Chapter 9: Electrical Properties

9.1 Introduction

Laboratory measurements of electrical properties (formation factor and resistivity index) are intended to complement those made during down hole logging operations. The data are used to refine values of n, a and m in Eq. (9.1) and (9.2) below:

$$F = \frac{R_o}{R_w} = \frac{a}{f^m} \qquad (9.1)$$

where;

F = Formation factor
R_o = Resistivity of brine saturated rock
R_w = Resistivity of brine
a = Constant
f = Porosity
m = Cementation exponent

and,

$$I = \frac{R_t}{R_o} = \frac{1}{S_w^n} \qquad (9.2)$$

where;

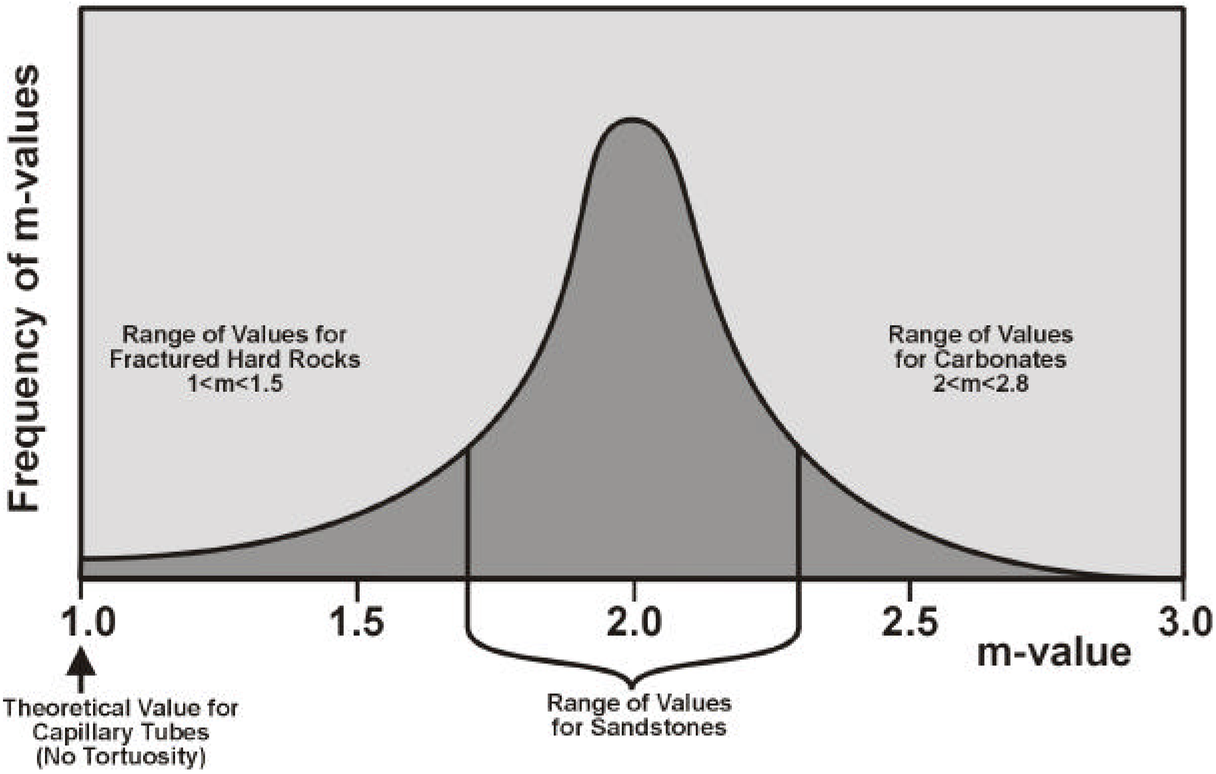
I = Resistivity index
R_t = Resistivity of rock at $S_w < 100\%$
n = Saturation exponent

Without prior laboratory data, n is generally assumed to have a value of 2. Typically, laboratory derived data gives values between 1.7 and 2.4 (Figure 9.1).

Equations (9.1) and (9.2) are empirical in nature. They are generally adhered to by ‘clean’ samples, but where clays (usually described as shales in this context) are present large deviations can occur. Empirical corrections for shale effects, i.e. for m to m* and n to n* are possible but the best procedures are in doubt. The shale effect, which is primarily due to enhanced surface conduction in the high surface area clays, can now also be corrected for using fundamental theory, but the governing equations for the physical processes involved are complex.

As with other SCAL tests, samples should be prepared and brought to the initial brine saturated state without drying. The displacing phase used in resistivity index measurements is air, thus these tests are carried out in conjunction with air-brine capillary pressure measurement, most commonly using the porous plate method.

Figure 9.1 Distribution of Cementation Exponents

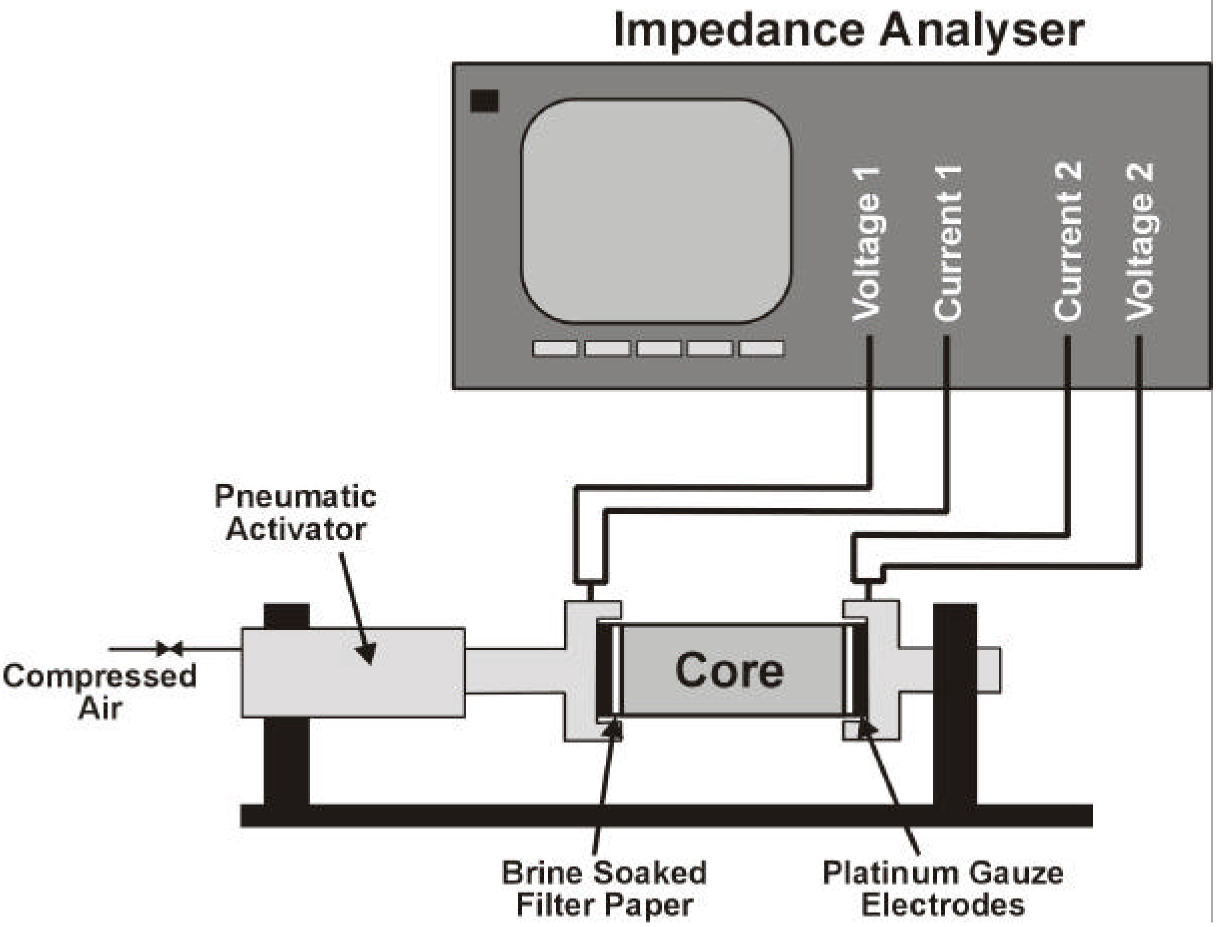


9.2 Formation Factor

Formation factor is a function of porosity and pore geometry and is defined above in Eq. (9.1). Laboratory measurements are made at room conditions or at overburden conditions, the apparatus is sketched in Figures 9.2 and 9.3 respectively. Normally plugs require 2 weeks for equilibration with formation brine. For room condition tests, measurements are made at intervals of a few days until constant values are obtained. In the case of overburden measurements, it is possible to flow brine through the plug in the cell and equilibrium is achieved more rapidly.

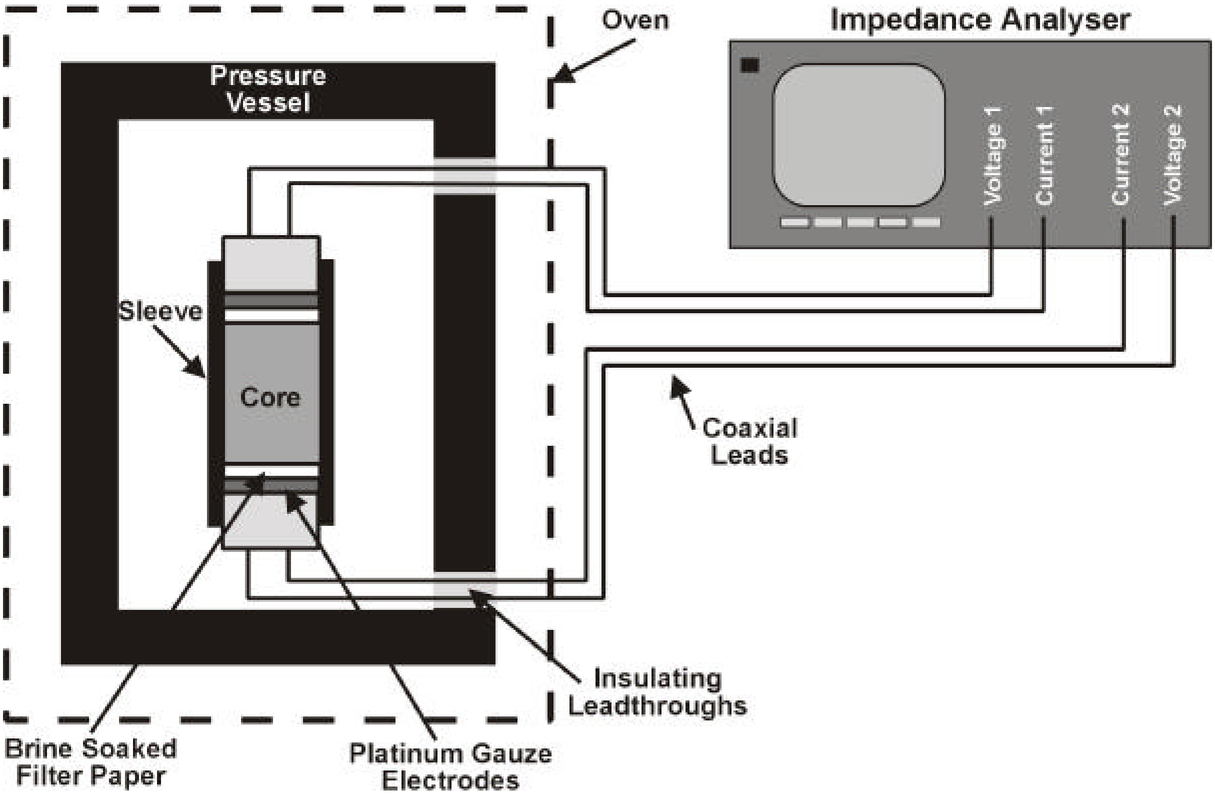
Overburden resistance measurements are made at increasing pressures, but time has to be allowed for equilibrium to be achieved. This is generally due to varying rates of compaction under overburden pressures and, in the case of low permeability samples, it can take many hours for brine to be fully expelled. Rates for compaction vary according to material, 24 hours often being required for full equilibration. Repeat determinations cannot be made without allowing plugs sufficient time to relax back to the unconfined state. This can take many weeks and in some cases, where the pore structure is irreversibly damaged, the rock never returns to its initial state. Once a rock has been used for resistance measurements at high overburden pressures, it should never be used for further study for this reason. Overburden formation factor measurements are generally combined with pore volume compressibility determinations.

Figure 9.2 Ambient Condition Electrical Rig



The actual electrical measurements of resistance in themselves are very precise (better than 0.1%), but care has to be exercised in setting up the plug for the measurements. The most important thing is that the electrodes at each end of the sample do not have any electrical connection except through the rock. This may seem obvious and trivial to arrange, but this one proviso causes the greatest difficulty when setting up a plug to be measured either at high overburden pressures, during rare triaxial deformation experiments, or using high electrical frequencies. The first and second of these situations arises from the need to electrically isolate the electrodes at each end of the sample from each other and the pressure vessel. Insulation is shown schematically in Figure 9.3, but in reality it is not always easy to arrange a robust electrically insulating and pressure-proof leadthrough. In the last situation, it is the capacitance of the leadthroughs and the pressure vessel itself that causes the problems. Even though there is no direct conductive connection, high frequency current can leak from one electrode to the other through the body of the pressure vessel by charge induction, even though there is an insulator in between.

Figure 9.3 Reservoir Condition Electrical Rig



High quality in-phase and out-of-phase resistance (conduction, and permittivity) measurements can be made anywhere in the frequency range from DC to 10 MHz using impedance analysers. The whole range of frequencies is generally used in academic rock physics, where the technique is called impedance spectroscopy. In the oil industry, only one frequency is used. This is usually 1 kHz, or near it, and is usually taken as the frequency at which the out-of-phase component of the resistance is minimised, i.e. the frequency at which the conduction is most ohmic. Note that this frequency avoids the highest frequencies where current leakage can be a problem. It also avoids the low frequencies, where electrode polarisation can be a problem.

The electrodes are commonly made of platinum gauze, upon which a fine dendritic structure of amorphous black platinum has been electro-deposited. This increases the surface area of the electrodes by several orders of magnitude, helping to reduce electrode polarisation effects to negligible values. Often a pad of filter paper soaked in the pore fluid is inserted between the rock and the platinum electrode to (i) homogenise the current flow, (ii) improve the electrical connection, and (iii) avoid conductive minerals channelling current into the rock.

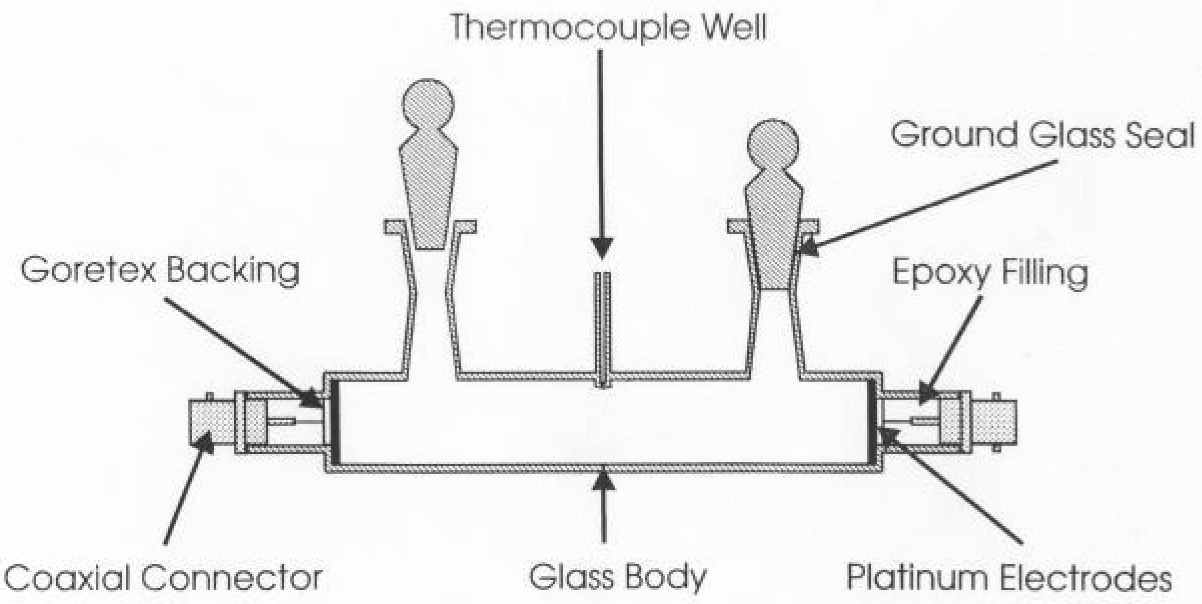
For room condition tests, care has to be taken to remove excess surface moisture from the plug (so that the conduction along the plug surface is not measured) and to ensure that *just sufficient* brine is contained in the electrode ends to give good contact. Contact problems are less pronounced in the overburden cell as brine is flowed through the system before measurements are taken, and good electrical contact is assisted by the hydrostatic load on the end pieces. Plug surface conduction is removed by placing the plug in a rubber sleeve, which is squeezed tightly onto the plug by the confining pressure.

The main measurement is sample resistance, r. This is clearly dependent upon the length, L, and the cross sectional area, A, of the sample. In order to compare samples, the resistance, length and cross sectional area of the sample are used to calculate the resistance per unit length and per unit cross sectional area of the sample rock; this is called the resistivity, R:

$$R = r\frac{A}{L} \tag{9.3}$$

Note from Eq. (9.1) that the resistivity of the pore fluid is also required. This can be done in a standard dip cell, but this method is prone to large systematic errors. More commonly a specially designed fluid cell is used (Figure 9.4). This cell is connected to the same impedance analyser as used for the main measurements, and at the same frequencies. The fluid resistance obtained in this way is converted to a fluid resistivity by multiplication by a cell constant, that varies from cell to cell, and with temperature and pressure. The cell constant is obtained by calibrating the cell with fluids of accurately known composition and resistivity.

Figure 9.4 Fluid Resistivity Cells



The precision of measurement is dependent upon operator skills and sample permeability. For lower permeability samples (with small pores) repeat determinations should fall within a few percent. For friable, high permeability samples repeatability is poorer, and in extreme cases room condition tests may be impossible due to too rapid drainage of fluid from the sample.

Cementation exponent, m, for a particular sample can be calculated directly from Eq. (9.1) if it is assumed that a=1. More commonly, cementation exponent for a group of samples is calculated graphically using a minimum of 10 samples covering a wide a permeability range as possible. A typical data set is shown in Figure 9.5. Equation (9.1) can be rewritten as:

$$\log F \quad = \quad \log a - m \log f \tag{9.4}$$

A log-log plot of formation factor against porosity gives a straight line, with a gradient equal to the negation of the cementation exponent, and with a y-intercept at f=1 equal to log (a). It is common to see cementation data from a best fit through the data giving both m and a, but most commonly the linear regression is forced through (f=1, F=1) corresponding to a=1.

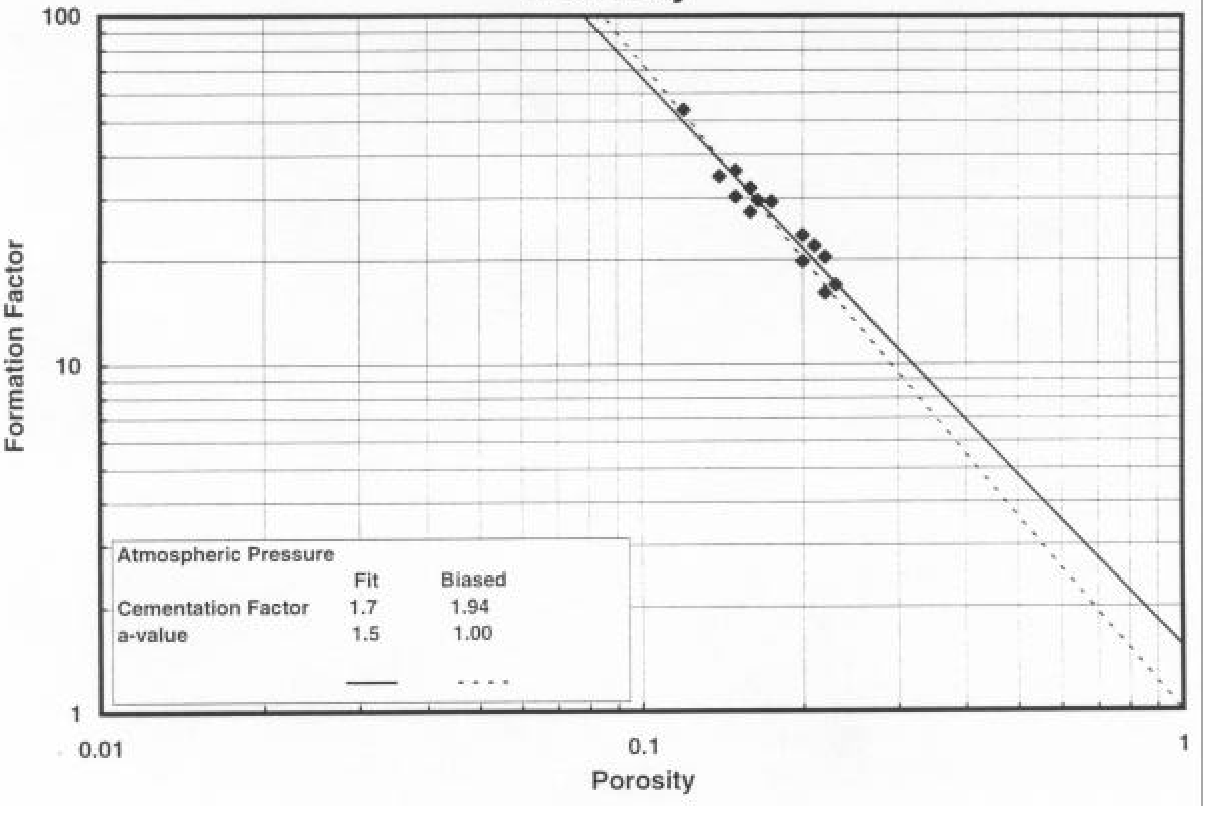
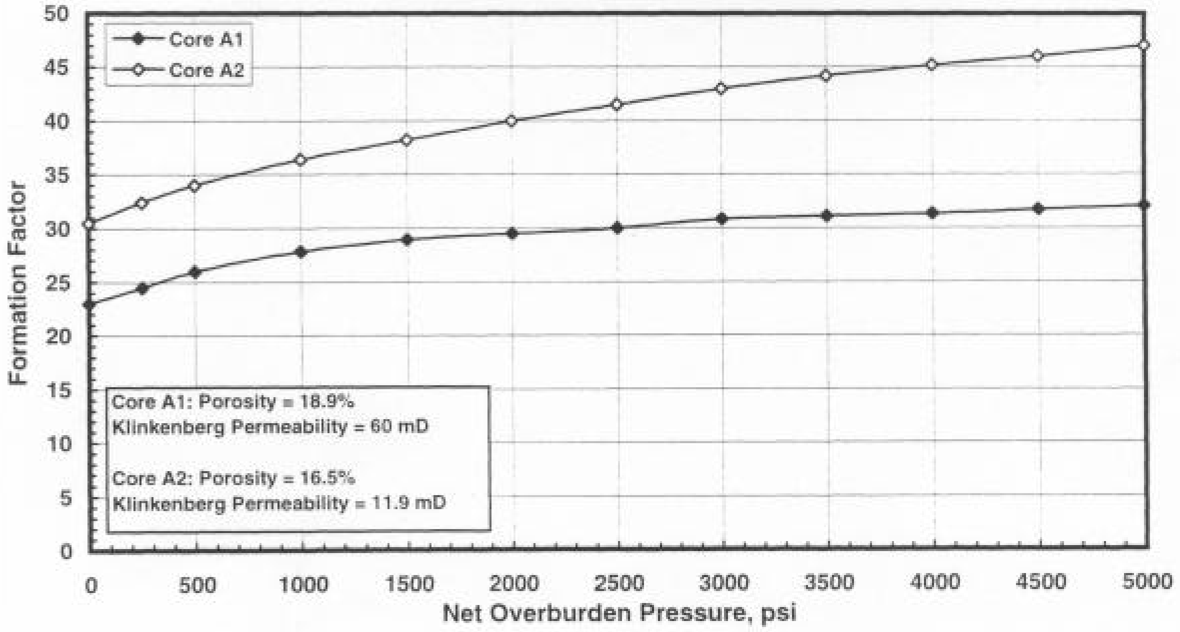


Figure 9.5 Formation Factor as a Function of Porosity

Some typical overburden measurements are shown in Figure 9.6.

Figure 9.6 Formation Factor as a Function of Overburden Pressure



9.3 Resistivity Index

This involves similar measurements to formation factor except that resistance is measured at values of S_w less than 100%. Plots of resistivity index and S_w give n, the saturation exponent (Figure 9.7). The methods of desaturation include porous plate and centrifuge, thus resistivity index measurements are conveniently combined with air/brine capillary pressure measurements.

Note that Eq. (9.2) can be written as:

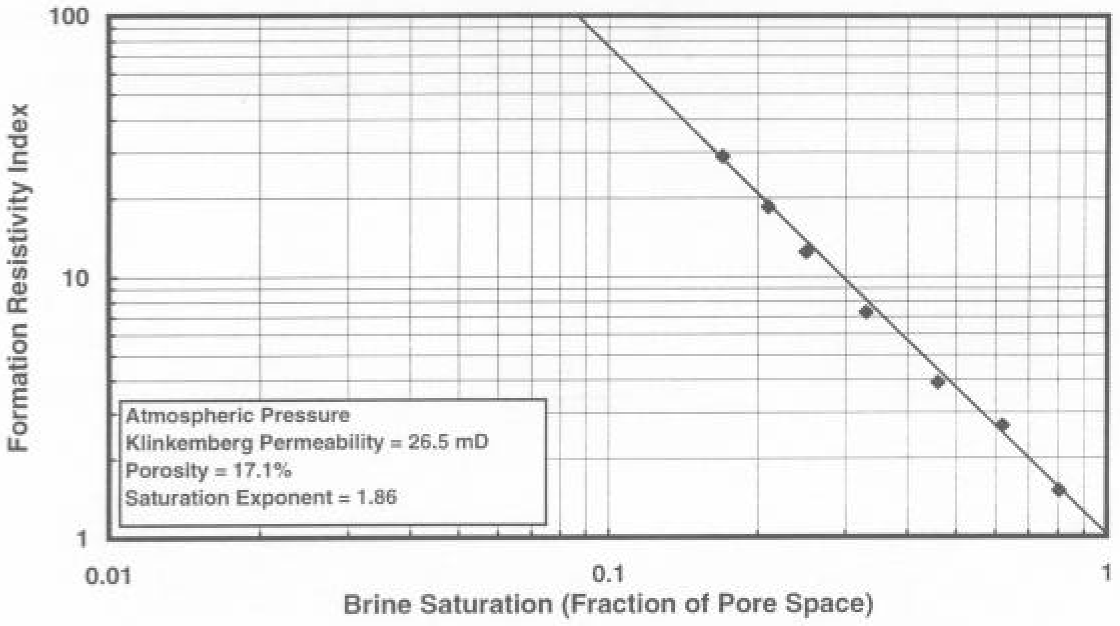
$$\log I = 1 - n \log S_w \qquad (9.5)$$

So the saturation exponent, n, is the negation of the gradient of the log I versus log S_w plot (Figure 9.7 shows typical data), and that the line should always pass through (S_w=1, I=1).

The practical considerations for these electrical measurements are similar to those for formation factor, except that the tendency for brine to drain from the plug is essentially removed because of the lower saturations. The electrical measurements can be performed to better than 0.1% and saturation changes determined to ± 0.5 S_w%.

Care has to be taken to avoid evaporation losses during desaturation and measurement of resistance. Plugs are stored in closed weighing bottles and only removed for the minimum possible period.

Figure 9.7 Resistivity Index as a Function of Brine Saturation



9.4 Shale Effects

Very little data is available on the reproducibility of m and n. Repeat determinations of n by a skilled operator should result in good agreement, probably within a few percent.

Plots of S_w versus resistivity index often give very good straight lines, but this is not always the case. Some scatter is likely at high values of S_w (above 80%) and at low values (below 20%).

The reasons for this are not well understood. Scatter at high values of S_w is difficult to account for; but at low values of S_w it could be due to genuine clay effects, i.e. 'excess' conductivity of clays, or to water vapour loss and concentration of brine in the test plug.

Correction of m and n to m* and n* is still under general discussion within the industry. These are generally corrected from cation exchange capacity (CEC), which can be obtained from laboratory measurements on crushed rock. Unfortunately, the values obtained for CEC can depend upon the amount of crushing the core has been subjected to, and the method used. It is possible that measurement of formation factor at various salinities can give a better guide to correction of m and n. A plot of core conductivity against brine conductivity (Figure 9.8) can give a value for BQ_V/F^*, which has then at least been obtained from direct electrical measurements on intact core with the fluids of interest in place.

This topic requires deeper discussion than can be covered here, but it should be borne in mind that the relationships between electrical properties and saturations are empirical; linear relationships cannot always be expected.

A more comprehensive discussion on the accuracy of electrical measurements are given in references [2] and [3].

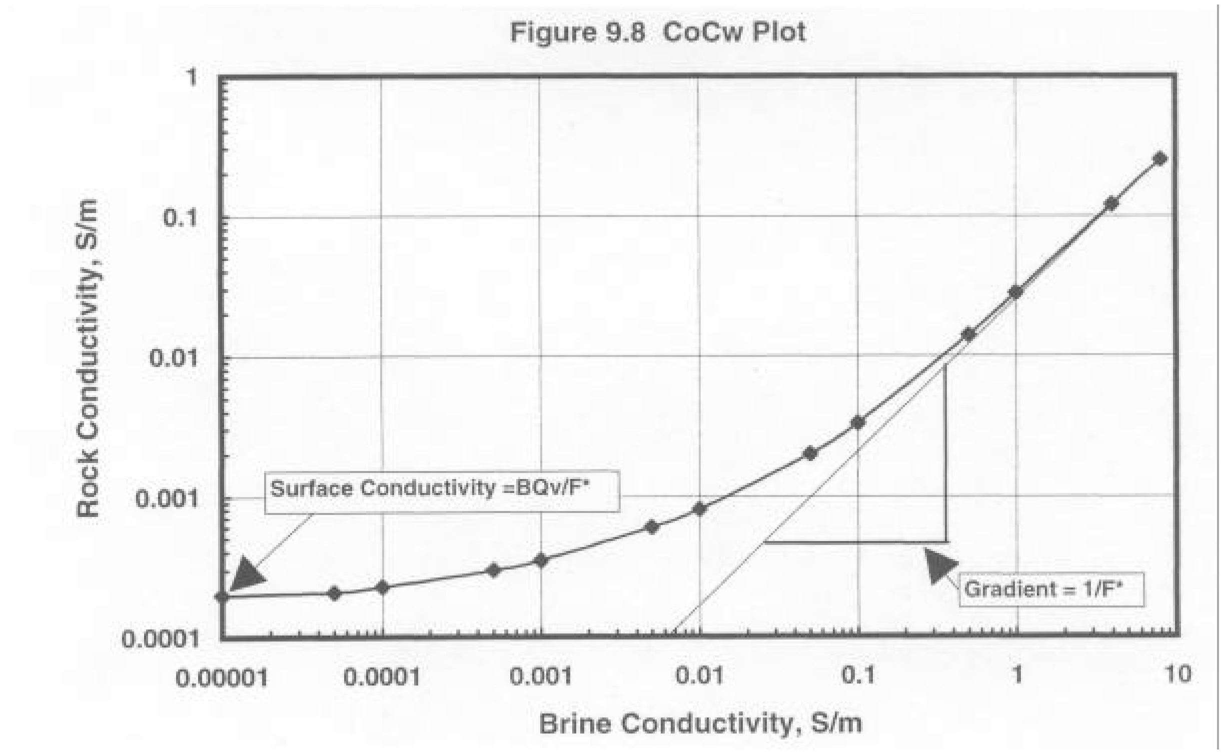


Figure 9.8 CoCw Plot