WELL LOGGING TECHNIQUES AND FORMATION EVALUATION -
AN OVER VIEW
By Shri S. Shankar, DGM(Wells)

INTRODUCTION:

Once the prospect generation is made based on seismic and geological surveys, location for drilling is released based on the most probable structure in the hydrocarbon point of view. The most probable structure is based on the structure identified with

1. A mature source rock
2. A migration path connecting source rock to reservoir rock
3. A suitable reservoir rock (porous & permeable)
4. A trap
5. An impermeable seal

After the identification of the structure, location is released for drilling. Once the well is drilled, the need arises for ascertaining the worthiness of the well. Till the time the well is being drilled it is not sure that the well drilled will bear hydrocarbon. To ascertain the potential of the well it is required to Log the well.

WHAT IS LOGGING

Logging, electro logging or well logging means continuous recording of a physical parameter of the formation with depth. The primary objectives of the wire line logging are

- The identification of reservoir
- The estimation of hydrocarbon in place.
- The estimation of recoverable hydrocarbon.

Well logs are results of several geophysical measurements recorded in a well bore. They consist of key information about formation drilled ie.,

1. To identify the productive zones of hydrocarbon.
2. To define the petrophysical parameters like porosity, permeability, hydrocarbon
saturation and lithology of zones.
3. To determine depth, thickness, formation temperature and pressure of a reservoir.
4. To distinguish between oil, gas and water zones in a reservoir.
5. To measure hydrocarbon mobility.

METHOD OF LOGGING AND ACQUIRED DATA FORMAT

A schematic below shows a well logging setup.

WELL LOGGING SERVICES
Well logging services are broadly classified into open hole logging, cased hole logging, production logging and other services such as Plug setting, Perforations String shot etc.,
PROCEDURE FOR LOGGING OPERATIONS

Type of Logging operations to be carried out at various rigs is decided based on the requirement of the well. These jobs are carried out by truck mounted logging units. These units are placed in front of catwalk of the rig. The logging tools are lowered into the well with the help of logging cable. For lowering the tools with logging cable two sheaves are used. The bottom sheave is tied with derrick floor and placed near the well mouth and the top sheave is hung to the traveling block so that the tools are lowered into the well. The tools are assembled and connected to logging cable through a rope socket on the catwalk and tested/calibrated prior to lowering into the well. The tool is lowered to the desired depth and data is acquired while the tool is pulled up. After completing the survey the Tool is pulled out and rig down process is initiated.

The logging procedure covers the following steps

1. Parking of logging unit in front of cat walk.
2. Rig up (Fixing of top & bottom sheaves)
3. Stacking the tools and testing before lowering the tools.
4. Lowering the tool in to the well at the desired depth.
6. Pulling out the tool in to the surface
7. Rig Down.

Logs are recorded to measure different physical parameter of a well to ascertain the capacity of the well to flow hydrocarbon as mentioned above. It is also called as the electronic eye of a well. There are many physical parameters that can be recorded in Logs depending upon the need. However there are a very few basic parameters which are essential to be recorded in every well. They are broadly classified as

1) Resistivity Logs
2) Porosity/Radioactive Logs.
3) Sonic/Acoustic Logs
4) Sampling and coring
5) Cement evaluation Logs
6) Production Logs.

We shall now see then one by one.

RESISTIVITY LOGGING

The resistivity of a substance is its ability to impede the flow of electric current through the substance. Formation resistivities usually fall in the range from 0.2 to 1000 ohm meter. Resistivities higher than 1000 ohm·m are uncommon in permeable formations. In a formation containing oil or gas, both of which are electrical insulators resistivity is a function of formation factor, brine resistivity and water saturation which in term depends on true resistivity. Of the formation parameters resistivity is of particular importance because it is essential for saturation determination mainly of the hydrocarbon. Depending upon the environment under which resistivity logs are recorded. There are two types of resistivity Logs. They are Latero logs and Induction logs.

DUAL LATERAL LOG

The dual lateral log has been one of primary resistivity measurement device. DLL is a focused electrode device designed to minimize influence from borehole fluids and adjacent formations.

The DLL consists of an electronics section and a mandrel section. The mandrel supports the electrodes which are connected to the electronic circuity. The measurement current emitted from centre electrode is forced to flow laterally into the formation by the focusing action of electrodes surrounding the centre electrode. It provides two measurements of the subsurface resistivity simultaneously. The two measurements have differing depth of investigation are called deep resistivity ($R_d$) and shallow resistivity ($R_s$).

THEORY

DLL consist of a current emitting centre electrode positioned between guard electrodes. A known current is passed through the current electrode with a return electrode at the surface. Simultaneously a potential is applied to the focused electrode to keep zero potential difference between guard and centre electrode thereby the current is focused into the formation. Thus the potential difference produced is equivalent to the formation resistivity. The lateral log current path is basically a series circuit consisting of the drilling fluid, Mud cake, flushed zone,
invaded zone and the virgin zone, with the largest voltage drop occurring over the highest resistance zone.

The total amount of current emanating from an electrode must flow through any Medium that encompasses the electrode. The depth of investigation of a lateral log is defined as the depth at which 50% Of the total measured voltage is dropped.

$$R_s = K_s \frac{V_{Ms}}{i_{Os}}$$

$$R_d = K_d \frac{V_{Md}}{i_{Od}}$$

Standard 4 cycle log grid(DLL)

MICRO LATEROLOG/MICRO SPHERICALLY FOCUSSED LOGS.

MLL is pad device. MIL has small vertical resolution and depth of investigation. Used to determine

$$R_{xo}$$, Exact thickness of formation beds. 

$$R_{xo}$$ can be used with archie’s equation to calculate the saturation of the flushed zone.

$$S_{xo} = \sqrt{\left(\frac{a}{\varnothing_m}\right) \times \left(\frac{R_{xo}}{R_{mf}}\right)}$$
Archie’s equation, rewritten for saturation of the flushed zone, to determine moveable oil.

**THEORY**

Current from a measure electrode is forced into the flushed zone by guard electrodes returning to the return electrode. The current to the measure electrode is measured as is. The voltage w.r.t. the ground.

The MLL is a single tool contains an arm with the pad attached. The central electrode is the measure electrode. The eight other electrodes are guard electrodes.
INDUCTION LOGGING

PRINCIPLE

Induction tools are based on principles of electromagnetic induction. A magnetic field is generated by an AC electrical current flowing in a continuous loop/transmitter coil. The magnetic field from the transmitter coil induces ground loop currents in the formation. These ground current loops will in turn have an associated alternating magnetic field which will induce a voltage in the receiver coil, the magnitude of which is proportional to the formation conductivity.

- It works in oil based muds and air filled holes where latero tool fails.
- Tool accuracy is excellent for formations having low to moderate resistivity (up to ~100 Ohm.m.
- The Dual Induction Latero (DIL) tool records three resistivity curves having different depths of investigation (ILD, ILM & LL3)

APPLICATIONS OF RESISTIVITY LOGS

- True formation resistivity and flushed zone resistivity.
- Mud filtrate Invasion profile.
- Quick look hydrocarbon detection.
- Indication of producible hydrocarbon
Correlation of different formations

**POROSITY LOG**

Porosity values can be obtained from sonic log, a formation density log or a neutron log. In addition to porosity these logs are affected by other parameters, such as lithology, nature of the pore fluids, and shaliness. For more accurate porosity is obtained from combination of logs. The readings of these tools are determined by the properties of formation close to the borehole. The sonic log has the shallowest investigation. Neutron and density logs are affected by a little deeper region, depending somewhat on the porosity, but generally within the fluigated zone.

**NEUTRON LOG**

**Principle**

In neutron log we use a chemical source such as Americium – Beryllium/Neutron bulb which provides the emission of neutrons as continuous source of energy of about 4.5 MeV/14 Mev. When neutron collides with nucleus of the atoms in the formation the neutron losses its energy and excites the nucleus of the atoms in the formation. When the exited nucleus returns back to its normal state, it emits Gamma ray characteristic to the atom. The analysis of the $\gamma$-ray spectrum identifies the composition of the elements in the formation viz. C,H, Cl, O etc. when the energy of the neutron reduces to thermal level and collides with Hydrogen atom its energy reduces to 0.025eV, also the neutrons are captured emitting gamma ray. Thus the uncaptured neutron reaching the detector is a measure of Hydrogen index of the formation..
PRINCIPLE OF NEUTRON TOOL

ADVANTAGES

➢ Determination of Porosity.
➢ Lithology identification
➢ Water saturation.
➢ Gass detection.
➢ Location & Monitoring of gass / oil and water / oil contacts.
➢ Correlation with open hole resistivity logs.
➢ Shale indicator.

BOREHOLE COMPENSATED SONIC LOG

PRINCIPLE

The sonic tool measures the interval transit time, $\Delta t$, or the time in microsecond for an acoustic wave to travel through one foot formation, along a path parallel to the borehole,
which is the reciprocal of the velocity of the compressional sound wave. Wyllie proposed the following empirical relation for determination of porosity from the sonic log:

$$\varnothing = \frac{(\Delta_t - \Delta_m)}{(\Delta_{tt} - \Delta_m)}$$

Where $\Delta_{tt}$ and $\Delta_m$ are the transit times in the pore fluid and rock matrix, respectively. This time average relation is good for clean, compacted formations of intergranular porosity containing liquids.
**TOOL CONFIGURATION**

The tool mainly consists of upper transmitter, lower transmitter and two pairs of receiver. The transmission from T1 is recorded by the receiver followed by T2 and vice versa for compensating the effects as sonde tilt and rugose hole condition.

First ‘t’ reading = (T1 - R1) – (T1 – R2)

Second ‘t’ reading = (T1 – R2) – (T2 – R2)

\[ T = \frac{\text{(Memorized first ‘t’ reading) plus (Second ‘t’ reading)}}{2 \times \text{span}} \]

**ADVANTAGES**

- Effects of cement coverage can be easily measured by comparing both open and cased hole data. (The transmit time overlaying each other for good cement).
- Detection of hydrocarbon in high porosity sand.
- Lithology can be identified.
- Integrated travel time useful in seismic interpretation.

**LIMITATION**

- In unconsolidated formations.
- Formation fractures.
- Gas saturations.
- Aerated muds.
- Rugose salt sections.
DENSITY LOG

PRINCIPLE

The density measures formation bulk density and photo electric absorption index of the lithologic column penetrated. The $\delta_b$ density depends on fluid density and matrix density in porous formation, and $P_e$ depends on atomic number used to determine the lithology of formation. To measure $\delta_b$ and $P_e$ gamma rays are directed to the formation. The detectors measure the gamma ray flux resulting from scattering and absorption effect of the formation. The higher the formation density, the lower the gamma ray intensity at the detectors.

TOOL CONFIGURATION

The density utilizes
A Cesium 137 gamma ray source
Two sodium iodide scintillation detectors
Small Cesium 137 source near the detectors

All of which are mounted on an articulated pad.

The SS detectors count rates associated with Compton scattering used only in the determination of bulk density because it is covered by cadmium shield which absorbs all gamma rays of energy less than 140 KeV. The LS detector count rate depends on Compton scattering and photo electric effect used to determine both $\delta_b$ and $P_e$. The LS detector is covered by beryllium shield absorbs rays of energy less than 160 KeV.

LIMITATION

- Primarily in open hole operation.
- Limited cased hole operation.
- Maximum hole diameter 22 inches.
- Minimum hole diameter 6 inches.

GAMMA RAY LOG

The standard gamma ray tool contains no source and it responds only to gamma ray emission from the downhole environment. Pottassium (K40), Uranium (U238), Thorium (32) are the main radioactive materials. The main types detectors are Geiger Muller detector or Scintillation Counters with NaI, CsI or BGO crystals (Photomultiplier, to measure incident gamma radiation.). The detector is unshielded and will thus accept radiation from any direction.

APPLICATION

- The gamma ray is particularly useful for defining shale beds when sp curve is rounded.
- It is used as a quantitative indicator of shale content.
Detection and evaluation of radioactive minerals.
Delination of non radioactive minerals including coal beds.
Correlation in cased hole operations.
The gamma ray log used in connection with radioactive tracer operation.

SPONTANEOUS POTENTIAL LOG

PRINCIPLE
SP arises due to salinity contrast between formation water and mud filtrate against permeable beds. No current is sent into the formation. The SP log is recorded by measuring the potential difference in milli-volts between an electrode in the borehole and a grounded electrode at the surface. The change in voltage through the well bore is caused by a build up of charge on the well bore walls. Shales and clays will generate one charge and permeable formations such as sandstone will generate an opposite one. This build up of charge in turn caused by differences in salt content and formation water.
A Schematic for measurement of SP

APPLICATION

- To delineate porous and permeable reservoir rocks
- To determine bed boundaries and bed thickness
- To evaluate the formation water resistivity
- To estimate the fraction of clay
- Correlation of permeable beds

DENSITY, $\gamma$–RAY AND NEUTRON LOG
NMR Logging

Before a formation is logged by an NMR logging tool, the protons in the formation fluids are randomly oriented. When the tool passes through the formation, the tool generates magnetic fields that activate those protons.

First, the tool's permanent magnetic field aligns, or polarizes, the spin axes of the protons in a particular direction. This process, called polarization, increases exponentially in time with a time constant, designated as $T_1$.

Next, the tool's oscillating field is applied to tip these protons away from their new equilibrium position in the same way a child’s spinning top precesses in the Earth’s gravitational field. **Precession** occurs as a body rotating about one axis slowly rotates around a second axis. In the NMR case, this second axis is the static magnetic field. This is shown in figure (Spin precession).

![Spin precession](image.png)

When the oscillating field is subsequently removed, the protons begin tipping back toward the original direction in which the static magnetic field aligned them. In NMR terminology, this tipping-back motion is called **relaxing**, and measurement of the ‘**relaxation time**’ is the fundamental measurement of NMR logging tools.

**APPLICATIONS**
• Total and Effective Porosity measurements without mineralogy effects
• Accurate Bulk Volume Irreducible/Free Fluid Index measurements
• Permeability determination
• Pore-size distribution
• Measurement of viscosity
• Hydrocarbon typing and quantification
• Accurately Identifies: Fluid contacts, By-passed pay zones, Low contrast/low resistivity pay zones

SIDEWALL CORING (SAMPLE TAKER)

There are many methods of taking samples of formations during drilling of a well.
1. Cutting Cores with special angular bit.
2. Collecting and cutting from mud with logging stream.
3. Sidewall coring with logging cables.

ADVANTAGES OF SWC

➢ Rig time saving
➢ Cost saving
➢ Exact depth control
➢ Quick handling of cores at surface
➢ Sampling of very soft formation also possible
➢ Sampling of any time before casing.

CASED HOLE LOGGING UNIT

Cased hole logs are run to assess well integrity, improve reservoir management and scan the well for bypassed production before plugging and abandoning. It is extremely
important in secondary & tertiary recovery programs. Cased hole logs can be placed into two categories

**Well bore integrity**

Evaluate cement sheath around the casing, mainly

- Cement top location.
- Fraction of annular fill.
- Cement compressive strength.
- Casing condition. (Depth & extent of damage).

**Fluid movement**

This category detects channels behind pipe in both injection and production wells.

**CASED HOLE OPERATIONS**

**CASING COLLAR LOCATOR**

The CCL detects casing collars and perforations in tubing and casing.

**DESCRIPTION**

The CCL is a magnetic devices that detects changes in metal mass, such as those induced by the relatively high mass of a casing collar vis-a-vis the casing. The disturbance to the magnetic field is detected as a voltage difference. The CCL detects changes in metal volume as it moves through tubing or casing. The tool detector is comprised of a coil mounted between two opposing permanent magnets. As the tool passes a collar, the lines of magnetic flux between the magnets are disturbed, inducing a low frequency voltage in the coil. The signal is amplified and gated onto the wireline.

**PURPOSE**

To determine the location of casing collars.

**APPLICATIONS**

Depth correlation.

**CEMENT BOND TOOL**

**CEMENT & ISOLATION**

The main purpose of cement over the production interval is to provide isolation between neighbouring zones. Failure in isolation can cause problems like water production, depletion of gas drive mechanism, loss of production to neighbouring zones,
Contamination of fresh water sands etc. The remedy, is to squeeze cement job but it is not much benefit.

**DESCRIPTION**

The CBT evaluates cement bond integrity. The tool typically has a single omni directional acoustic transmitter and two receivers. One receiver at three feet and another receiver at 5 feet. The tool has no azimuthal capability; instead the received signal is an average from all around the pipe.

**PRINCIPLE**

The CBT measures based upon the principle of sonic wavetrain attenuation, detecting the amplitude of a sonic signal passing along the casing as an analog waveform. The signal is reduced where the casing is bonded to the cement, clearly identifying cement bond. The primary amplitude is detected at 3 feet receiver and variable density log is generated at 5 feet receiver.

**PURPOSE**

Cement bond integrity is requisite to hydraulic isolation.

**APPLICATIONS**

Cement bond evaluation.
Tool Positioning-Must run centralized

THE CBL-VDL DATA FORMAT ACQUIRED

PERFORATION

To establish fluid communication between well bore and formation for production / injection. It uses high explosives with shaped charges.

Perforators uses

- Initiator / detonator
- Detonating chord
- Shaped charges
The two types of perforations are

Over balanced method (+Ve head).

Under balanced method (-Ve head).

The positive head is achieved by keeping higher density mud in the borehole as compared to formation pressure. The advantage is it is easy to handle the well during perforation.

The negative head is achieved by keeping lower density borehole fluid compared to formation. The advantage of the well is it can be straightway connected to the production pipeline. However caution is exercised to avoid blowouts.

**BRIDGE PLUG SETTING BY WIRE LINE**

Bridge plug are mainly used for isolation of zones in casing. This prevent the movement of fluid from either direction.
**Back off services**

Some times the drill string or tubing gets stuck in the bore hole. To release it a shock at a joint just above free point is given. When detonating cord is fired it release the string.

**Puncture job**

It is a perforation operation with specially design small charge so as to have big holes with lesser depth of penetration.

**PRODUCTION LOGGING**

- Production logging provides down hole measurements of fluid parameters on a zone by zone basis to yield information on the type of fluid movement within and near the well bore.
- Major application of production logging include:
  - Evaluating completion efficiency.
  - Detecting mechanical problems, breakthrough, coning.
  - Monitoring and profiling of production and injection.
  - Detecting thief zones, channeled cement.
  - Single layer and multilayer well test evaluation.
  - Identifying reservoir boundaries for field development.

**RADIOACTIVE FLUID DENSITY TOOL**

**PRINCIPLE**

The density tool responds to the electron density of the fluid in the bore-hole. It is used to differentiate the various types of fluids in the bore-hole depending upon their densities.

This tool measures borehole fluid density by radioactive technique. Part of the fluid flow passes through the tool between low activity Cs 137 gamma source and a Scintillation gamma ray detector. An increase in the average fluid density in the sample volume causes a reduction in received counts.

**PURPOSE**
The purpose of the FDR is to measure fluid density of a sample as it flows through the tool. The average density of this volume is measured whether the flow is single or multiphase.

APPLICATIONS

- Multiphase production drilling
- Fluid identification
- Horizontal /Highly deviated wells
- High fluid flow rates.

PRODUCTION GAMMA RAY TOOL

CONFIGURATION AND PRINCIPLE

The production gamma ray tool comprises a sodium iodide scintillation crystal and photomultiplier to measure incident gamma radiation. The single conductor passing through the tool carries telemetry and power. The detector is unshielded and will thus accept radiation from any direction.

PURPOSE

- Lithology identification
- Depth correlation
- Identification of radioactive scale, possible sign of water entry.
- Monitoring of radioactive flow tracer.
- Gravel pack density monitoring. (With addition of gamma source)
- Evaluation of shale volume.
- Delination of nonradioactive mineral including coal beds.

It can be run in both open and cased horle.

CAPACITANCE TEMPERATURE FLOWMETER
The sondex capacitance water hold up, temperature, flowmeter tool (CTF) provides these three basic Production logging measurements within a short tool length. In the case of standard tools the equivalent three sensors will be at least six times further apart and so in heterogeneous flow are less likely to be providing measurements within the same fluid simultaneously.

**PURPOSE**

To provide a continuous log of fluid capacitance (water hold up), Temperature, Flowrate and flow direction.

**APPLICATION**

- Fluid composition from average dielectric constant.
- Fluid ID from temperature response.
- Location of leaks and crossflow by temperature response.
- Quantitative measurement of flow rate in casing and tubing.
- Production and injection log interpretation.
- Cement top determination.

**CALIPER LOG**

It is used to measure the Variation of borehole diameter with depth. Caliperlog presents the bore hole cross-sectional variation.

**CLASSIFICATION**

All borehole calipers use arm, fingers, or pads which act as sensor feeder and remain in contact continuously with borehole wall during the recording of the log in borehole.

It is classified as

- Single arm or pad calipers
- Two three or four arm springs calipers.
- 40 or 60 arm calipers.
APPLICATIONS

- High-resolution lithology discrimination.
- Depth calibration of different log suites.
- Fracture identification.
- Measurement of borehole rugosity.
- Estimation of mudcake thickness. The information is used to correct the micro resistivity log readings.
- The evaluation of temperature and CBL logs in combination with caliper data help to diagnose quality of cementation.

FORMATION EVALUATION

The ultimate objective of well logging in the petroleum industry is to economically establish the existence of producible hydrocarbon reservoirs (oil and gas).

A reservoir may be defined as a rock which has both porosity and permeability. The factors which determine porosity and/or permeability are the:

- Depositional environment
- Subsequent diagenesis.

Hence, identifying or understanding of such phenomena is important prior to any well evaluation.

OBJECTIVES OF RESERVOIR EVALUATION:

The following are the essential objectives of reservoir evaluation by using well log.

- The location of a reservoir vertically within drilled section & if possible, spatially.
- Determination of fluid type- gas, oil, water, bitumen etc.
- Calculations of reserves, both movable & inplace. This involves:
Computation of porosity (total, primary, secondary, effective).
Computation of water saturation.
Calculation of pay thickness.
Selection of cutoffs.
Determination of reservoir geometry.

Determination of the productivity of the well. This involves:

- Determination of mobility.
- Calculation of permeability.
- Determination of formation pressure.

- Determination of the lithology, facies and depositional environment to get an idea of reservoir geometry as well as petrophysical properties of the reservoir.

- Exact nature (number & type) of the principal minerals and, if possible, of the accessory ones, since any error in mineral type can lead to significant errors in calculation of porosity, of saturation, and of reserves.
- Percentage of the principal minerals.
- Percentage of clay, clay type & distribution.
- Estimation of texture, grain size distribution, sorting, and grain shape.

LITHOLOGY IDENTIFICATION:

Porosity determination using different logging devices relies on the knowledge of the rock type. In the case of the density tool, the density of the rock matrix must be known. The matrix travel time must be known to determine porosity from sonic log. In order to get porosity from neutron log the matrix setting for the neutron tool must correspond to the rock type. Determining these parameters is not much of a problem if one has good geological knowledge of the formation or if the lithologies encountered are simple, such as,
clean sandstone formation. If opposite is the case or if one is not sure about lithology, the best way will be to adopt graphical methods.

**OVERLAY OF POROSITY LOGS ON A COMMON REFERENCE SCALE:**

The three types of porosity log, which are available (sonic, density, neutron), are recorded in drastically different units (microseconds per foot, grams per cubic centimeter, and neutron counts or percentage porosity unit). However, the logs can be directly compared if calibrated on a common reference scale. The most widely used scale for this purpose is defined in terms of equivalent units of limestone percentage porosity. The density scale may be transformed by setting the grain density of calcite (2.71) to zero porosity, the fluid density (1.00 for fresh water) to 100% porosity and interpolating intermediate values. By an analogous procedure the transit time of the sonic log can be converted to the limestone porosity equivalents by setting the matrix transit times of calcite & pore fluid as the two porosity extremes for interpolation. Limestone porosity scale is the most common reference of the neutron logs and hence requires no scaling.

An overlay of any combination of the three porosity will give immediate indications of the lithology of logged units by virtue of the different responses of matrix minerals to the individual porosity logs. This point is illustrated by comparing the hypothetical response of a mixed sequence of lithologies to the density & neutron logs.

In log interpretation the main focus is to identify the formations susceptible of containing displaceable fluid. These formations are porous and permeable formations. Once the porous and permeable formations have been identified, the next great thing to do is to determine the nature of the fluid content in the pores. The fluid can be water or hydrocarbon and water, with rare instances of gases like nitrogen or carbon dioxide being present.

G.E. Archie's work relating permeability to porosity resulted in empirical relationships between resistivities, fluid types and porosity. In undisturbed formations, Archie's (empirical)
law states that the ratio of formation resistivity to connate water resistivity (Ro/Rw) is constant. That is

\[ F = \frac{Ro}{Rw} \quad \text{(eqn 1)} \]

Where:

- F is called the formation factor,
- Ro is bulk resistivity if pore space is filled 100% with brine (connate water),
- Rw is resistivity of the connate water itself. This relation applies best for clean (clay free) rocks of constant porosity when Rw < 1 Ohm-m, at 25°C.

This is useful, except that Ro is not really measurable in the field. But the relation can be made useful because Archie also found that this resistivity ratio (i.e. F) changes consistently as porosity changes.

- Formation factor and porosity are usually related via
- \[ F = \frac{a}{\phi^m} \quad \text{(eqn 2)} \]
  - where \( \phi \) is porosity expressed as a percent (a value between 0 and 1).
  - a is a constant between 0.6 and 1.5. It is often left at 1.
  - m is the cementation exponent and is usually 1.5-1.8 in sandstones and 2.0 in limestones, dolomites and tight consolidated sandstones.
  - One example of a particular version is \( F = 0.62/\phi^{2.15} \) (the so-called "Humble relation", suitable for many granular rocks).

AN ALTERNATIVE RELATION IS:

- \[ F = 1/\left(1.87+0.019\phi\right)^{1.87} \quad \text{(The Shell relation, best used for low-porosity carbonates)} \]

Finally, water saturation (Sw) and formation resistivity were also found to be related. Water saturation is the percentage of the pore space filled with water, which is of course important when evaluating a potential hydrocarbon reservoir. Sw=1 means all fluids are water,
and $Sw=0.1$ means 10% of fluids are water, implying 90% are non-conductive or oil/gas. The relation is $Sw = (R_0/R_T)^{1/n}$ (eqn 3) where

- $n$ is a saturation exponent, usually close to 2.0. ($n$ is not porosity in this relation),
- $Ro =$ rock resistivity with 100% brine for fluid
- $Rt =$ true resistivity (with hydrocarbons and water in pore space).

Now the Archi equation relating quantities of interest to measurable quantities can be derived based upon eqns 1, 2, 3:

$$Sw = (FR_W/R_T)^{1/n} \text{ (eqn 4)}$$

This relation is commonly used for oil / gas reservoir characterization. Three parameters must be measured: (i) porosity, (ii) resistivity of the undisturbed formation, and (iii) resistivity of connate water. Symbols are $\phi$, $R_t$ and $R_w$ respectively. $R_w$ can be obtained from:

- Water catalogues of the area you're working in;
- Laboratory analysis of samples extracted from the formation rocks;
- Obtainable from the spontaneous potential or SP log;
- "Apparent" water resistivity from $R_t = F * R_{wa}$ when $Sw = 1$, e.g. in "clean water sands";
- By relating invaded & uninvaded resistivity in clean zones;
- From resistivity - porosity crossplots;
- From $R_wa$ - SP crossplots.

$R_t$ is true resistivity of undisturbed formation. Of course drilling disturbs the formation, so choosing the right tool and interpreting various resistivities is important. Methods must account for bore hole environment, invasion, effects of adjacent beds, and technical aspects of tools themselves.

In the oil / gas context, porosity, $\phi$, is obtained from the porosity well logging tools, or possibly from resistivity where $Sw$ is known to be 100%. Porosity logging tools are also used in hydrogeology and engineering situations, though this is not routine as in the oil / gas industry.
CONCLUSION:

Thus Logs are an explorationist’s eye. Log measurements can give the majority of the parameters required by all. Specifically, logs can provide either a direct measurement or a good indication of porosity, both primary and secondary (fractures and vugs), permeability, water saturation and hydrocarbon movability, hydrocarbon type (oil, gas, or condensate), lithology, formation (bed) dip and strike, sedimentary environment, travel times of elastic waves in a formation.

From this data, it is possible to obtain good estimates of the reservoir size and the petroleum hydrocarbons in place.

Logging techniques in cased holes can provide much of the data needed to monitor primary production and also to gauge the applicability of waterflooding and to monitor its progress when activated.

In producing wells, logging can provide measurements of flow rates, fluid type, pressure, residual oil saturation. From these measurements, dynamic well behavior can be better understood, remedial work can be planned, and secondary or tertiary recovery proposals can be evaluated and monitored.

In summary, when logging is properly applied, it can help to answer a great many questions from a wide spectrum of special interest groups on topics ranging from basic geology to economics. Of equal importance, however, is the fact that logging by itself cannot provide answers to all formation evaluation questions. Coring, core analysis, and formation testing are integral parts of any formation evaluation effort. This is an instrument which gives maximum information at a very minimal cost. This also acts as a driller’s tool during complication— a third hand for a completion engineer. Thus no hydrocarbon can be produced without the intervention of Logs.