Applied Radiation and Isotopes 129 (2017) 189–195

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

A method to describe inelastic gamma field distribution in neutron gamma density logging

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HIGHLIGHTS

- The method is proposed to describe the inelastic gamma field distribution in NGD.
- Effects of formation parameters on the field distribution is individually analyzed.
- The detector-spacing combination on density sensitivity is studied by the method.
- The method can provide theoretical guidance for NGD instrument design.

ARTICLE INFO

Keywords:
Inelastic gamma
Field distribution
Formation parameters
Quantitative calculation

ABSTRACT

Pulsed neutron gamma density logging (NGD) is of great significance for radioprotection and density measurement in LWD, however, the current methods have difficulty in quantitative calculation and single factor analysis for the inelastic gamma field distribution. In order to clarify the NGD mechanism, a new method is developed to describe the inelastic gamma field distribution. Based on the fast-neutron scattering and gamma attenuation, the inelastic gamma field distribution is characterized by the inelastic scattering cross section, fast-neutron scattering free path, formation density and other parameters. And the contribution of formation parameters on the field distribution is quantitatively analyzed. The results shows the contribution of density attenuation is opposite to that of inelastic scattering cross section and fast-neutron scattering free path. And as the detector-spacing increases, the density attenuation gradually plays a dominant role in the gamma field distribution, which means large detector-spacing is more favorable for the density measurement. Besides, the relationship of density sensitivity and detector spacing was studied according to this gamma field distribution, therefore, the spacing of near and far gamma ray detector is determined. The research provides theoretical guidance for the tool parameter design and density determination of pulsed neutron gamma density logging technique.

1. Introduction

Pulsed neutron gamma density (NGD) logging, adopting a D-T neutron generator to measure formation density instead of a Cs-137 radioisotope source, has presented more advantages over gamma-gamma density (GGD) on the aspects of health, safety and environment (Badruzzaman, 2014; Inanc, 2014; Alakeely and Meridji, 2014). However, due to the complexity of the induced gamma source and physical process of gamma rays, the logging mechanism of NGD is more complicated than that of GGD, and the theory on neutron-gamma field distribution has not been perfect.

In recent decades, major oilfield companies have been developing the density logging using controllable sources instead of the radioisotopes (Xu et al., 2010; Smith et al., 2013; Badruzzaman, 2014; Liu et al., 2016). Computalog updated the pulsed neutron decay system (PND-S) for cased-hole density logging and obtained the formation density by measuring inelastic gamma diffusion length. (Odom et al., 2001). Halliburton used the pulsed neutron capture tool (PNC/PNS) for formation density prediction and measured formation by inelastic gamma and capture gamma count ratio (Jacobson et al., 2004; Quirein

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http://dx.doi.org/10.1016/j.apradiso.2017.08.024
Received 1 April 2017; Received in revised form 20 June 2017; Accepted 18 August 2017
Available online 21 August 2017
0969-8043/

et al., 2005). Schlumberger developed a new generation LWD platform (EcoScope) including neutron gamma density logging, which measured the formation by a D-T source. (Weller et al., 2005; Evans et al., 2012; Reichel et al., 2012). However, these studies are based on the experimental and Monte Carlo simulation methods. Neither of these methods can analyze the influence of relevant parameters on the inelastic gamma field distribution individually. That is not beneficial for clarifying the NGD logging mechanism and technological development.

In this paper, a method to describe the inelastic gamma field distribution in NGD logging was proposed. Based on the fast-neutron scattering and gamma attenuation, the inelastic gamma field distribution was characterized by the inelastic scattering cross section, fast-neutron scattering free path, formation density and other parameters. Then, the effects of the relevant parameters on the inelastic gamma field distribution were individually analyzed and quantitatively compared. Finally, the relationship of density sensitivity and detector spacing was studied according to this gamma field distribution.

2. Methodology

Pulsed neutron gamma density (NGD) is a newly-developing density logging method which can measure formation density using the secondary gamma rays from the interactions of neutrons and formation nuclides. The deuterium-tritium (D-T) generators emit 14.2 MeV fast neutrons into the formation, and neutrons with energy higher than 1 MeV interact with the formation nuclides through inelastic collisions. These inelastic interactions are typically followed by the emission of a variety of high energy gamma rays. Similar to the case of the GGD measurement, the transport and attenuation of these gamma rays are strong functions of the formation density. Therefore, the formation density can be measured by detecting the inelastic gamma rays.

Note that there are obvious differences between NGD and GGD. Firstly, the gamma source of NGD is a spatially distributed source and its energy is not monoenergetic, while GGD deploys a monoenergetic and collimated point source. In addition, the extent of the induced gamma source region depends on the transport of the fast neutrons from the source to the point of gamma-ray production. Besides, the attenuation distance of gamma rays is also closely related to the distance from the points of gamma-ray production to the detector.

The method can theoretically describe the distribution of inelastic gamma field, which is a key to clarify the NGD logging mechanism. To elaborate the method, an infinite and uniform spherical model is established, shown in Fig. 1. The neutron source is placed in the center of the model (O) and emits 14.2 MeV fast neutrons into the formation evenly. A spherical surface detector is set to record the inelastic gamma rays from the infinite formation.

According to fast neutron scattering theory (Tittle, 1961), the distribution of fast neutrons with energy higher than 1 MeV can be given as

$$\phi_f(r) = \frac{S_0}{4\pi r^2}\ e^{-r/\lambda_s} \tag{1}$$

where λ_s is the fast-neutron scattering free path, which is associated with hydrogen index (HI), S_o is the neutron source strength, r is the distance from the source.

According to inelastic scattering cross section from ENDF/B-VII.0 nuclear database (Chadwick et al., 2006), Fig. 2 gives the inelastic scattering cross sections of different formation materials. As shown in Fig. 2, the inelastic collisions occurring in the high fast-neutron energy range, especially in the energy range from 7.5 to 14.2 MeV, dominates the total inelastic collisions. Besides, the inelastic scattering cross section almost varies little with the fast-neutron energy in the range. Therefore, the inelastic scattering cross section of the energy range from 7.5 to 14.2 MeV can be viewed as the total neutron inelastic scattering cross section in some cases

In view of the above analysis, we neglect the effect of fast-neutron energy on the inelastic scattering cross section. And, the number of inelastic gamma photons generated in the spherical shell with thickness dr and radius r is

$$dI(r) = n\Sigma_{in}4\pi r^2\phi_f(r)dr = n\Sigma_{in}S_0 e^{-r/\lambda_s}dr \tag{2}$$

where n is the average number of gamma photons from inelastic collisions of a fast neutron, Σ_{in} is the inelastic scattering cross section.

The formation attenuation needs to be considered on the transport of the gamma rays from their origin to the detector. Here, we neglect the effect that gamma rays of different energies can have different mass attenuation coefficients, the number of gamma photons induced from the spherical shell and recorded by the detector A can be expressed as

$$dI'(r) = dI(r)e^{-\rho\mu_m|r-R|} = n\Sigma_{in}S_0 e^{-r/\lambda_s}e^{-\rho\mu_m|r-R|}dr \tag{3}$$

where ρ is the formation density, μ_m is the mass attenuation coefficient.

The total number of gamma photons from the whole formation detected by the detector can be described as

$$I'(R) = \int_0^\infty dI'(r) = n\Sigma_{in}S_0\int_0^\infty e^{-r/\lambda_s}e^{-\rho\mu_m|r-R|}dr \tag{4}$$

Finally, the inelastic gamma field distribution can be written as

$$\phi_{in}(R) = \frac{I'(R)}{4\pi R^2} = \frac{n\Sigma_{in}S_0}{4\pi R^2}\left[\frac{2\rho\mu_m e^{-R/\lambda_s} - (\rho\mu_m + 1/\lambda_s)e^{-\rho\mu_m R}}{(\rho\mu_m)^2 - (1/\lambda_s)^2}\right] \tag{5}$$

From Eq. (5), it can be seen that the inelastic gamma field distribution is determined by the neutron source strength S_o, the distance from the source R (referred to the detector spacing in the following study), inelastic scattering cross section Σ_{in}, fast-neutron scattering free path λ_s, formation density ρ, and other parameters.

By the method, the quantitative studies on NGD logging can be

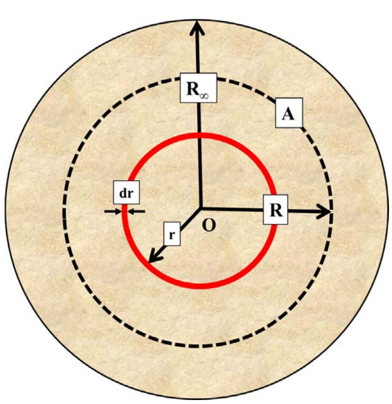

Fig. 1. Schematic model of the infinite uniform spherical formation. The dashed circle with radius R represents the spherical surface detector A, the solid circle with radius r represents the spherical shell with thickness dr and radius r.

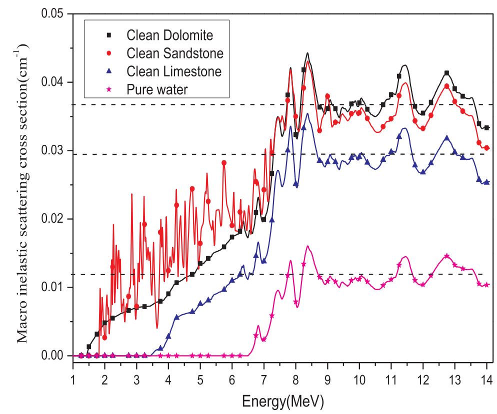

Fig. 2. Inelastic scattering cross section of different formation materials.