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Electronic neutron sources for compensated porosity well logging

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ABSTRACT

The viability of replacing Americium–Beryllium (Am–Be) radiological neutron sources in compensated porosity nuclear well logging tools with D–T or D–D accelerator-driven neutron sources is explored. The analysis consisted of developing a model for a typical well-logging borehole configuration and computing the helium-3 detector response to varying formation porosities using three different neutron sources (Am–Be, D–D, and D–T). The results indicate that, when normalized to the same source intensity, the use of a D–D neutron source has greater sensitivity for measuring the formation porosity than either an Am–Be or D–T source. The results of the study provide operational requirements that enable compensated porosity well logging with a compact, low power D–D neutron generator, which the current state-of-the-art indicates is technically achievable.

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1. Introduction

Compensated neutron logging (CNL) is a common method used in the petroleum industry to examine formations in the earth for determining whether valuable reserves are present. In comparison to other neutron logging methods, residual borehole and formation parameters have minimal effects on the measurements obtained through CNL [1], making it one of the more robust well-logging techniques. Presently, Am–Be is the most commonly used neutron source in CNL because of its high neutron emission intensity, compact size, and long half-life (Am-241 has a half-life of 432 years). In an Am–Be neutron source, alpha particles emitted by the decay of Am-241 bombard a Be-9 target producing a broad spectrum of neutrons having an average energy of approximately 4 MeV and maximum energy of 10 MeV (see Fig. 1). Typical Am–Be sources used in CNL have activities ranging from 10 to 20 Ci and produce $\sim 10^7$ n/s. Both Am-241 and Be-9 are hazardous materials and, because of its high radioactivity, Am-241 presents additional environmental concerns if a source is lost down the borehole as well as national security concerns if it is stolen or cannot be accounted for [2]. Because of these issues, there has been strong interest in the well logging community to develop alternative accelerator-based technologies for replacing radiological sources such as Am–Be.

2. Porosity well logging

A typical compensated neutron logging tool consists of a neutron source and two thermal neutron detectors (usually He-3 gas-filled detectors) that are located upstream from the neutron source at different locations. The source emits fast neutrons into the rock formation where scattering and absorption processes occur to slow down the neutrons to thermal or epithermal energies. Eventually, some of the thermal/epithermal neutrons diffuse into one of the He-3 detectors and register counts. The presence of hydrogen in the formation increases the amount of scattering and absorption, which affects the neutron diffusion length, L, and results in different count rates observed in each of the detectors. This difference in detector count rates implies that the porosity can be correlated to the neutron diffusion length in the formation. It can be shown that the ratio of neutron fluxes, Φ_N/Φ_F, tallied in the near and far He-3 detectors is given by [1]

$$\frac{\Phi_N}{\Phi_F} = \frac{r_F}{r_N}\exp\left(\frac{r_F - r_N}{L_e}\right) \tag{1}$$

where r_N and r_F are the distances from the source to the near and far detectors respectively, and L_e is the epithermal neutron slowing down length. In practice, the exact values of r_N and r_F are approximate since the detectors have finite volume with characteristic lengths comparable to r_N and r_F. Residual effects from the borehole and formation parameters as well as statistical uncertainties of the detector add to this obscurity. Due to these approximations, a more generalized form of Eq. (1) which preserves the fundamental physics can be written as

$$\frac{\Phi_N}{\Phi_F} = C_1\exp\left(\frac{C_2}{L}\right) \tag{2}$$

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where C_1 and C_2 are positive constants and L is the average track length traveled by a neutron in the formation. Eq. (2) provides the correlation between the hydrogen content in the formation and the porosity if the two detector flux tallies are measured at different porosities with all other parameters held constant. Since the neutron flux at a location is directly proportional to the measured count rate at that location, the ratio of the near detector count rate to that of the far detector is the parameter used by log analysts to assess the formation porosity.

3. Computational model

The Monte-Carlo computer code MCNP [3] was used to simulate the porosity log in a borehole. In the present simulations, three different neutron sources (D–D, D–T, and Am–Be) were analyzed within two different formation matrices, limestone, $(CaCO_3)_{1-x}(H_2O)_x$, and sandstone, $(SiO_2)_{1-x}(H_2O)_x$. The borehole and neutron tool geometries were based on those published by Peeples et al. [4] and correspond to an 8 in. borehole and 3 in. diameter tool (see Fig. 2). The three neutron sources were modeled as isotropic point sources with their respective neutron energy spectra shown in Fig. 1. The energy spectrum of the Am–Be source was derived from the ISO-8529-1 reference spectrum [5] having its corresponding probability density function, while the two accelerator-driven sources produced monoenergetic neutrons at 2.45 MeV (D–D) and 14 MeV (D–T). The near and far detectors were modeled as cylinders containing He-3 at different densities based on their respective pressures of 1.5 and 4.0 atm at a temperature of 293 K. As neutrons enter the cylindrical volume of the detectors, a tally of the ^{3}He(n,p) ^{3}H neutron capture reaction was used to represent the detector count rate.

The neutron cross-section data in MCNP were taken from the standard ENDF/BVII library [6]. In all cases, simulations were run with 10^8 particles to obtain the proper scaling for the relative error of the measurement. The relative error of an MCNP tally is defined as the ratio of the standard deviation to the expected value of the tally. For the well logging problem, both the expected value and the relative error of the near-to-far detector count ratio were computed. The expected values and relative errors obtained from MCNP correspond to a predefined and fixed borehole/tool configuration. In practice, the well-logging measurements obtained by the detectors will differ from the MCNP results due to perturbations and uncertainties in the composition and geometry. However, the above model using a fixed geometry is suitable for comparing relative neutron source performance for CNL.

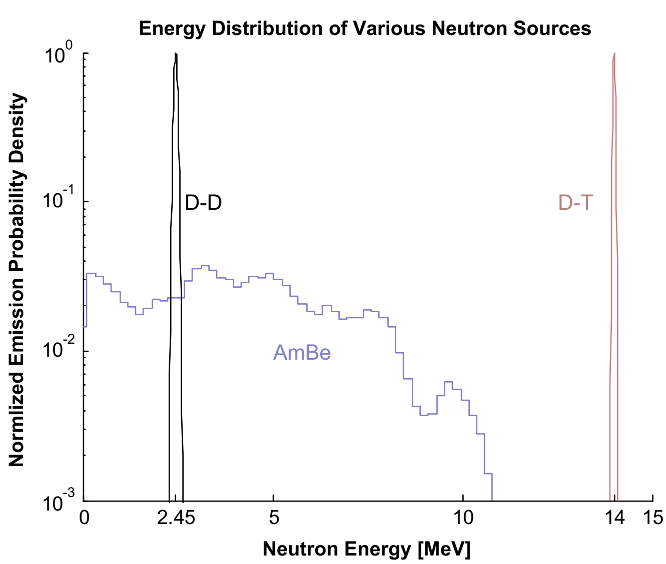

Fig. 1. Energy spectra of the various neutron sources used in the MCNP model.

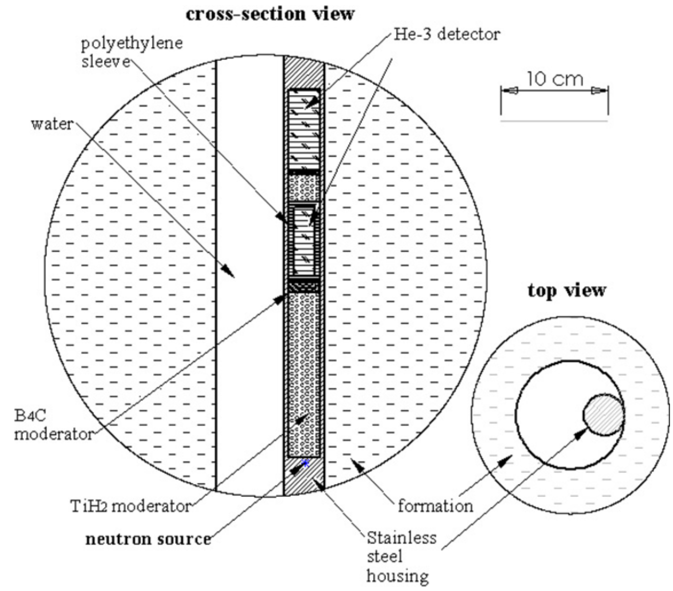

Fig. 2. Magnified section of the CNL tool and borehole model used in MCNP. Note that the formation extends out to a radius of 60 cm and height of 120 cm.

4. Simulation results

The near-to-far detector count rate ratios for the three different neutron sources (D–D, D–T, and Am–Be) are shown in Fig. 3a (sandstone) and Fig. 3d (limestone) with error bars representing one standard deviation from the expected value. As seen in the graphs, the D–D neutron source has the highest sensitivity to the change in porosity fraction while the D–T source is the least sensitive. The D–D neutron source also has the highest relative error in the well log. The D–T source shows significantly lower relative errors compared to the other two suggesting that the D–T source can be operated at a lower output flux without compromising precision.

The dissimilarity in sensitivity between different neutron sources can be analyzed in terms of the average neutron interaction mean free path (T_{mfp}) of the formation defined as the average track length that a neutron particle travels before absorption or scattering occurs. It is equivalent to the neutron flux tally with the volume set to unity. As seen in Fig. 3d and Fig. 3e, a quadratic least-squares regression yields very good correlation between the inverse of T_{mfp} and the change in porosity fraction. An exponential least squares regression gives a good fit between the near-to-far ratio and the inverse of T_{mfp} (Fig. 3c and Fig. 3f). This correlation is more precise in the lower porosity range, likely as a result of lower uncertainty in the neutron flux. Because of its lower neutron energy (compared to D–T and Am–Be), the D–D neutron source has shorter T_{mfp} at the same porosity since D–D neutrons are easier to thermalize in the formation. This implies that detectors can be positioned much closer to the source leading to a more compact CNL tool and a lower intensity source requirement.

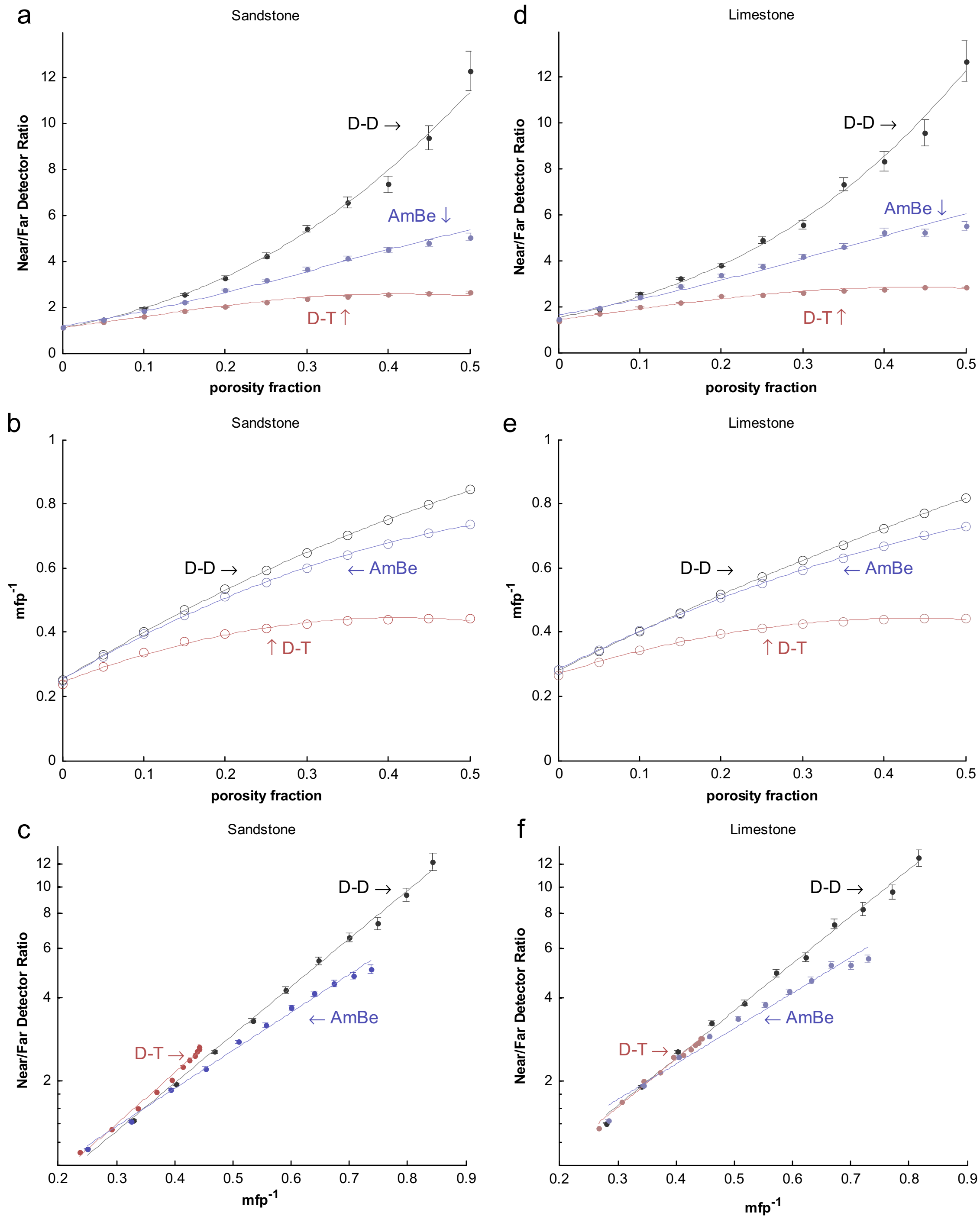

Fig. 3. (a–f): MCNP results of sandstone and limestone formations using different neutron sources with 10^8 particle histories used in all cases.

5. Technologies for compensated nuclear logging tools

Compensated porosity well logging tools typically consist of an Am–Be neutron source, two He-3 neutron detectors located upstream from the source, and some shielding material between the neutron source and detectors to minimize interferences in the signal. The present study has shown that a D–D neutron source has higher sensitivity to the formation porosity than either a D–T or Am–Be neutron source. He-3 neutron detectors are commonly used in CNL tools because of their high sensitivity to thermal neutrons, but the supply of He-3 is rapidly decreasing so the cost of these detectors is becoming a critical factor. The following sections consider some neutron source and detector technologies that could potentially lead to the next generation of well logging tools for measuring formation porosity.

5.1. Neutron generator technologies

Am–Be neutron sources are routinely used in nuclear well logging today, but these sources are extremely radioactive because of the high neutron intensities needed for CNL. In addition, Am–Be sources are “always on” which means thick shielding is needed during handling and for the detectors in the well logging tool. In the last decade, compact D–T neutron generators have become more prevalent in the well logging industry [7], but these devices contain several curies of tritium which is also a radioactive and hazardous material. In contrast to the Am–Be and D–T sources, a D–D neutron source has the advantage of having no radiological or chemical hazards associated with its operational use and handling.

The main drawback with current commercially available D–D sources is their rather low neutron outputs of $\sim 10^6$ n/s, primarily due to their use of inefficient Penning discharge ion sources. Improvements to the Penning discharge source for materials engineering [8–10] could potentially increase the D–D neutron output to 10^8 n/s making such devices viable for well-logging applications. Since the production of monatomic ions in a Penning source is very low ($<10\%$), the development of an improved ion source having $>90\%$ monatomic deuterium ions and that also takes advantage of the directionality of D–D neutrons and/or operation in pulsed mode would lead to a source having the required neutron intensity at about the same total input power. Research is underway [11–13] to develop field emission-type ion sources that can lead to extremely compact, low power and high yield neutron generators. Recent advances in alternative ion source technologies have also significantly increased neutron yields by employing ultra-compact RF or microwave discharge ion sources that produce high fractions of monatomic ions for efficient neutron production [14,15]. The latter types of neutron sources can also operate in pulse-mode for use in other well-logging techniques, such as neutron–gamma logging [1].

The advanced D–D neutron generator technologies described above are capable of producing 10^8 n/s source intensities with only around 100 W of power. For example, the current required to generate 10^8 n/s at 100 keV is approximately 400 μA (40 W) [16], which leaves 60 W available for the ion source. State-of-the-art microwave ion sources are capable of sustaining an inductively coupled plasma with no more than 50 W of power and can provide current densities of up to 1000 μA/mm^2 [17]. While it is more difficult to achieve the inductive mode at low power in RF-driven plasma sources, current densities of ~ 2 μA/mm^2 have been achieved in capacitive discharge mode operating at 50 W [18]. In the latter systems, the total beam current can further be increased by extracting multiple ion beamlets from the ion source. In addition, it has recently been shown that Penning sources operating at a discharge power of around 40 W can reach ion current densities up to 50 μA/mm^2 [19]. While a typical Penning source only has about 10–20% atomic ion fraction (most are molecular ions which contribute less to neutron production), atomic ion current densities around 5 μA/mm^2 are achievable.

5.2. Neutron detector technologies

Neutron detection is a key component of applications in national and homeland security, industry, and science. For example, the federal government uses radiation portal monitors and other neutron detectors at the US border to prevent smuggling of nuclear and radiological material, and the oil and gas industry uses neutron detectors for well logging. He-3 neutron detectors are commonly used in these applications because of its high thermal neutron capture cross-section ($\sim$5000 b) as well as its capability for gamma radiation discrimination [20]. Before about 2001, production of helium-3 exceeded consumption but, in the past decade consumption has risen rapidly and the stockpile of helium-3 has decreased significantly causing prices to skyrocket [21]. For example, the price of He-3 has shot up almost 40 times from $\sim$\$80 per liter in 2008 to $\sim$\$3000 per liter in 2011 [22].

One way to address the helium-3 shortage is to move to alternative technologies that are available and could satisfy detection sensitivity requirements for these applications. These technologies use either boron-10 or lithium-6 rather than helium-3 to efficiently detect thermal neutrons and, further, provide gamma radiation discrimination. For example, some candidate technologies include boron-10 lined proportional detectors, boron trifluoride proportional detectors, and lithium-6 scintillators. Typical boron-lined proportional detector tubes are about 10 to 15% as efficient at detecting neutrons as a helium-3 tube but, by arraying them, boron-lined tubes can achieve detector efficiency comparable to a single tube He-3 neutron detector. In addition, these detectors are more expensive than He-3 and B-10 is an export controlled material. While boron trifluoride proportional detectors are relatively inexpensive, BF_3 is a hazardous material and also exhibits a somewhat higher sensitivity to low energy photons which would reduce the signal-to-noise ratio in neutron detection [20]. Generally, BF_3 tubes are about 30 to 50% as efficient at detecting neutrons compared to helium-3, but multiple tubes can achieve the desired detector efficiency. Similar to boron-lined proportional counters, Li-6 scintillators are much more expensive than He-3 and Li-6 is also an export controlled material. There are also issues with Li-6 scintillators in that the gamma radiation discrimination may not be adequate for some applications, and the detector may not be able to count neutrons at high rates.

The suitability of a detector for an application depends both on the characteristics of the detector material and design. Factors such as how a neutron absorbing isotope is integrated into the conversion material, the arrangement of the moderator relative to the conversion material, and the signal processing for the detector influence the detector's characteristics and response. While alternative detector technologies for He-3 are under development, further work in modeling and experimentation are also needed to fully assess the impact of replacing He-3 in nuclear well logging and other applications.

6. Conclusion

The viability of replacing Am–Be radiological neutron sources with accelerator-driven neutron sources in compensated porosity nuclear well logging was investigated. The results show that D–D neutrons provide greater sensitivity to the formation porosity than either Am–Be or D–T. Greater sensitivity translates to improved signal-to-noise ratio in the detection system and, therefore, a less intense D–D neutron source could be used to obtain well logs comparable to current Am–Be radiological sources. A previous study by Peeples et al. did not include the analysis of a D–D source because of the low neutron intensity available in commercial neutron generators [4]. However, recent ion source research has shown promise for developing compact, low power D–D neutron generators that can achieve the intensities needed in CNL.

Acknowledgments

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