EVALUATION AND ASSESSMENT OF UNCERTAINTY IN ELECTRICAL PROPERTIES FOR ARABIAN CARBONATE RESERVOIR

Taha M. Okasha and James J. Funk
Saudi Aramco EXPEC Advanced Research Center,
Dhahran, Saudi Arabia

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ABSTRACT

Electrical logging is the most widely used method for identifying hydrocarbon intervals in a wellbore. Standard methods relating oil saturations in clay-free reservoirs to electrical resistivities are based on the Archie equation. Accurate determination of Archie's parameters (saturation exponent, n, and cementation exponent, m) is essential for better estimation of water saturation and log calibration especially for heterogeneous carbonates reservoirs.

In this study, sixty (60) plugs recovered from different wells across an Arabian carbonate reservoir were used to evaluate Archie's parameters. Experimental measurements using state of the art equipment were done by five core analysis service companies. The test results were reviewed for consistency and measurement accuracy. Quality control and statistical analysis of electrical parameters (n and m values) and capillary pressure data addressed uncertainties and errors in measurements. Despite some differences in procedures and experimental conditions, the mean petrophysical values, standard deviations, and ranges of n and m values are consistent.

INTRODUCTION

Major hydrocarbon reservoirs in the Middle East are in carbonate formations. Arabian carbonate reservoirs need accurate evaluation of water saturations either in the early life of the reservoir or during development stage for better assessment of hydrocarbon reserves.

Accurate determination of water saturation from resistivity logs depends on the correct assignment of the electrical parameters a, m, and n in the Archie equations [1]. These are determined from values of porosity, water saturation, water resistivity, and sample resistivity measured on representative core samples. Empirically the parameters are related by the equations:

$$FRF = R_o/R_w = a/\phi^m \quad (1)$$

$$FRI = R_t/R_o = 1/(S_w)^n \quad (2)$$

$$S_w = [a/\phi^m . R_w/R_t]^{1/n} \quad (3)$$

Where:
a = Structural parameter = 1(in this study), S_w = Water Saturation, FRF = Formation Factor, FRI = Resistivity Index, ϕ = Porosity, R_o = Sample Resistivity at 100% Brine Saturation, R_w = Brine Resistivity, R_t = Measured (true) Sample Resistivity, n = Saturation Exponent, m = Cementation Exponent

Numerous papers from different laboratories have been published on the measurement and analysis of Archie parameters. The effects of laboratory procedures on the measurement and analysis of the saturation exponent have shown this variable to be one of the most difficult petrophysical variables to quantify [2-5].

In this study, sixty (60) plugs recovered from different wells across an Arabian carbonate reservoir were used to evaluate Archie's parameters using state of the art equipment. The experimental measurements were done by five core analysis service companies. The test results were reviewed for consistency and measurement accuracy. The quality control and statistical analysis of electrical parameters (n and m values) and capillary pressure data for the tested samples were conducted to address uncertainties and errors in measurements.

EXPERIMENTAL APPROACH

Each vendor laboratory was requested to execute the measurement program based on experimental protocols and procedures recommended by Saudi Aramco. The laboratories that provided results along with the number of samples tested are listed in **Table 1**. Test temperatures, hydrostatic confining pressures, calculated brine salinities, and electrode current frequencies are listed in the **Table 2**.

Table 1. Number of Sample Selected for testing laboratories

Laboratory	Well No.	Number of Samples	Laboratory	Well No.	Number of Samples
Lab-A	1	15	Lab-D	3	11
Lab-B	2	8		4	12
Lab-C	2	10	Lab-E	5	5

Table 2. Test Conditions

Well No.	T (^oF)	Confining Pressure (psi)	Salinity (ppm)	Frequency (kHz)	Rw (ohm/m)	Maximum Capillary Pressure (psi)
1	194	2,500	58,008	20.0	0.048	80
2	194	2,500	58,008	20.0	0.048	140
2	190	2,500	57,630	1.0	0.0493	100
3	77	2,130	50,000	10.0	0.079	101
4	135	1,500	200,000	1.0	0.0264	80
5	135	3,000	70,609	10.0	0.063	101

RESULTS AND DISCUSSION

Data Set Averages and Confidence Intervals

Average values, standard deviations and composite results for all wells are listed in **Table 3**. Composite values are obtained by combining the results from all tested samples prior to the linear regression for determination of the Archie model parameters. These are shown in **Figures 1** and **2**. Mathematically this is different than the simple arithmetic averaging of the exponents. The occasional 1% variations between average and regression methods are in line with the R^2 values in the 0.97 and 0.99 ranges.

Table 3. Average Properties of Samples Selected from Different Wells

Well	Porosity (%)	Permeability (mD)	Cementation Exponent (m)			Saturation Exponent (n)		
	Mean	Log Mean	Composite	Mean	Standard Deviation	Composite	Mean	Standard Deviation
1	16.37	13.2	1.98	2.02	0.16	1.97	1.99	0.16
2	14.16	10.0	2.10	2.08	0.18	2.04	2.03	0.06
2	11.38	5.6	2.11	2.11	0.10	1.95	1.95	0.22
3	19.06	91.1	1.99	2.01	0.10	2.05	2.05	0.04
4	21.28	90.1	2.18	2.19	0.13	1.90	1.90	0.07
5	21.04	30.9	2.05	2.09	0.10	2.06	2.10	0.10
All Samples	17.09	24.5	2.06	2.077	0.14	1.98	1.99	0.137

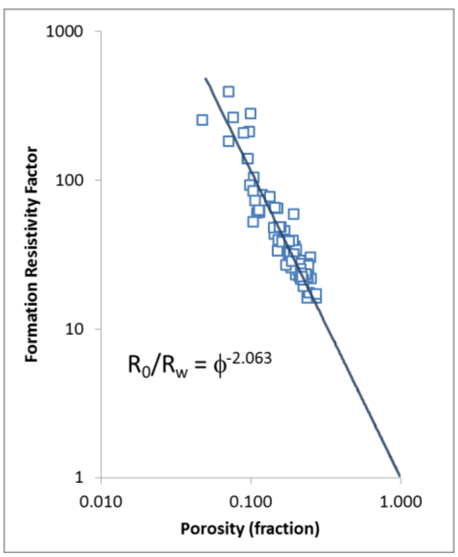


Figure 1. Composite plot of m.

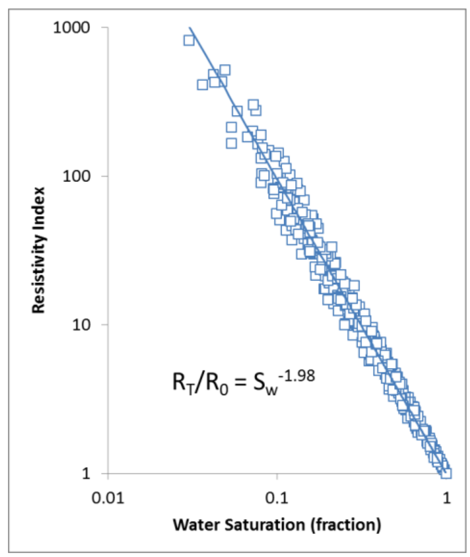
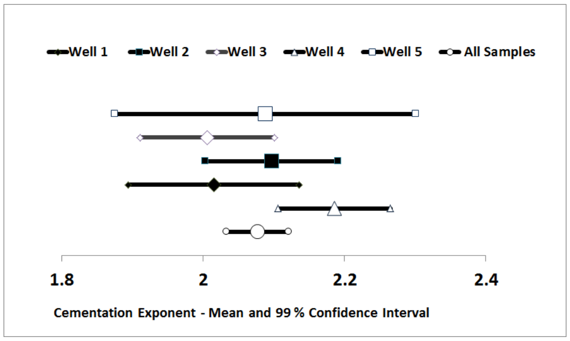


Figure 2. Composite plot of n.

Using t-distribution values and a 99 % confidence interval for the mean of the population, the tabular data (m and n) from **Table 3** can be presented graphically to show the range and correspondence of measured values of m an n between the wells (**Figures 3** and **4**).



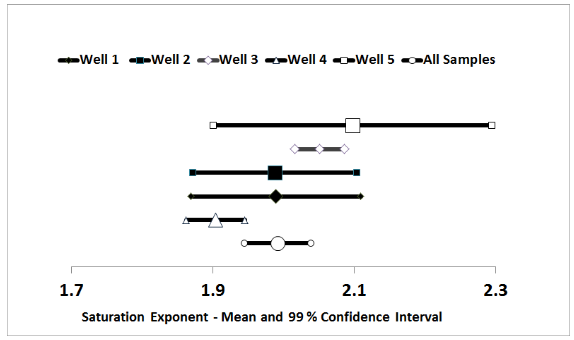


Figure 3. Mean and 99% Confidence Interval for m.

Figure 4. Mean and 99% Confidence Interval for n.

Well 4 samples tended to group at the highest average cementation exponent and the lowest average saturation exponent. The larger mean cementation exponent for Well 4 shown in **Figure 3** and the lower Well 4 mean saturation exponent shown in **Figure 4** indicates that there may be a statistically significant difference between the methods or samples tested from Well 4.

Uncertainties and Statistical Tests

All of the labs used similar electronic and volumetric systems so that uncertainties in the measurements for individual samples are similar. Standard conventions for estimation of measurement uncertainty along with the ISO and EURACHEM [6] methods for determination of expanded uncertainty were used to calculate the uncertainties associated with resistivity measurements. Uncertainties for all basic resistivity index measurements and modeled parameters are listed in **Table 4**. Expanded uncertainties are based on the product of the standard uncertainty and a coverage factor (k) determined from standard distributions normally set at a value of two (2).

Table 4. Average Properties of Samples Selected from Different Wells

Modeled Value	Standard Uncertainty (%)	Expanded Uncertainty (%)	Measured Value	Standard Uncertainty (%)	Expanded Uncertainty (%)
Formation Resistivity Factor	0.719	1.43	Pore Volume	0.227	0.45
Resistivity Index	0.731	1.46	Porosity	0.251	0.50
Cementation Exponent	0.773	1.55	Water Saturation	0.302	0.60
Saturation Exponent	0.779	1.56	Resistivity	0.517	1.03

The values in **Table 4** represent the uncertainty associated with individual measurements. They serve as a reference point as we look for variability within a population. Uncertainties in measurements on the same sample in multiple labs will generally be larger. For carbonates, coverage factors in the range of ten (10) to twenty (20) have been reported in the literature [5 and 7].

Reviewing the cementation and saturation exponent distributions in **Figures 3** and **4**, along with the test parameters as listed in **Table 2**, the salinity used in the Well 4 tests stands out. Tests done in Well 2, Well 4, and Well 5 generally eliminate the other factors of confining pressure, test frequency, and temperature as contributing factors to the variation of the mean values. These tests point to the following:

- Confining pressure variations are minimal in the range of less than 1%.

- Data from literature references [8] and earlier in-house tests on carbonate plugs indicate that variations in resistivity index due to the test frequency are insignificant in the range from 1 kHz to 20 kHz.

- Temperature variations are generally insignificant with changes of less than 3% between ambient and reservoir temperature and variations of only 1% expected for temperatures between 135 and 194 ^{o}F [9-10].

The impact of the increased brine salinity is less certain. Statistical tests and comparisons along with the uncertainty evaluation of the measurements indicate that the variable salinity should not preclude the grouping of the Well 5 samples. The lack of conductive clays or conductive matrix materials in samples from Well 5 indicates that the formation conductivity should not be affected by the conductivity of the solution.

SUMMARY

Based on the results of the measurements from all wells and laboratories, trends and average values for the electrical properties can be established. In summary:

- Uncertainties in the measurements for individual samples are considered similar. Calculated uncertainties with standard single lab coverage factor for m ~ 1.55 and for n ~ 1.56.
- Average values for the tested sets of carbonate plugs (Arab-D reservoir) establish the 99% confidence intervals for the means as: Average cementation exponent (m) 2.08 $\pm$ 0.04 and average saturation exponent (n) 1.99 $\pm$ 0.05.
- Based on the porosity and permeability ranges and averages, the sample sets evaluated in this study are considered representative. The mean values, standard deviations, and ranges from this set of wells are expected to be similar to those in other Arab-D wells.
- Based on the statistics, the higher salinity (equivalent to 200,000 ppm NaCl) used for the Well 4 samples cannot be ruled out as a contributor to the higher cementation exponent.

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