

Title: Myths and Methods for Electrical Properties of Porous Rocks.
Author: Rob T. Wittebrood
Company: Hycal Energy Research Laboratories , Electrical Properties Division

Abstract

Quite a few mythical misconceptions exist around the Formation Resistivity Factor and the Resistivity Index of porous rocks. This paper addresses some of these misconceptions. Should the FRF versus porosity line always go through the origin? Should a variable m be used? Must the saturation exponent always be greater than one? How large is the effect of the tortuosity? Does the temperature affect the FRF? Does the Overburden Pressure affect the RI ?

Archie originally tried to predict permeability from the resistivity and did not have success. However, it can be done. Extra information is needed and Petrographic Image Analysis can play a significant role here.

Different methods are used to measure the electrical properties. A few of the methods are compared. The centrifuge method has so many drawbacks, that it only has limited usefulness. A few points of general concern are mentioned.

Section 1 : Introduction

The Formation Resistivity Factor (FRF) and the Resistivity Index (RI) are two of the most widely used formation properties in log analysis in the oil industry. The Formation Resistivity Factor is usually correlated to the porosity in the form of the first Archie relation (1) :

$$\text{FRF} = \phi^{-m} \quad [1]$$

with

FRF	R_o/R_w
R_o	resistivity of 100% brine saturated rock
R_w	resistivity of saturating brine
ϕ	porosity
m	cementation exponent (cementation factor)

The Resistivity Index (RI) is usually correlated to the water saturation in the form of the second Archie relation (2)

$$\text{RI} = S_w^{-n} \quad [2]$$

with

RI	R_t/R_o
R_t	resistivity of rock desaturated to S_w
S_w	water saturation
n	saturation exponent (saturation factor)

If the values for m and n are known from lab measurements, R_w from produced fluid analysis, and the correct R_t and ϕ from wireline logs, the water saturation can be calculated from equation [3].

$$S_w^n = (R_w/R_t) / \phi^m \quad [3]$$

Originally the equations were considered to be totally empirical, with no foundations in theory. In 1988 these equations were analytically derived in the above form by Spalburg (3) using the Effective Medium Model. Other models (geometric and computer models) also led to the same relations with numerical results. However, as with all models the results are only relevant as long as the conditions for the model are obeyed and as long as the model is valid. Over the years many models have been tried. The ones that did not confirm to the observations never were published, the ones that did indeed describe the observations to some level of satisfaction were published. However, that does not necessarily mean they are physically meaningful. All models fail in some respect.

The Archie relations [1] and [2] are still empirical relations. There has been a significant amount of discussion published in the literature on the validity of Archie's relations. And it is no wonder that over the years a number of stubborn myths were passed around along the grapevine.

This paper will deal with three issues in three sections. First addressed are some of these myths, such as:

- | | |
|---|-------|
| Myths | |
| 1. FRF versus porosity line has to pass through the origin. | False |
| 2. Saturation exponent [n] must be greater than 1.0 | False |

- | | |
|---|-------|
| 3. Variable m-exponent [$m = m(\phi)$] is useful. | False |
| 4. Tortuosity has a large effect on m. | False |
| 5. Temperature affects the FRF. | False |
| 6. Overburden Pressure affects the RI . | False |
| 7. Four electrode measurement is better than two electrodes method. | False |
| 8. When m increases n increases (or decreases) | ? |
| 9. At lower water saturations n decreases (or increases) | ? |

Next the relation between permeability and resistivity will be examined. Archie's original aim was to use the resistivity to predict the permeability. However, he did not have success. Nevertheless, the two are very much related. The permeability can be predicted from the resistivity with some extra information i.e. the pore throat size. The pore throat size is difficult to measure in the well bore. Sometimes NMR is used to predict permeability. The NMR yields a measure of surface area. So, as long as surface area and pore throat size are correlated this may have some success. In the lab the pore throat size can be obtained rather inexpensively using Petrophysical Image Analysis (PIA) on SEM photographs. In our last section some of the methods which are used to measure the electrical properties are discussed. There are a number of different methods in use especially for the RI. Which method should be used? Some methods actually have so many drawbacks, that they only have limited usefulness.

Section II : Myths

This section examines a few of the most common myths around the Formation Factor and the Resistivity Index.

1. FRF versus porosity line has to pass through the origin False

When the FRF- porosity line passes through the origin ($FRF = 1$ when $\phi = 1$) the usual Archie relation applies:

$$FRF = 1 / \phi^m \tag{1}$$

When this line does not pass through the origin it is usually written with a coefficient a as

$$FRF = a / \phi^m \tag{4}$$

with
intercept , cementation coefficient

The fundamental concept behind this myth is that when the porosity is equal to 100% the sample resistivity (R_0) and the brine resistivity (R_w) should be the same. So $FRF = R_0/R_w$ should be equal to 1 and the line should go through the origin. Although this makes sense, it is not necessarily true.

Imagine a sample made from a cylinder 100% filled with brine. This cylinder will have an FRF equal to 1. When across this sample a plate of infinite resistivity is inserted the measured resistivity of the sample will become infinitely large and so will the FRF. When the thickness of the resistive plate is reduced the resistivity remains very large no matter how thin the plate is made. In this way 100% porosity can be approached as close as wanted by making the plate continuously thinner while the resistivity remains extremely high. In this case the FRF can not be defined nor the value of the cementation exponent.



Next imagine a model for a dead end vug as illustrated. The vugs are connected to a straight pore by a relatively small hole. The FRF will equal D/d . It is also evident that the vug can be filled with any amount of rock or cement without affecting the resistivity, but reducing the porosity at will. So the FRF versus porosity line is horizontal with an intercept of D/d and a cementation exponent of zero in equation [4]. In vuggy rocks usually intercepts greater than one are found, with smaller corresponding cementation exponents.



2. Saturation exponent [n] must be greater than 1.0 False

If the vugs in the second model in the previous case are filled with oil, the water saturation of the sample decreases. However, the resistivity remains constant ($FRF = D/d$) and RI remains equal to 1.0 and is now independent of the saturation. So in this case, from the second relation of Archie :

$$RI = S_w^{-n} \tag{2}$$

n=0 will be obtained. This clearly illustrates that the saturation exponent can have values lower than one.

3. Variable m-exponent [$m = m(\phi)$] is useful False

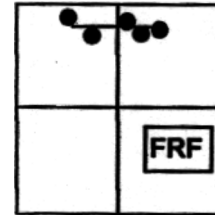
Consider the second model of the first case again. As an example assume that $FRF = D/d = 100$. (The actual value does not matter at all) So the FRF-porosity line is horizontal, crossing the axis at 100. Values of $a=100$ and $m=0.0$ should be used in equation [4]. In a variable m-approach the value for a is forced to remain 1.0 but m may vary with porosity as follows :

$$FRF = 1 / \phi^{m(\phi)} = 1 / \phi^{(c + d \cdot \phi)} \tag{5}$$

In the above case m obeys the following relation in the range of porosities between 5% and 30%

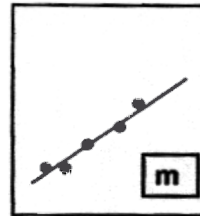
$$m = 1.10 + 8.83 \cdot \phi \tag{6}$$

which is a very good approximation, within 1% for most of this range. The number of constants fitted in equation [4] is two a, m and in equation [5] it is also two c, d.. So the number of coefficients is not a matter of consequence. However, in the variable m approach m is first determined as $m = \log(FRF) / \log(\phi)$. So m is parameter defined by porosity. Next m is correlated a second time to the porosity. That introduces fundamental problems from a statistical point of view, because m is already calculated using the porosity.



Using a data set of randomly varying FRF-values around an average value of $FRF=100 \pm 25$, and a random porosity between 0.03 and 0.35, the correlation coefficient (r2) between FRF and porosity equals zero, whereas the correlation coefficient between m and porosity equals 0.995. This clearly shows that the variable m approach is incorrect from a statistical point of view.

Next, it was assumed that the FRF was constant, with no dependence on porosity whatsoever. In using equation [5] this constant FRF value is forced into a dependency on porosity. By twisting the cementation exponent around, in making it a function of the porosity, this dependency on porosity is to be eliminated again from the final result. This does not make sense at all. This is very clear in the case of a constant FRF-value. However, the same arguments apply when the FRF-porosity line has a slope. The same conclusion is not evident quite as clearly, because in this case the correlation coefficient for the FRF increases and for the m-exponent it decreases. The variable m approach was applied in a highly acclaimed paper by Focke and Munn (4). The paper has some good information, but it was found to be incorrect as far as its objective of the variable m approach was concerned.

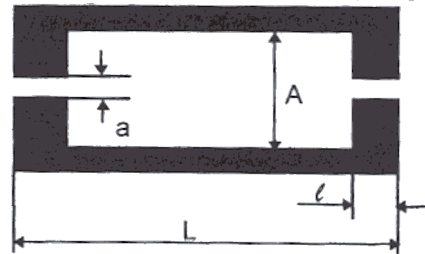


So the conclusion is there is no gain to be had from the variable cementation exponent approach. This myth illustrates a very good statistical example in which a very high correlation coefficient is obtained, without any physical meaning or cause. This high degree of correlation is an artifact resulting from incorrect procedures, not one due to a natural cause.

4. Tortuosity has a large effect on m False

This myth often gets bogged down in semantics. So it is necessary to define what is meant by tortuosity. Tortuosity (τ) is defined here as the average effective path length of the current divided by the length of the sample ($\tau = L_e / L$), which is a number that is greater than one or equal to one, when the current path is straight. There is also an effect of the pore geometry. The effect of the pore geometry is captured in what will be called here the pore geometric factor (Γ). To illustrate these concept imagine an example pore as shown to the side with the following dimensions:

- A cross sectional area of the pore
- a cross sectional area of the pore throat
- L length of the sample
- ℓ length of the pore throat



For this pore shape it can be found that

$$FRF = \Gamma \cdot \tau^2 / \phi \tag{7}$$

with

$$\Gamma = (2\ell / L \cdot (A/a - 1) + 1) \cdot (1 - 2\ell / L \cdot (1 - a/A))$$

$$\tau = L_e / L = 1.0$$

$$\phi = \text{porosity}$$

geometric factor
tortuosity
porosity

The geometric factor (Γ) can be made as high desired by reducing the size of the pore throat, while the tortuosity in this case remains very close to 1.0. The factor: $2. A \ell / a L$ dominates the geometric factor. This demonstrates that the geometric factor has the dominating effect on the FRF, not the tortuosity. The behaviour of the resistivity is understood better when more attention is focused on the pore geometry. In equation (7) the porosity appears in the denominator. This is the case in all geometric models. The product FRF. ϕ equals 1.0 for straight tubes for all cross sectional shapes. For any other geometry the product FRF. ϕ is greater than 1.0. Actually in the detailed study of the FRF behaviour this linear dependency on the porosity should be removed first. It is much better to use a parameter proposed by Herrick and Kennedy (5) in 1993. The proposed parameter was called the Electric Efficiency Factor (EEF):

$$EEF = 1/\phi.FRF = 1/\Gamma.\tau^2 \quad [8]$$

Correlating this parameter to observed geometry effects (e.g. using Petrophysical Image Analysis) is recommended. In carbonates the Electric Efficiency Factor is quite often not correlated to the porosity at all, which means that the tortuosity and the geometry vary at random. However, correlating FRF to porosity still will show some porosity dependence, with correlation coefficients $r^2=0.5$, which only reflects the fundamental linear dependency on porosity.

5. Temperature affects the FRF False

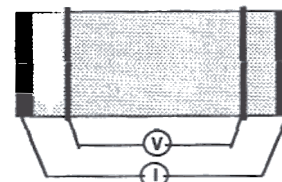
In a few papers observations are reported that the FRF appears to vary with temperature. This is incorrect. The FRF is only dependent on the geometry and tortuosity as shown in the previous section. When a temperature effect is observed it may indicate that the sample is changing its geometry when the temperature changes. It also may indicate that the laboratory procedures to measure FRF are incorrectly applied. The temperature effect that occurs with shaly samples is the result of the counter ion behaviour. It can be accounted for as shown by Waxman and Smits (6)

6. Overburden Pressure affects the RI False

The overburden pressure has an effect on the pore geometry, but not on the fluid pressure as such. The effect of the overburden pressure is accounted for by the Formation Resistivity Factor. The fluid pressure affects the interfacial tension between brine, oil and rock, which generally speaking affects the Resistivity Index. However, the direction of the effect up or down with pressure is not a priori known. So fluid pressure may have an effect on RI, but overburden pressure has no effect.

7. Four electrode measurement is better than two electrodes method False

This myth is a remnant of the old days. The four electrode method uses two disk electrodes at each end of the sample that carry the current. There are two extra ring electrodes, which do not carry any current but are only used to measure a potential difference. These electrodes are placed at some distance of the current electrodes. It is supposed that in this case only the current carrying electrodes are subjected to polarization effects. Polarization occurs when a current passes through an ionic solution. The positive electrode (anode) will collect excessive amounts of anions, and the negative electrode (cathode) will collect excessive amounts of cations. A second effect may occur at the transfer of the electric charge between the ions and the electrons in the electrode. When this requires extra energy the current flow is and a fraction of the voltage is lost over the electrode-fluid interface. These increased concentrations and charge transfer energy are referred to as polarization. They will tend to block the current through the fluid and the current is no longer proportional to the voltage. So, polarization will increase the apparent resistivity and should be avoided or eliminated.



Polarization due to charge transfer can be avoided by using proper equipment. With modern electronic equipment concentration polarization can actually be eliminated from the measurement even with clean stainless steel electrodes. Thus using proper procedures, materials and electronics, no polarization concerns are necessary. Four electrodes would only lead to more operational problems. Also, only about half the sample is used to measure the resistivity, so the measurement error increases. Usually the two voltage electrodes are at a fixed distance imbedded in the rubber sleeve around the sample, which limits the sample size that can be measured.

So four electrode measurements no longer have advantages, only disadvantages. Comparing results between these two methods prove the above statements.

When m increases n increases (or decreases) ?

In vuggy carbonates quite often higher cementation exponents (m) and lower saturation exponents (n) are observed. In angular sandstones higher m -exponents are often accompanied by higher n -exponents. A survey of all measured measurements available in Western Canada by Mahood and Boyd (7), failed to show any correlation

between the two exponents for any lithology. So any rule of thumb that may be observed for a correlation between m and n may have only very local validity. In various reservoirs both trends could be inferred.

9. At lower saturations n decreases (or increases) ?

Quite often it is difficult to obtain low water saturations during resistivity index measurements. To evaluate reservoir at even lower saturations it is sometimes assumed that the RI-Sw curve is bending downwards at lower saturations. This is quite often observed in laboratory measurements. But this may be an artifact. Especially in commercial measurements the samples are often cleaned using methods that are expected to make them fully water wet. In this case the value for the n -exponent is expected to approach 1.0 at very low saturations, when the water is distributed like a thin continuous film. However, if there is some oil wetting left, then the water films are interrupted and the n -exponent will increase. If the samples are fully oil wet, the conductive path between the pores will be serrated at a certain oil saturation and the saturation exponent will become infinite.

What happens in the reservoir is generally not known. Restoring the core, before RI measurements are conducted, may help to shed some extra light on the issue, but does not necessarily restore the core to undisturbed reservoir conditions. The use of preserved core will also be beneficial in the proper measurement of n -exponents.

Section III . Permeability and FRF

In this section resistivity to permeability are related to each other. The main reason that this section is included is that in the above most of the tools to do this have been developed.

To relate permeability to resistivity is not a novel idea (8). Archie's original attempt was to do just this. Although he was not successful, looking at the physics, most of us would intuitively expect that such a relation should exist, just as he did. The permeability is such an important evaluation parameter that attempts to find such a relation appear in the literature every now and then. Equation [7] for a square pore can be used as a starting point:

$$FRF = \Gamma \cdot r^2 / \phi \quad [7]$$

The permeability can be treated in a similar manner. A very similar relation will be obtained

$$a/k = \Gamma^* \cdot r^2 / \phi \quad [9]$$

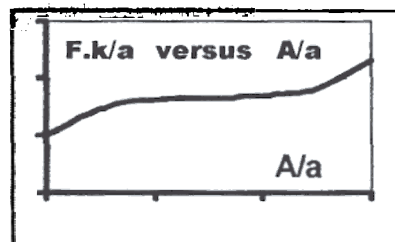
with

k	: permeability
Γ^*	: geometrical factor for the permeability
a	: cross sectional area of the pore throat

It can be easily proven that the ratio of: Γ / Γ^* is constant over a significant range of the ratio of pore size / pore throat size. This also is true for many other pore shapes. By dividing equations [7] and [8] the following relation is obtained:

$$FRF \cdot k/a = \Gamma / \Gamma^* = \text{constant} \quad [10]$$

under a large range of conditions. This dimensionless group becomes independent of porosity, of tortuosity, of geometry, of pore size and many other factors. However, the pore throat size is the connecting factor here. Currently there is no down hole measurement that will provide this information. However, using a Scanning Electric Microscope (SEM) and Petrographical Image Analysis (PIA) on samples from previous wells, or similar rock, the reservoir can be finger printed and correlated to a down hole measurement.



Equation [10] shows that permeability estimates which are derived from surface area measurements only work when the surface area is related to the pore throat size. In other words when the pore geometry is fairly constant. This explains why the NMR derived permeability, which is calculated from the measured surface area, often works in sandstones but is not reliable in carbonates.

So permeability and resistivity are very much related, but they are connected via the pore throat size, which is not available down hole from wireline logs, but may be inferred from NMR, but is easily investigated using PIA.

Section IV Methods

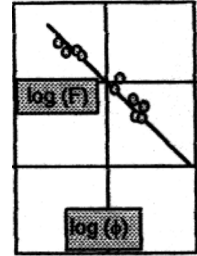
In this section methods to measure FRF values and RI values are discussed.

Single Point FRF

In a Single Point FRF determination the sample is usually saturated outside the cell. Then it is mounted in a sleeve inside a pressure cell with electrodes on either end. The sample is subjected to overburden pressure and the resistivity of the sample is measured after some equilibration time. The porosity is assumed to be the routine porosity or it is calculated from the routine porosity using a previously established stress correction factor. In the graph an example with $a=10$ and $m=1.0$ (FRF = 100 at 10% porosity) is shown

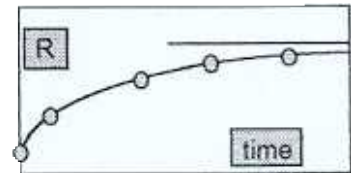
In this method it is not possible to adjust the data at a later stage for stress corrections, if a uniaxial stress value is required, or when the reservoir is being depleted, because FRF and porosity are not known as a function of stress.

The time to achieve equilibrium may vary significantly with rock type, depth etc.



Multi point FRF

In a multi point FRF determination the sample is usually saturated outside the cell, but sometimes when it is mounted in the cell. The last procedure is time consuming and expensive, but allows for excellent porosity estimates. When the sample is saturated outside the cell, the porosity has to be back calculated. Commonly the overburden pressure is increased in steps and at each step the equilibration of the resistivity is monitored. When the equilibrium value is established the resistivity and the amount of expelled brine are measured. Then the overburden pressure is raised to the next level. And the procedure is repeated.



Usually 5 points are measured. The FRF and the porosity are fitted to a non linear function e.g. a rational function

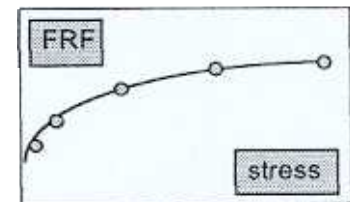
$$F = (F_0 + F_{\infty}\sigma_r) / (1 + \sigma_r) \quad [11]$$

and

$$\Phi = (\Phi_0 + \Phi_{\infty}\sigma_p) / (1 + \sigma_p) \quad [12]$$

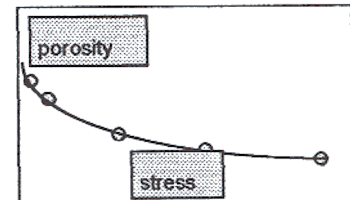
with

$$\begin{array}{ll} F_0, \Phi_0 & \text{values at zero stress} \\ F_{\infty}, \Phi_{\infty} & \text{values at infinite stress} \\ \sigma_r, \sigma_p & \text{normalized stress values (OBP / c)} \end{array}$$



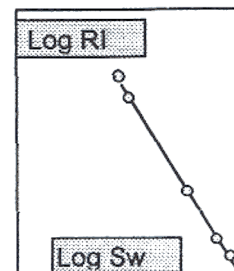
When the routine (Archimedes) porosity is known, the other porosity values can be calculated from the amount of expelled fluid. So in effect a pore volume compressibility can also be measured using this method.

With these two functions, eqn. [11] and [12], at hand the cementation exponent can be calculated at any stress value. The cementation exponent can increase with stress, decrease with stress or stay about the same. It all depends on how the pore geometry changes as a function of stress. Sometimes the cementation exponent can change by as much as 0.3, which means that the resistivity changes by a factor of two. So this information is important to know.



3. Porous Plate RI

Most commonly the Resistivity Index is determined by the Porous Plate Technique. A porous plate is a porous material in which the pore throat size is so small, that the capillary forces needed to displace the wetting phase are very much larger than for the samples. When the samples are put on the porous plate in good capillary contact with the plate the wetting phase can be displaced from the sample through the porous plate. This is usually done in a pressure pot where the samples are surrounded by gas. The gas pressure is increased in steps and the samples will desaturate according to the capillary pressure curves. The graph illustrates a case where a sample was desaturated at five different pressures. The results are usually plotted on a log-log scale. The line goes through the origin, because the desaturation starts at $S_w=1.0$. The slope is equal to the saturation exponent.

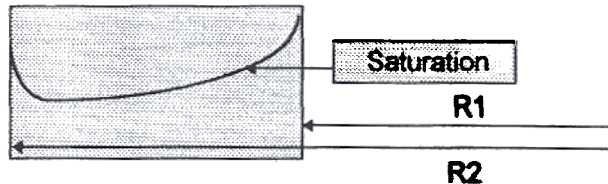


Repeated handling of the sample, grain loss, capillary disturbance, end effects, evaporation etc. will introduce large errors. This method can only be recommended for end point determinations, where the sample is desaturated in one step and only the last point in the graph is determined.

4. Centrifuge RI

The fastest method to decrease the water saturations is using a centrifuge. Is it possible to measure the Resistivity Index in a proper manner this way? The answer is definitely no! In this method the saturation throughout the sample is not very uniform, especially at the end faces of the sample where the capillary continuum is disturbed. It has the same handling problems as the porous plate method and additionally problems due to disturbed saturations. It is also not useful for end point determinations because of the saturation discontinuity at the end faces of the sample.

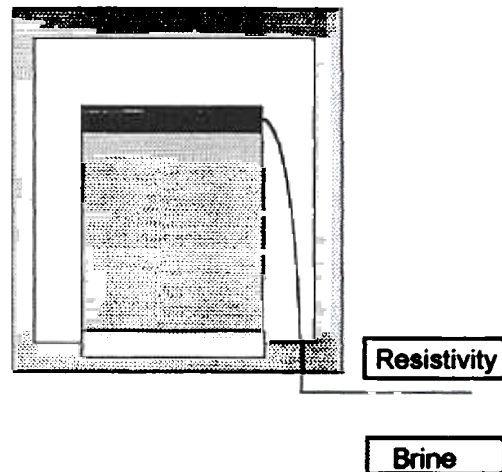
The adjacent illustration shows how the water saturation may vary as a function of the sample length. The increase in saturation at the end face is due to the fact that here the water has to leave the samples in droplets and no capillary continuum exists. To equilibrate the sample again after desaturation by centrifuge would take as much time (or more) as needed in the porous plate method. So if you do it right the desired time advantage is illusionary with the centrifuge method.



5. Equilibrium RI

In the equilibrium method the same principle is applied as with the porous plate method. However, in this case the sample is provided with electrodes and the amount of expelled fluid is measured for each sample. This means that the sample stays in the cell and no extra handling is required. The pressure steps are applied and the resistivity and saturation are monitored as a function of time. It is not uncommon to have to wait more than two weeks before the capillary equilibrium is achieved per step.

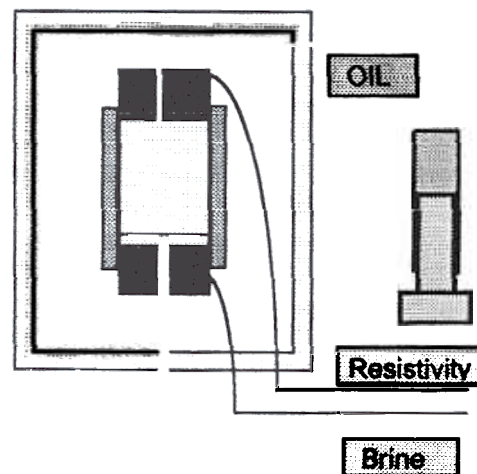
The illustration shows on top of the sample one electrode. The cell housing is the ground electrode. At the bottom of the sample is the porous plate, through which the brine is expelled and its volume measured. The gas pressure or the oil pressure may be applied around the sample. When oil is used, the temperature control is critical, because the amount of oil will be very large in comparison to the pore volume, and the oil may expand when the temperature rises. When gas is used the temperature effect is significantly smaller.



6. Continuous Injection RI

This method uses a slow injection technique (9). The sample is placed on a porous plate and mounted individually in a cell inside a sleeve with two electrodes on either side. Before injection of the displacing fluid, extra brine is flushed through the sample to have fresh end faces. Because the fluid lines need to have a small diameter, it is very time consuming to saturate the samples inside the cell. They have to be evacuated first, and at low pressures the gas molecules leave the sample only by diffusion. This makes the evacuation times very long. Saturating the samples outside the cell has the problem that all lines have to be full of brine during mounting. So excessive brine surrounds the sample, and to establish a proper starting point some extra brine has to flow through the sample. Desaturation can be done with any fluid that does not wet the core. Usually kerosene is selected, unless the samples have been restored.

A pump is used to inject the displacing fluid at very small injection rates. Injection rates in the order of one microliter per hour, which is in the order of one milliliter per month, are not uncommon when 1 inch samples are used. The idea is to keep the viscous forces resulting from the flowing fluid, significantly smaller than the capillary forces, so that capillary equilibrium can be established. At high water saturations capillary equilibrium is difficult to achieve, but that is the case with any other technique also.



General comments.

1. Temperature control is essential

All RI techniques (except the centrifuge) need good temperature control. This is especially true for the continuous injection method, because there the pump contains a relatively large amount of fluid, which can expand into the sample at a rate significantly higher than the set injection rate if the temperature varies.

2. Pressure cycling introduces Capillary Hysteresis

It is not a good idea to relieve the fluid between various pressures to take the samples out and measure the saturation and the resistivity. When a pore is entered by the displacing phase the capillary pressure (P_c) equals

$$P_c = \sigma (1/r_1 + 1/r_2)$$

with

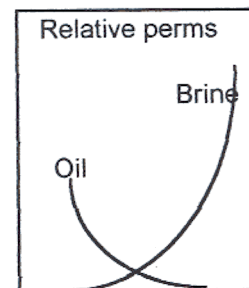
σ : surface tension
 r_1, r_2 : curvature radii of the fluid interface

just before entering the pore the two curvature radii of the displacing fluid are both equal to the pore throat radius. However, after breaking through the throat the second curvature radius becomes large and negative. This means that the P_c drops to less than half the value and the pore fills in one big gulp until the curvature is such that it equals the original fluid pressure again. When the pressure is relieved the fluid will snap off at the pore throat. The pressure inside the pore will remain at P_c more or less. To enter the pore again the next capillary pressure has to overcome both the pore pressure and the entry pressure. So it has to be twice as high. As with all capillary measurements the pressure may only go up and not cycle.

3. Desaturation rates can be very slow

When the water saturation is high the relative permeability to the desaturating phase (oil or gas) is low. This means that with the low pressures that have to be used, equilibration times can become very long. Also when the water saturation becomes low, the relative permeability to the brine becomes very low, and it takes a long time to remove the brine from the samples.

At the end of the desaturation during continuous injection it is often noticed that the flowing pressure is significantly higher than the equilibrium pressure. This means that the viscous forces are larger than the capillary forces. This does not mean that the Resistivity Index data are invalid. At this point the saturation usually falls in the very steep part of the capillary pressure curve and the water saturation throughout the sample remains more or less uniform. However, it does mean that capillary pressure measurements made during continuous injection must be done, when the oil is not flowing and the pressure is stabilized. This may take days.



Literature

1. Archie, G. E., 1942, Transactions AIME. Vol. 146, pp. 54-67. "The Resistivity Log as an Aid in Determining Some Reservoir Characteristics".
2. Archie, G. E., 1950, Bulletin of the American Association of Petroleum Geologists Vol. 31 pp. 943-961. "Introduction to Petrophysics of Reservoir Rocks".
3. Spalburg, M.R. 1988, Transactions of the 11-th European Formation Evaluation Symposium, September 11-16, Paper O, "The Effective Medium Theory used to derive Conductivity Equations for Clean and Shaly Hydrocarbon Bearing Reservoirs".
4. Focke, J. W. , Munn, D. 1987, SPE Formation Evaluation June pp. 155-167, "Cementation Exponents in Middle East Carbonate Reservoirs".
5. Herrick, D. C., Kennedy, W. D, 1993 , SPWLA 34-th Annual Logging Symposium June 13-16 paper HH. "Electrical Efficiency, a Pore Geometric Model for the Electrical Properties of Rock".
6. Waxman, M. H., Smits, L. J. M. , 1968, Soc. Petr. Eng. J. Vol. 8. pp. 107-122. "Electrical Properties in Oil Bearing Shaly Sands".
7. Mahood, B. C., Boyd, D. A. 1993 SPWLA 34-th Annual Logging Symposium, June 13-16 paper FF. "Formation Factor Relationships of Western Canada".
8. Schlueter, E. M., Cook, G. W., Zimmerman, R. W., Witherspoon, P.A., 1991, in Rock Mechanics as a Multidisciplinary Science, Hoeglers (ed.) "Predicting Permeability and Electrical Conductivity of Sedimentary Rocks from Microgeometry".
9. de Waal, J. A., Smits, R. M. M., de Graaf, J. D., Schipper, B. A., 1991, The Log Analyst, September pp. 583-595. "Measurement and Evaluation of Resistivity Index Curves".