Water Saturation Calculation Using Neutron Log - Study Case on Well in Tanjung Field, South Kalimantan

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Abstract. Water saturation (Sw) calculation based on data logging has been used since the 1940s where the basic formula is based on the resistivity log (resistivity log was run for the first time in Pechelbron field in France by Conrad and Marcel Schlumberger). The simplest formula for water saturation calculation was proposed by Archie (BSc in Mining and Electrical Engineering University of Wisconsin) in 1942 who assumes lithology of calculation on clastic, clean sandstone (does not have or nearly zero clay content). Over time, several formulas were proposed for improvement where the presence of clay content is taking into account. Furthermore the formula develops by taking into account how clay exist which can be structural, laminated, and dispersed.

In principle, water saturation formulas which are developed are based on formulas proposed by Archie. Even though Archie equation is simple, implementing the water saturation calculation requires parameters input obtained in laboratory measurements such as formation water resistivity (Rw), rock cementation value (m), saturation value (n), and rock tortuosity value (a) constant. Determination of the value of the Archie input parameter is critical for best estimation a water saturation value.

In practices due to time or budget constraint, water saturation calculation sometime does not use data (Rw, m, n, a) from the laboratory measurement. Petrophysicist, has an option and tend to use Rw based on calculations or estimation but not from laboratory, one of which by pickett plot. Pickett plot method was proposed by a mathematician named Dick Pickett in 1966 (SPE). Values of m, n, and a in many occasion uses a database value that is common, for example as m = 2, n = 2, and a = 1 for sandstone reservoir.

On this writing, the authors propose a simpler method or approach compare to Archie method which uses a resistivity log to calculate water saturation values. The alternative method of this writing proposed is to calculate water saturation value using a neutron log.

In oil and gas industry, neutron log is often used as qualitative data together with a density log. These two logs are often seen as the value of the crossover where the higher the separation value the more it indicates the gas hydrocarbons, and less separation value indicates the oil hydrocarbons. If there is no separation value or even inverted crossover value of the density neutron log, it may indicates the presence of water.

Starting from this basic idea, the writer tries to develop it further, so that the neutron log can be used quantitatively to calculate water saturation estimate. An examples of the water saturation calculation using log neutrons will be applied to the Tanjung field (South Kalimantan), where the average water cut of oil production has been increase up to 94% recently. The value of calculated water saturation using neutron log method will be compared to water saturation using resistivity method (Indonesian Equation). As validation for water saturation calculation, water cut production will be used for the well.

By using this new method, petrophysicist is expected to calculate the value of water saturation easily without having to do or wait a laboratory analysis result of water samples and rock samples. Of course, determining water saturation value using the density log does not make the determination of water saturation using the resistivity log incorrect, but instead an alternative or as a comparison of one method with another. Also, the result of Sw calculation using neutron log does not mean to make Archie formula wrong, but for comparison or second opinion purpose.

Keyword: Petrophysics, Archie, Water Saturation, Neutron Log

1 Introduction

Tanjung field location is ± 240 km northeast of Banjarmasin city, in Tabalong district, South Kalimantan. Tanjung Field was discovered in 1898 with the successful drilling of the exploration well T-001 by the Dutch company "Mijnbouw Maatschappij Martapoera".
Until 2020, there were 188 wells drilled in the Tanjung structure, where in 2019 5 wells had been drilled. PT Pertamina EP, with the spirit of increasing national oil production, has an agenda to see the possibility of a tertiary phase by conducting several pilots first.

A thorough evaluation is needed for the success of an old field advanced development program such as the Tanjung structure. One approach or the approximate distribution of oil saturation needs to be considered using several methods. By using several methods, it is hoped that it can provide an estimate that is closer to the actual situation or condition of the Tanjung field which has been in production for approximately 80 years.

2 Methodology

2.1 Basic Idea of Formula

The basic formula for calculating water saturation is as follows:

$$S_w = \left(\frac{R_o}{R_t}\right)^{1/n}$$

Where:
Sw : water saturation value
Ro : the resistivity value of the rock with 100% water filling
Rt : log resistivity reading value
n : Archi parameter for rock cementation values

Some of the drawbacks of Archie's calculations are as follows:
- Applies or can be used on clean sandstones
- Requires the Rw parameter, the value of which is obtained from measurements in the laboratory using a sample of formation water
- Requires parameters m, n, and a whose values are obtained from measurements in the laboratory using a rock sample (core).

The calculation of the saturation value using the neutron log is obtained from the basic equation as follows:

$$Net_1 = \emptyset . Net_f + (1 - \emptyset)[\{(1 - V_s) . Net_m\} + \{V_s . Net_s\}]$$

Where:
Net_1 : neutron value with Sw = 1
Φ : rock porosity value
Net_f : fluid neutron value
Net_s : neutron shale value
Net_m : the neutron value of the matrix
V_s : volume value of shale / clay

If we want to calculate the neutron value with Sw = 0, it can be calculated as follows:

$$Net_0 = (1 - \emptyset)[\{(1 - V_s) . Net_m\} + \{V_s . Net_s\}]$$

Where:
Net_0 : neutron value with Sw = 0

From this basic equation, the formula for water saturation can be derived, namely the ratio of the value of the neutron reading of the rock log to the neutron value of a rock filled with 100% water, as shown below:

$$S_w = \frac{Net_l - Net_0}{Net_1 - Net_0}$$

Where:
Sw is the water saturation value
Net_l is the log reading rock neutron value
Net_1 is the neutron value of a rock filled with 100% water

Net_0 is the neutron value of a rock with 0% water content

Below is the prediction value of neutron value as reference for some major lithology.

Table 15.1 Hydrogen index calculations for some reservoir minerals and fluids.

Compound	Formula	A_i	n_i	n_H	ρ_b	HI
Pure water	H_2O	16	1	2	1.000	1.000
Oil	$(CH_2)_x$	12	1	2	0.780	1.003
Methane	CH_4	12	1	4	ρ_m	$2.25\times\rho_m$
Gas	$C_{1.1}H_{4.2}$	12	1.1	4.2	ρ_g	$2.17\times\rho_g$
Quartz	SiO_2	28, 16	1, 2	0	2.654	0.000
Calcite	$CaCO_3$	40, 12, 16	1, 1, 3	0	2.710	0.000
Gypsum	$CaSO_4.2H_2O$	40, 32, 16	1, 1, 6	4	2.320	0.4855

(Dr. Paul Glover, Petrophysics Msc Course Note)

Component	ϕ_N
Water, fresh	1
Water, 200 000 ppm NaCl	0.9
Oil, average	0.96 … 1.02
Gas, average, 15 °C, 0.1 MPa	0.0017
Gas, average, 93 °C, 48 MPa	0.54
Calcite	0
Dolomite	0.01 … 0.02
Quartz	– 0.02
Gypsum	0.49
Shale, average	0.2 … 0.4

Table 4-10: Neutron response of some rock components, expressed as neutron porosity ϕ_N (after Baker Atlas 2002; Schlumberger 2000; Fricke and Schön, 1999).

Table: Neutron value for some major lithology

2.2 Data For Calculation

For calculation we take well that was just drilled in the Tanjung field, namely the TX-5 borehole which was drilled in 2019 with a final drill depth of 1151.5 MD meters. The well was drilled using a water base mud with a maximum temperature measurement of 62.2 degC.

The log acquisition measured is the quad combo log (Gamma ray, Resistivity, Neutron Density, and Sonic). Petrophysical analysis was carried out at depth intervals of 860 - 1151.7 meters.
Below is a triple combo data plot and petrophysical calculation prior to Sw Calculation.

NO	Point	Litology	Interval (m)	Zona	Logging Reading				
					GR	Resistivity (Deep)	Density	Neutron	Sonic
					API	Ohm.m	gr/cc	pu	us/ft
1	932	Sandstone	921-934	C	33,46	27,08	2,18	0,23	99,8
2	944	Shale	-	-	125,2	5,46	2,48	0,32	101,8
3	1042	Conglomerate	1042 - 1051	A	128,1	10,81	2,36	0,19	83,05

Table: Well data of well TX-5

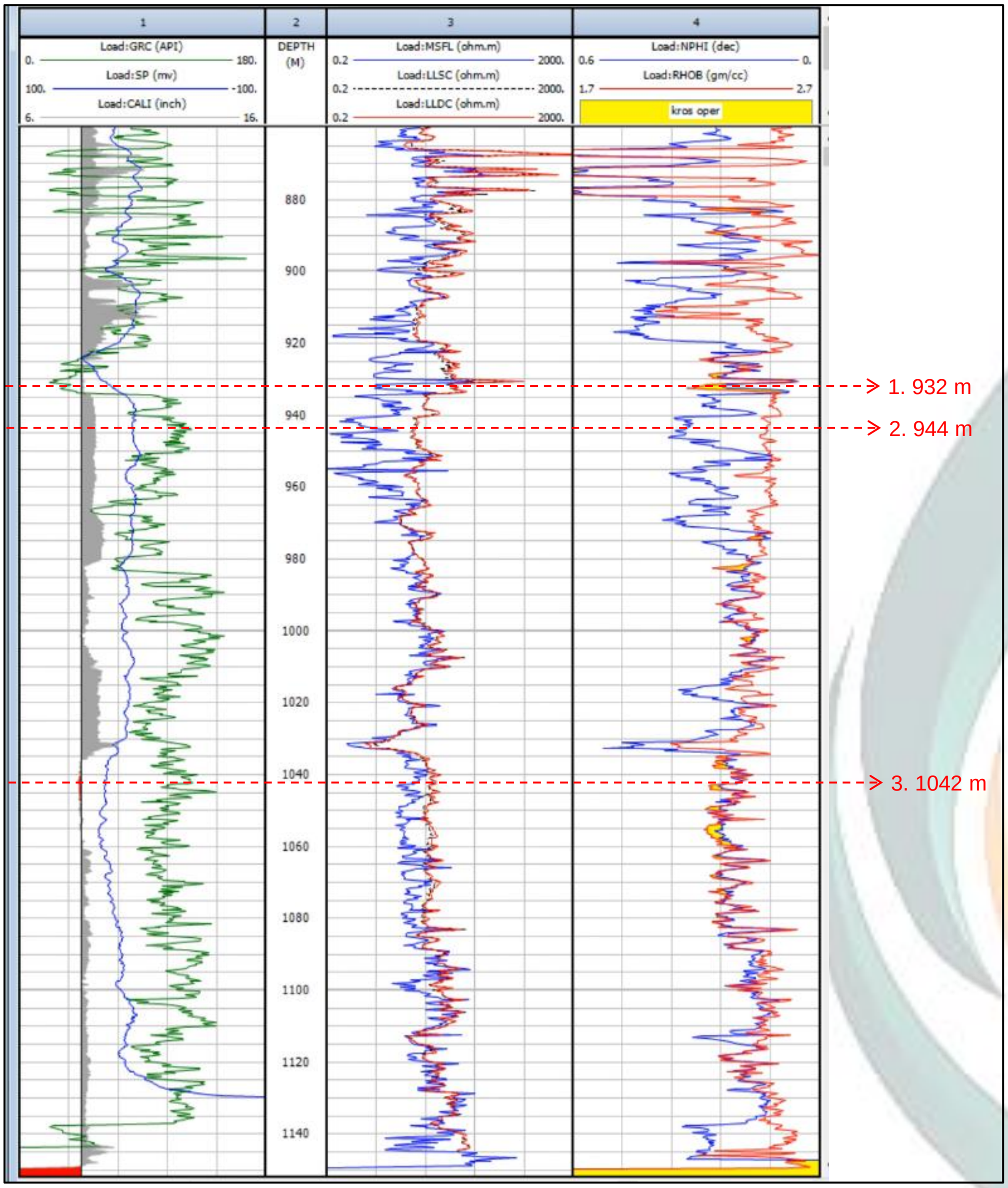

Figure: Data logging for Triple Combo Plot Well TX-5

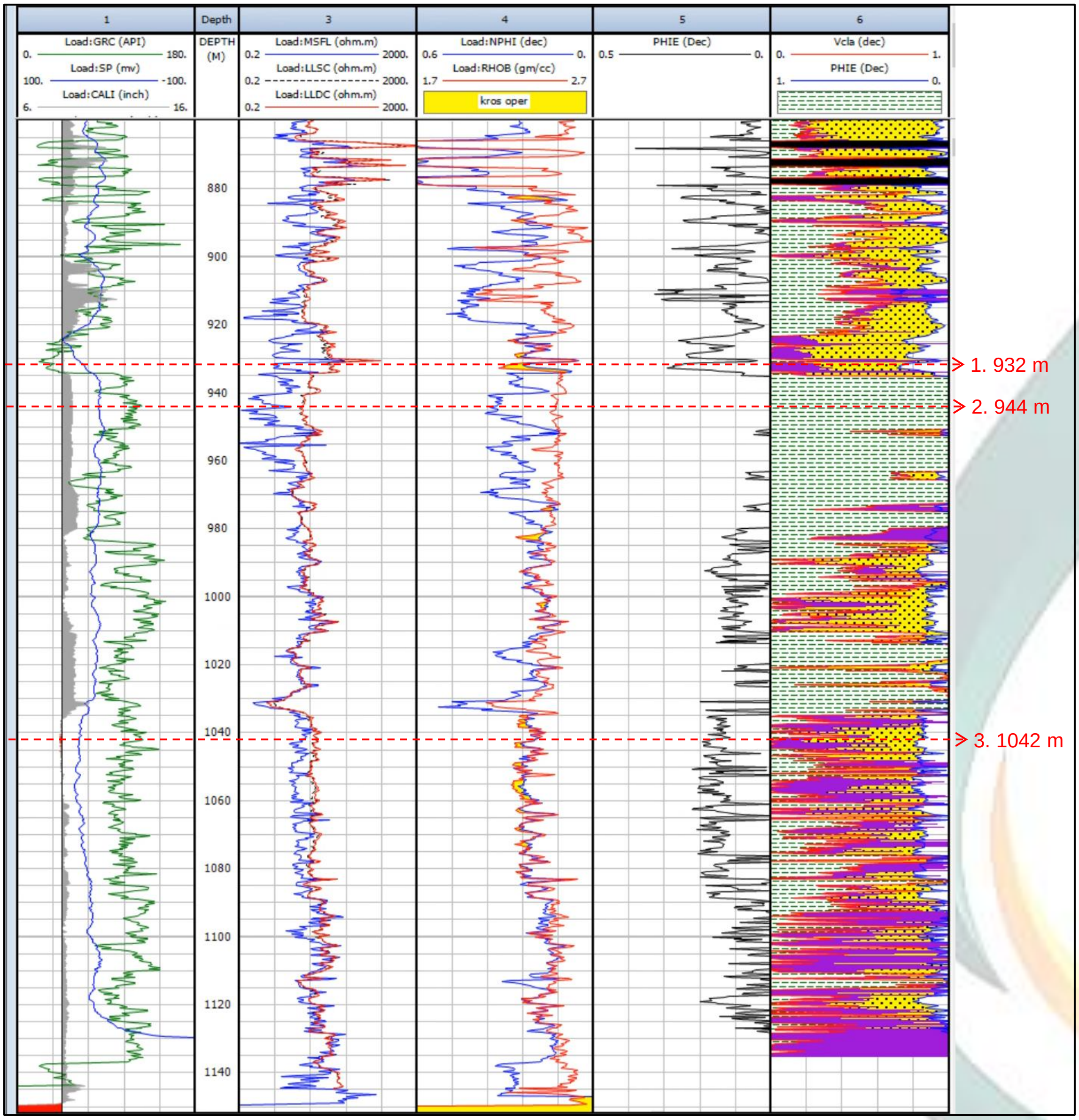

Figure: Petrophysical Calculation TX-5 prior Sw Calculation

Our calculation takes one of the less porous zones, which is at the depth interval of 1042 - 1051 m. At this depth, the mudlog data shows lithology with a dominant conglomerate with alternating between sandstone and claystone. Due to the presence of conglomerates, sandstones and claystones, we need to calculate the percentage of the presence of these lithological volumes. In the interactive petrophysic application, you can choose the multi mineral option so that the three lithological compositions can be calculated using a combination of density log and sonic log. In Interactive Petrophysic (IP) applications it can be solved with the help of the density versus sonic crossplot. For the use of log data, PEF (photo electric factor) cannot be used for the determination of the third volume of lithology.

The third volume of lithology is used to calculate the porosity value using the combined density grain input (porosity calculation in this paper uses the density method). Because it uses a multi-mineral method, so the author does not use the clay volume value using another method.

For information, in this zone conglomerate lithology contains k-feldspar minerals, where this mineral contains radioactive properties which make gamma ray log readings unable to distinguish which rocks are porous (little or no clay) and which rocks are not porous (contain lots of clay). Therefore, calculating clay volume using the log gamma ray method does not produce a valid value for the example case here. As a guide and quality control from calculating clay volume using multi-mineral, the author also calculates clay volume using the log self-potential (SP) method.

$$V_{shale} = \frac{SP_{clean} - SP_{log}}{SP_{clean} - SP_{shale}}$$

The following is the formula for calculating the clay volume using the SP log:

Calculation of water saturation using the Simandoux formula (derived from Archie's formulation for non-clean clastic reservoirs) obtained a water saturation value with a value that is quite optimistic / over estimate.

The following is the formula for calculating water saturation using the Simandoux formula:

$$\frac{1}{Rt} = \frac{\phi^m \times Sw^n}{a \times Rw} + \frac{Vcl \times Sw}{Rcl}$$

Then by using the Indonesian equation (Poupon-Leveaux) with a formula similar to the Simandoux equation it can be displayed as follows:

$$\boxed{\frac{1}{Rt} = \left(\frac{V_{cl}^{\left(1-\frac{V_{cl}}{2}\right)}}{\sqrt{R_{cl}}} + \frac{\phi_e}{\sqrt{R_w}}\right)^2 S_w^{\,2}}$$

So that:

$$S_w = \sqrt{\frac{1}{R_t}\left(\frac{V_{cl}^{\,1-\frac{V_{cl}}{2}}}{\sqrt{R_{cl}}} + \frac{\emptyset_e}{\sqrt{R_w}}\right)^{-2}}$$

2.2.1 Let's do calculation for Saturation water value using proposed neutron log formula as follow:

1. Calculation of the neutron value of the rock matrix with 100% filled with water (Net) for a depth of 932m by entering the neutron matrix value of -0.02, neutron shale 0.26, neutron fluid 1, then we can calculate the total neutron value of the rock filled with 100% water as follows:

$$Net_1 = \emptyset . Net_f + (1-\emptyset)[\{(1-V_s).Net_m\} + \{V_s.Net_s\}]$$

$$Net_1 = 0{,}274.1 + (1-0{,}274)[\{(1-0).-0{,}02\} + \{0.0{,}26\}]$$
$$Net_1 = 0{,}274 + 0{,}736[\{-0{,}02\} + \{0\}]$$
$$Net_1 = 0{,}274 + 0{,}736[-0{,}02]$$
$$Net_1 = 0{,}274 - 0{,}01472$$
$$Net_1 = 0{,}25928$$

Then, the total neutron value of the rock is filled with 0% water as follows:

$$Net_o = \emptyset . Net_f + (1-\emptyset)[\{(1-V_s).Net_m\} + \{V_s.Net_s\}]$$

$$Net_o = (1-0{,}274)[\{(1-0).-0{,}02\} + \{0.0{,}26\}]$$
$$Net_o = 0{,}736[\{-0{,}02\} + \{0\}]$$
$$Net_o = 0{,}736[-0{,}02]$$
$$Net_o = -0{,}01472$$

Then we calculate the water saturation value with the formula previously described as follows:

$$S_w = \frac{Net_l - Net_0}{Net_1 - Net_0}$$
$$S_w = \frac{0{,}23 + 0{,}01472}{0{,}25928 + 0{,}01472}$$
$$S_w = \frac{0{,}24472}{0{,}274}$$
$$S_w = 0{,}893139$$

2. For the 944m depth point by entering the neutron matrix value of -0.02, neutron shale 0.26, neutron fluid 1, then we can calculate the total neutron value of the rock filled with 100% water as follows:

$$Net_1 = \emptyset.Net_f + (1-\emptyset)[\{(1-V_s).Net_m\} + \{V_s.Net_s\}]$$
$$Net_1 = 0{,}0001.1 + (1-0{,}0001)[\{(1-0{,}99).-0{,}02\} + \{0{,}99.0{,}26\}]$$
$$Net_1 = 0{,}0001 + 0{,}9999[\{-0{,}0002\} + \{0{,}2574\}]$$
$$Net_1 = 0{,}0001 + 0{,}9999[0{,}2572]$$
$$Net_1 = 0{,}0001 + 0{,}257174$$
$$Net_1 = 0{,}257274$$

Then, the total neutron value of the rock is filled with 0% water as follows:

$$Net_o = \emptyset.Net_f + (1-\emptyset)[\{(1-V_s).Net_m\} + \{V_s.Net_s\}]$$
$$Net_o = 0{,}0001.0 + (1-0{,}0001)[\{(1-0{,}99).-0{,}02\} + \{0{,}99.0{,}26\}]$$
$$Net_o = 0 + 0{,}9999[\{-0{,}0002\} + \{0{,}2574\}]$$
$$Net_o = 0{,}9999[0{,}2572]$$
$$Net_o = 0{,}257174$$

Then we calculate the water saturation value with the formula previously described as follows:

$$S_w = \frac{Net_l - Net_0}{Net_1 - Net_0}$$
$$S_w = \frac{0{,}32 - 0{,}257174}{0{,}257274 - 0{,}257174}$$
$$S_w = \frac{0{,}062826}{0{,}0001}$$
$$S_w = 628{,}26$$

3. Calculations at a depth of 1042m, by entering the neutron matrix value of 0.23, neutron shale 0.26, neutron fluid 1, then we can calculate the total neutron value of the rock filled with 100% water as follows:

$$Net_1 = \emptyset.Net_f + (1-\emptyset)[\{(1-V_s).Net_m\} + \{V_s.Net_s\}]$$
$$Net_1 = 0{,}13.1 + (1-0{,}13)[\{(1-0{,}07).0{,}10\} + \{0{,}07.0{,}26\}]$$
$$Net_1 = 0{,}13 + 0{,}87[\{(0{,}93).0{,}10\} + \{0.0182\}]$$
$$Net_1 = 0{,}13 + 0{,}87[\{0{,}093\} + \{0{,}021\}]$$

$$Net_1 = 0{,}13 + 0{,}87[0{,}114]$$
$$Net_1 = 0{,}13 + 0{,}09918$$
$$Net_1 = 0{,}22918$$

Then, the total neutron value of the rock is filled with 0% water as follows:

$$Net_o = (1 - \emptyset)[\{(1 - V_s).Net_m\} + \{V_s.Net_s\}]$$
$$Net_o = (1 - 0{,}13)[\{(1 - 0{,}07).0{,}10\} + \{0{,}07.0{,}26\}]$$
$$Net_o = 0{,}87[\{(0{,}93).0{,}10\} + \{0.0182\}]$$
$$Net_o = 0{,}87[\{0{,}093\} + \{0{,}021\}]$$
$$Net_o = 0{,}87[0{,}114]$$
$$Net_o = 0{,}09918$$

Then we calculate the water saturation value with the formula previously described as follows:

$$S_w = \frac{Net_l - Net_0}{Net_1 - Net_0}$$
$$S_w = \frac{0{,}19 - 0{,}09918}{0{,}22918 - 0{,}09918}$$
$$S_w = \frac{0{,}09082}{0{,}13}$$
$$S_w = 0{,}698615$$

2.2.2 Lets do calculation for Saturation water value as comparison using Archie base formula as follow:

1. Calculation of Water Saturation for a depth of 932 m using the Indonesian Equation is described as follows:

$$S_w = \sqrt{\frac{1}{R_t}\left(\frac{V_{cl}^{1-\frac{V_{cl}}{2}}}{\sqrt{R_{cl}}} + \frac{\emptyset_e}{\sqrt{R_w}}\right)^{-2}}$$

$$S_w = \sqrt{\frac{1}{27{,}08}\left(\frac{0^{1-\frac{0}{2}}}{\sqrt{6{,}2}} + \frac{0{,}2751}{\sqrt{0{,}3599}}\right)^{-2}}$$

$$S_w = \sqrt{0{,}0369\left(\frac{0}{\sqrt{6{,}2}} + \frac{0{,}2751}{\sqrt{0{,}3599}}\right)^{-2}}$$

$$S_w = \sqrt{0{,}0369\left(0 + \frac{0{,}2751}{0{,}5999}\right)^{-2}}$$

$$S_w = \sqrt{0{,}0369(0 + 0{,}4585)^{-2}}$$

$$S_w = \sqrt{0{,}0369.4{,}7555}$$

$$S_w = \sqrt{0{,}175611}$$

$$S_w = 0{,}41906$$

2. Calculation of Water Saturation for a depth of 944 m using the Indonesian Equation is described as follows:

$$S_w = \sqrt{\frac{1}{R_t}\left(\frac{{V_{cl}}^{1-\frac{V_{cl}}{2}}}{\sqrt{R_{cl}}} + \frac{\emptyset_e}{\sqrt{R_w}}\right)^{-2}}$$

$$S_w = \sqrt{\frac{1}{5{,}46}\left(\frac{1^{1-\frac{1}{2}}}{\sqrt{6{,}2}} + \frac{0}{\sqrt{0{,}3583}}\right)^{-2}}$$

$$S_w = \sqrt{0{,}18315\left(\frac{1}{\sqrt{6{,}2}} + 0\right)^{-2}}$$

$$S_w = \sqrt{0{,}18315\left(\frac{1}{2{,}48998}\right)^{-2}}$$

$$S_w = \sqrt{0{,}18315(0{,}40161)^{-2}}$$

$$S_w = \sqrt{0{,}18315.6{,}2}$$

$$S_w = \sqrt{1{,}135531}$$

$$S_w = 1{,}065613$$

3. Calculation of Water Saturation depth of 1042 m using the Indonesian Equation is described as follows:

$$S_w = \sqrt{\frac{1}{R_t}\left(\frac{V_{cl}^{1-\frac{V_{cl}}{2}}}{\sqrt{R_{cl}}} + \frac{\emptyset_e}{\sqrt{R_w}}\right)^{-2}}$$

$$S_w = \sqrt{\frac{1}{10{,}81}\left(\frac{0{,}07^{1-\frac{0{,}07}{2}}}{\sqrt{6{,}2}} + \frac{0{,}1357}{\sqrt{0{,}3462}}\right)^{-2}}$$

$$S_w = \sqrt{0{,}092507\left(\frac{0{,}07^{0{,}965}}{\sqrt{6{,}2}} + \frac{0{,}1357}{0{,}58838}\right)^{-2}}$$

$$S_w = \sqrt{0{,}092507\left(\frac{0{,}076828}{2{,}48998} + 0{,}23063\right)^{-2}}$$

$$S_w = \sqrt{0{,}092507(0{,}030855 + 0{,}23063)^{-2}}$$

$$S_w = \sqrt{0{,}092507(0{,}261485)^{-2}}$$

$$S_w = \sqrt{0{,}092507.14.62534}$$

$$S_w = \sqrt{1{,}352945}$$

$$S_w = 1{,}163$$

3 Result and Discussion of Calculation

Here, after the author calculates the water saturation using the new method, we gets a more appropriate water saturation value. The table summarize calculation with comparison to IP software result.

NO	Point	Litology	Interval (m)	Zona	Petrophysical Calculation						
					Rw at25degC	Rw atDepth	Rclay	Vclay	Phie	Sw (Indonesian)	Sw (Netron)
					Ohm.m	Ohm.m	Ohm.m	m3/m3	%	%	%
1	932	Sandstone	921-934	C	0,6	0,3599	6,2	0	27,51	41,90	89,31
2	944	Shale	-	-	0,6	0,3583	6,2	0,99	0,0001	100	100
3	1042	Conglomerate	1042 - 1051	A	0,6	0,3461	6,2	0,07	13,57	39,91	69,86

Table: Well Petrophysical Calculation of well TX-5

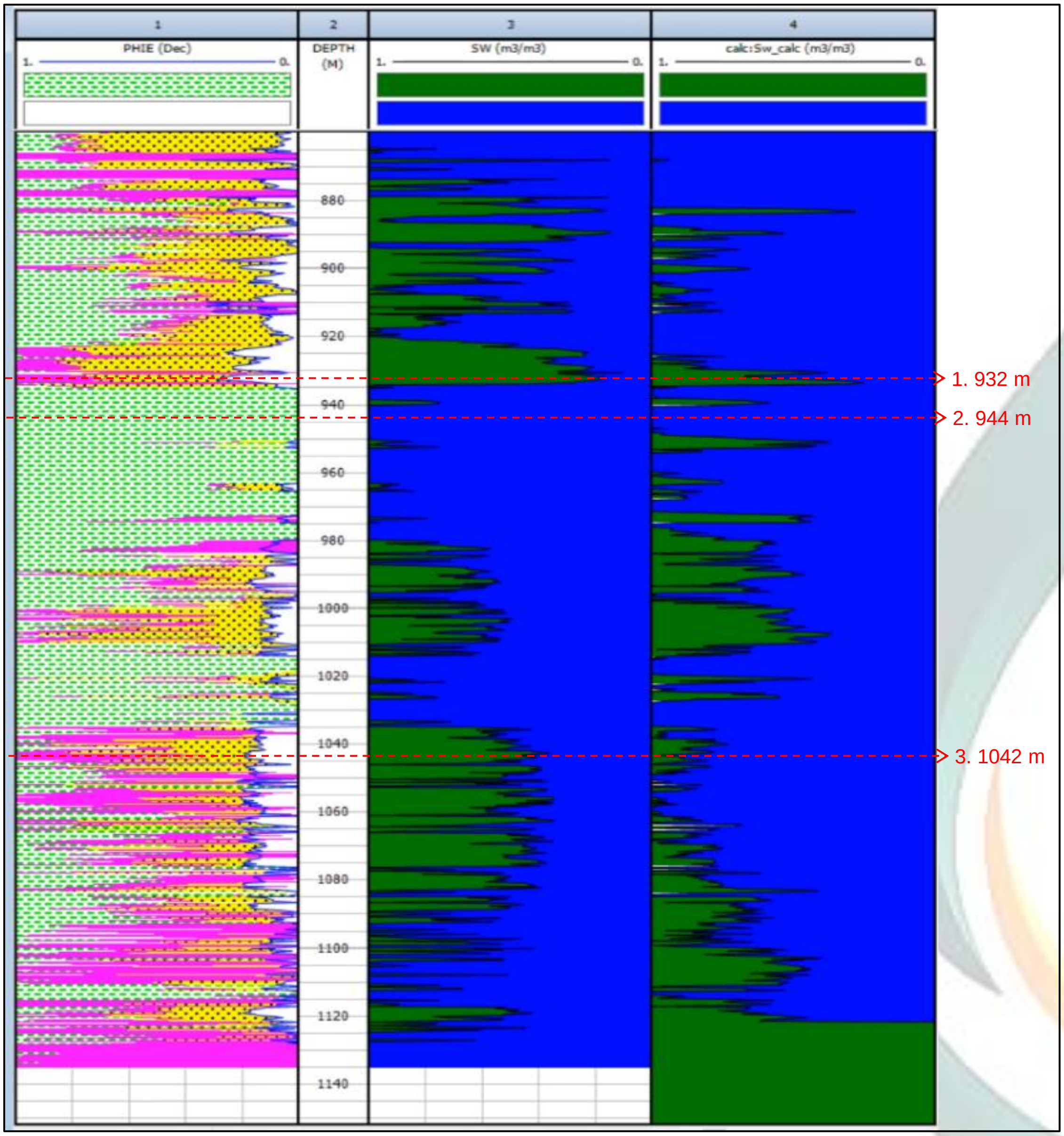

Figure: Plot of Comparison of Water Saturation Values Using the Resistivity Log Method Using Neutron Logs

For validation of the water saturation calculations for well TX-5, we see the well production results at this interval. The oil production in this well from the initial production was 82 blpd / 18 bopd with an average water cut of 78% (data on February 14, 2020).

Based on the actual production data of TX-5 after completion, the well produced oil with water cut as predicted by water saturation. Below is the production profile of TX-5 after well completion.

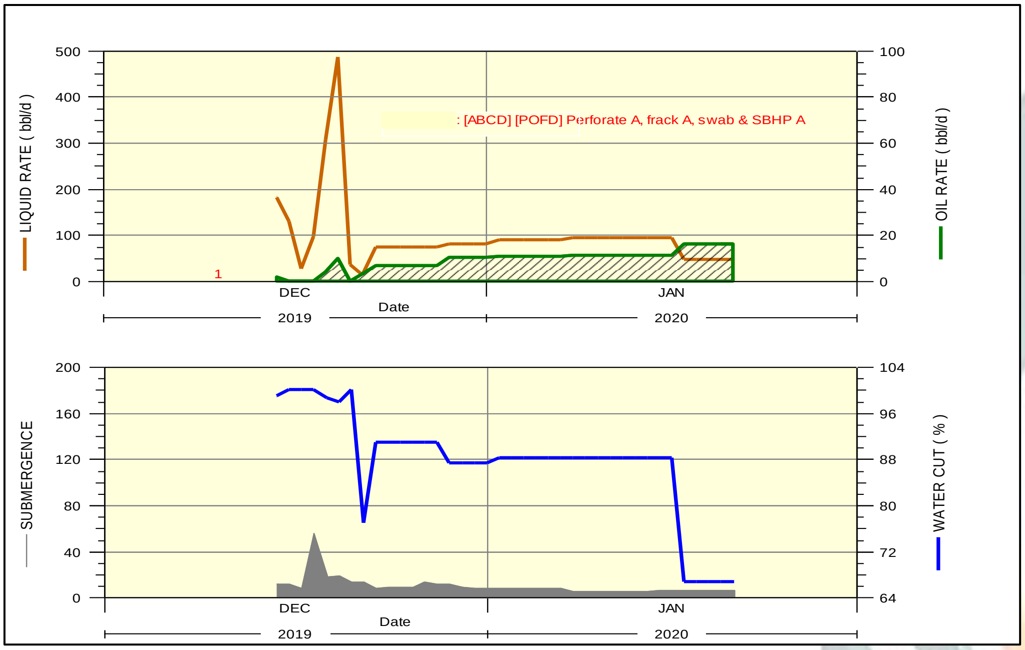

Figure: TX-5 Well Initial Production Profile in Zone A

4 Conclusion

At a depth of 932m with clean sandstone lithology, the result of the calculation of Sw value is not much different between the method using the resistivity log and the log neutron. Calculations using log neutrons tend to give a more pessimistic Sw value. Calculations on claystone lithology at a depth of 944m where the effective porosity value is zero, the method using the resistivity log gives the same value as the method using the log neutron. Calculations on conglomerate / sandstone lithology at a depth of 1042m, the method using the resistivity log gives a more optimistic / small Sw value. From the calculation at a depth of 1042m, the Sw calculation gives a value closer to the actual production water cut value.

Using the neutron log method has the following advantages:
- Can be used on almost all types of rock
- Not required to use data from laboratory analysis results
- Can be used in areas that have rock character with low resistivity
- Using a simple formula without requiring temperature data
- As an alternative to calculating Sw or as a comparison of Archie's formula and its derivatives

After this writing, author suggest for:

- Calculation of water saturation using the neutron log can be done by entering the cementation factor of the rock (m).
- Water saturation calculation method using the neutron log can be developed so as to produce a more accurate calculation value.

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