HISTORICAL PERSPECTIVES

The dual-spaced neutron logging tool to measure formation porosity consists of a neutron source and count rates from two spaced neutron detectors NEAR and FAR. A NEAR to FAR RATIO (R) is developed and a ratio-porosity transform, usually a series expansion in powers of R, is used to compute actual porosity:

$$f = f(R) = A_0 + A_1 R + A_2 R^2 + \ldots + A_n R^n . \qquad (1)$$

Generally n lies in the range 3 to 6; segmentation into several porosity intervals is common. The coefficients An are determined by combining laboratory, field data, and Monte Carlo modeling.

The count rates NEAR and FAR have standard deviations that lead to a RATIO standard deviation and so a standard deviation on the computed porosity:

$$\Delta f = (\partial f / \partial R)\Delta R = (\Delta R / R) / (1 / R(\partial R / \partial f)) = (\Delta R / R) / S \qquad (2)$$

The logarithmic derivative in (2) is called the **porosity measurement sensitivity (S)**.

The main objective is to maintain DELTA phi as small as possible. The historical discussion was completely dominated by consideration of the **fast neutron slowing down length, Ls - the mean distance a neutron travels as it just reaches thermal energy.** It will be seen that neutron sources with highest energies reduced the numerator of (2), while sources with lowest energies increased the denominator.

The slowing down length scales the count rate seen by a neutron (and gamma!) detectors. Look at equation (3) to see this *exponential* scaling. Consider a fixed detector spacing: the ratio method's porosity sensitivity favors a scale of several/many slowing down lengths, whereas the detector's count rate and measurement precision/repeatability favors little/few slowing down lengths. The slowing down length is a function of neutron source energy and formation porosity.

Figure 1 below was taken from **US Patent 3,906,224**. One of the objectives of its supporting work was to determine if one particular **neutron source energy** offered advantage in dual-spaced epithermal neutron porosity logging tools.

This figure was based on experimental data acquired with a dual-spaced He3 logging tool with four different neutron sources having average neutron energies that ranged from 2.5 Mev for Cf252 to 14 Mev for a neutron generator in limestone at a fixed porosity of 25%. The He3 detectors were wrapped in cadmium and had NEAR and FAR spacings from the neutron source of 50 and 80 centimeters, respectively.

According to the teachings of this patent, the neutron generator system produced the WORST **porosity measurement sensitivity** whereas the Cf252 based system yielded the BEST. Crudely speaking, sensitivity determines the slope of the ratio-porosity transform on a ratio versus porosity crossplot. The slope for the 14 Mev generator system was worse than just being nearly flat: beyond a porosity of about 60%, it changed signs with the result that the transform became double-valued! This observation held whether a continuous or pulsed operational mode was used with the neutron generator.

For a typical dual-spaced neutron porosity measurement system, the ratio of NEAR to FAR count rates is given in elementary 2-group theory by

$$R = (N_0 / r_{NEAR}) e^{-r_{NEAR}/L_S} \Big/ (F_0 / r_{FAR}) e^{-r_{FAR}/L_S} = R_0 e^{\Delta / L_S}\ , \qquad (3)$$

where R0 is the ratio of the NEAR counting efficiency to the FAR counting efficiency times the ratio of the FAR spacing to the NEAR spacing; DELTA is the FAR spacing minus the NEAR spacing; and Ls is the **fast neutron slowing down length**. Use of the chain rule shows that the porosity measurement sensitivity is given by

$$S = (1/R)(\partial R / \partial \phi) = -(\Delta / L_S)(1/L_S)(\partial L_S / \partial \phi)\ . \qquad (4)$$

Values of Ls, for any fluids and any minerals mixed in any proportion to form any formation, are not that easy to come by: historically, they were the raison d’etre for nuclear micro geophysical models like SNUPAR, MSTAR, and LVPM. **Within the context of these models, neutron sources with higher energies have larger slowing down lengths than sources with lower energies**. Equation (4) clearly indicates that, for modest changes in the logarithmic derivative in Ls for different neutron energies, porosity measurement sensitivity is inversely proportional to the slowing down length. No wonder that 14-Mev neutron generator systems had the worst sensitivity when measuring porosity by the dual-spaced ratio method! Conversely, since Cf252 has the lowest mean fast neutron energy in this study, it follows that it would have the best sensitivity.

The next topic covered by **US Patent 3,906,224** was the impact of the actual values for the NEAR and FAR count rates and their standard deviations on **porosity measurement resolution**, i.e. the factor DELTA R / R in equation (2). From “DATA REDUCTION AND ARROR ANALYSIS FOR THE PHYSICAL SCIENCES” by Bevington and Robinson, page 46, equation (3.26), and neglecting the cross term, we can write

$$\Delta R / R = \sqrt{(\Delta N / N)^2 + (\Delta F / F)^2}\ . \qquad (5)$$

Since the count rates NEAR (N) and FAR (F) obey Poisson statistics, we can write for their standard deviations in time interval Δt just

$\Delta N = \sqrt{N\Delta t}$ and $\Delta F = \sqrt{F\Delta t}$, so that

$$\Delta R / R = \sqrt{(\Delta t)(1/N + 1/F} \; . \qquad (6)$$

Combining equations (2), (4), and (6) then yields

$$\Delta \phi = \sqrt{(\Delta t)(1/N + 1/F} \Big/ (S) \; . \qquad (7)$$

It is desirable to maintain DELTA phi as small as possible, meaning high sensitivity (S) and high NEAR and FAR count rates N and F. In view of the individual count rate expressions in (3), sources with higher energy neutrons will, for the same neutron output, have higher count rates at fixed NEAR and FAR spacings – this means that the 14 Mev neutron generator would be BEST and Cf252 the WORST at producing a low DELTA phi value in the numerator of (7). This was indeed observed in the experiments supporting US Patent **3,906,224.** For a given spacing from the neutron source, best is that source that has the longest slowing down length, since the count rate is scaled by distance divided by slowing down length.

In summary, small values for DELTA phi involved a compromise between the numerator and denominator of equation (7). In the end, this patent chose the AcBe neutron source as a compromise between the two extremes represented by Cf252 and a 14-Mev neutron generator.

HOMELAND SECURITY / NUCLEAR NON-PROLIFERATION ISSUES

A new consideration has recently surfaced regarding neutron sources for oil well logging: **homeland security / nuclear non-proliferation** issues. The half lives for Cf252, AmBe, and AcBe in years are 2.645, 440, and 22, respectively. Most sources are now AmBe – AcBe has not caught on. (At present, the program LVPM uses only AmBe as its neutron source.) Some Cf252 sources are in use, particularly where small physical size and/or mechanical integrity are at a premium; however, serious maintenance issues remain because of its short half-life. Sources like AmBe and AcBe with relatively long half lives are prime candidates for dirty bomb manufacture and US regulations for their possession, use, transport, and storage have tightened. Now, only the major players like Schlumberger and Halliburton can afford to meet these new regulations and provide 24/7 guard services to protect them. Delivery dates have stretched out to 3 plus years. Particularly dear are neutron sources with high neutron output (“19-Ci”). Cf252 is convenient for security gurus in that it has a short half life of about 2.5 years. Neutron generators remain difficult to manufacture and maintain and rarely work beyond 200 hours without maintenance/repair.

IMPROVED POROSITY MEASUREMENT SENSITIVITY WITH A PULSED NEUTRON GENERATOR

The biggest disappointment for using 14-Mev neutron generators for dual-spaced neutron logging by the ratio method was its very poor porosity measurement sensitivity.

The clearest expression of this problem could be seen from the ratio-porosity transform graph: for the neutron generator source it rolled over at about 50-60 pu, making quantitative work in high porosity formations difficult and calibrations in a 100% water bath impossible. This feature was present in both continuous and pulsed modes of generator operation. This was particularly unfortunate in view of the many other excellent uses of pulsed neutron generators to measure carbon/oxygen ratios, silicon/calcium ratios, and formation capture cross sections.

Would it be possible to improve the porosity measurement resolution for a neutron generator based system, while maintaining its dynamic range? The answer was provided by **US Patent 3,818,225:** directly measure the **thermal neutron diffusion coefficient D** and use it to measure formation porosity with good resolution and sensitivity throughout the full range of porosities from 0% to 100%! In this case, the neutron generator must be operated in pulsed mode.

From a physics point of view, for a pulsed neutron generator operating at 1 KHz, after about 300 microseconds, two neutron processes remain – diffusion and capture. Why not directly measure the diffusion coefficient and extract all available information?

In today's market, Chappell Hill Logging goes well beyond the scope of this earlier work in a number of very significant ways. For example, **detection of thermal capture gamma rays** in place of thermal neutrons utilizes higher count rates with better statistical precision. Moreover, Chappell Hill Logging employs **short, equal time sampling** (10 microseconds/sample) for all detectors permitting direct use of powerful standard digital signal processing and non-linear least squares methods to extract the maximum possible information from each detector in real time. Moreover, certain key issues related to time averaging and integration, both required for wide time gates, are avoided.

Of course, measurement of the formation capture cross section SIGMA remains the primary objective for Chappell Hill Logging. However, by directly measuring the thermal neutron diffusion coefficient, SIGMA can be immediately corrected for diffusion. Also, since accurate porosity values are provided, reservoir volumetrics and water saturations are also more accurately computed.

Another advantage is that D is independent of formation salinity, a prediction that can easily and directly be verified from the nuclear micro geophysical model LVPM. This means that porosity values need not be corrected for formation SIGMA values! The thermal neutron diffusion coefficient D is related to Σ by the equation

$$D = L^2\Sigma \,, \tag{8}$$

where L is the thermal neutron diffusion length. Although L and SIGMA are strong functions of formation salinity, D is essentially independent of salinity!

Figure 2 below shows the results from the LVPM model in which formation porosity is plotted versus the thermal neutron diffusion coefficient. The curves shown are for the standard lime, sand, and dolomite formations. The logging software uses polynomial expansions to compute porosity, given the diffusion coefficient.

Not provided at this time are the details whereby the thermal neutron diffusion coefficient is measured or how it is used to correct Σ for diffusion – this is done to protect the competitive advantages the Chappell Hill Logging is seeking to exploit. Suffice it to say that the same physical model is used as taught in US Patent **3,818,225,** save that a multitude of 10 microsecond time gates are now used in place of just two wider gates for each detector. Also, more sophisticated mathematical methods are employed to extract the thermal neutron diffusion coefficient in real time.