Monte Carlo Numerical Models for Nuclear Logging Applications

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Abstract

Nuclear logging is one of most important logging services provided by many oil service companies. The main parameters of interest are formation porosity, bulk density, and natural radiation. Other services are also provided from using complex nuclear logging tools, such as formation lithology/mineralogy, etc. Some parameters can be measured by using neutron logging tools and some can only be measured by using a gamma ray tool.

To understand the response of nuclear logging tools, the neutron transport/diffusion theory and photon diffusion theory are needed. Unfortunately, for most cases there are no analytical answers if complex tool geometry is involved. For many years, Monte Carlo numerical models have been used by nuclear scientists in the well logging industry to address these challenges. The models have been widely employed in the optimization of nuclear logging tool design, and the development of interpretation methods for nuclear logs. They have also been used to predict the response of nuclear logging systems for forward simulation problems. In this case, the system parameters including geometry, materials and nuclear sources, etc., are pre-defined and the transportation and interactions of nuclear particles (such as neutrons, photons and/or electrons) in the regions of interest are simulated according to detailed nuclear physics theory and their nuclear cross-section data (probability of interacting). Then the deposited energies of particles entering the detectors are recorded and tallied and the tool responses to such a scenario are generated. A general-purpose code named Monte Carlo N–Particle (MCNP) has been the industry-standard for some time.

In this paper, we briefly introduce the fundamental principles of Monte Carlo numerical modeling and review the physics of MCNP. Some of the latest developments of Monte Carlo Models are also reviewed. A variety of examples are presented to illustrate the uses of Monte Carlo numerical models for the development of major nuclear logging tools, including compensated neutron porosity, compensated density, natural gamma ray and a nuclear geo-mechanical tool.

Key words: Monte Carlo models, oil well logging, variance reduction, logging tool design

1. Introduction

Oil well logging has been an essential part of drilling and evaluation since 1926 when electric well logging was introduced. Oil well logs are based on physical measurements made by devices (called Sondes) that are lowered into the hole. The three major types of logging measurements include electrical, nuclear, and acoustic. Though each has its own value, nuclear logs are probably the most important of these techniques. Important oil well parameters like formation porosity, bulk density, and natural radiation and lithology/mineralogy are provided by using complex nuclear logging tools. Commonly used nuclear log types include the natural gamma ray, gamma-ray density, neutron porosity, and pulsed-neutron mineralogy instrument.

Natural gamma-ray logs usually contain long spaced Sodium Iodine (NaI) detectors so that spectra can be obtained and one can determine the quantity of the three natural radioisotopes potassium, uranium, and thorium present in the formation rock. These logs are often used to determine where layers of shale or oil-bearing rock (sandstone) exist.

The gamma-ray density logs are very important as they can be used to determine the lithology (rock type) and porosity (pore volume). The system usually consists of a gamma-ray source (normally Cs-137 with a 0.662-MeV gamma ray) and two collimated NaI detectors at different distances from the source. A typical log of this type is shown in Fig. 1. Gamma rays from the Cs-137 source are emitted into the rock surrounding the borehole, and some are scattered several times until they are detected by one of the NaI detectors. The responses from this log can be used to measure density and, under certain restrictive assumptions, the porosity of the surrounding rock.

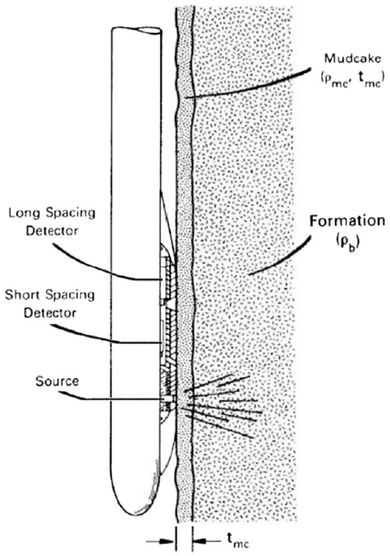

Fig 1: Schematic diagram of a gamma-ray density logging tool

Neutron porosity logs consist of a high-energy source of neutrons like Am–Be, Cf-252 or a D–T accelerator source and usually two primarily thermal neutron detectors like proportional counters filled with He-3 at different distances from the neutron source. Usually, the ratio of the data from the two neutron detectors is used to obtain porosity, as it has been found that this ratio is relatively independent of rock lithology/mineralogy.

Finally, the pulsed-neutron elemental analyzer log is becoming more important today. It consists of a neutron source (Am–Be, Cf-252, or a D–T pulsed-neutron source) with a NaI detector or other scintillation detectors. The prompt gamma rays produced by neutron activation are detected and both qualitative and quantitative measures of the elements (and subsequently the lithology/mineralogy) in the formation rock are obtained. This log is recognized as providing valuable information, and it is receiving more attention and widespread use by oil companies, although it is relatively expensive to operate.

To understand the response of nuclear logging tools, an explanation of the neutron transport/diffusion theory and photon diffusion theory are needed. The general, time-dependent neutron transport equation for the non-fission problem is:

$$\frac{1}{v}\frac{\partial\Psi}{\partial t} + \hat{\Omega}\cdot\nabla n + \Sigma_t\Psi\left(\vec{r},E,\hat{\Omega},t\right) = \int_{4\pi} d\hat{\Omega}'\int_0^\infty dE'\,\Sigma_s\left(E'\to E,\hat{\Omega}'\to\hat{\Omega}\right)\Psi\left(\vec{r},E',\hat{\Omega}',t\right) + s\left(\vec{r},E,\hat{\Omega},t\right) \quad \ldots\ldots\ (1)$$

where ψ is the neutron angular flux, v is the neutron velocity, Σ_t is the total neutron cross section, Ω is the neutron direction vector, and s is the neutron source term. In this case, Σ_t includes the cross sections from both the borehole and formation components.

In most neutron analysis, details of the angular flux dependence are not required. However, what is needed is the angle-integrated neutron flux. If the neutron transportation equation is integrated over all angles (Ω) and some approximations are made, the neutron diffusion equation can be derived from the neutron transportation equation.

Equation 2 shows the multi-group diffusion equation for energy group g:

$$\frac{1}{\upsilon_g}\frac{\partial\phi_g}{\partial t} - \nabla\cdot D_g\nabla\phi_g + \Sigma_{tg}\phi_g\left(\vec{r},t\right) = \sum_{g'=1}^{G}\Sigma_{sg'\to g}\phi_g{}' + s_g \quad \ldots\ldots\ldots\ (2)$$

$$g = 1,2,\ldots\ldots G$$

Unfortunately, for most cases there are no analytical answers if complex tool geometry is involved. Nuclear oil well logging scientists and engineers were quick to realize the importance of Monte Carlo simulation in the study of nuclear logs, calculation of corrections and correction factors for nuclear log interpretation, and nuclear log design optimization areas.

2. Monte Carlo Models

Monte Carlo models are a class of computational algorithms that rely on repeated random sampling to compute their results. These models have often been used in simulating physical and mathematical systems and have been applied widely in space exploration and oil exploration. In nuclear oil well logging, the Monte Carlo models are built on the geometry and materials that represent the real scenario of a logging tool environment. The simulation code is used to track each particle's life cycle from its birth to end. For each particle's life, comprehensive nuclear physics models for the neutron/gamma/electron transportation and interaction are used to calculate the particle's property (energy, direction, position, etc.) at each step. The amounts of the energy deposited in the regions of interest (e.g., detectors) are recorded to form different kinds of tallies (total counts, surface flux, volume flux, and pulse height spectrum).Generally, millions of such particles are simulated and the mean behavior of these particles' random contributions generates meaningful tool responses for further interpretation. Commonly, total counts or pulse height spectra are obtained in laboratory or field measurement, and the Monte Carlo models are benchmarked with experimental data to guarantee the accuracy of the modeling.

3. Results and Analysis

A typical pulsed-neutron elemental configuration for oil well logging is shown in Figure 3. Generally, it consists of the tool, the borehole and formation. The Monte Carlo N-Particle (MCNP) transport code uses Monte Carlo models to solve the very complicated neutron transport equations. It is especially useful in attempting to understand the spatial distribution of the neutrons in the borehole and formation environment when a pulsed-neutron tool is employed. It is assumed that the tool moves upward through a water-filled 7⅞-in. borehole. The gamma ray scintillation detector is located above the pulsed-neutron source. The spatial distribution for the fast neutrons is illustrated in Figures 4a and 4b at the X-Y plane at the bottom edge of the detector, which is nearest to the neutron source. In Figure 4a, it shows the spatial distribution for fast neutrons flux. In Figure 4b, thermal neutrons flux is shown. The large black circle at the center of each plot represents the borehole boundary and the small circle inside represents the tool. It is observed that more fast neutrons are at the formation side close to the source, while most thermal neutrons are observed at the borehole because water in the borehole is an effective material to thermalize (slow down) the fast neutrons. The spatial distribution helps nuclear scientists choose the best tool designs to minimize noises from the borehole and tool body, and to maximize the signals from the formation.

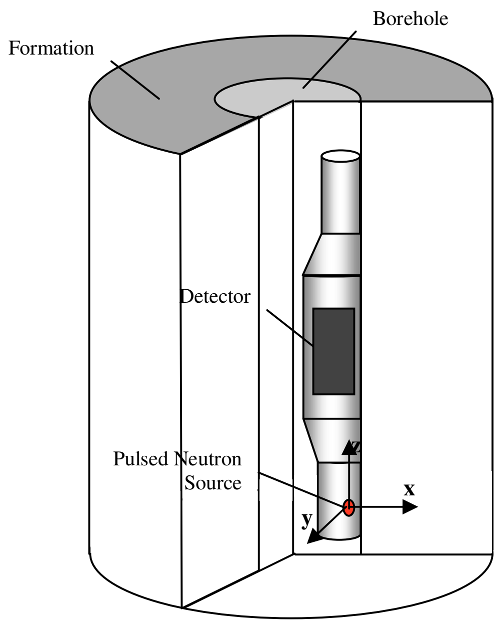

Fig. 3: Tool geometry used for MCNP simulation to illustrate the neutron and neutron-induced photon spatial distributions in the subsurface environment

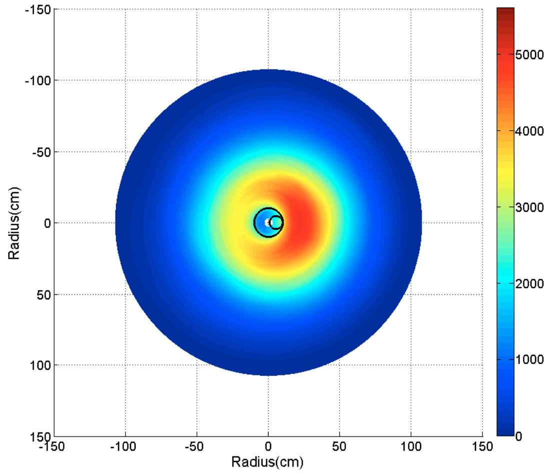

Fig. 4a: Fast neutron spatial distribution at X-Y plane aligned with the bottom of the tool detector

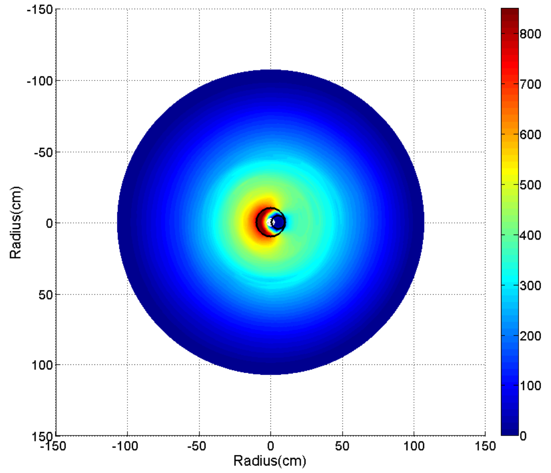

Fig. 4b: Thermal neutron spatial distribution at X-Y plane aligned with the bottom of the tool detector

Special patches were developed in Monte Carlo models to separate the various neutron-gamma interactions. For the gamma rays of interest, tallies were made for neutron interaction type (such as inelastic or capture), energy of the gamma ray flux incident to the surface of the detector, interaction zone of origin, including tool, borehole, or formation and element type with respect to parent atom of origin, such as C, Ca, O, S, etc. These features help us to study the elemental sensitivity and develop elemental standards by using Monte Carlo models. The known parameters include chemical composition, tool configuration and environments. The forward Monte Carlo Models are used to predict the gamma-ray energy spectra for each element in the formation. Figure 5 shows the example of Monte Carlo simulated inelastic gamma-ray energy spectrum, with respect to each elemental component, for an oil-saturated carbonate formation.

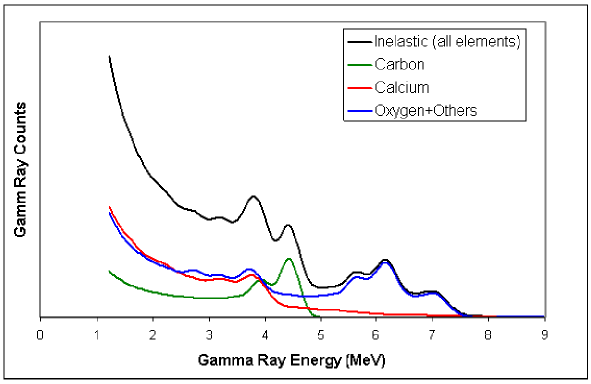

Fig. 5: Computed simulated inelastic gamma ray energy spectrum

Monte Carlo models using the well-accepted MCNP program have been used to characterize the basic porosity response and environmental corrections for the compensated neutron porosity tool. The tool can be in complicated environments which are totally different to the laboratory calibrated conditions, for example, the borehole mud weights and chemical composition could be changed from one well to another. The apparent readings of porosity from tool are deviated from the true values and Monte Carlo models can be used to correct those deviations. Figure 6 shows an example of the correction chart for the neutron porosity tool in an 8½-in. borehole filled with specified Formate brine. The X-axis shows the apparent porosity readings, and the Y-axis is the corresponding corrected porosity for both invaded and non-invaded cases based on the Monte Carlo simulation models.

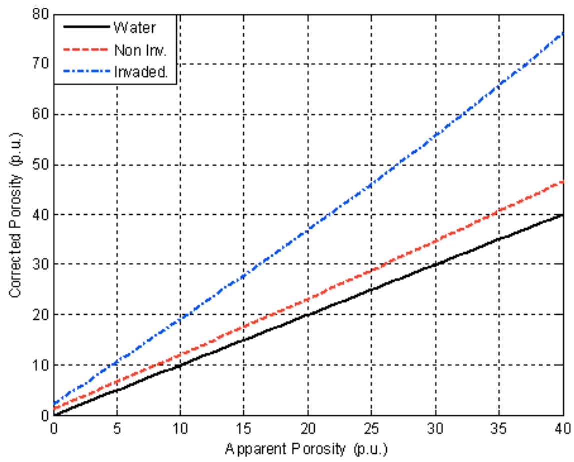

Fig. 6: Correction chart for the neutron porosity tool centered in an 8.5-in. borehole filled with Formate mud

Furthermore, Monte Carlo models can also be used to perform complex nuclear logging tool designs for all nuclear oil well logging tools such as natural gamma ray, gamma-ray density, neutron porosity, and pulsed-neutron mineralogy instruments. For example, it can optimize the placement of the source, detector package, tool shielding, tool body material and the routine supports to generate the necessary parameters needed for tool response interpretation, such as the Reservoir Performance Monitor™ (RPM™) tool series. It has been proven an effective and powerful tool to reduce laboratory workload and expenses for oil well logging companies.

4. Discussion and Conclusions

The authors introduced and discussed the functions of major nuclear oil well logging tools presently used in oil exploration. As oil exploration technology develops, the pulsed-neutron elemental analyzer log plays an increasingly important role today because it can provide useful and comprehensive information such as formation porosity, density, lithology and mineralogy, and so on. Therefore, there is a need to understand the tool behavior: how the neutrons and the induced prompt gamma rays interact and transport within the regions of interest. The complicated geometry in oil well logging environments makes it very difficult, almost impossible, to solve neutron transportation and diffusion equations analytically. However, Monte Carlo models provide an alternative method to solve these complicated equations by tracking each nuclear particle (neutron, gamma, and electron) according to nuclear physics interaction models and nuclear cross section (probability of interacting) databases. The methods are well established and successfully used in scientific applications for at least 75 years. A long time ago, the nuclear scientists and engineers working for oil exploration realized the importance of Monte Carlo modes as a useful tool for nuclear logging tool design optimization and generate necessary parameters for nuclear logging tool operations. Several examples are given to demonstrate the successful applications of Monte Carlo models in the oil well logging industry.

5. References

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