Rock Electrical Properties from Porous Plate and Resistivity Experiments: Tips to Maximize Data Quality

F. Pairoys
Schlumberger

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ABSTRACT

Oil and gas reserve estimates based on measurements by downhole electrical tools require input data such as the cementation factor *m* and saturation exponent *n* obtained from core measurements in the laboratory. Thus, the quality of both the laboratory measurement and downhole measurement determines the overall uncertainty of the data interpretation. The uncertainty associated with the laboratory measurement can be minimized by designing an adequate special core analysis (SCAL) program and taking care of quality assurance.

There are several parameters to be controlled to ensure good data quality during a porous plate test with resistivity measurements, such as representative applied net confining stress, equilibrium criteria, corrections of sleeve conformance and brine squeeze off, pore volume compressibility, resistance contribution of the porous plate, excess of conductivity due to clay, temperature variation, or even saturation derived from the material balance. Moreover, comprehensive quality control of these tests requires knowledge of rock characteristics, such as mineral composition and routine core analysis data.

This paper presents a description of the porous plate experiment combined with measurement of the rock resistivity at capillary equilibrium. A sensitivity analysis of the resistivity measurement with respect to the various parameters evaluates the degree of impact on the cementation factor and the saturation exponent. Some parameters have a small effect on data quality whereas others can lead to significant error in the calculation of the Archie's exponents *m* and *n*. Precautions are necessary in the laboratory to obtain good data quality and avoid large errors in water saturation calculated from electrical logging techniques.

INTRODUCTION

It is well known that resistivity logs are crucial in formation evaluation because they allow estimating the oil and gas reserves. Regardless of the complexity of the reservoir, the Archie approach [1] is always used to calculate the water saturation S_w. From the Archie equation, the resistivity of the brine can be obtained using field samples. The reservoir resistivity is measured by the logging tool, generally using a deep-reading resistivity from laterolog, and porosity is measured downhole using density, neutron, and/or sonic tools. The Archie parameters, known as lithology factor *a*, cementation factor m, and saturation exponent n are determined in the laboratory. The resistivity logs must be calibrated according to the laboratory measurements. In the laboratory, the Archie parameters are generally determined during a porous plate resistivity test.

In this work, a resistivity porous plate test was performed on a rock sample containing some amount of clays. The primary drainage capillary pressure test was performed with brine and humidified nitrogen. A two-electrode configuration was used to conduct a multiple salinity C_o-C_w (conductivity of the 100% brine-filled rock C_o versus conductivity of the brine C_w) test and tests of resistivity index (*RI*) at capillary pressure (P_c) equilibrium, (P_c-*RI*). Finally, the Dean-Stark irreducible water saturation S_{wi} value was compared to the S_{wi} value obtained at the end of the porous plate test from material balance.

This paper discusses the theoretical background behind the test, describes the experimental protocol, and then provides tips for achieving accurate results from the test.

BACKGROUND

To derive the water saturation S_w from electrical logs in siliciclastic reservoirs free of clay, the second Archie's equation is used:

$$S_W = \left(\frac{a}{\phi^m} \cdot \frac{R_W}{R_t} \right)^{\frac{1}{n}} \qquad \text{Eq. 1}$$

The lithology factor a (taken equal to 1 here), the cementation factor m and the saturation exponent n are determined in the laboratory on representative core plugs. The formation factor *FF* and the cementation factor m are first calculated after measuring the 100% brine-saturated rock R_o and formation brine resistivity R_w using the following Archie's equation:

$$m = -\frac{log(FF)}{log(\phi)} = -\frac{log\left(\frac{R_O}{R_W}\right)}{log(\phi)} \qquad \text{Eq. 2}$$

Then, measuring the resistivity R_t of the sample at different saturations, the saturation exponent n can be obtained using the second Archie's (Equation 1):

$$n = -\frac{log(RI)}{log(S_W)} = -\frac{log\left(\frac{R_t}{R_O}\right)}{log(S_W)} \qquad \text{Eq. 3}$$

In Equation 3, *RI* is the resistivity index. When plotted against S_w on a log-log scale, it generally leads to a linear trendline that can be fitted with a power law, the power coefficient being the saturation exponent n ($-n$ to be more precise).

In the laboratory, the porous plate desaturation method is generally the preferred method for obtaining the saturation exponent n because it allows determining both capillary pressure P_c and resistivity at capillary equilibrium (P_c-RI). Nevertheless, the continuous injection method (CI) with resistivity monitoring also provide a reliable saturation exponent n while measuring resistivity under pseudo-equilibrium [2], but cannot determine equilibrium P_c versus S_w relationship.

To correct for the excess conductivity in case of presence of clay minerals, the CEC is measured using wet chemistry (destructive method) or by a multiple salinity *Co-Cw* test (non-destructive method). It is preferred to measure *Co-Cw* on the same plug that will be later used to measure porous plate P_c and resistivity. The resistivity of the sample has been measured using four different brines of known conductivities (brine salinity > 50 kppm).

The Waxman-Smits [3] method is then used to correct Equation 2. It results in an intrinsic cementation factor m^* (Equation 4):

$$m^* = -\frac{log\left(FF^*\right)}{log\left(\phi\right)} = -\frac{log\left(FF\left(1+BQ_vR_w\right)\right)}{log\left(\phi\right)} \qquad \text{Eq. 4}$$

The BQ_v value is obtained from the *Co-Cw* plot, using the ratio between the intercept and slope of the linear fit from the four *Co-Cw* points.

If required, the cation mobility factor B can be calculated from the Juhasz equation [4]:

$$B = \frac{-1.28+0.225\,T-0.0004059\,T^2}{1+R_W^{1.23}\left(0.045\,T-0.27\right)} \qquad \text{Eq. 5}$$

Then, Q_v (normalized CEC) can be calculated from the graphically determined BQ_v value.

Equation 3 is also corrected to obtain the intrinsic saturation exponent n^*:

$$n^* = -\frac{\log\left(RI\left(\frac{1+\frac{BQ_vR_w}{S_w}}{1+BQ_vR_w}\right)\right)}{\log\left(S_w\right)} \qquad \text{Eq. 6}$$

It is preferred to plot the corrected resistivity index RI^* versus water saturation S_w on log-log scale, using the following equation:

$$RI^* = RI\left(\frac{1+\frac{BQ_vR_w}{S_w}}{1+BQ_vR_w}\right) \qquad \text{Eq. 7}$$

A temperature correction needs to be applied to ensure all resistivity values are reported at same standard temperature T_2. Because the temperature in the laboratory can vary, Arps' equation [5] for temperature correction (in ^{o}C) is applied:

$$R_2 = R_1\left(\frac{T_1 + 21.5}{T_2 + 21.5}\right) \qquad \text{Eq. 8}$$

EXPERIMENTAL PROTOCOL AND RESULTS

One sandstone sample, S1, was selected for the porous plate resistivity test. The selection of this sample was driven by the XRD analysis results and CT images. The sample contained clay (overall clay content from XRD was 3% illite/smectite, 3% illite+mica, 1% kaolinite, and 1% chlorite, for a total clay content of 8%) and was free of fractures or large vugs. Correction of the excess conductivity from clay was required, and the multiple salinity *Co-Cw* test was then performed prior desaturating the sample during the nitrogen-brine porous plate resistivity test. Without correction, the cementation factor *m* and the saturation exponent *n* would have been found to be too low, leading to an overestimation of the oil or gas saturation if CEC correction is not applied.

Before measuring the routine core analysis properties (RCA), sample S1 was first cleaned using cool Soxhlet cleaning and dried in humidity oven (60^{o}C, 40% relative humidity) to avoid dehydrating and damaging the clays. It is crucial to ensure the rock is initially water-wet, so cleaning is necessary for obtaining representative data quality results [6]. Porosity and permeability were measured at net confining stress (NCS) of 5,000 psi following the protocol detailed in [7]. RCA properties are reported in Table 1:

ID	L (cm)	D (cm)	ϕ (frac.)	PV (cc)	ρ_g (g/cc)	K_g (mD)	K_{kl} (mD)
S1	5.181	3.81	0.194	11.46	2.66	80.1	78.5

Table 1: RCA properties for sample S1

The sample was first evacuated under vacuum then hydrostatically saturated with a 160 kppm NaCl brine under a pressure of 3,000 psi. The porosity by weight was compared to the ambient helium porosity obtained during the grain volume measurement (< ±2% difference). It is also important when loading the sample in the resistivity cell at net confining stress to correct for the "squeeze off" effect due to the extra surface water and the pore volume compressibility.

Three additional brines of different salinity were then prepared to perform the multiple salinity *Co-Cw* test. The sample was loaded in a two-electrode resistivity cell to monitor the change of resistivity during the replacement of one brine by another. A net confining stress of 5,000 psi was applied. Both brine and 100% brine-filled rock conductivities at ionic equilibrium conditions were calculated at 20^{o}C, using Eq. 8.

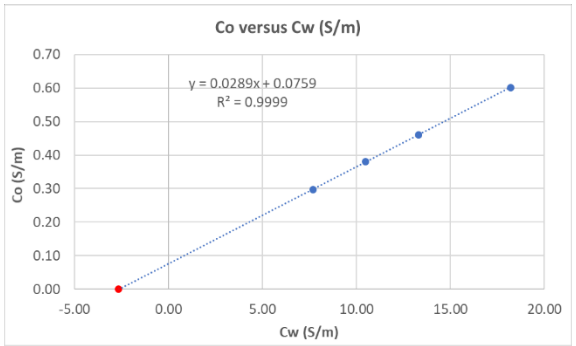

Figure 1: Co-Cw plot at 20^{o}C and at 5,000 psi of NCS

Using Equation 4, the intrinsic cementation factor m^* was found to be equal to 2.16 whereas the uncorrected cementation factor m was 1.98 (BQ_v=2.626 mho cm^2/cc from Figure 1).

Porous plate test design is then important for the determination of the capillary pressure P_c, less for the resistivity measurements as mentioned in [8]. Because there was no mercury injection capillary pressure (MICP) data available for this sample, the core analysis software CYDAR was used to determine the P_c steps and to obtain an estimate of the experimental duration. Seven P_c steps were planned. The entry capillary pressure P_{ce} was estimated using Equation 9:

$$P_{ce} = \frac{4.617\sigma\cos\theta}{\sqrt{\frac{K}{\phi}}} J_e \qquad \text{Eq. 9}$$

with J_e the entry Leverett J function (0.15 for sandstone rocks) [9], σ the air/brine interfacial tension (72 dyne/cm), and θ the contact angle (0^o). The calculated P_{ce} was found to be equal to 2.5 psi, explaining the choice of the first P_c step at 2 psi.

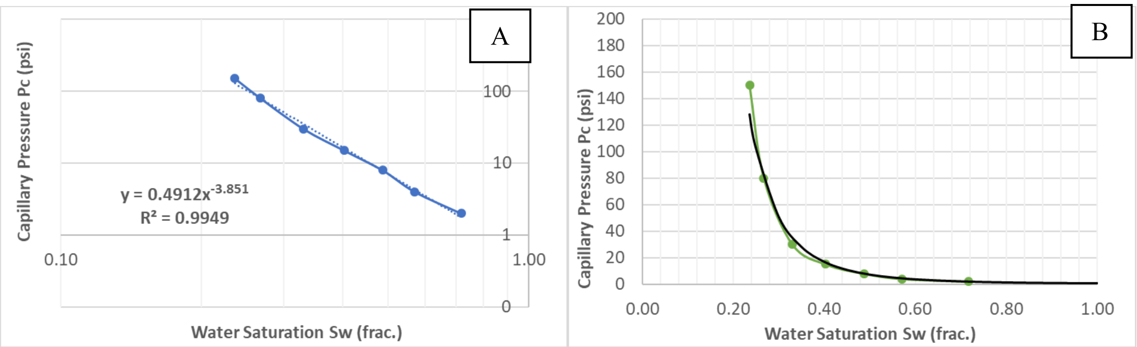

Figure 2: Capillary pressure curves on log-log scale (A) and linear scale (B)

Figure 2 shows the log-log P_c curve (A). The regression curve is used to fit the P_c curve in (B), using Corey's model. From (A), the P_{ce} is estimated at 0.49 psi, the pore size distribution index λ from the Corey's equation is equal to 0.26 (λ=1/slope coefficient).

During the P_c-RI test, the water saturation S_w was calculated by recording the water volume produced in a burette. Since this test is time consuming, a layer of oil was added above the water in the burette to avoid water evaporation and S_w overestimation.

Note that the phase angle φ can increase when the water saturation decreases (in this study, from -0.1° at 100% S_w to -1.84° at S_{wi}). Our acceptance criterion was ±2° maximum. A correction for the phase angle shift should be performed if an impedance meter is used.

The applied frequency for running the test should be set according to the lowest measured phase angle (generally above 1 KHz). The frequency could also be set at a frequency applied downhole by the electrical tools (20 KHz was applied to match the frequency of the induction tool in this study). The homogeneity of the sample is then crucial, as the resistivity response can be affected by the frequency if the rock is heterogeneous [10].

Another correction sometimes neglected is the correction for the additional resistance from the porous plate during the resistivity Pc-RI test using the two-electrode configuration. Especially for highly conductive and short rocks containing clays, the porous plate resistance or resistivity can be significant. In this study, the presence of the porous plate contributed for an additional resistance δr of 25.9 ohms at the reference temperature of 20°C. This resistance was subtracted from the resistance values measured during the porous plate test, assuming the porous plate resistance does not change during the test.

Figure 3 shows the acquired raw data, water production and resistance (A), and the CEC uncorrected and corrected resistivity index curves (B):

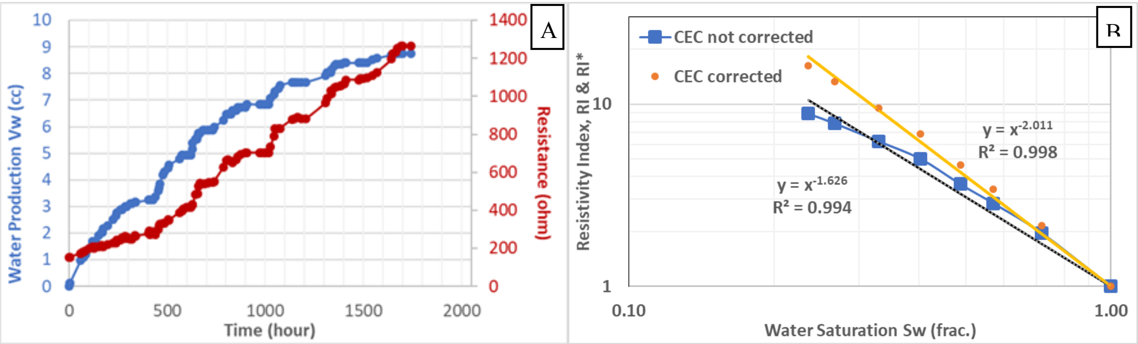

Figure 3: Brine production in blue and raw resistance versus time in red (A) and CEC uncorrected RI vs CEC corrected RI curves (B)*

For this study, the production criterion for equilibrium was 0.5% PV change for 24 hours. Using Equation 6, the intrinsic saturation exponent n^* was found to be equal to 2.01 whereas the uncorrected saturation exponent n was 1.63.

The irreducible water from the sample was then extracted using the Dean-Stark (DS) method. DS S_{wi} was observed to be higher than the S_{wi} from the porous plate test. The discrepancy is most likely related to the presence of clay-bound water, extracted during the DS process, but not considered when measuring the RCA PV and ϕ. A NMR T_1T_2

map at S_{wi} would confirm if the extra volume produced during DS extraction was from clay-bound water.

It is important to note that all measured resistances have been converted to a reference temperature of 20^{o}C and subtracted for the excess resistance δr before calculating the resistivity index in Figure 3 (B). The influence of incorrected CEC, additional porous plate resistance and temperature on S_w calculation are discussed in the following section.

SENSITIVITY ANALYSIS AND KEY CONSIDERATIONS

A sensitivity analysis to incorrected CEC, additional resistance δr and temperature was performed to assess the influence of these three parameters on the final water saturation S_w calculation. It is assumed that the porosity ϕ, brine resistivity R_w (0.13 ohm.m), and water production V_w were correctly determined. The cementation factor m and m^* were obtained during the *Co-Cw* test: the data were converted to the reference temperature of 20^{o}C without extra resistance δr correction because this test is always performed without porous plate. The sensitivity analysis results are detailed in Table 2:

Raw Number	CEC corrected	δr corrected	T^{o}C corrected	m, m^*	n, n^*	R_t (ohm.m)	S_w (%)	Error ε (%)
1	**YES**	**YES**	**YES**	**2.16**	**2.01**	**30.0**	**38.9**	**---**
2	YES	NO	YES	2.16	2.04	30.0	39.4	+0.5
3	YES	NO	NO	2.16	1.96	30.0	38.0	-0.9
4	YES	YES	NO	2.16	1.94	30.0	37.6	-1.3
5	NO	YES	YES	1.98	1.63	30.0	26.0	-12.9
6	NO	NO	YES	1.98	1.66	30.0	26.7	-12.2
7	NO	YES	NO	1.98	1.56	30.0	24.5	-14.4
8	NO	NO	NO	1.98	1.57	30.0	24.7	-14.2

Table 2: Sensitivity analysis summary

The derived S_w is calculated using Equation 1. As example, a R_t value of 30.0 ohm.m was taken to calculate the saturation S_w. The errors ε on S_w are relative to the true result in raw number 1 in bold.

a) CEC corrected (raw 1-4): Table 2 shows that the sensitivity to lab temperature variation and δr for S_w calculation was low if resistivity is corrected for CEC. A maximum absolute error ε of 1.3% was obtained if the data are not corrected for temperature only.

b) CEC incorrected (raw 5-8): not correcting resistivity for CEC leads to significant error on S_w. A maximum absolute error ε of 14.4% was obtained if the data are also not corrected for temperature.

To summarize, it is obviously highly recommended to apply all corrections to minimize the errors and ensure the best estimate of oil or gas reserves obtained from logs.

Recommendations for improved laboratory data quality are listed in Table 3:

Parameter	**Comments**
Rock characteristics	
Rock integrity	It is preferable to select homogeneous cores, using computerized tomography (CT) images. The rock must be representative of the reservoir lithology.
Clay content and type/structure	The presence or absence of clay is of importance in core cleaning/drying and in determining the Archie's exponents. The cation exchange capacity (CEC) is measured to correct for excess conductivity in the presence of clay minerals.
Preparation and prerequisites	
Salinity test for BQ_v determination	A multiple salinity C_o-C_w test must be performed if there is significant clay content.
Cleaning/drying	Appropriate cleaning/drying, especially for samples containing clays, is necessary.
Porosity comparison	The porosity by weight method should be comparable to the ambient helium porosity (±2% difference).
Porosity and permeability data	Porosity and permeability at net confining stress (NCS) should be available. The measured base petrophysical properties help in designing an adequate experimental protocol. Obtaining mercury injection capillary pressure (MICP) data results before starting a porous plate test is recommended.
NMR T_2	NMR T_2 could be measured both before and after the porous plate resistivity test for comparison of the porosity and S_{wi} values. T_1T_2 fluid mapping can also be helpful to assess the amount of clay-bound water
Equipment setup	The porous plate method is recommended for obtaining uniform saturation profiles. Appropriate porous plate must be selected; ceramic discs with different air-brine entry pressures are available. The addition of silver paint on the edges of the disc enhances the current conduction path from the disc to the rock.
Formation brine preparation	Synthetic formation brine must be prepared as per formation brine composition recipe. Brine properties (density, R_w, viscosity) should be measured at representative temperature conditions.
Porous plate effect	The effect of the porous plate on resistivity must be determined. The presence of the porous plate affects the overall resistivity measurement in the two-contact electrode configuration. The effect is pronounced on highly conductive rocks.
Laboratory procedures	
Monitoring squeeze-off and compressibility	Squeeze-off and pore volume compressibility when applying NCS should be monitored. Axial and radial deformation could be monitored to correct the bulk volume and highlight a potential damage due to too high NCS
Resistivity measures and temperature	Brine resistivity and rock resistivity variation during the desaturation process using a porous plate must be reported at same temperature. R_t equilibrium must be achieved for each P_c step.

Capillary equilibrium	Capillary equilibrium at specific capillary pressure step must be reached. Both P_c and resistivity are reported at capillary equilibrium.
Capillary contact	There should be no loss of capillary contact. A loss of capillary contact can lead to too high irreducible saturation S_{wi}, sometimes in conjunction with an increase in resistivity and phase angle. Diatomaceous earth powder can be added between the porous plate and the rock to enhance the capillary contact.
Optimal frequency	The correct frequency must be selected. When measuring the resistivity on a core plug using an impedance meter, it is preferable to have a phase angle lower than ±2°. If rocks are heterogeneous, containing fractures or vugs, for instance, the resistivity response is dependent on the applied frequency.
Additional testing	
Dean-Stark (DS) extraction	A final DS extraction should always be done to confirm the final water saturation. DS results should be careful evaluated in case of CBW presence.
NMR T_2	NMR T_2 could be measured both before and after the porous plate resistivity test for comparison of the porosity and S_{wi} values.

Table 3: Key considerations before, during, and after a porous plate resistivity test

CONCLUSIONS

In this paper, a description of the porous plate experiment with measurement of the rock resistivity at capillary equilibrium was presented. A sensitivity analysis of the resistivity measurement with respect to the various parameters evaluates the degree of impact on the cementation factor and the saturation exponent. A list of tips is provided to minimize the error on the measured parameters.

Some parameters have a small effect on data quality, others can lead to significant error in the calculation of the Archie's exponents m and n. If temperature and additional resistance corrections are of importance, the main error on S_w came from the uncorrected CEC. This shows the importance of performing XRD analysis prior starting the P_c-RI experiment. The oil or gas reserves are overestimated if the CEC correction is not applied.

The QC check of S_{wi} using Dean-Stark extraction only is not helpful when the sample contains a considerable amount of clay-bound water CBW: NMR measurements at 100% S_w and S_{wi} could be helpful for distinguishing the different water types (free, capillary, and clay bound waters).

It is shown that some precautions are necessary in the laboratory to obtain reliable data quality and avoid large errors in water saturation calculated from electrical logs.

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