# THE EFFECT OF RESERVOIR CONDITIONS ON SATURATION EXPONENT AND CAPILLARY PRESSURE CURVE FOR WATER-WET SAMPLES.

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## ABSTRACT

Saturation exponents have been determined at ambient conditions and at reservoir conditions on sandstone core plugs from a North Sea reservoir. The samples were drained for water using the porous plate method.

Five samples were first measured at ambient conditions with nitrogen displacing water, then at reservoir conditions with refined oil displacing water. After the test at reservoir conditions the samples were measured at ambient conditions with refined oil displacing water.

At the end of the reservoir conditions measurements, the effect of reductions in the reservoir pore-pressure on the water saturation and the resistivity index were investigated.

The wettability preference of the samples was tested, showing that the plugs remained water-wet throughout the measurements.

The results from the electrical measurements both for the tests at ambient conditions and for the tests at reservoir conditions confirm the relationship between the resistivity index and water saturation described by Archie.

The results from the electrical resistivity measurements show that the saturation exponents obtained at reservoir conditions are lower than the saturation exponent obtained at ambient conditions with refined oil displacing water.

The formation resistivity index and thus the saturation exponent slightly increased when the net confining pressure was increased.

For this water-wet reservoir it is found that the capillary pressure obtained at ambient conditions is

directly proportional to the capillary pressure obtained at reservoir conditions.

## INTRODUCTION

In the recent years research has shown that core analysis at ambient conditions does not always reproduce the reservoir data.

An error in the saturation exponent,n, from Archie's equation (Archie, 1942),

$$RI = S_w^{-n}$$

obtained at ambient conditions will cause an incorrect estimation of the amount of hydrocarbons in the reservoir.

Longeron *et al.* (1989), have determined saturation exponents at reservoir conditions. The resistivity index and capillary pressures were measured first with refined oil.The samples were restored and then measured with crude oil. They found that the saturation exponents were higher when crude oil was used than when refined oil was used in the measurement. For the samples changing wettability to oil-wet during the restoration the differences were significant. The conclusion confirms previous studies on the effect of wettability on the saturation exponent at ambient conditions (Keller, 1953; Sweeney and Jennings, 1960; Morgan and Pierson, 1964; Donaldson and Siddiqui, 1987; Lewis *et al.*, 1988; Lile *et al.* (1988).

Longeron *et al.* (1986) have also compared capillary pressure data and saturation exponents obtained at reservoir conditions with refined oil displacing water and at ambient conditions with gas displacing water. The samples were water-wet. They found that the saturation exponents obtained at reservoir conditions are higher than the saturation exponents obtained at ambient conditions. They also found the irreducible water saturation to be lower in the test at reservoir conditions than in the test at ambient conditions.

Mahmood *et al.* (1988) have measured the electrical resistivity at reservoir conditions on water-wet samples. They varied the temperature and the confining pressures. They found that the saturation exponents decrease at increasing temperature and slightly increase at increasing confining pressure. The total effect of temperature and confining pressure shows that the saturation exponents were lower at reservoir conditions than at ambient conditions.

Søndenå *et al.* (1989) have compared capillary pressure measurements on samples of neutral wettability preference at ambient conditions and samples of neutral wettability preference which changed to oil-wet preference during the capillary pressure measurement at reservoir conditions. The water saturated samples used at ambient conditions were displaced with refined oil and the twin samples used at reservoir conditions were displaced with live crude oil and refined oil. They found that the irreducible water saturations obtained at reservoir conditions were higher than the irreducible water saturations obtained at ambient conditions. From the results of the electrical resistivity measurements they found that the resistivity indexes obtained at reservoir conditions were higher than the resistivity indexes obtained for the same water saturation at ambient conditions. The largest differences were found at low water saturations in the measurements where the water was displaced with live crude oil. They related the differences in irreducible water saturations and resistivity indexes to a change in the wettability preference.

The effect of effective stress on the saturation exponent, n, has been investigated by Glanville, (1959); Longeron *et al.*, (1986); and Mahmood *et al.* (1988). Longeron *et al.* (1986) showed that the saturation exponent slightly increased with increasing effective stress for sandstone samples and slightly decreased for limestone samples. Glanville (1959) found that the saturation exponent increased with an increase in effective stress. Mahmood *et al.* (1988) found that saturation exponent increased slightly with an increase in effective stress.

The intention of this study is to see if there is any difference between the capillary pressure curves and the water saturation exponent obtained at ambient conditions and those obtained at reservoir conditions for water-wet samples for a North Sea reservoir. The effect of effective stress is also studied.

The porous plate method has been chosen to drain the samples for water since the initial distribution of saturation in the reservoir is established by capillary forces. Using the porous plate method, the saturation distribution is established, by capillary forces acting only.

## DESCRIPTION OF THE TESTS

Prior to the tests, all samples were gently flushed alternately with methanol and toluene, then dried with a lenient air flow and finally saturated with synthetic formation water. 100% water saturation at the start of the measurement was checked by comparing the pore volume with the difference in weight between water saturated and dry samples.

## Ambient Condition Test

### Gas/Water Test

The water-saturated samples were placed on a porous plate in a pressure chamber. Clay powder was used between the sample and the porous plate to keep hydraulic contact during the test. No sleeve was placed around the samples. The samples were drained for water using humid nitrogen at 8 different pressures. The capillary pressures were 0.1, 0.2, 0.4, 0.8, 1.6, 3, 5 and 15 bar respectively.

The stability time at each pressure was at least seven days. The different saturations were determined by weighing the samples individually. Afterwards the resistivity of the samples was calculated from the measurement of the plug resistance by pressing electrodes on the end faces. The samples were checked for grain loss by comparing the weight of the dry samples before and after the test.

### Refined Oil/Water Test

The procedure is identical to the one used previously by Søndenå *at al.* (1989). The capillary pressures were 0.05, 0.10, 0.3, 1.0 and 1.5 bar respectively.

The resistivity index (RI) versus water saturation ($S_w$) distribution for the calculation of the saturation exponent (n) was determined at each capillary pressure.

## Reservoir Condition Test

### Description of the equipment

In Figure 1 a diagram of the apparatus is presented.

### Experimental procedure

The core plugs and the porous plates were saturated with synthetic formation water and mounted in the coreholders (Figure 2) which were subsequently filled with hydraulic oil. The confining pressure was increased to the net overburden pressure of the reservoir, i.e. 180 bar, whereupon both the confining pressure and the pore pressure was increased simultaneously to reservoir pressure, i.e. 594 bar and 414 bar while keeping the net confining pressure at 180 bar.

Then the coreholders were heated up to the reservoir temperature of 98°C.

When the core plugs had been stabilized at reservoir conditions for one week, the formation resistivity factors were

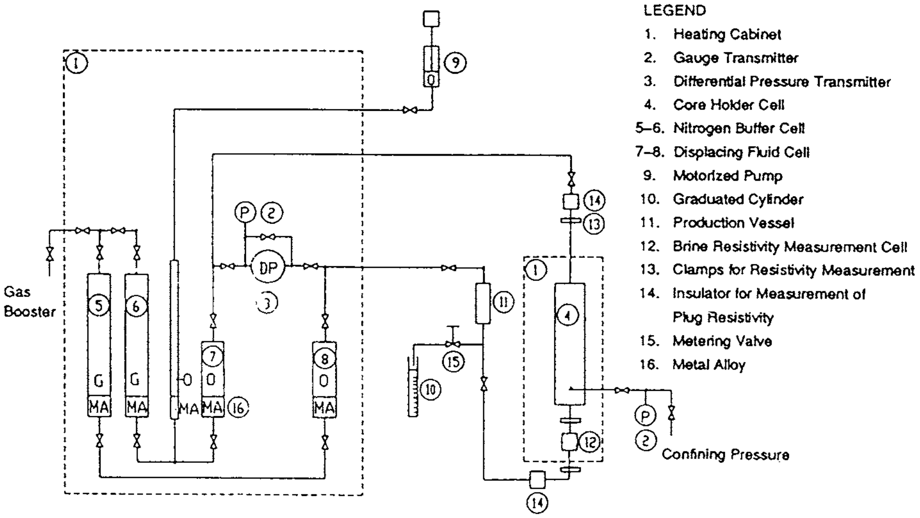

FIGURE 1 Diagram of the apparatus used for measurements at reservoir conditions.

determined.

The differential pressure over the plugs, i.e. the capillary pressure, was set by increasing the pressure on the high pressure side with the motorized pump.

The samples were drained for water with refined oil at 7 different capillary pressures. The pressures applied were 0.05, 0.10, 0.15, 0.20, 0.30, 0.50 and 0.93 bar, respectively.

The test proceeded to the next pressure if the production during a three-day interval was less than 1% of the pore volume.

After the capillary pressure measurements, some water was imbibed into the plugs through the porous plates by reducing the capillary pressure to zero. The effective stress was then increased to 244 bar, by reducing the pore pressure to 350 bar. The capillary pressure was then set to 0.93 bar. When the water saturation had ceased, the formation resistivity was measured. Then the same procedure was applied for an effective stress of 344 bar (pore pressure of 250 bar).

Finally the coreholders were dismounted and the water saturations from a Dean and Stark extraction for four of the samples were used to calibrate the water saturations from the capillary pressure measurements.

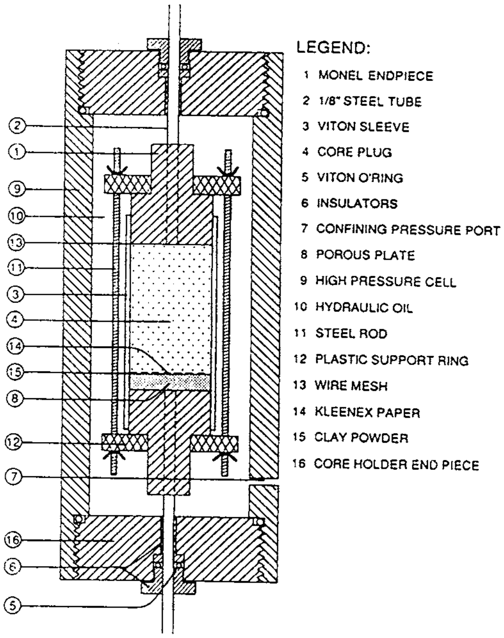

FIGURE 2 Schematic diagram of the coreholder.

One plug was tested for wettability preference using the Amott method.

During the tests, the resistivity index (RI) versus water saturation (Sw) and thus the saturation exponent (n) were determined. The pore volume and thus the water saturation was corrected for effective stress. The resistivity of the samples was corrected for the resistivity of the porous plate by subtracting the resistivity of the porous plate, corrected for temperature, from the measured resistivity. The resistivity of the porous plate was checked by measuring the resistivity of the plate before and after the test.

## RESULTS AND DISCUSSION

The reservoir conditions applied and the properties of the fluids are listed in Table 1-3. The results from the wettability tests are presented in Table 4. The sandstone samples are from the same reservoir and they are all well consolidated. It should be stressed that the conclusions can not be extended to all sandstone reservoirs, especially not unconsolidated reservoirs.

TABLE 1 Reservoir conditions.

| | | |
|---|---|---|
| Reservoir Temperature (°C) | | 98 |
| Reservoir Pressure (bar) | | 414 |
| Calculated overburden pressure (bar) | | 594 |
| Effective stress (bar) | 594 - 414 = | 180 |

TABLE 2 Chemical composition of formation water.

| | | |
|---|---|---|
| $Na^+$ | 16 034 | mg/l |
| $Ca^{2+}$ | 5 300 | mg/l |
| $Mg^{2+}$ | 360 | mg/l |
| $Sr^{2+}$ | 1 120 | mg/l |
| $K^+$ | 0 | mg/l |
| $Cl^-$ | 36 092 | mg/l |

TABLE 3 Physical properties of fluids.

| | *Formation water* | *Refined oil Isopar-M* |
|---|---|---|
| Density (20°C) | 1.04 g/cm$^3$ | 0.78 g/cm$^3$ |
| Viscosity (20°C) | 1.12 cp | 2.45 cp |

TABLE 4 Wettability preference, Amott test.

| | *Wettability Index* | |
|---|---|---|
| *Sample no.* | *WWI*[a] | *OWI*[b] |
| Prior to the test at reservoir conditions | | |
| 1 | 0.99 | 0 |
| 2 | 1.00 | 0 |
| 3 | 0.93 | 0 |
| 4 | 0.98 | 0 |
| 5 | 0.98 | 0 |
| After the test at reservoir conditions | | |
| 3 | 0.87 | 0 |

[a] $WWI = \frac{\text{Volume of spontaneous displaced water}}{\text{Volume of total displaced water}}$

[b] $OWI = \frac{\text{Volume of spontaneous displaced oil}}{\text{Volume of total displaced oil}}$

## Capillary pressure curves

The endpoint water saturation obtained at reservoir conditions and the water saturations obtained from the tests at ambient conditions at the same capillary pressure are presented in Table 5. The capillary pressure curves are presented graphically in Figure 3. The capillary pressure data have not been corrected for interfacial tension.

The endpoint water saturations obtained at reservoir conditions are lower than the water saturation obtained at the same capillary pressure at ambient conditions with refined oil displacing water, and lower than the water saturation obtained at the same capillary pressure at ambient conditions with nitrogen displacing water.

The results from this study are different compared to the results from the study by Søndenå *et al.* (1989). They compared capillary pressure measurements on samples of neutral wettability preference at ambient conditions and samples of neutral wettability preference which changed to oil-wet preference during the capillary pressure measurement at reservoir conditions. They found that the irreducible water saturations obtained at reservoir conditions were higher than the irreducible water saturations obtained at ambient

TABLE 5 Results from the capillary pressure measurements.

| | | Ambient Conditions | | | | Reservoir Conditions | |
|---|---|---|---|---|---|---|---|
| | Fluid: | gas | | oil | | oil | |
| Sample | Air perm (mD) | $S_w$ (frac.) | n | $S_w$ (frac.) | n | $S_w$ (frac.) | n |
| 1 | 226 | 0.39 | 2.37 | 0.33 | 2.52 | 0.26 | 2.26 |
| 2 | 73.7 | 0.43 | 2.26 | 0.37 | 2.43 | 0.28 | 2.37 |
| 4 | 190 | 0.39 | 2.29 | 0.34 | 2.42 | 0.26 | 2.23 |
| 5 | 23.3 | 0.48 | 2.00 | 0.41 | 2.42 | 0.34 | 2.24 |

conditions. The differences in irreducible water saturations they related to a change in the wettability preference. In this study the wettability preference remains water-wet throughout the measurements.

The nitrogen/water capillary pressures at ambient conditions are higher than the oil/water capillary pressures at ambient conditions which are higher than the oil/water capillary pressures at reservoir conditions for all water saturations. The differences between the capillary pressure curves in Figure 3 are systematic.

The ratio of nitrogen/water capillary pressure obtained at ambient conditions to refined oil/water capillary pressure obtained at reservoir conditions as a function of water saturation are presented in Figure 4. A linear regression has been taken of all the data points in the figure. The average value for the capillary pressure ratios of the samples lies between 2.58 and 2.72 and the mean value is 2.66.

The ratio of refined oil/water capillary pressure obtained at ambient conditions to refined oil/water capillary pressure obtained at reservoir conditions as a function of water saturation is presented in Figure 4. A linear regression has also been taken of all the data points in this figure. The avarage value for the capillary pressure ratios of the samples lies between 1.57 and 1.84 and the mean value is 1.70.

The average value for the ratios of nitrogen/water capillary pressure to refined oil/water capillary pressure for the samples, both obtained at ambient conditions, lies between 1.44 and 1.64. The mean value is 1.56.

If the correlation

$$\frac{(P_c)_{g/w}}{(P_c)_{o/w}} = \frac{\sigma_{g/w}}{\sigma_{o/w}}$$

is used for the measurement at ambient conditions, the ratio is 1.52.

This correlation, which neglects contact angle, appears to be valid experimentally in uniformly wetted porous media with contact angle less than 50°, because the rough surfaces of the pores make the effective contact angle zero (Anderson; 1987).

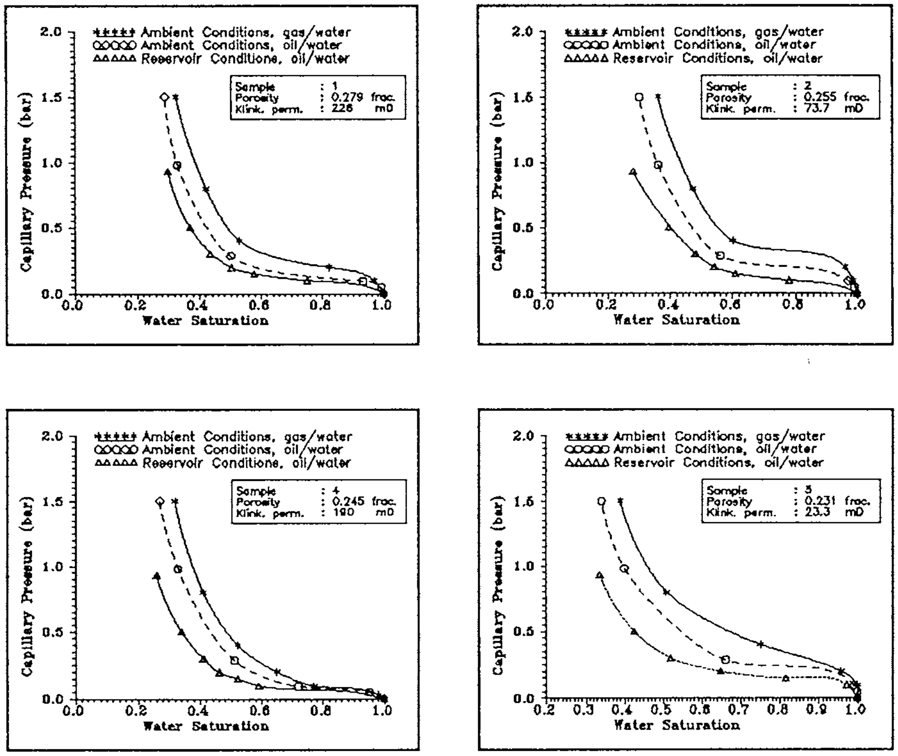

FIGURE 3 Capillary pressure curves at ambient conditions and at reservoir conditions

The interfacial tension of the oil/water at reservoir conditions is not measured. But the theoretical correlation between the oil/water capillary pressure at ambient conditions and the oil/water capillary pressure at reservoir conditions is larger than 1 since the interfacial tension of oil/water decreases as a function of temperature. The mean ratio of the capillary pressure from the experiment was 1.70 on average.

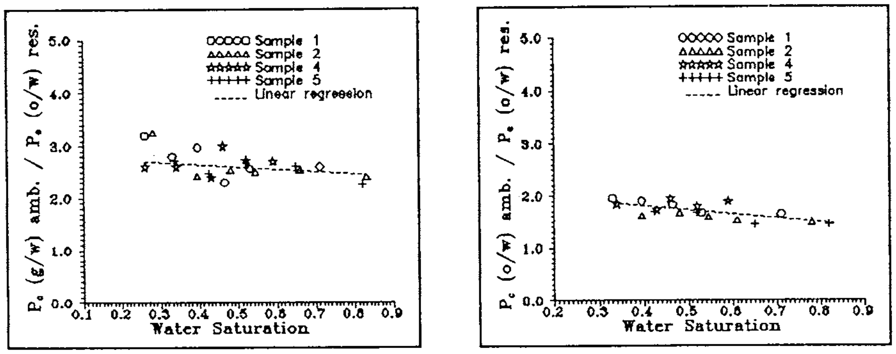

FIGURE 4 Ratio of capillary pressure at ambient conditions to capillary pressure at reservoir conditions vs. water saturation.

### Saturation exponent - n

The saturation exponents, evaluated with the least square method are presented in Table 5. The resistivity index versus water saturation is presented graphically in Figure 5.

The results from the electrical resistivity measurements show that the saturation exponents obtained at reservoir conditions are lower than the saturation exponent obtained at ambient conditions with refined oil displacing water.

The saturation exponent is 2.26 on average for the test at reservoir conditions where water was displaced by refined oil. For the test at ambient conditions where water was displaced with refined oil the saturation exponent was 2.45 on average. For the test where water was displaced with nitrogen at ambient conditions the saturation exponent was 2.23 on average.

The difference between the saturation exponent obtained from the gas/water test and the oil/water test, both at ambient conditions, could be due to a systematic error in the gas/water test. In the gas/water test the resistivity measurement and the desaturation process took place separately. The resistivity of the samples were measured by pressing electrodes on the end faces. De Waal *et al.* (1989) found that when the electrodes were kept slightly too wet, the saturation exponent was systematically too low in a gas/water test.

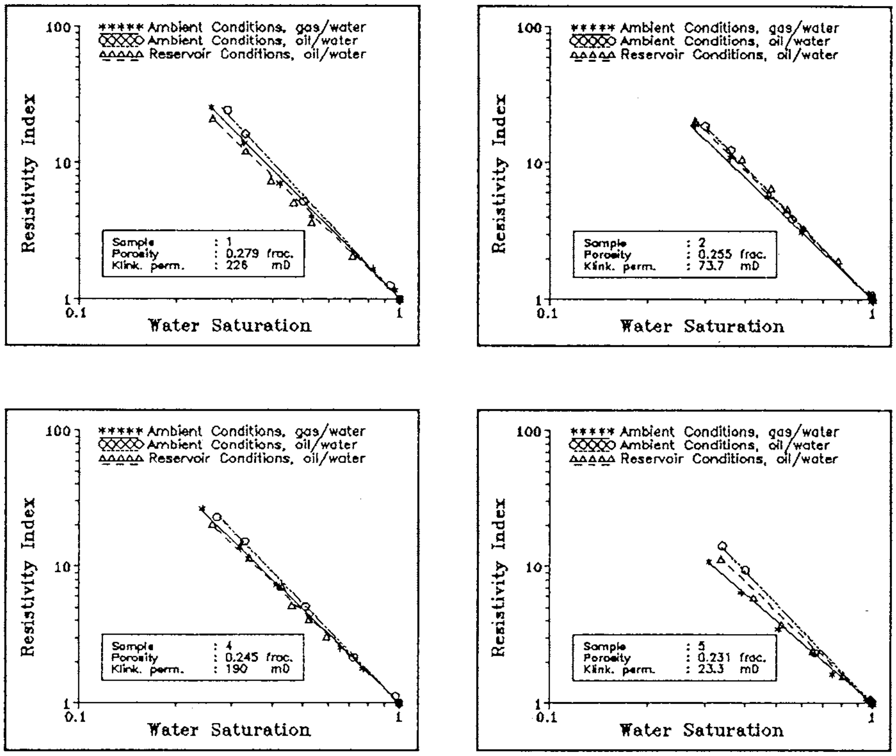

FIGURE 5 Resistivity index vs. water saturation.

The results confirm the study by Mahmood *et al.* (1988). They found that the saturation exponent was lower at reservoir conditions than at ambient conditions for a oil-water system.

The results from the electrical resistivity measurements both for the tests at ambient conditions and for the tests at reservoir conditions confirm the relationship between the resistivity index and water saturation described by Archie.

The results from this study are different from those of Søndenå *et al.* (1989). They compared electrical resistivity measurements on samples of neutral wettability preference at ambient conditions and samples of neutral wettability preference which changed to oil-wet preference during the electrical resistivity measurements at reservoir conditions. They found that the resistivity indexes obtained at reservoir conditions were higher than the resistivity indexes obtained for the same water saturation at ambient conditions. The largest differences were found at low water saturations in the measurements where the water was displaced with live crude oil. The differences in resistivity indexes they related to a change in the wettability preference. In this study the wettability preference remained water-wet throughout the measurements.

### Effect of effective stress

The formation resistivity indexes and the saturation exponents versus effective stress at endpoint saturation are presented in Table 6. The resistivity of the 100% water saturated samples, $R_o$ *vs.* effective stress was determined in a separate test before the test at reservoir conditions. The effect of stress on $R_o$ was insignificant, (error less than 1%). The endpoint water saturations did not change as a function of effective stress.

The results of the electrical measurements (Table 6) show that the formation resistivity indexes and thus the saturation exponents slightly increased when the effective stress was increased.

The saturation exponent,n, increased by 5% when the effective stress was increased from 180 to 344 bar. Since the error in the RI is less than 1%, the incremental change in the saturation exponent is probably not due to experimental errors.

**TABLE 6** Formation resistivity indexes and saturation exponents versus effective stress at endpoint saturation.

| *Effective stress (bar)* | *180* | | *244* | | *344* | |
|---|---|---|---|---|---|---|
| *Sample no.* | *RI* | *n* | *RI* | *n* | *RI* | *n* |
| 1 | 21.2 | 2.33 | 21.8 | 2.35 | 23.6 | 2.41 |
| 2 | 20.3 | 2.71 | 20.9 | 2.74 | 23.3 | 2.84 |
| 3 | 19.4 | 2.60 | 21.0 | 2.67 | 22.3 | 2.72 |
| 4 | 20.3 | 2.05 | 19.0 | 2.00 | 23.0 | 2.13 |
| 5 | 11.2 | 2.50 | 10.8 | 2.47 | 12.1 | 2.59 |

The electrical measurements confirm the study by Glanville, (1959); Longeron *et al.*, (1986); and Mahmood *et al.* (1988). Longeron *et al.* (1986) showed that the saturation exponent slightly increased with increasing effective stress for sandstone samples and slightly decreased for limestone samples. Glanville (1959) found that the saturation exponent increased with an increase in effective stress. Mahmood *et al.* (1988) found that saturation exponent increased slightly with an increase in effective stress.

## CONCLUSION

The results from the electrical measurements both for the tests at ambient conditions and for the tests at reservoir conditions confirm the relationship between the resistivity index and water saturation described by Archie.

The saturation exponent slightly increased when the effective stress was increased.

The results from the electrical resistivity measurement from this reservoir show that the saturation exponents obtained at reservoir conditions are lower than the saturation exponent obtained at ambient conditions with refined oil displacing water.

For this water-wet reservoir it is found that the capillary pressure obtained at ambient conditions is directly proportional to the capillary pressure obtained at reservoir conditions.

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## NOMENCLATURE

| | |
|---|---|
| $n$ | Saturation exponent |
| $(P_c)_{g/w}$ | Capillary pressure, gas displacing water |
| $(P_c)_{o/w}$ | Capillary pressure, oil displacing water |
| RI | Resistivity Index = $R_t/R_o$ |
| $R_o$ | Resistivity of the fully water saturated sample |
| $R_t$ | Resistivity of the partly water saturated sample |
| $S_w$ | Water saturation (fraction of pore volume) |
| $\sigma_{g/w}$ | Surface tension of water |
| $\sigma_{o/w}$ | Interfacial tension of oil and water |