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Numerical study of an alternative to a deuterium-tritium source in gas saturation logging based on the inelastic gamma spectrum

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HIGHLIGHTS

- Assessed D-Li7 neutron generator to replace D-T neutron generator for logging.
- Factors that affected the inelastic gamma ray count were investigated.
- Gas sensitivity variations with two types of neutron generators analyzed.

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ABSTRACT

In this study, we investigated the feasibility of using a D-Li7 neutron generator to replace a deuterium-tritium (D-T) neutron generator in gas saturation logging. The logging response and gas sensitivity of gas saturation logging based on the inelastic gamma spectrum were simulated with the Monte Carlo method, and the factors that influenced the gas sensitivity and inelastic gamma counts were analyzed based on the spatial response distribution. The results showed that the logging response based on the D-Li7 source was similar to that based on the D-T neutron generator after calibration, which validated the feasibility of this method. Using the D-Li7 neutron generator, the sensitivity of gas saturation was higher when the scattering cross section of formation was not high.

1. Introduction

The development of pulsed neutron logging has diversified the logging interpretation methods based on inelastic scattering (Guo et al., 2012; Liu et al., 2017; Kim et al., 2017). Logging tools have also been improved gradually and inelastic scattering is now used more widely in logging (Trcka et al., 2006; Odom et al., 2008; Rose et al., 2015). The gas saturation can be measured accurately based on the inelastic gamma count during low porosity formation (Iglesias et al., 2016).

The deuterium-tritium (D-T) neutron generator has a short life and pulsed neutron logging based on this method has low sensitivity to porosity, and thus there is still the possibility of formations being polluted (Lou, 2003; Seabury et al., 2007). Pulsed neutron porosity logging based on the D-Li7 neutron generator is more sensitive to the formation of porosities (Badruzzaman et al., 2017). If the D-Li7 neutron generator can be used to replace the D-T neutron generator in a logging instrument based on inelastic scattering, then the multi-detector pulsed neutron logging tool based on the D-Li7 neutron generator can be employed in pulsed neutron logging tools.

In this study, we compared and analyzed the differences between the two types of neutron generators used in gas saturation logging based on the inelastic gamma spectrum, thereby providing a theoretical basis for the development of an instrument in the future.

2. Background

Li7 is used as the target in the D-Li7 neutron generator. The reaction is exothermic with a high Q value. The reaction function is similar to the DT reaction, as shown in Eq. (1). The Q value is 15.031 MeV. The energy of emitting neutrons can be 13.35 MeV, which can produce a generally monoenergetic (± 0.5 MeV) high-energy neutron spectrum in all of the emission angles (Chichester et al., 2012). The D-Li7 neutron generator is an attractive alternative to the D-T neutron generator when high energy neutrons are needed. The neutron spectrum of the D-Li7 neutron generator is similar to the Am-Be spectrum but it has an extra neutron peak at 13.3 MeV. The difference between the D-Li7 neutron generator and the D-T neutron generator is shown in Fig. 1.

$$^{7}\text{Li} + {}^{2}\text{H} \rightarrow {}^{8}\text{Be} + \text{n} \quad (1)$$

The interpretation of traditional neutron lifetime logging is based on

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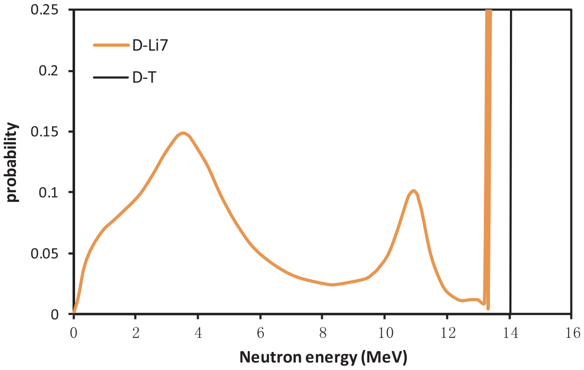

Fig. 1. Difference between the D-Li7 neutron generator and the D-T neutron generator (Badruzzaman et al., 2017).

the macroscopic capture of the cross section of each component in the formation. In contrast to neutron lifetime logging, the measurement principle for gas saturation logging based on the inelastic gamma spectrum is shown in Eq. (2), where I is the fast neutron count recorded by the detector, I_0 is the fast neutron output of the source, and Σ is the fast neutron macroscopic cross section of the formation. According to Eq. (2), the fast neutron count is related to the macroscopic cross section of the fast neutrons. The fast neutron is replaced by inelastic gamma rays in order to measure the fast neutron cross section because fast neutrons are difficult to record. However, inelastic gamma rays are attenuated in the formation before their detection, which results in a poor correlation between the inelastic gamma ray counts and the inelastic scattering cross section, but there is a good correlation between the 14-MeV elastic scattering cross section and the inelastic gamma ray count (Zhou et al., 2016). The source output is recorded based on the inelastic gamma count rather than the fast neutron count. This relationship is represented by Eq. (3), where RIND is the inelastic gamma ray count recorded by the detector and RINC is the fast neutron output of the source. The ratio of RINC to RIND is defined as the inelastic gamma count normalized by the source output. The relationship between the 14-MeV elastic scattering cross section of the formation and the inelastic gamma count of the detector is shown in Eq. (4), where ESCS is the 14-MeV elastic scattering cross section of the formation and RICD is the inelastic gamma count normalized by the source output.

$$\log\left(\frac{I}{I_0}\right) \propto -\Sigma \tag{2}$$

$$\log\left(\frac{RIND}{RINC}\right) \propto -\Sigma \tag{3}$$

$$\mathrm{ESCS} = \frac{\log(RICD)}{b\bullet\log(RICD) + a} + c \tag{4}$$

3. Modeling

A detector is placed near the source in order to record the output. The output is affected little by the borehole environment because the detector is close to the source. However, the count obtained by the near detector is affected more by the borehole environment than that by the far detector. Using the output from the source to normalize the detector count is affected less by the borehole environment than by the ratio of the near detector relative to the far detector. This model is shown in Fig. 2 and the specific model parameters are as follows. In order to facilitate comparative analyses, the D-T neutron generator and D-Li7 neutron generator were simulated in the same model. The inelastic gamma count can be obtained using many methods in practice but the inelastic gamma count was obtained by setting a high neutron cutoff energy in this study. The cutoff energy was 0.1 MeV.

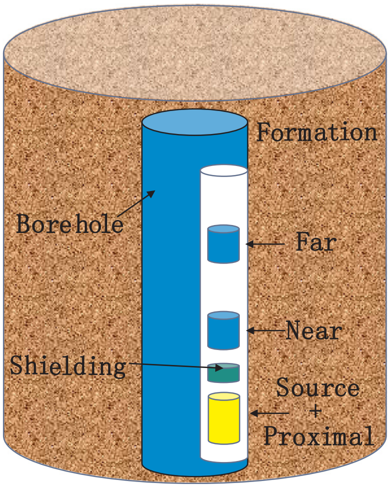

Fig. 2. Monte Carlo simulation model.

- We modeled the multi-detector pulsed neutron(MDPN) tool, with three detectors and a diameter of 0.043 m.
- The proximal detector was close to the source in order to record the source output variations, and it measured 0.0254 m × 0.0254 m.
- The spacings of near detector and far detector were 0.3048 m and 0.6096 m, respectively. The sizes of the near detector and far detector were 0.0254 m × 0.1016 m. The detector was made of $LaBr_3$.
- The fluid in the borehole was fresh water and the borehole diameter was 0.2 m.

ESCS is the 14-MeV elastic scattering cross section of the formation. The ESCS for each material in the simulation is shown in Table 1. Using the data in the table, the logging response was calibrated with Eq. (3).

4. Logging response

Saturation analysis has always been the main function of pulsed neutron logging, such as traditional pulsed neutron lifetime logging and the carbon/oxygen(C/O) logging. The inelastic gamma ray count will increase significantly in a gas-bearing formation. Therefore, calculating gas saturation based on inelastic scattering is the main method used for saturation logging. Table 1 shows that the ESCS values vary for different materials. Thus, ESCS can be used to accurately calculate gas saturation. The logging responses based on two types of neutron generators were simulated for different pores saturated with oil, gas, and water. The density of the gas used in the model was 0.1 g/cc. The density of water used in the model was 1 g/cc. The density of the oil used in the model was 0.89 g/cc. The formation matrix was SiO_2.

In Fig. 3, the solid, dot, and dash lines are the theoretical ESCS values for pores saturated with gas, water, and oil, respectively. According to Fig. 3, the logging responses based on the two types of neutron generators were close to the theoretical values and the gas layer could be identified clearly because the ESCS values varied for the different materials. The formula used for calculating gas saturation was established based on the physical volume model, as shown in Eq. (5), where φ is the porosity, $ESCS_{ma}$ is the ESCS for the matrix, and $ESCS_w$ is the ESCS for water.

Table 1
ESCS values for the formation components in the model (Zhou et al., 2016).

Material	Quartz	Water	Oil	Gas	Illite	Calcite	Dolomite
ESCS (1/m)	6.85	7.8	7.98	1.3408	8.06	7.51	8.51