Neutron Log

Introduction

This summary focuses on the basic interactions between the tool's signal and measured information, that help characterize the formation. It is not intended to be a comprehensive review. Excellent references are listed at the end of this summary.

The neutron, density and acoustic logs are frequently referred to as porosity logs, as this traditionally has been their principal purpose. In each log, a signal is emitted, interacts as it passes through the formation and is detected either up or down hole of the source, as follows:

- **Acoustic Log** – Source are sonic waves, formation refracts the waves and the receiver detects transmitted acoustic waves (compression, shear and Stoney waveforms) and identifies travel time.
- **Density Log** – Source emits gamma rays which are considered energy photons, interacting with electrons (Compton's scattering) causing loss of energy. From the loss of energy, the density of the formation can be obtained.
- **Neutron Log**- A reaction between radioactive elements emits fast neutrons, which collide with the nuclei of other atoms, most importantly hydrogen nuclei. Detectors count the slowed neutrons deflected back to the tool. An apparent neutron porosity can be obtained based on the hydrogen index.

All the above logs are shallow reading devices. For the neutron log, Schlumberger suggests that the depth of investigation is about 9" and this can vary with the hydrogen index of the formation.

A number of innovations have been made to the neutron log, and the petrophysicist frequently must choose which neutron log to run. It is no longer an option to state that a compensate neutron log is to be run.

Basic Physics of Neutron Log

The neutron log contains a radioactive source, which by means of a reaction between elements[1] emits fast (high energy) neutrons. As the neutrons enter the formation, they collide with the nuclei of other atoms and slow down (loss of energy). Note, the terms "high energy neutrons" and "high velocity neutrons" are the same, since the mass of the neutron is constant.

Based on the conservation of momentum, the most energy loss occurs when a neutron collides with a nucleus of an atom of equal mass. The mass of hydrogen's nucleus is almost equal to the mass of a neutron.

Within microseconds of entering the formation, the successive collisions reduce the energy of neutrons to "thermal energy." Neutrons in this state are called "thermal neutrons." A thermal neutron continues to diffuse randomly at low energy through the formation. The average distance that a neutron will travel from the source in a straight line before it reaches the thermal velocity is called the "slowing down length."

[1] Newer tools do not require nuclear reaction to generate high velocity neutrons.

Neutron slowing down power expressed at the number of collisions required to thermalize* a neutron		
Element	# Collisions	Atomic Mass Unit
Hydrogen	19	1
Carbon	120	12
Silicon	271	28
Calcium	384	40

* Thermalize is considered to be to reduce the energy of the neutron from 4 MeV to less than 0.10 MeV (See Reference 2, V-257 for full table)

Eventually, the thermal neutrons are "captured" or absorbed by the nuclei of the atoms of the formation.

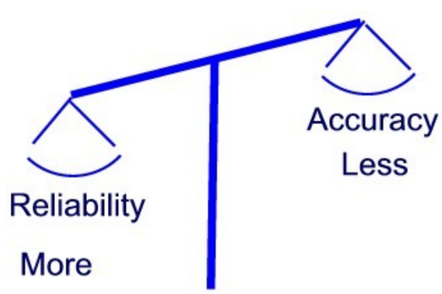
Earlier neutron logs did not detect neutrons directly, instead they measured the gamma rays that were emitted when hydrogen and chlorine captured the thermal neutrons. The level of radiation reaching the detector is inversely related to the hydrogen content as shown in the table below:

High hydrogen content	**Low hydrogen content**
Neutrons are slowed rapidly	Neutrons are slowed down less rapidly
Neutrons are captured close to source	Many neutrons captured close to source
Little radiation reaches the detector	Significant radiation reaches the detector

=> High Porosity = High hydrogen content = Low GR counts,

=> Low Porosity = Low hydrogen content = High GR counts

The neutrons that do not reach thermal velocities and are not subject to nucleus capture are called epithermal neutrons. The compensation neutron log uses two detectors, a near and far detector. An estimate of the size of the neutron cloud around the source is calculated based on the ratio of the count rates at these detectors.



The two detector log counts both epithermal and thermal neutrons. It does this so that a meaningful populations of neutrons can always be counted. This makes the log reliable in a sense, but creates an inaccuracy problem, because the thermal neutrons population has been reduced by capture/absorption making the hydrogen index less accurate.

Note, that in reference 2, page V-269, this option of trading reliability for accuracy is discussed for LWD tools.

One would like to base porosity on epithermal neutrons if there were in sufficient quantity to count.

Apparent Thermal Neutron Porosities of Some Common Reservoir Materials	
Material	**Apparent Neutron Porosity, $\varnothing_{CNL}$**
Quartz	-0.020
Calcite	0.000
Dolomite	0.020
Siderite	0.120
Kaolinite	-0.370
Illite	-0.030
Anhydrite	-0.020
Water	1.000
Brine (200 kppm)	0.920
Gas (reservoir conditions*)	0.540
Oil	-0.900

* Reservoir conditions, 200 deg F and 7000 psia

Source: Reference 2, V-273.

Environmental corrections and tool selection

The neutron log needs corrections for borehole size, formation temperature, formation pressure, mud salinity and barite content in mud. The borehole size is automatically adjusted based on the caliper log readings. The correction charts are shown on page 178 of reference 2. The corrections are additive.

There are a number of tools available from the service companies. The absorption of thermal neutrons causes a less precise estimate of apparent porosity, so it would be preferable to rely exclusively on the epithermal neutron count. Improvements in the neutron source have led to the development of neutron logs which determine porosity using only epithermal counts.

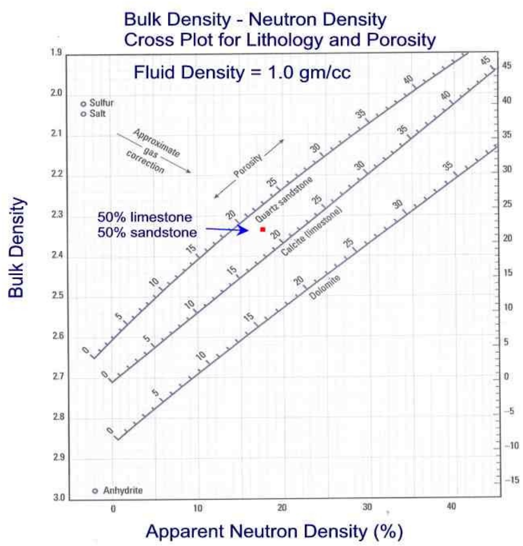
In air or gas filled wells, the thermal porosities can not be calculated. It is possible to improve gas detection using four detectors, two for epithermal porosity detection and two for thermal porosity detection. Schlumberger refers to this as CNL-G.

Newer LWD tools have additional complications, as discussed in Reference 2, V-268. LWD tools are evolving rapidly. I will try to update this area later.

Interpretation

If the lithology is known, the neutron log can be used to calculate porosity. Generally, the neutron and density logs are run together. The Pe (photoelectric log) may also be run to further improve the lithology description.

The effects of components of the matrix on neutron porosity and bulk density are proportional to their fraction in the matrix. For example a rock matrix with a 50% limestone and 50% sandstone, with 20% porosity will be half way between the limestone and sandstone lines, as shown on the crossplot on the left. The crossplot is correct for readings in the invaded zone using fresh water muds.



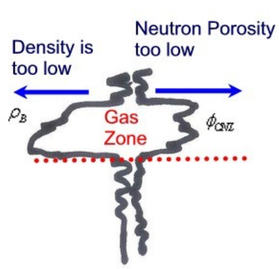
The M/N lithology plot is used to identify a complex mixture of sandstone, dolomite and limestone using all three porosity logs. The rational for the M/N plot is that the porosity should be the same in all three porosity logs for the same composition of lithology.

Modern log analyses today allows the inclusion of numerous minerals, including shale and various clays into a lithology model. The computer program then must calculate the percentage of each component, based on all relevant logs, including acoustic, spectral gamma ray, and NMR, if available. The Pe log is particularly useful in complex lithology determinations, as the readings are much more sensitive to lithology than porosity.

All log analyses is solution to an inverse problem. With log analyses software, the solution to the forward problem (assume the reservoir formation and borehole properties and generate what the theoretical log readings) can also be obtained and compared to the readings from the actual raw logs.

Gas Effects

Gas has a very marked effect on both density and neutron logs. If it is assumed that the formation fluid is water and the invasion zone is shallow, then gas will result in a lower bulk density (note on the cross plot, this results in a point higher on the y-axis), and a lower apparent neutron porosity.

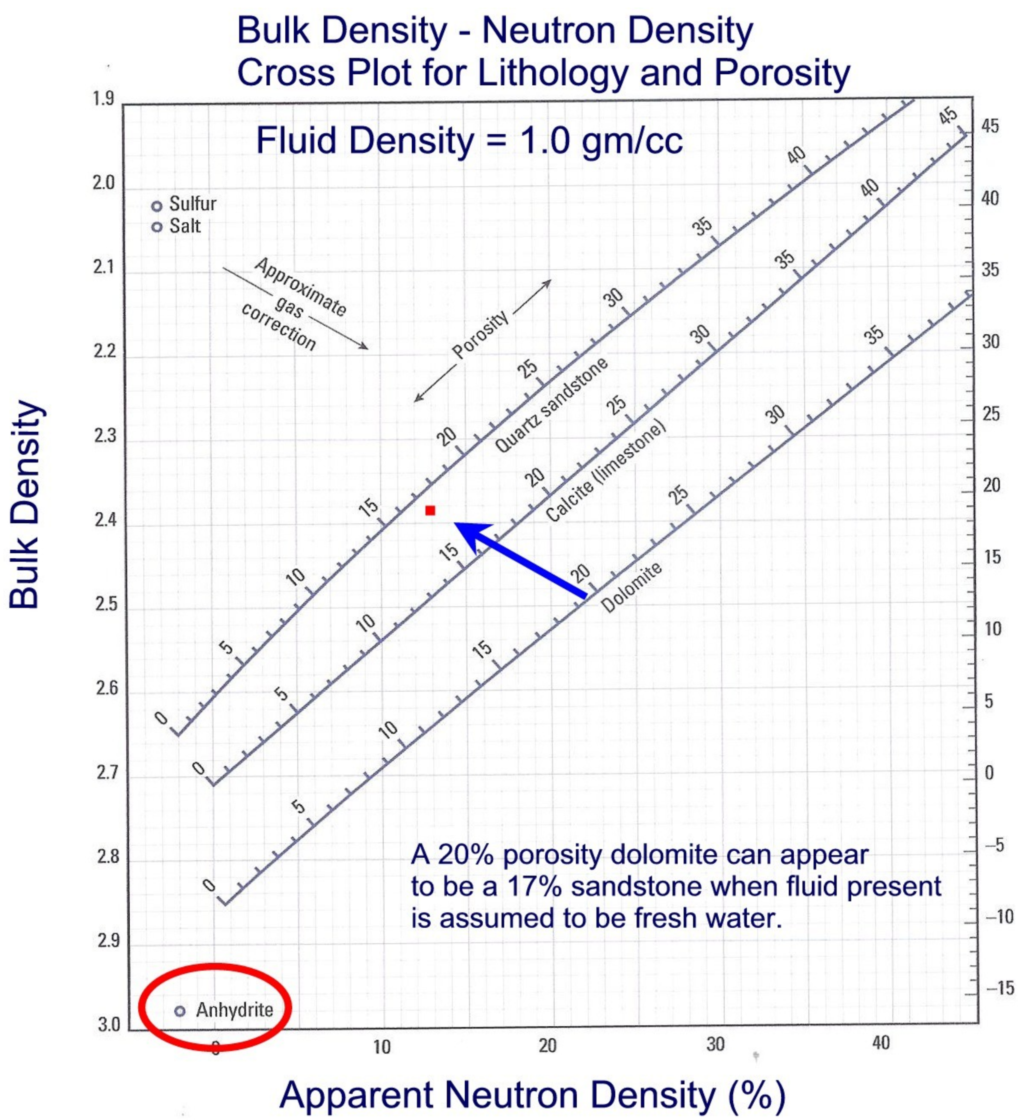


In limestone and dolomites, the lithology of a gas zone may show up as a sandstone (a move up and to the left). The correction for gas is then down and to the right. The gas contact can sometimes be easily identifiable in carbonates from the raw logs, as they are frequently plotted on a limestone scale ($\emptyset_{CNL} = 0,\ \rho_B = 0$). The gas will cause the density log to be abnormally low, at the same time, the neutron porosity will read too low.

GAS ---- Bulk density too low, density porosity too high

GAS ---- Neutron --- More hydrogen – lower neutron count -- porosity too low

A 20% porosity clean dolomite, when interpreted to using a formation fluid of 1 gm/cc results in a calcareous sandstone with about 17% porosity. Shales generally have the opposite affect on the crossplot- down and to the right. In complex lithologies, the gamma ray is used as a clay or shale indicator.



Also note that evaporites are clearly identified both by the bulk density and the apparent neutron density of approximately zero.

Additional Topics

LWD tools have a number of difficulties. I hope to add more on this topic.

References:

A number of excellent publications are available from the SPE bookstore and from the websiites of service companies. Schlumberger's oilfield review is available from its website.

1. Myers, G., Nuclear Logging, Chapter 3D, Reservoir Engineering and Petrophysics Volume V(A), Petroleum Engineering Handbook, Edward Holstein, Editor, 2007. (Pages V-267 to V-287 for neutron logs).

2. Bassiouni, Z., Theory, Measurement and Interpretation of Well Logs, SPE Textbook Volume 4, 1994.

3. Log Interpretation Principles/ Applications, Schlumberger, 1991.

References

1. Myers, G., Nuclear Logging, Chapter 3D,