

LABORATORY ANALYSIS OF ELECTRICAL ROCK PROPERTIES AND CAPILLARY PRESSURE IN FULL DIAMETER CORE SAMPLES

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ABSTRACT

Laboratory electrical properties and capillary pressure analysis of core samples are useful tools in understanding and calculating oil and gas reserves. Vugular and conglomerate core material present challenges that standard laboratory methodologies can only partially address. This paper presents recent laboratory advances that have been developed to measure capillary pressure and electrical resistivities (a, m and n) in full diameter non-uniform pore geometry systems.

First, is a review of the basic methodologies of resistivity measurements (the determination of m and n exponents) and capillary pressure analysis that establish superior data quality. Secondly, the use of a 1000 psi Air/Brine porous plate system with full diameter samples will be demonstrated. The capture on non-uniform electrical and plate capillary pressure response will be discussed.

BASIC LABORATORY METHODS

Sample Selection

Sample selection for advanced core testing is a defining process for subsequent laboratory test results. Ideally a specific uniform rock type (pore geometry) should be represented in each sample and unconformities should be avoided as a rule. For the most part, traditional rotary sidewall samples and conventional core based plug samples are sufficient in size to accomplish those goals. However, vugular carbonates and clastic conglomerates offer significant challenges to appropriately capturing a specific rock type within the limited sample size obtained from conventional core analysis. Full diameter sample size (4") is advanced as a solution to the issue of selecting a sample that is representative with these two rock types. Since most cores are vertical in orientation, full diameter core analysis is not recommended for advanced core analysis where bedding / lamina define the rock type. The exception are deviated to horizontal wells, where the bedding / lamina may be parallel or oblique to the long axis of the core.

Plug and core samples must meet basic physical requirements regardless of sample size. These include; parallel and even end-faces, uniform cross sectional area and preserved rock fabric. (Uniform cross-sectional area is particularly difficult to obtain with some full

diameter samples.) In addition, initial sample screening via CT imaging is highly recommended to confirm sample integrity.

Full diameter samples often present additional challenges. With conglomerate material sample selection is mostly straightforward: the reasonable capture of a specific rock type without undue anomalies. Two main considerations are: first, that cobbles are not disturbed with respect to the cement or pore linings and second, no cobble completely intersects the core axis thereby obstructing fluid and current flow. With vugular materials, sample selection is somewhat more subjective. The basic criterion remains, the selection of samples that are representative of a specific rock type while avoiding anomalies. The orientation of any surface vugs must be taken into consideration with respect to representative structure. In addition, any fractures present must be assessed with regard to their being representative of the rock type as opposed to having been induced by coring, sampling and / or handling. Vugs or features that might contribute to sleeve failure should be avoided from a practical standpoint. End faces should be representative of the matrix without large surface vugs. As mentioned before, rock types having lamina / bedding, should have the bedding oriented parallel to the long axis of the core.

Sample Preparation

Most advanced core analysis is conducted on clean, dry and stable samples of known physical properties. The physical properties (aside from grain volumes) need to be determined at the same net confining stress as the analysis. With cleaning and drying it is particularly important not to damage or alter the rock fabric. Specific technical constraints do exist when analyzing basic properties of full diameter samples. The shear size of the samples (often 4" in diameter by 8" in length) require a greater time for dry weight stabilization and stress pore volume determination when compared to conventional samples. It is often helpful to plot the measured variable against time to determine when stability has been reached.

ELECTRICAL PROPERTIES / PLATE CAPILLARY PRESSURE

A basic discussion of laboratory methods used in the determination of electrical properties and porous plate capillary pressure is in order prior to addressing issues related to full diameter sample analysis. These methods include: the analysis being conducted at a net confining stress matched to reservoir conditions, a single compression cycle for the advanced testing, desaturation conducted as a drainage cycle using humidified gas to displace the brine and the use of ambient temperature. (Additional electrical measurement issues are addressed following the resistivity index and capillary pressure sections.)

Electrical properties as defined in the pioneering work done by Archie (i) include the formation factor (F_{rw}), the cementation factor (m) and the saturation exponent (n). Basic formulas are:

$$\begin{aligned}
 Fr_w &= R_o / R_w \\
 m &= \log Fr_w / \log \phi \\
 n &= \log (R_t / R_o) / \log S_w
 \end{aligned}$$

where R_o is the resistivity of a sample 100 % saturated with a brine of known resistivity, R_w , ϕ is the fractional rock porosity and R_t is the sample resistivity at fractional brine saturation S_w .

Porous plate capillary pressure analysis can be determined separately or in conjunction with the saturation exponent analysis. The plate provides the means whereby a sample can be uniformly desaturated along the entire sample length in a step-wise set of discrete increasing pressures. Plate capillary pressure, although time consuming, is recognized as the method best suited in modeling the dynamics of capillary pressure within a reservoir.

Formation Factor

The initial step in most electrical properties testing involves the determination of the formation factor, Fr_w . This analysis is straightforward but basic protocols must be followed to avoid error and data artifacts. Each sample must be flushed with a sufficient volume of synthetic formation brine to establish rock / brine equilibrium and 100% saturation with brine. Samples that are non-uniform and are of low porosity will exacerbate the problems associated with equilibrium and entrained gas. In particular, the samples must be flushed with brine against back pressure, soak cycles employed and resistances monitored on a daily basis with the time base set against the permeability range of each sample. For example, high permeability high porosity sandstones may well equilibrate electrically within 4 to 6 days. With a low porosity materials, stability might not actually be reached until 4 to 6 weeks have elapsed. Independent assessment for any remaining gas must also be done to assure that all gas is removed.

Resistivity Index and Capillary Pressure

Typically, the saturation exponent is determined on previously cleaned and dried samples proceeding from 100% brine saturation to a final irreducible brine saturation, S_{wi} . (Issues of fresh/preserved state analysis, wettability and elevated temperature are outside of the scope of this study.)

The determination of the saturation exponent n (or of incremental n values) is dependant upon two main precepts: the control of an even desaturation process over the length of a sample through use of a porous plate and the material balance confirmed and defined value of the final brine saturation percent, S_{wi} . With the desaturation process, ultimately the rock fabric determines the desaturation pressures needed and minimum time required for the process. Typical pressure steps can be found within the following pressure sequence: 1, 2, 4, 7, 10, 20, 40, 60, 100, 140, 200, 400, 600 and 1000 psi. Many rock types are susceptible to desaturation that is too rapid, leading to non-uniform saturation profiles and the related disconnect with the electrical response. Therefore, interim

pressure steps should be employed to control the desaturation process. (Low porosity materials generally mitigate this issue.) The determination of volumetric equilibrium at each pressure step is best approached with a conservative definition of stability. In practice, three days of no volumetric change is reasonable standard of equilibrium for most rock types.

The second critical element in determining laboratory based saturation exponents, is the ability to verify S_{wi} values. This cannot be overstated. Low porosity rotary sidewall and conventional plug samples are particularly susceptible to errors in S_{wi} due to the relatively small pore volumes involved. Specifically, production-based S_{wi} values should be confirmed by the differences between pre and post-test dry weights and the S_{wi} weight as well as final Dean-Stark extraction. (Dean-Stark extraction must be carefully assessed with regard to the potential damage to rock structure as well as considerations to free and bound water issues.) With 1 inch diameter samples uncertainties less than 0.01 cc can introduce un-acceptable error. However, full diameter samples are actually much easier to handle with regard to S_{wi} simply because of the large pore volumes involved.

General Electrical Property Measurement Considerations

There remain several laboratory technique issues that need to be briefly addressed; 2 vs 4 electrode measurements, test frequency, volumetric errors and temperature errors.

2 electrode and 4 electrode arguments distill down to two major concerns: rock / endstem (electrode) interference and sample uniformity. Experience has shown that the control and the minimization of phase angles (at or less than one degree) will maximize the reliability of the 2 electrode measurements. In addition, any lithology variation over a sample's length will actually introduce error in 4 electrode measurements due to non-uniform saturation profiles, unless 4 electrode measurements are conducted over the full length of a sample. Temperature uncertainties can introduce significant errors in resistance readings, therefore internal temperature probes and a controlled laboratory environment are a necessary requirement. Most electrical property analysis is conducted using AC frequencies between 1 kHz and 20 kHz, noting that brine resistivities must be determined at the same test frequency. Test frequency influence remains relatively minor and is far less of an issue than the previously mentioned considerations. Finally, volumetric error via gas diffusion through the plate at high drive pressures must be corrected.

1000 psi PLATE / MEMBRANE SYSTEM

The 1000 psi plate/membrane system was designed primarily to improve saturation exponent accuracy by lowering the final S_{wi} saturation obtained in low porosity materials (3 to 8 % porosity). This is due to the fact that uncertainty in saturation exponent values is usually unacceptable if low porosity samples are desaturated to only 70 or 80 percent using an industry standard 15 bar plate with a maximum 200 psi air/brine desaturation pressure. Fortunately full diameter samples have much greater

volumes of pore structure and therefore the uncertainties in n are minimized, even if porosities are as low as 2 or 3 percent. However, where pore structures exhibit varied micro and macro pore throat components, the higher desaturation pressure allows for a more inclusive investigation of the resultant variable saturation exponent n . This is particularly evident with carbonates. If the resultant n values are basically linear over the full desaturation range, the gained confidence of response is none-the-less an added benefit.

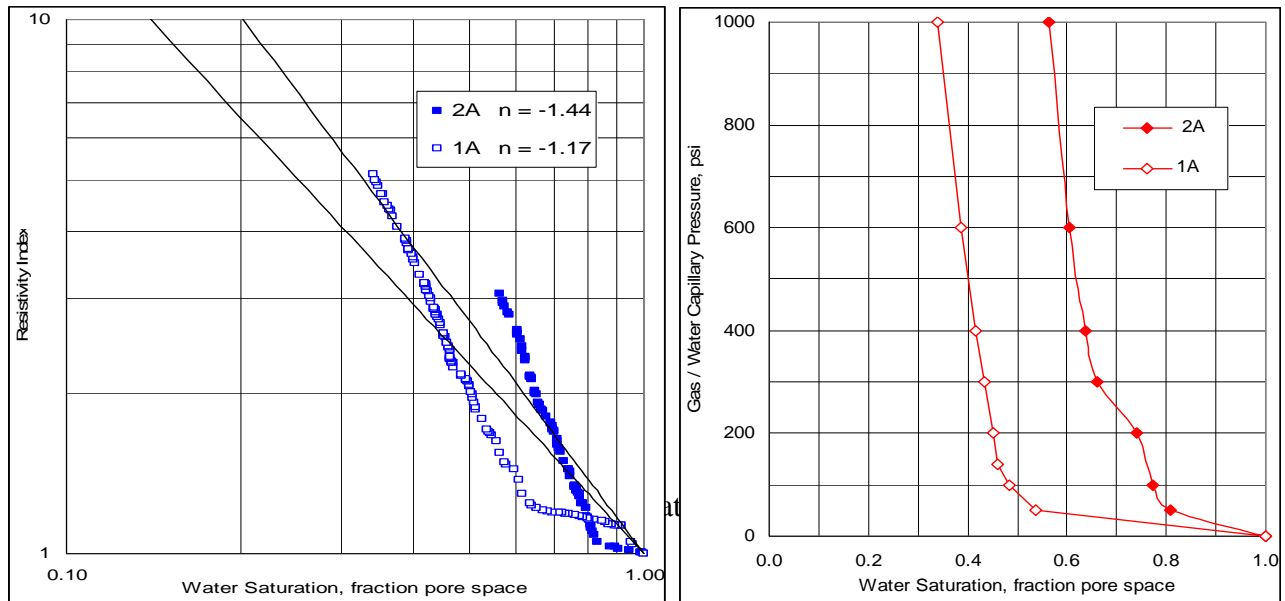
Within the investigation of electrical response vs brine saturation clearly the most important element (aside from analysis accuracy) is the ability to desaturate the sample to at or below field condition brine saturation and to use the saturation exponent associated with the appropriate brine saturation /capillary pressure value. Extrapolation of electrical response from only partially desaturated samples (as compared to field saturation values) can introduce error through the assumption that resistance/saturation functions remain constant and predictable in their trends. (See example 4C)

For samples with non-uniform pore structure (typically vugular carbonates), the saturation exponent will typically vary with saturation in direct response to anomalies and changes in the pore structure. Because the saturation exponent is no longer either constant or defining a simple trend, several techniques must be employed to better describe the electrical response. First it is recommended that a significant number of desaturation / resistivity index points be recorded throughout the desaturation process so that a clear pattern of response is discerned. (Most analysis involved a minimum of 120 desaturation / incremental saturation exponent points for a given sample with capillary pressure equilibrium determined at 6 to 8 pressure steps.) Secondly, since the n value is often changing as a function of saturation, the calculation of an average n is of less significance than with conventional samples. Of greater importance are the incremental n values calculated from daily readings taken throughout the desaturation process.

Conglomerate samples follow conventional sample electrical properties trends much more closely than do vugular carbonates with respect to variation of n values. Even so, it is highly recommended that any investigation captures a significant number of incremental desaturation data points to ensure data quality.

FULL DIAMETER DATA EXAMPLES

The following set of graphs (figures 1 and 2) summarize typical electrical properties and capillary pressure response in two vugular carbonate full diameter samples.

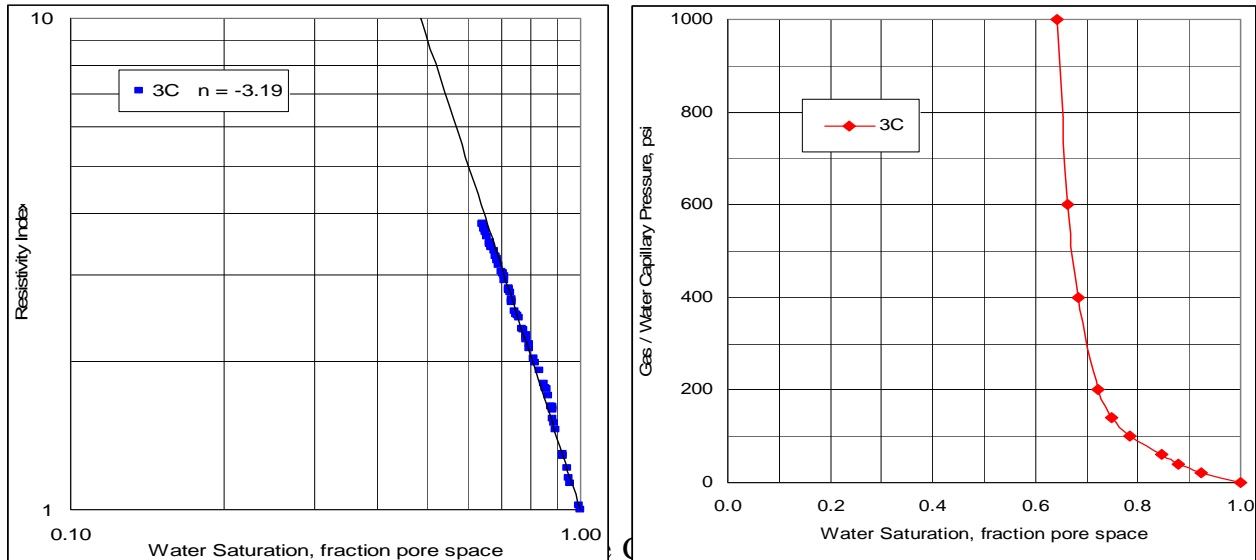


The first sample (1A), has a porosity of about 4 percent. The presence of vugs is in evidence in the resistivity index plot with the minimal resistance response when compared to the early saturation changes. The transition to matrix porosity is then clearly recorded in the abrupt change in incremental saturation exponent values. Incremental saturation exponent values increase to a maximum of -1.51 at the end of the desaturation process as obtained using a final desaturation pressure of 1000 psi air / brine although the average saturation exponent is -1.17. The associated capillary pressure curve however, follows a much more typical response. The second sample (2A) has a porosity of about 2 percent. The presence of vugs is also in evidence in the resistivity index plot with the suppressed resistance response when compared to the initial saturation changes. The transition to matrix porosity is also noted in the linear but definitive shift in incremental saturation exponent values. Incremental saturation exponent values increase to a maximum of -1.95 at the end of the desaturation process as obtained using a final desaturation pressure of 1000 psi air / brine with an average saturation exponent of -1.44. The associated capillary pressure curve indicates a more complex pore structure.

If conventional samples of 1.5" diameter had been used in this analysis, the vugs could have easily been misrepresented or have been missed all together yielding significantly different electrical response.

The third sample (3C), a conglomerate, has a porosity of about 2.5 percent. This sample exhibits a fairly uniform pore structure even with the presence of large cobbles as

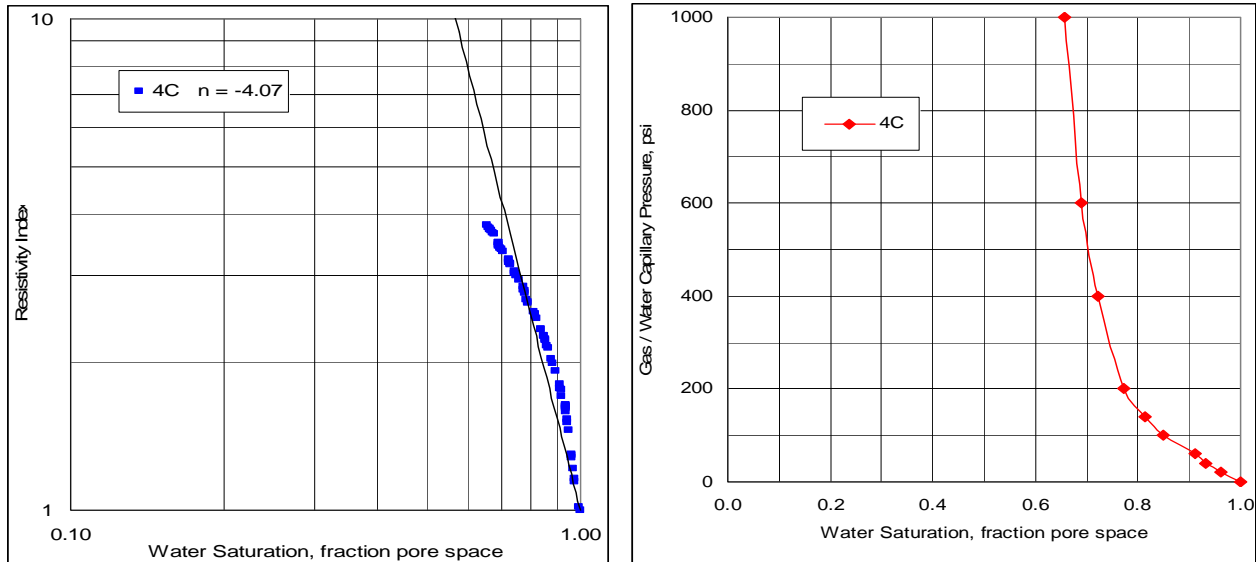
evidenced by the relatively constant saturation exponent and uniform capillary pressure curve. The final incremental n value is -3.05 and the average n value is -3.19 . The cementation exponent is -2.03 . Figures 3 and 4 summarize this data.



Full Diameter Sample

The fourth sample (4C), also a conglomerate, has a porosity of about 4.0 percent. The cementation exponent is -2.08 . The saturation exponent, while averaging -4.07 , is characterized by a significant lowering of incremental n values as the brine saturation decreases. The incremental n values reach a maximum of -7.10 within the mid 90 percent saturation range and by the terminal brine saturation, the incremental n values are approaching -3.20 . The capillary pressure curve captures small pore structure variance within the 85 to 90 percent saturation range, yet overall remains rather uniform. Figures 5 and 6 summarize this data.

Clearly the limitations of traditional methodologies, specifically the 200 psi A/B porous plate and plug samples of 1.5" in diameter, would have yielded significantly different (and misleading) results if used in the investigation of this sample. With conglomerates characterized by similar large cobble size, results may not be obtainable with any plug sample less than full diameter.



Figures 5 and 6. Resistivity Index and Plate Capillary Pressure Data in a Conglomeritic Full Diameter Sample

Conclusion

Incomplete electrical response and non-representative pore geometry can combine to provide sub-standard electrical property and capillary pressure analysis results. Full diameter sample size, the use of a 1000 psi plate membrane system and “best practice” methodology combine to provide quality electrical properties and plate capillary pressure data in unconventional and demanding rock types.

References

- (i) Archie, G E “The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics” *Petroleum Transactions of the AIME* 146 (1942)