# E07 • Pulsed Neutron Logging

## E07.1 • Basic principle of the Pulsed Neutron Logging (PNL) measurement.

The PNL measurement involves bombarding the formation with a high density flux of fast, high energy neutrons. Whenever any of these neutrons interacts with heavy formation atoms, it bounces back without much loss in energy. Whenever the interaction is with a light atom like hydrogen, however, there is a significant energy loss at each interaction. This means that the neutrons will gradually lose energy until they reach 'thermal' velocities, at which they are likely to be 'captured' by elements having the appropriate 'capture cross-section' (parameter $\Sigma$ in PNL log analysis). Thermal neutron capture is accompanied by emission of gamma rays, and the PNL measurement is a measurement of the decay of the population of capture gamma rays as a function of time, in the region investigated by PNL tools (typically, 8 to 10 inches of depth from the borehole wall).

The capture gamma ray 'decay time', $\tau$, is modelled differently with different PNL tools. The ultimate objective is to derive the most accurate $\tau$ possible. $\tau$ is related to the formation capture cross-section, $\Sigma$, by the equation:

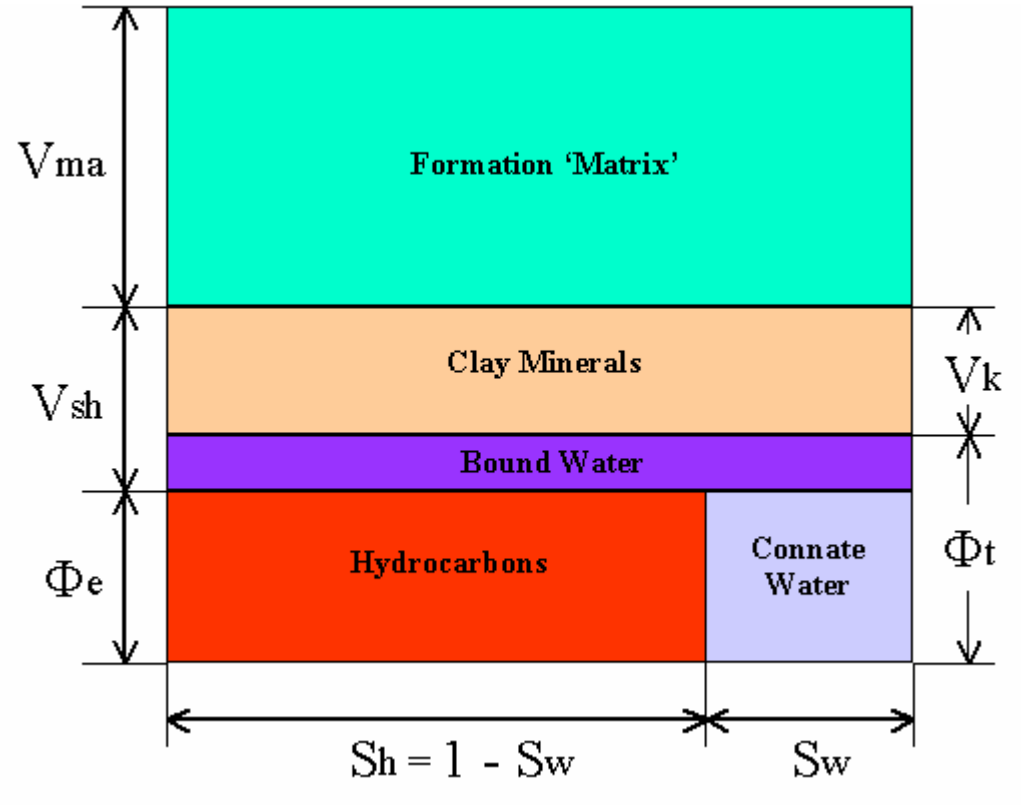
$$\tau \text{ (msec)} = 4.545 / \Sigma \text{ (c.u.)}$$

The main objective of PNL logging resides in the determination of the water saturation in the formation, Sw. Sw is determined at the initial stage by open hole logging, but it changes continuously during the production stage because of the removal of oil and its replacement in the porous system by water, mostly by encroachment from the aquifer. It is important to monitor these changes in saturation along the producing life of oil and gas reservoirs, because such changes govern the economics of the reservoir.

The interpretation principle of PNL logging rests essentially on the fact that chlorine (Cl) has a high capture cross-section, compared to other elements like Si, Ca, C, O, H, and possibly others, which are relatively more abundant than Cl in the bulk volume. Hence a measurement of the formation capture cross-section will be directly related to the bulk volume of chlorine in the formation, which in turn is related to the water saturation (because the salinity of the water results from its dissolved chlorine content). This is of course contingent to the water salinity being not only known, but also high enough to provide an appropriate resolution to the measurement. A typical requirement is that the formation water salinity must be (barring exceptions) in the range of 30000 ppm Cl or higher, for the PNL measurement to be worthwhile in practical field engineering applications.

Until the early 1990's, traditional PNL logging was carried out with tools designed solely around the thermal neutron capture physics. Because of the manifold petrophysical applications of neutron logging, modern tools are no longer limited to capture logging, but also address neutron slowing-down applications (porosity determination and gas identification), inelastic interaction applications (lithology and saturation determination), oxygen activation (for production logging), and other applications.

## E07.2 • Volumetrics and definition of parameters.




The above figure describes the partitioning of the total formation volume into its basic constituents as follows:

- Vma is the volume of non-clayey solids (e.g. quartz, limestone etc…), often called 'matrix'. Silt (fine particles of sand-type mineralogy) is usually included into the 'matrix' fraction, but appropriate 'shaly sand' models can differentiate between the silt and the rock fractions.
- Vsh is the volume of shale, itself made up of clay minerals (Vk) and 'bound water'.
- Φe is the effective (or interconnected) porosity. Φe is made up of the 'free' water fraction, Sw, and the hydrocarbon fraction, Sh. The total porosity Φt is the sum of the effective porosity and of the bound water fraction.

All these volumes are commonly expressed in percentages (e.g. Φe is 25%), but whenever they are considered as parameters into equations, they must be entered in decimal fractions.
The measurement of the formation capture cross-section, called Σf, is a linear measurement. This means that each constituent of the formation bulk volume contributes to Σf in proportion to its volumetric fraction, and to its specific capture cross-section.

For example, in the most simple models, the bulk volume would be made up of fluid (fraction Φe) and matrix (fraction 1 - Φe). The formation Σ, Σf, would then be

$\Sigma f = \Phi e * \Sigma fl + (1 - \Phi e) * \Sigma ma$ (Eq. 1)

in which

| | |
|---|---|
| $\Sigma f$ | is the formation $\Sigma$ measured by the tool, |
| $\Sigma fl$ | is the fluid capture cross-section, |
| $\Sigma ma$ | is the matrix capture cross-section; |

## E07.2 • Clean formation interpretation

In this model the shale fraction is assumed to be zero. (Eq. 1) applies, and the fluid $\Sigma fl$ is itself a proportion of the water ($\Sigma w$) and of the hydrocarbon ($\Sigma h$), in weights equal to their volumetric fractions, which are Sw and Sh = 1 – Sw respectively. Hence:

$\Sigma fl = Sw * \Sigma w + (1 - Sw) * \Sigma h.$ (Eq. 2)

Combining (Eq. 1) and (Eq. 2) together:

$\Sigma f = \Phi e * Sw * \Sigma w + \Phi e * (1 - Sw) * \Sigma h + (1 - \Phi e) * \Sigma ma$ (Eq. 3)

If $\Phi e$ is known (OH logging), and if $\Sigma h$ and $\Sigma w$ can be determined or assumed, the measurement of $\Sigma f$ yields the value of Sw at any depth in the well, by

$Sw = [(\Sigma f - \Sigma ma) - \Phi e * (\Sigma h - \Sigma ma)] / [\Phi e * (\Sigma w - \Sigma h)]$ (Eq. 3a)

It is obvious from (Eq. 3a) that the resolution of the measurement will depend on the difference between $\Sigma w$ and $\Sigma h$, which will be the greater the higher the formation water salinity. As an example, $\Sigma h$ will be in the about 21 for oil reservoirs, and $\Sigma w$ will range between 21 for fresh waters (no salts) to some 120 for salt-saturated waters (250000 ppm Cl). At 30000 ppm Cl, $\Sigma w$ equals about 30.

## E07.3 • 'Single Water' shaly reservoir interpretation

Most reservoirs are 'shaly', that is includes a - sometimes large - fraction of shale in the bulk volume. In traditional petrophysical interpretation this fraction, called Vsh, can be determined using a number of available shale indicators, which are measurements that are affected to some extent by the presence of shale. Such are, among others, the SP (Spontaneous Potential), the natural radioactivity (so-called 'Gamma Ray'), the formation resistivity, and most of the porosity logging measurements. For example, in the case of the Gamma Ray, which is one of the most common used indicators, an estimation of Vsh would be given by:

$VshGR = I_{RA}{}^{N}$ with $I_{RA} = (GRlog - GRclean) / (GRsh - GRclean)$ (Eq. 4)

| | |
|---|---|
| GRlog | being the Gamma Ray reading at the depth of interpretation, |
| GRclean | being the Gamma Ray reading in a clean formation (Vsh = 0), |

GRsh being the Gamma Ray reading in a shale formation (Vsh = 1),

N being an empirical exponent determined locally,

$I_{RA}$ being the Radioactive Index.

The following correlations can be used as an alternative to the above estimation :

**Clavier, et al :** $V_{sh} = 1.7 - \sqrt{3.38 - (I_{RA} + 0.7)^2}$ (Clavier)

**Stieber :**

*South Lousiana Miocene and Pliocenne :* $V_{sh} = I_{RA} / (3.0 - 2.0 \times I_{RA})$ (Stieber 1)

*Variations :* $V_{sh} = I_{RA} / (2.0 - I_{RA})$ (Stieber 2)

$V_{sh} = I_{RA} / (4.0 - 3.0 \times I_{RA})$ (Stieber 3)

**Larionov:**

*"Older" rocks* : $V_{sh} = 0.33 \times (2^{2 * I_{RA}} - 1.0)$ (Larionov 1)

*"Tertiary" rocks* : $V_{sh} = 0.0083 \times (2^{3.7 * I_{RA}} - 1.0)$ (Larionov 2)

In petrophysical analysis, the logic for the determination of Vsh at any depth involves calculating the values VshXX determined by all the available 'XX' indicators, and picking the minimum of all of them as the best estimate of Vsh at that depth.

In a shaly formations the measured formation Σ, Σf, will include a shale term in addition to the fluid and matrix terms. Thus, if we write from (Eq. 3):

Σclean = Φe * Sw * Σw + Φe * (1 - Sw) * Σh + (1 - Φe) * Σma (Eq. 5)

then:

Σf = Vsh * Σsh + (1 - Vsh) * Σclean (Eq. 6)

Σclean being the Σ of the non-shale fraction of the formation,
Vsh being the bulk volume of shale,
Σsh being the Σ of shale beds (Vsh = 1).

By eliminating Σclean between (Eq. 5) and (Eq. 6), Sw can be calculated at any depth if, on top of the previously described parameters, Vsh can be calculated at that depth and if Σsh can be picked from shoulder shale beds.

## E07.4 • 'Dual Water' shaly reservoir interpretation

A proven sophistication to the Single Water shaly reservoir model involves that the particles of clay minerals are surrounded by bound water. Bound water consists of molecules of water that are tied to the surface of the clay particles by electrostatic forces. These forces easily overcome drag forces such as created by pressure differentials during the production stage of the reservoir, in such a way that the bound water will not be produced and therefore poses no threat to the production engineers. But because of its salinity, the bound water will affect logging measurements (amongst which PNL logs). Hence it is important to differentiate the bound water from the connate, free water, which is a difficult task owing to the different properties of the two types of water. The need to cope with this situation has made necessary the development of the so-called Dual Water model, and the adaptation of PNL logging to the requirements of this model.

### Preliminary definitions

Referring to the partitioning of the bulk volume, we define the total porosity $\Phi t$:

$\Phi t = \Phi e + Vwb$ (Eq. 7)

Vwb being the bulk volume of bound water.

Also:

$Vsh = Vk + Vwb$ (Eq. 8)

Vk being the bulk volume of dry clay minerals.

The saturation of the bound water is termed Swb, such as:

$Swb = Vwb / \Phi t$ (Eq. 9)

and the free water saturation, Sw, is such as:

$Swf = Vwf / \Phi t$ (Eq. 10)

Vwf being the bulk volume of free water.

The total water saturation Swt is defined as:

$Swt = (Vwf + Vwb) / \Phi t = Swf + Swb$ (Eq. 11)

and by combining (Eq. 7), (Eq. 9), (Eq. 10) and (Eq. 11), one can show that:

$Sw = Vwf / \Phi e = (Swt - Swb) / (1 - Swb)$ (Eq. 12)

**Determination of Swb**

Swb is determined by petrophysical analysis using Swb indicators, pretty much in the same way Vsh is determined by shale indicators in the Single Water model, with the difference that the presence of two types of water in the formation is taken into the formulation of the derivation of Swb from the corresponding measurements.

In particular, the Gamma Ray, which is of specific interest in cased hole applications such as PNL logging, affords a determination of Swb using the formula

$$SwbGR = [(GRlog - GRw) / (GRwb - GRw)]^{**M} \quad \text{(Eq. 13)}$$

This formulation has the same shape as (Eq. 4). However, here, the selection of parameters is different,

GRlog being the Gamma Ray reading at the depth of interpretation,

GRw being the Gamma Ray reading in a 100% free water zone (typically, reservoir),

GRwb being the Gamma Ray reading in a 100% bound water zone (typically, shale),

M being an empirical exponent derived locally.

Because of the similarity between the Swb and Vsh derivations from the Gamma Ray, it has been suggested to use Swb = Vsh as a first approximation (and this option is proposed in Emeraude). It should be noted, however, that making this assumption is equivalent to assuming that the proportions of dry clay and bound water in the shales are the same as the proportions of total solids (dry clay + matrix) and total liquids in the bulk volume. In other words, the 'porosity' of the shales would equal the porosity of the formation. This in theory has no reason for being true, but nevertheless the tradition persists.

A good solution for PNL logging consists in using a Swb computation previously performed on the set of open hole logs by using a suitable Dual Water shaly reservoir model.

**Determination of the saturation**

In the Dual Water model, the response equation of PNL logs simplifies when the porosity and saturation are taken as $\Phi t$ and Swt, not as $\Phi e$ and Sw. $\Phi e$ and $\Phi t$ are related by (Eq. 7), which, given that

$$Sw = Vwf / \Phi e \quad \text{(Eq. 13a)}$$

yields, after combining with (Eq. 9):

$$\Phi e = \Phi t * (1 - Swb) \quad \text{(Eq. 14)}$$

Now the PNL response equation can be written as:

$$\Sigma f = Vma * \Sigma ma + Vwf * \Sigma wf + Vwb * \Sigma wb + Vh * \Sigma h + Vk * \Sigma k \quad \text{(Eq. 15)}$$

Vma being the bulk volume of matrix,

Vh being the bulk volume of hydrocarbons,

Σwf being the Σ of the free water,

Σwb being the Σ of the bound water,

Σk being the Σ of the dry clay minerals.

Now

$$Vma = 1 - \Phi t - Vk \quad \text{(Eq. 16)}$$

and one makes the assumption that Σk= Σma. This assumption is valid whenever the shales are primarily composed of silts and very small rock fragments, and also holds true whenever clay fractions are small in the bulk volume. Under this assumption, (Eq. 15) simplifies to

$$\Sigma f = (1 - \Phi t) * \Sigma ma + Vwf * \Sigma wf + Vwb * \Sigma wb + Vh * \Sigma h \quad \text{(Eq. 15)}$$

Further from (Eq. 11)

$$Vwf = \Phi t * (Swt - Swb) \quad \text{(Eq. 16)}$$

and again from (Eq. 11)

$$Vh = \Phi t - Vwf - Vwb = \Phi t * (1 - Swt) \quad \text{(Eq. 17)}$$

So that (Eq. 15) becomes

$$\Sigma f = (1 - \Phi t) * \Sigma ma + \Phi t * (Swt - Swb) * \Sigma wf + \Phi t * Swb * \Sigma wb + \Phi t * (1 - Swt) * \Sigma h \quad \text{(Eq. 17a)}$$

or, rearranging:

$$\Sigma f = \Sigma ma + \Phi t * [(\Sigma h - \Sigma ma) + Swt * (\Sigma wf - \Sigma h) - Swb * (\Sigma wf - \Sigma wb)] \quad \text{(Eq. 18)}$$

In (Eq. 18) Φt is derived from Φe and Swb through (Eq. 14); Σwf and Σwb are derived from the PNL log, so that Swt can be calculated if one has previously determined parameters Σma and Σh.

Sw, which is the objective of the interpretation, is eventually derived from Swt and Swb through (Eq. 12).

It can be seen that Vsh has no direct input in the calculation of Sw in the Dual Water model, which rather relies on an accurate determination of Swb.

It can also be seen that (Eq. 18) reduces into (Eq. 3) in clean formation cases in which Swb = 0, Φt = Φe and Swt = Sw.

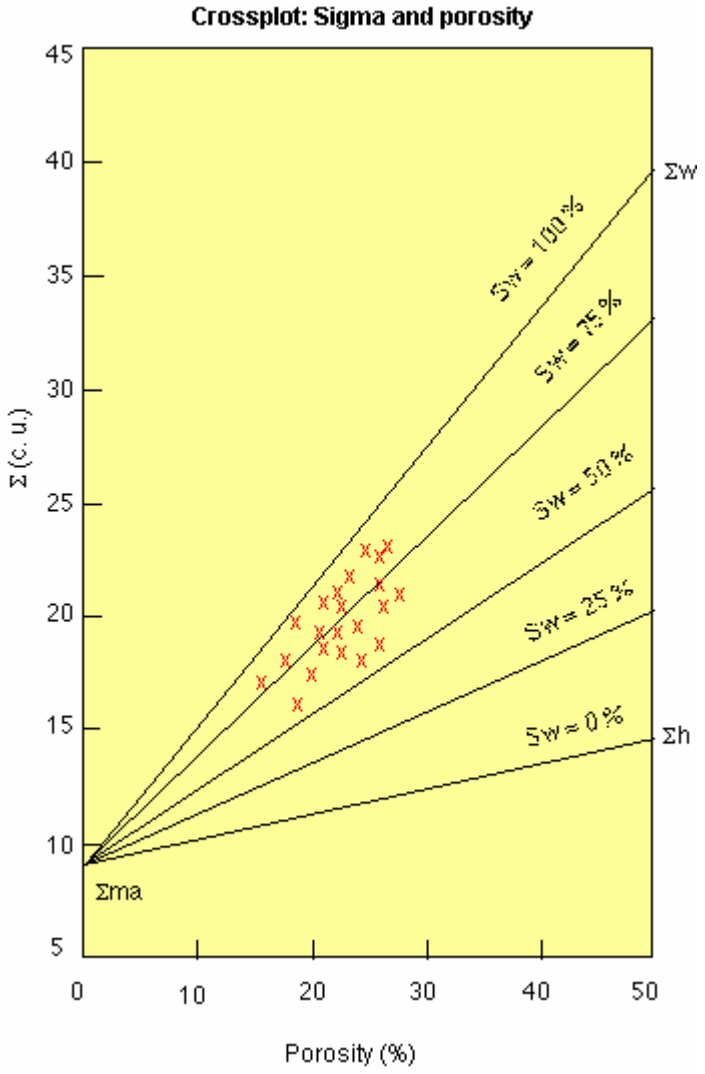
## E07.5 • Use of crossplots

Like in all petrophysical analyses, in PNL log interpretation crossplots can be used in three ways:

- To help in the determination of zoned parameters,
- To solve graphically for the interpretation target outputs such as Sw,
- To quality control the results.

### S - Porosity crossplot

In clean formations and when using a Single Water shaly model (once the shale correction on Σ has been performed), this crossplot will help tie down the values of Σma and Σw if a zone with 100% water saturation is available. It will also be used to graphically determine Sw for any data point once the shale correction has been performed. In Emeraude, the input porosity needs to be an effective porosity, extracted for example from the interpretation of openhole logs.




The shale correction is calculated as:

$\Sigma fcorr = \Sigma f - Vsh * (\Sigma sh - \Sigma ma)$ (Eq. 19)

### Σ - Neutron Porosity crossplot

In some cases and especially on old wells in which PNL log data is the only petrophysical data available, the only porosity values come from the so-called PNL ratio porosity. That porosity can be converted into an effective porosity by correcting for shaliness, by applying the equation:

$\Phi corr = \Phi r - Vsh * \Phi sh$ (Eq. 19)

$\Phi r$ being the 'ratio porosity' from the PNL log,
$\Phi sh$ being the 'ratio porosity' reading in shale beds (Vsh = 1).

### Σeq - Φeq crossplot

This crossplot is used to determine Σw and Σma when the saturation is available from an external source (for example, from the open hole logs).
The PNL saturation equation in a clean formation has been written as:

$\Sigma f = \Phi e * Sw * \Sigma w + \Phi e * (1 - Sw) * \Sigma h + (1 - \Phi e) * \Sigma ma$ (Eq. 3)

It can also be written as:
$\Sigma eq = (1 - \Phi eq) * \Sigma ma + \Phi eq * \Sigma w$ (Eq. 20)

if we define
$\Sigma eq = [\Sigma f - (1 - Sw) * \Phi e * \Sigma h] / [1 - \Phi e * (1 - Sw)]$ (Eq. 21)

and

$\Phi eq = (\Phi e * Sw) / [1 - \Phi e * (1 - Sw)]$ (Eq. 22)

In the Σeq - Φeq crossplot the influence of hydrocarbons has been eliminated, so that the data points should lie on a straight line joining the matrix point and the fluid point. This helps in the determination of Σma and Σw, provided there is a sufficient spread in the values of Σf of all the data points.

Of course this presupposes that the saturation has not changed since the initial values which serve as a reference for the calculation of Σeq and of Φeq. Any further change in saturation will distort the crossplot, which however may still be useable in sections in which the saturation has not changed.

**Σma - Vma crossplot**

Here again, this crossplot is used to determine Σma when the saturation is available from an external source, for example from the open hole logs. The method involves calculating Σma from the set of (Eq. 5) and (Eq. 6), as:

$$\Sigma ma\ (calculated) = [\Sigma f - Vsh * \Sigma sh - \Phi e * (Sw * \Sigma w + (1 - Sw) * \Sigma h)] / Vma \quad \text{(Eq. 23)}$$

With

$$Vma = 1 - \Phi e - Vsh \quad \text{(Eq. 24)}$$

The Σma (calculated) - Vma crossplot will then show a trend of data points funnelling towards the value of Σma at high values of Vma (for which Φe = Vsh = 0), where the log values approximate Σma.

**Σwa - Swb crossplot**

This crossplot provides a graphical solution to the determination of the water saturation when using a Dual Water model.

First, Swb is calculated by means of bound water indicators as described above. Then, Σwa is calculated assuming that the formation is shale-free (Swb = 0) and water-bearing (Swt = 1), as

$$\Sigma wa = [\Sigma f - \Sigma ma\ (1 - \Phi e)] / \Phi e \quad \text{(Eq. 25)}$$

On the Σwa - Swb crossplot three remarkable points are located: the 'free water' point and the 'hydrocarbon' point on the Σwa axis (Swb = 0) with their respective Σwf and Σh values, and the 'bound water' point (value Σwb with Swb = 1). Σwb is obtained from the PNL log in shale intervals using (Eq. 25), in which it is recalled that Φe is the effective porosity (not an uncorrected Neutron porosity).
The distance between the free water and hydrocarbon points is linearly divided into constant Swt (total water saturation) lines drawn parallel to a line connecting the free water and bound water points. Thus Swt is determined graphically, and Sw is finally calculated using (Eq. 12):

$$Sw = (Swt - Swb) / (1 - Swb) \quad \text{(Eq. 12)}$$

## E07.5 • Time-Lapse interpretation

PNL logs are often run at repeated time intervals ('time-lapse') to check for hydrocarbon depletion and encroachment of water. The use of time-lapse PNL logs has the advantage that many of the parameters that are needed to derive the water saturation, keep an assumed constant value. Such are Σma, Σh, and if there is no replacement of fluid by injection water, Σw.

When the above conditions are met, and also assuming that the effective porosity Φe remains constant, the change in saturation in a reservoir can be directly inferred from the change in Σ values from an early run (run1) to a later run (run2), as follows:

$$Sw2 - Sw1 = (\Sigma f2 - \Sigma f1) / [\Phi e * (\Sigma w - \Sigma h)] \quad \text{(Eq. 26)}$$

Particular cases in which the formation lithology varies from time step 1 to time step 2 (for example because of production of fines, or following an acid treatment), or in which the water salinity changes (for example due to encroachment from a water injection system) are more complex and need specific modeling.

Changes in saturation are best visualised by calculating the Bulk Volume of Water (BVW) for each run of the PNL log, and by plotting BVW1, BWV2, … BWVn on the same User View representing the total pore space. BWV is defined as the product of the porosity by the water saturation:

$$BVWn = \Phi e * Swn \quad \text{(Eq. 27)}$$

In Emeraude, the 'Pore Volume Analysis' (PVA) automatic view presents the stacked successive BVW curves with an appropriate color coding, allowing the user to visualize the extent to which hydrocarbons in the reservoir are gradually being replaced by water. The time-lapse technique also applies to such operations as 'Log-Inject-Log' and 'Acid Effect'. In the Log-Inject-Log technique, $\Sigma w$ is deliberately modified (e.g. by injection of high capture cross-section fluids such as salt-saturated or borated waters) to provide a higher than natural resolution in order to derive saturations (for example, residual oil saturation) with a better precision. In the Acid Effect technique, the target objective is rather the change in porosity resulting for example from dissolution of fines by the acid.

**Gas saturation monitoring**

Due to its lower capture cross-section than the oil $\Sigma$ (typically, $\Sigma$Gas could be between 0 and possibly 15 at reservoir conditions), gas detection and saturation monitoring presents an excellent case of application of PNL logs. Methods will involve modifying the value of $\Sigma h$ to reflect the expected change of fluid type in the reservoir as depletion proceeds, for example as the decrease in reservoir pressure draws gas from solution in the oil below the bubble point.