# Electrical Properties

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# Last Week..

Definition of Fluid Saturation and its importance to the petroleum industry

| Parameter | Symbol | Definition | Importance |
|---|---|---|---|
| Fluid saturation | $S_i$ (where *i* can be water, oil, or gas) | The fraction of pore volume occupied by the fluid. | We use fluid saturation to quantify the volume of oil and/or gas in the reservoirs. |

- Fluid saturation is a percentage that indicates how much fluid the pore space inside a rock contains, which is defined as the volume of fluid in a rock divided by its pore volume.
- In reservoir rocks, the fluids are usually hydrocarbons or water. Some extraction methods used to measure fluid saturation include retort distillation and the Dean-Stark method. In both of these methods, the fluid is extracted from the rock sample and then measured.
- The Dean-Stark method can only measure water saturation, unlike retort distillation that can measure both oil and water saturations. Therefore, material balance analysis is used to supplement the Dean-Stark method to calculate the oil saturation as well.
- Drilling muds make it difficult to evaluate the reservoir's saturation using extraction methods because they interfere with the saturation of the extracted samples.
- Similarly, extreme temperatures and pressures while extracting the core samples also cause changes within them, due to which the extraction methods cannot accurately determine the saturation within the reservoir

# Measuring Fluid Saturation

Fluid saturation measurements can be classified into two types:

**direct**

- include conventional core analysis techniques such as extraction methods (retort distillation and Dean-Stark method)

**indirect**

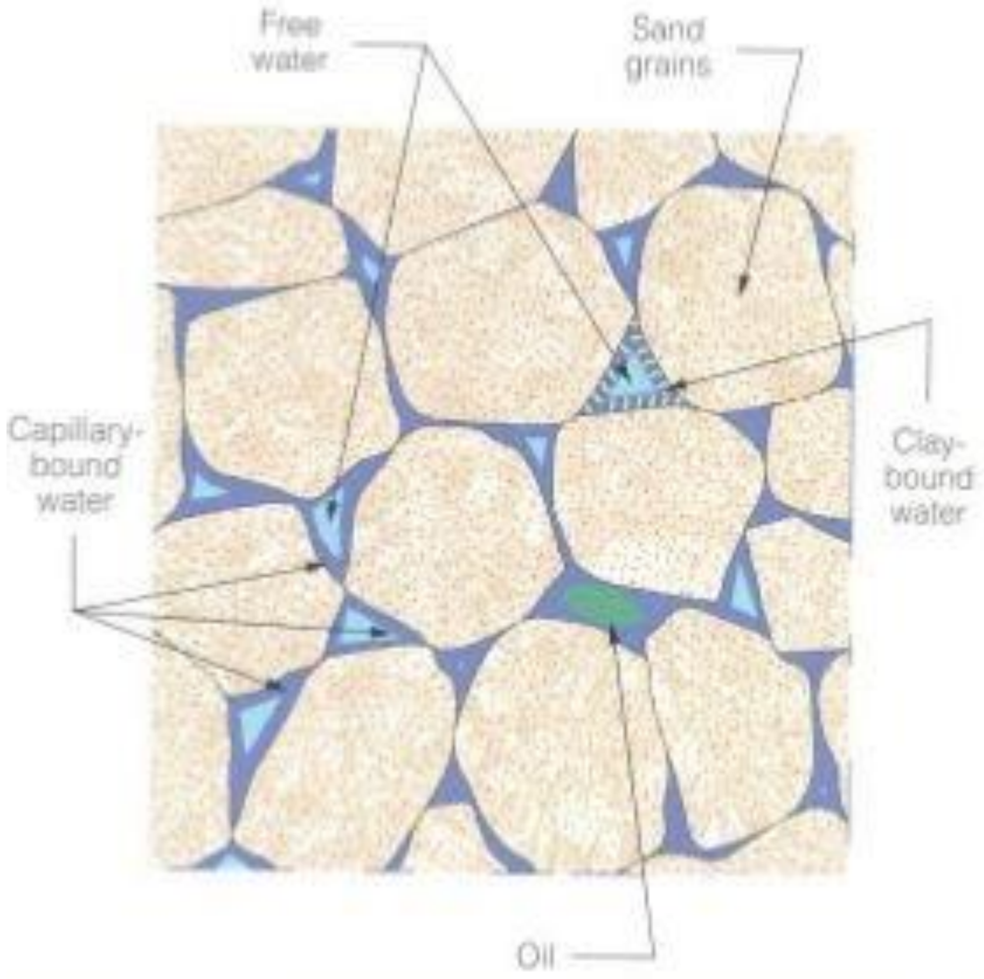
- include electrical properties and capillary pressure

# Concept of Electrical Properties

- One way of estimating fluid saturation indirectly in cores or reservoirs is by understanding and using electrical properties of reservoir rocks.
- Understanding the concepts of electrical properties in core samples is very simple, since the principles of electrical circuits apply here.
- The concepts rely on understanding that different materials conduct electricity differently. For instance, iron is considered a good conductor of electricity when compared with wood. Similarly, water is a better conductor of electricity when compared with hydrocarbons.
- Electrical conductivity is a measure of the ability of a material to transmit electricity. However, we will study resistivity, which is the inverse of conductivity and a measure of the material's ability to resist the flow of electricity.
- Obtaining fluid saturation from electrical properties involves correlating different resistivities by examining rocks at different experimental conditions.

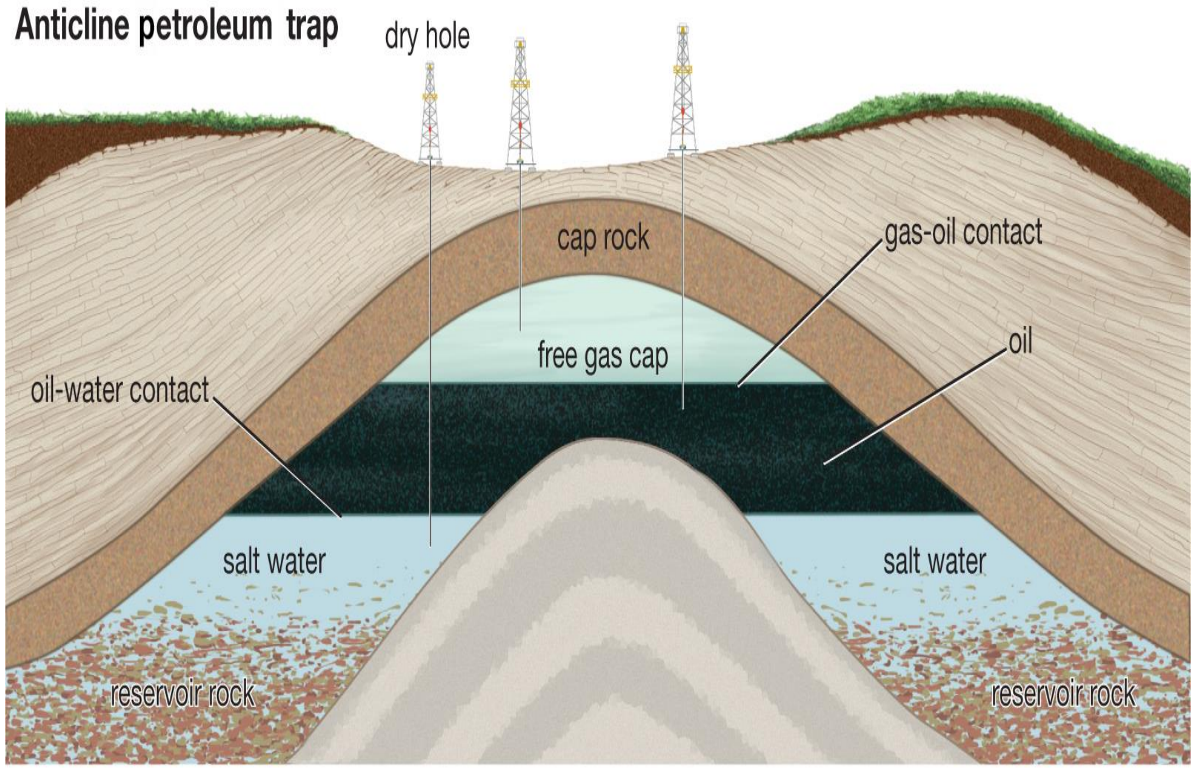
# Correlation between rock and electricity

- Batuan sedimen dapat menghantarkan listrik jika terisi oleh air atau fluida yang mengandung ion
- Dalam kondisi kering, batuan sedimen tidak dapat menghantarkan listrik
- Kemampuan batuan dalam mengahntarkan listrik ditunjukkan oleh parameter resistivitas atau konduktivitas



# Correlation between rock and electricity

- Di reservoir terdapat air (brine/fresh water), minyak dan gas
- Semakin tinggi konsentrasi garam pada fluida maka semakin kecil nilai resistivitasnya
- Low resistivity : brine/salt water
- High resistivity : fresh water, minyak dan gas
- Resistivitas formasi sangat bergantung pada fluida pengisinya (fluid saturation)



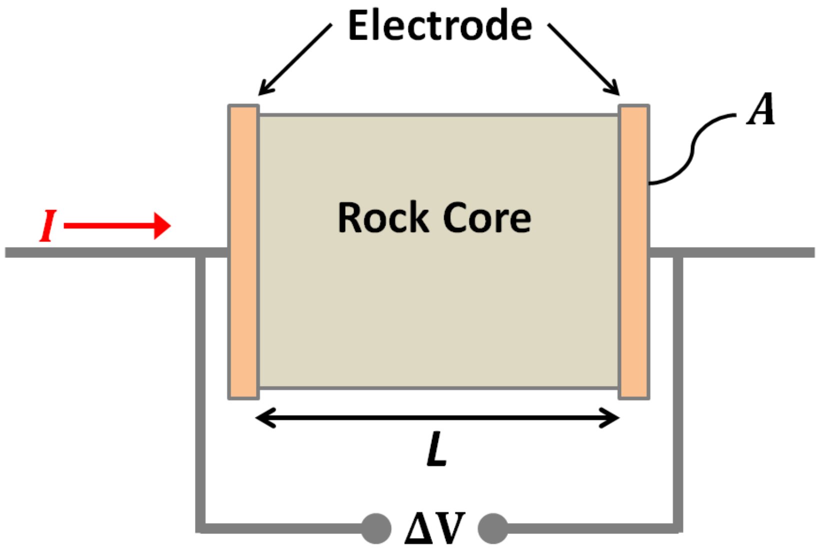
# Introduction to Ohm’s Law

$$\Delta V = Ir \qquad (1)$$

ΔV is the potential difference or voltage [V],
I is the electric current [A],
r is the resistance opposing the flow of electrical current [Ω]

$$R = \frac{rA}{L} \qquad (2)$$

R is the resistivity [Ω.m],
A is the cross-sectional area [m2],
L is the length [m]




- Resistance is an extensive property, which means it is size dependent; this means that differently sized samples will have different values of resistance. Another example of an extensive property is volume.
- Resistivity is an intensive property; this means that the property is independent of size. Density, for instance, is an intensive property, since a droplet of water and a giant pool of water both have a density of 1000 kg/m3 and change in size would not change the value of density

# Flow of Electrical Charges

Let us substitute Equation 2 in Equation 1 to obtain:

$$\Delta V = \frac{IRL}{A} \qquad (3)$$

Conductivity is the inverse of resistivity and is expressed as:

$$C = \frac{1}{R} \qquad (4)$$

where C is the conductivity [1/Ω.m or Siemens per meter, S/m].

Now, we substitute Equations 4 in Equation 3 and rearrange the equation to obtain:

$$I = \frac{CA}{L}\Delta V \qquad (5)$$

# Formation Factor

The formation factor is a ratio of water resistivity (Rw) to the resistivity of a core sample fully saturated with water (Ro ),

Mathematically, the formation factor is expressed as:

$$F = \frac{R_o}{R_w} \qquad (6)$$

F is the formation factor [dimensionless],
Rw is the resistivity of water [Ω.m],
Ro is the resistivity of the core when it is 100% saturated with water (Sw=1) [Ω.m].

Based on experimental observations, the formation factor can also be expressed as:

$$F = \frac{R_o}{R_w} = a\phi^{-m} = \frac{a}{\phi^m} \qquad (7)$$

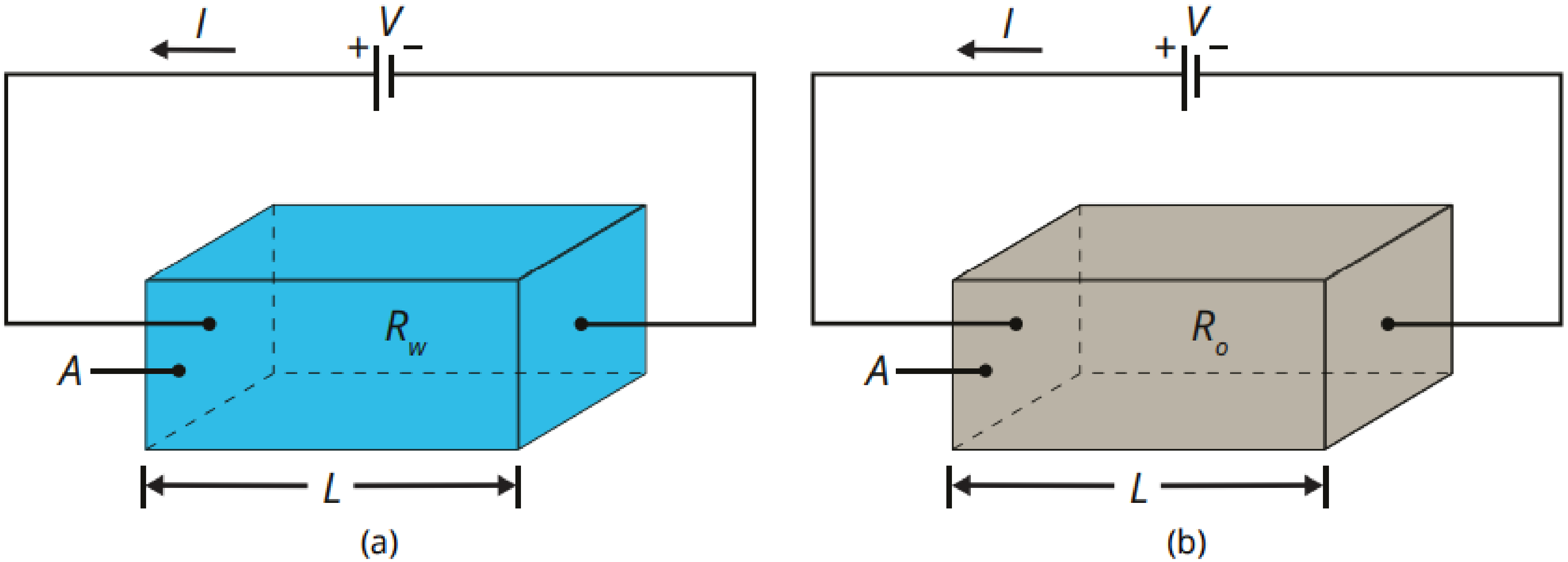
a is an empirical constant [dimensionless] and usually equals 1,
ϕ is the porosity [dimensionless],
m is a cementation factor or exponent and usually equals 2 (the higher the cementation in a rock, the higher the m value).

The correlation that will be used later on is:

$$\log F = \log a - m \log \phi \qquad (8)$$

where –m is the slope of the line. We can solve the equation at any point with m to find a. Bear in mind that m is positive and the negative sign is to account for the negative slope

# Formation Factor




Schematic showing a box with a length (L) and cross-sectional area (A) with (a) a box that is fully filled with water (the resistivity of this box is Rw) and (b) a box that resembles a rock with a certain porosity which is filled entirely with water (Sw =1) (the resistivity of this box is Ro).

# Formation Factor

## Example

A formation water's resistivity is 0.7 Ω.m, and the formation rock that is 100% saturated with this water has a resistivity of 20.4 Ω.m. Given that a = 1 and m = 2, determine the porosity of this formation rock.

### Solution

From the question, the values of $R_o$ and $R_w$ are given:

$$R_o = 20.4\ \Omega.m,\ R_w = 0.7\ \Omega.m$$

Hence, the formation factor $F$ can be found using **Equation 6.6**:

$$F = \frac{R_o}{R_w} = \frac{20.4}{0.7} = 29.14$$

Now, we can rearrange **Equation 6.7** to find porosity:

$$\phi = \left(\frac{a}{F}\right)^{1/m} = \left(\frac{1}{29.14}\right)^{1/2} = \mathbf{0.185}$$

# Resistivity Index

Mathematically, the resistivity index is expressed as:

$$I_r = \frac{R_t}{R_o} \qquad (9)$$

Ir is the resistivity index [dimensionless],
Rt is the true resistivity of a core sample [Ω.m],
Ro is the resistivity of the core when it is 100% filled with water [Ω.m].

Based on empirical (experimental) observation, the resistivity index is also equal to:

$$I_r = \frac{R_t}{R_o} = S_w^{-n} = \frac{1}{S_w^n} \qquad (10)$$

Sw is the water saturation [dimensionless] and n is the saturation exponent [dimensionless]; the saturation exponent is usually 2.

Now, we can apply the logarithmic rules

$$\log I_r = -n \log S_w \qquad (11)$$

where –n is the slope of the line. Again, n should be positive as the negative sign in the equation is to neutralize the decreasing slope

# Archie's Equation

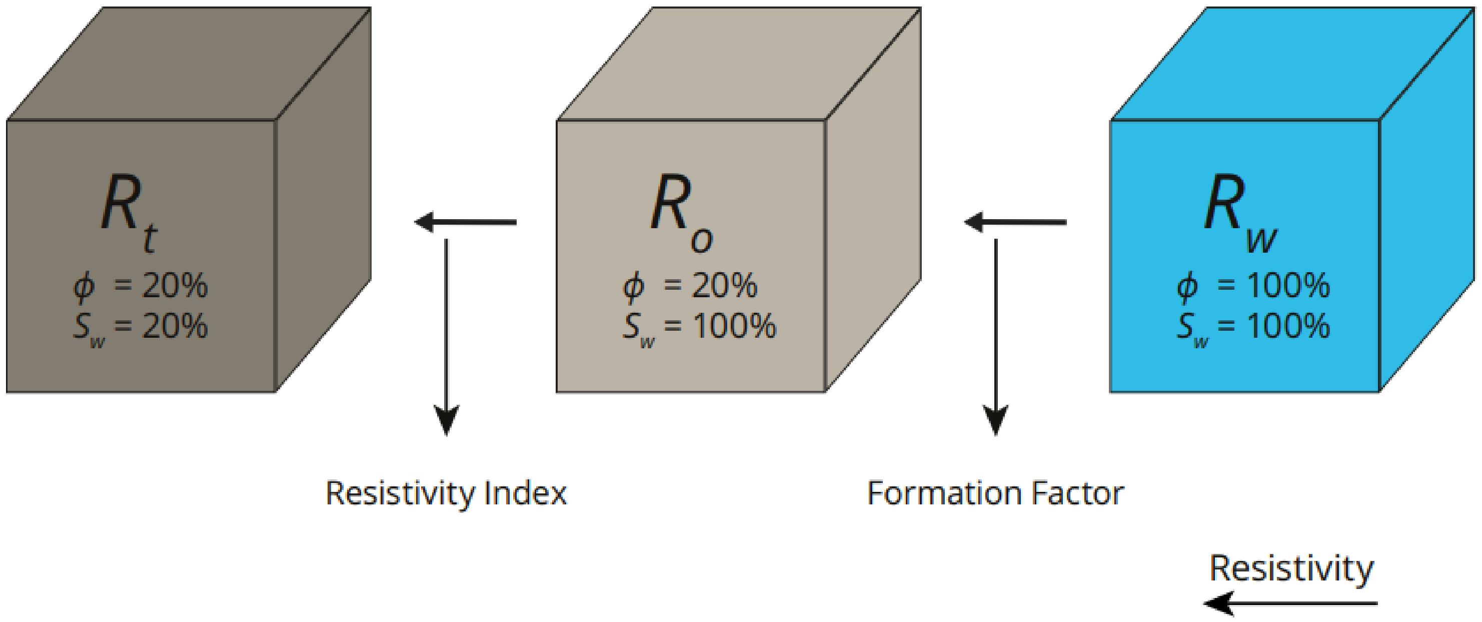
$$R_o = a\phi^{-m} R_w \qquad (12)$$

$$R_t = a\phi^{-m} R_w S_w^{-n} = \frac{aR_w}{\phi^m S_w^n} \qquad (13)$$

$$S_w^n = \frac{aR_w}{\phi^m R_t} \qquad (14)$$

Finally, we can take the nth root of both sides for this equation to obtain

$$S_w = \sqrt[n]{\frac{aR_w}{\phi^m R_t}} \qquad (15)$$




Schematic showing the two components of Archie's law: formation factor and resistivity index. Formation factor is a relationship between Ro and Rw, while resistivity index is a relationship between Rt and Ro. Ro is the common parameter between the two components.

# Example

A cylindrical core, of 2.5 cm in diameter and 5 cm in length, has a porosity of 23%. The retort distillation method was used in order to find the fluid saturation inside the core. Using this method, 3.2 $cm^3$ of water and 1.9 $cm^3$ of oil were extracted from the core.

**a)** What are the fluid saturations in the core?

**b)** If the formation factor is given by $F = 1.09\phi^{-2}$, the resistivity index is given by $I_r = S_w^{-2}$, and the water resistivity is 7.5 Ω.cm, calculate the true resistivity of the core which we would expect to have it measured before fluid extraction.

## Solution

**a)** First, the bulk volume of this core needs to be calculated. Since this is a cylinder:

$$V_b = \pi r^2 L = \pi \times \left(\frac{2.5}{2}\right)^2 \times 5 = 24.54 \text{ cm}^3$$

We now find the pore volume:

$$V_p = \phi V_b = 0.23 \times 24.54 = 5.64 \text{ cm}^3$$

The water saturation can be found using **Equation 5.1**:

$$S_w = \frac{V_w}{V_p} = \frac{3.2}{5.64} = \mathbf{0.567}$$

The oil saturation can be found using **Equation 5.2**:

$$S_o = \frac{V_o}{V_p} = \frac{1.9}{5.64} = \mathbf{0.337}$$

The gas saturation can then be found using **Equation 5.4**:

$$S_w + S_o + S_g = 1$$

$$S_g = 1 - S_w - S_o$$

$$S_g = 1 - 0.567 - 0.337 = \mathbf{0.096}$$

**b)** From the question, the values of *a*, *m*, and *n* are known:

$a = 1.09$, $m = 2$, $n = 2$

Therefore, **Equation 6.13** can be used to find the true resistivity:

$$R_t = \frac{aR_w}{\phi^m S_w^n} = \frac{1.09 \times 7.5}{0.23^2 \times 0.567^2} = \mathbf{480.7\ \Omega.cm}$$

# Refresh

Summary of all the parameters used in Archie's equation. The symbol [–] indicates that the parameter is dimensionless.

| Parameter | Definition | Unit |
|---|---|---|
| $S_w$ | Water saturation | - |
| $\phi$ | Porosity | - |
| $R_w$ | Water resistivity | Ω.m |
| $R_o$ | Rock resistivity when the rock is 100% saturated with water | Ω.m |
| $R_t$ | True resistivity (including hydrocarbons in the rock) | Ω.m |
| $m$ | Cementation exponent (usually 2) | - |
| $n$ | Saturation exponent (usually 2) | - |
| $a$ | Empirical constant (usually 1) | - |

# Example

The following data is given for a core:

Diameter = 2.35 cm
Water resistivity = 48 Ω.cm
Length = 4.1 cm
Current = 0.02 A

| Water Saturation, $S_w$ [%] | Voltage Across Core [V] |
|---|---|
| 100 | 7.83 |
| 86 | 10.64 |
| 76 | 13.71 |
| 63 | 19.95 |
| 55 | 26.86 |
| 49 | 33.98 |

Calculate the formation factor (*F*) and the saturation exponent (*n*) of the core.

## Solution

The cross-sectional area of the core is:

$$A = \pi r^2 = \pi \times \left(\frac{2.35}{2}\right)^2 = 4.34 \ \text{cm}^2$$

When the water saturation, $S_w$, is 100%, the voltage is 7.83 V.

By rearranging **Equation 6.3**, the resistivity $R_o$ can be found when $S_w$ is 100%:

$$\Delta V = \frac{I R_o L}{A}$$

$$R_o = \frac{\Delta V A}{I L} = \frac{7.83 \times 4.34}{0.02 \times 4.1} = 414.4 \ \Omega.\text{cm}$$

The formation factor *F* can be found using **Equation 6.6:**

$$F = \frac{R_o}{R_w} = \frac{414.4}{48} = 8.63$$

Using a rearranged **Equation 6.3**, the true resistivity $R_t$ can be found for each $S_w$ value:

$$R_t = \frac{\Delta V A}{I L}$$

Then, the resistivity index can be measured using **Equation 6.10**. Finally, using the given data, if we plot log $S_w$ against log $I_r$, the negative of the slope of the line of best fit will give the saturation exponent *n* (**Equation 6.11**):

$$\log I_r = -n \log S_w$$

# Example

The following data is given for a core:

Diameter = 2.35 cm    Length = 4.1 cm
Water resistivity = 48 Ω.cm    Current = 0.02 A

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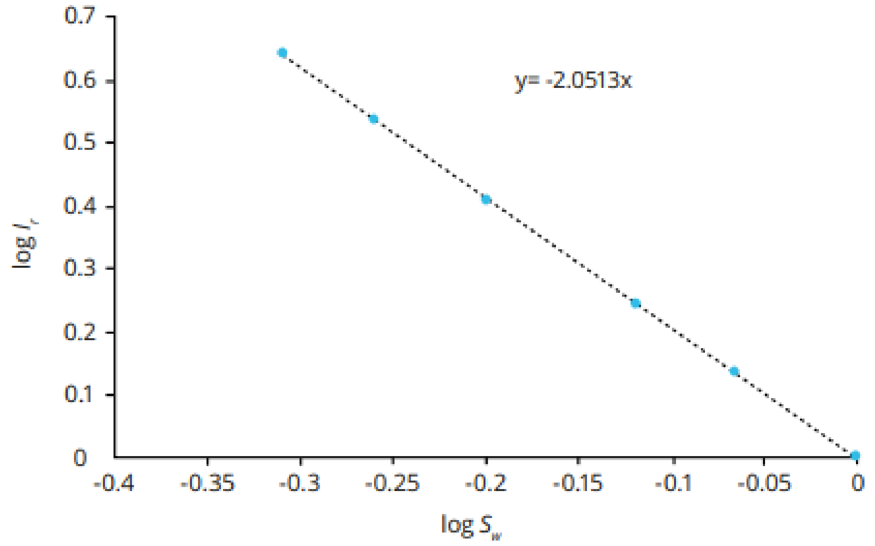
Calculate the formation factor (*F*) and the saturation exponent (*n*) of the core.

The data points are listed in the table below:

| **Water Saturation, $S_w$ [-]** | **log $S_w$** | **True resistivity, $R_t$ [Ω.cm]** | **$I_r$** | **log $I_r$** |
|---|---|---|---|---|
| 1 | 0 | 414.4 | 1 | 0 |
| 0.86 | -0.0655 | 563.1 | 1.359 | 0.133 |
| 0.76 | -0.1192 | 725.6 | 1.751 | 0.243 |
| 0.63 | -0.2007 | 1055.9 | 2.548 | 0.406 |
| 0.55 | -0.2596 | 1421.6 | 3.430 | 0.535 |
| 0.49 | -0.3098 | 1798.5 | 4.340 | 0.637 |

The graph of log $S_w$ against log $I_r$ is plotted below:




The line of best fit has been found using MS Excel, and its slope is -2.0513. Therefore, ***n* ≈ 2.05**. Note that this slope can also be calculated manually by taking any two data points on this plot.

# Example

The following data is given for a core:

| Porosity, $\phi$ [%] | Formation Factor, $F$ |
|---|---|
| 16.5 | 45 |
| 18.1 | 34 |
| 19.4 | 26 |
| 21.0 | 21 |
| 22.3 | 18 |
| 23.2 | 16 |

Calculate the cementation factor (*m*) and empirical constant (*a*) of the core.

## Solution

This question is similar to the previous example. **Equation 6.8** gives us:

$$\log F = \log a - m \log \phi$$

Therefore, using the given data, if we plot log $\phi$ against log *F*, the negative of the slope will give the cementation factor *m*, and the y-intercept will give the log of the empirical constant *a*.

The data points are listed in the table below:

| Porosity, $\phi$ [-] | Formation Factor, $F$ | log $\phi$ | log $F$ |
|---|---|---|---|
| 0.165 | 45 | -0.783 | 1.653 |
| 0.181 | 34 | -0.742 | 1.531 |
| 0.194 | 27 | -0.712 | 1.431 |
| 0.21 | 21 | -0.678 | 1.322 |
| 0.223 | 18 | -0.652 | 1.255 |
| 0.232 | 16 | -0.635 | 1.204 |

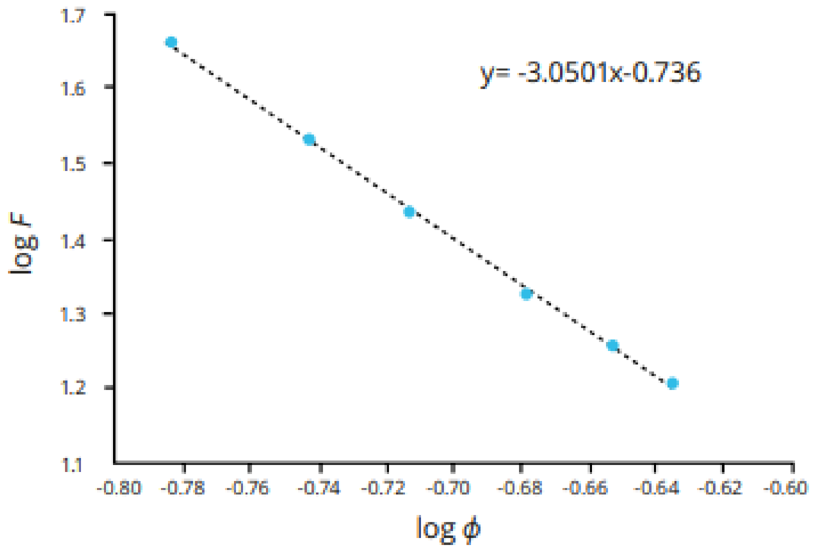
# Example

The following data is given for a core:

| Porosity, $\phi$ [%] | Formation Factor, $F$ |
|---|---|
| 16.5 | 45 |
| 18.1 | 34 |
| 19.4 | 26 |
| 21.0 | 21 |
| 22.3 | 18 |
| 23.2 | 16 |

Calculate the cementation factor ($m$) and empirical constant ($a$) of the core.

The graph of log $\phi$ against log $F$ is plotted below:




The line of best fit has been found using MS Excel, and its slope is -3.0501. Therefore, **m ≈ 3.05**.

Furthermore, the intercept of this line has been found to be -0.736. Since the intercept is log $a$:

$$\log a = -0.736$$

$$a = 10^{-0.736} = \mathbf{0.184}$$

# Factors Affecting Resistivity of Reservoir Rocks

1) The type of fluid in the pore spaces.
2) Porosity of the formation
3) Presence of clays in the rock
4) Degree of cementation

# Factors Affecting Resistivity of Reservoir Rocks

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For instance, water is a better conductor of electricity than oil, and oil is a better conductor than gas. If you examine water by itself, brine is more conductive than fresh water. This is because brine has ions such as Na+, Cl- , and K+ that provide better conductance of electricity. Nevertheless, resistivity is the inverse of conductivity, which means that among all fluids discussed, gas has the highest resistivity, while brine has the lowest.

# Factors Affecting Resistivity of Reservoir Rocks

1) The type of fluid in the pore spaces.
2) Porosity of the formation
3) Presence of clays in the rock
4) Degree of cementation

We can see from Archie's equation that porosity is a factor affecting resistivity. The higher the porosity, the lower the resistivity, as the rock on its own has a higher resistivity than the fluids present in it. By increasing the porosity, we subject the core to contain more fluids, which leads to a reduction in the core's resistivity.

# Factors Affecting Resistivity of Reservoir Rocks

1) The type of fluid in the pore spaces.
2) Porosity of the formation
3) Presence of clays in the rock
4) Degree of cementation

Clays are conductive to electricity due to high water/brine content and thus their presence in the rock increases the electrical conductivity, thus reducing the resistivity

# Factors Affecting Resistivity of Reservoir Rocks

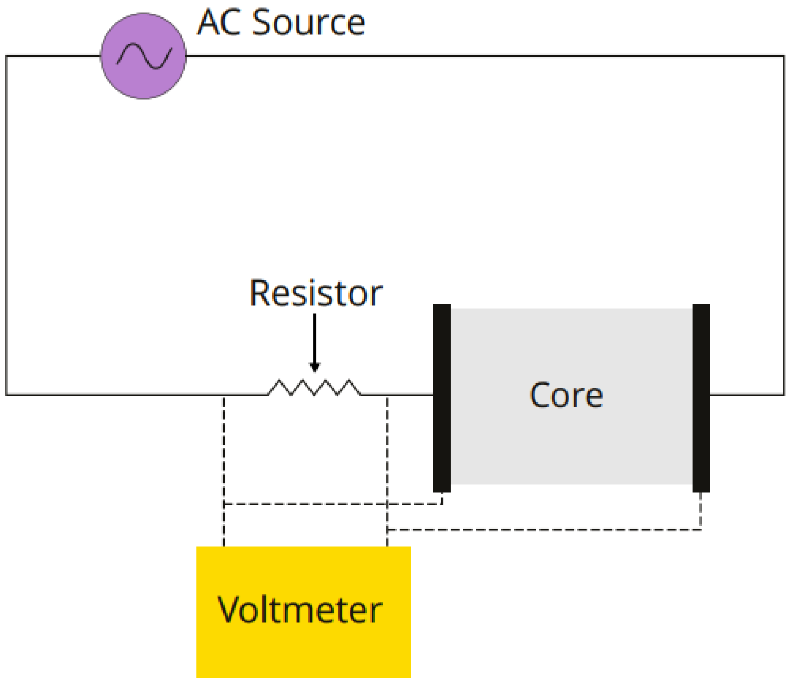
1) The type of fluid in the pore spaces.
2) Porosity of the formation
3) Presence of clays in the rock
4) Degree of cementation

Rocks with higher degree of cementation tend to have lower porosity, which leads to a higher resistivity

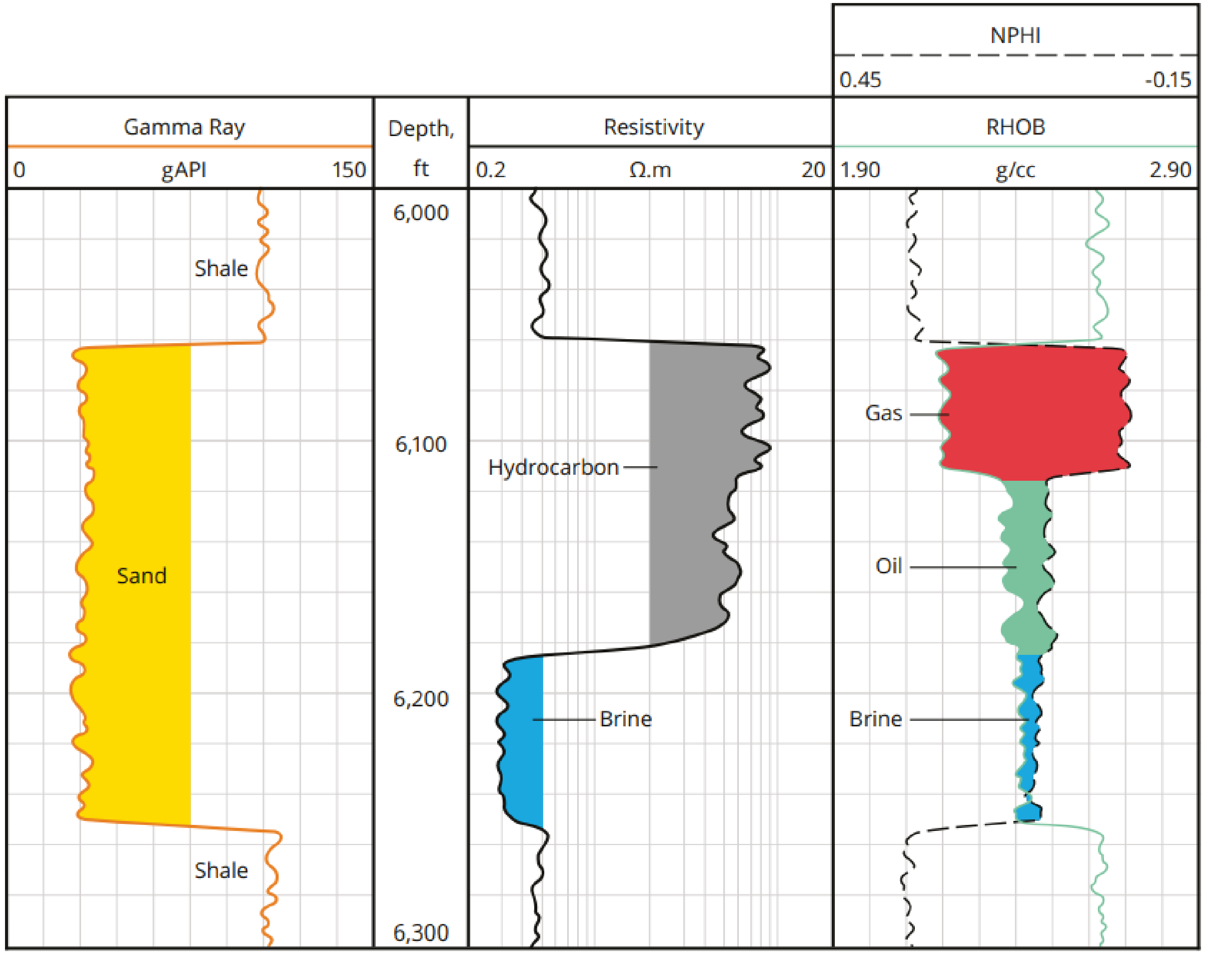
# Measuring Electrical Properties of Reservoir Rocks

## Measuring the formation factor

## Measuring the resistivity index



# Applications of Electrical Properties of Reservoir Rocks




**Schematic showing wireline logging tools with three tracks: (left) gamma ray, (middle) resistivity log, and (right) porosity logs**

- Electrical properties can help us find the water saturation not only in core samples but also in reservoirs by using resistivity wireline logging tools
- The main application of electrical properties is to calibrate the resistivity log in wireline logging
- We divide this log into three tracks: gamma ray, resistivity, and porosity tracks
- The gamma ray track would tell us whether the formation is a shale or reservoir rock. A high gamma ray response indicates the presence of shale, while a low gamma ray response indicates reservoir rock. From this track, we can identify the thickness of the reservoir formation, which in this case is sand.
- The deep resistivity log can distinguish the hydrocarbons from brine. As we can see in the figure, hydrocarbons have high resistivity when compared to brine.
- the density log gives low bulk density readings because the density of gas is low compared to that of oil and water
- the neutron log also gives low readings because gas has lower number of hydrogen atoms when compared to oil.

# Homework

**a)** Several core plugs (diameter 1 in and length 1.5 in) were taken from a given reservoir. Each was cleaned and its porosity was measured using a given gas expansion porosimeter. Then, all were saturated with brine having a resistivity of 7.5 Ω.cm. After that, each core plug was placed in a resistivity apparatus to measure the voltage drop under 0.01 A current. The porosity and voltage drop measured are listed below:

| Sample Number | Porosity, $\phi$ [%] | Voltage Across Core [V] |
|---|---|---|
| 1 | 17.8 | 1.60 |
| 2 | 18.8 | 1.46 |
| 3 | 16.5 | 1.96 |
| 4 | 22.0 | 1.09 |
| 5 | 15.5 | 2.14 |
| 6 | 14.5 | 2.41 |

Calculate $F$ and determine the parameters $a$ and $m$.