g/cm$^3$. Salt-saturated water (NaCl) density may be as high as 1.2 g/cm$^3$, and with the presence of CaCl$_2$, ...
values even as great as 1.4 g/cm³ may occur. It is fortunate that the uncertainty that can be tolerated in $\rho_f$ is much greater than that for $\rho_{ma}$.

For the moment, this problem of interpretation is overlooked while we discuss, instead, the measurement technique for density determination and how it naturally leads to an auxiliary measurement of the photoelectric factor $P_e$, which is closely related to the formation lithology.

12.2 DENSITY AND GAMMA RAY ATTENUATION

In Chapter 10 it is shown that the interaction of gamma rays by Compton scattering is dependent only upon the number density of the scattering electrons. This in turn is directly proportional to the bulk density of the formation. The reduction of the flux $\Phi_0$ in traversing a thickness of material $x$ is given by:

$$\Phi = \Phi_0 e^{-\rho_b \frac{Z}{A} N_0 \sigma x},$$

(12.2)

where the term $\rho_b \frac{Z}{A} N_0$ is the number density of electrons in a material of mass density $\rho_b$, and $\sigma$ is the cross section for Compton scattering.

It is natural, therefore, to exploit the attenuation of gamma rays for the determination of bulk density. An idealized device would consist of a detector and a source of gamma rays whose primary mode of interaction is Compton scattering. Finding such a source would be difficult for any arbitrary group of materials. However, for the types of earth formation generally encountered in hydrocarbon logging, the average atomic number rarely exceeds 13 or 14. It was seen from Fig. 10.7 that, for logging applications, there is a large range of gamma ray energies which will be predominantly governed by Compton interaction.

It is worth noting that the basic gamma ray flux attenuation law, Eq. 12.2, indicates that there is a slight difficulty in the interpretation of a flux attenuation measurement. The attenuation will be strictly related to the bulk density $\rho_b$ only if the ratio of $Z/A$ remains constant. For most elements the value of $Z/A$ is about $\frac{1}{3}$, but there are several significant departures; hydrogen, for example, has a $Z/A$ ratio of nearly 1. For this reason, it is convenient to define a new quantity, $\rho_e$, the electron density index, to be:

$$\rho_e \equiv 2 \frac{Z}{A} \rho_b.$$  

(12.3)

In this manner the tool response (or measured flux, $\Phi$) can be specified as:

$$\Phi \propto e^{-\rho_e x},$$

(12.4)

where $x$ corresponds to the source-detector spacing.

Table 12.1 lists the density and photoelectric parameters of a number of common elements, minerals and liquids. Of interest for this discussion are the two columns labeled $\rho_b$ and $\rho_e$. It can be seen by comparison that the bulk density and electron density index for the three major minerals (calcite, dolomite, and quartz) are practically identical in these three cases. However, for the case of water there is an 11%