Physics of Magnetic Resonance: Hydrogen Relaxation Time

Fundamental theoretical principles and applications to the characterization of porous media

1. Introduction to hydrogen relaxation times

In physics and imaging, hydrogen relaxation times refer to the time it takes for protons (the nuclei of hydrogen atoms) to return to their thermodynamic equilibrium state after being perturbed by an electromagnetic pulse. This phenomenon is central to NMR (Nuclear Magnetic Resonance) and MRI. Two main time constants characterize the return of magnetization:

- T_1 relaxation time (Longitudinal Relaxation)
  • Definition: This is the characteristic time (expressed in seconds) required for the hydrogen magnetization to return to 63% of its initial equilibrium value after excitation. It corresponds to the repulsion of the magnetization along the axis of the main magnetic field. • Mechanism: Hydrogen protons release the energy they have absorbed by transferring it to their immediate molecular environment (the lattice). • In MRI: The T1 signal is used to create anatomical contrast. It depends on the tissue: water-rich tissues (such as cerebrospinal fluid) have a long T1 signal, while fatty tissues have a short T1 signal.
- T_2 Relaxation Time (Transverse Relaxation)
  • Definition: This is the characteristic time (expressed in milliseconds) after which the transverse magnetization (perpendicular to the magnetic field) has decreased to 37% of its maximum value . It represents the loss of coherence or the phase shift of the protons.
  • Mechanism: This phenomenon is due to the interactions of protons with each other (spin-spin interactions). • In MRI: The T2 is always much shorter than the T1. It allows for images where fluids appear very bright (such as edema or cerebrospinal fluid).

2. The crucial distinction: T_2 versus T_2* (Effective relaxation)

In practice, the transverse magnetization decreases much more rapidly than the effect of spin-spin interactions alone (T2). This overall phenomenon is measured by the time constant T2*.

$$1/T2_{*} = 1/T2_{+} 1/T2_{,\text{inhomogeneous}}$$

2.1 Definition

In oil exploration, an **inhomogeneous** or **heterogeneous medium** refers to a reservoir rock whose physical properties (porosity, permeability, saturation) vary from one point to another. Unlike a perfectly uniform medium, this structural complexity directly influences the migration and flow of oil and gas.

Main characteristics of an inhomogeneous reservoir

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- **Spatial variations:** Petrophysical properties change depending on the location, whether on a microscopic scale (the pores of the rock) or macroscopic scale (the different sedimentary strata).
- **Impact on production:** These variations create preferential pathways for fluids, which can complicate drilling and optimal hydrocarbon extraction.
- **Multiscale modeling:** Reservoir engineers use stochastic modeling tools and multiscale parameterization methods to map this heterogeneity and simulate reservoir behavior.
- **The mechanism:** The loss of coherence of protons is accelerated by inhomogeneities of the main magnetic field (B0), induced in particular by differences in magnetic susceptibility at the interfaces between the solid rock matrix and the fluids.
- **Reversibility:** Unlike true T2, which depends on random molecular collisions, the phase shift due to inhomogeneities is fixed and static. It can be compensated and canceled by applying recentering pulses (Spin Echo sequence).

3. Petroleum and geological applications: NMR of porous media

In oil exploration and the study of drill cores, the measurement of relaxation times (particularly T2) is not used to create an anatomical image, but to map porosity and pore size distribution.

• The surface relaxation mechanism: In a reservoir rock, protons from fluids (water, oil, gas) relax much faster when they come into contact with the solid surface of the pores. The measured transverse relaxation time (T2) then becomes a direct indicator of the geometry of the medium:

$$1 / T_2 \approx \rho_2 \cdot (S / V)$$

Where ρ2 is the surface relaxivity of the rock, $_{S\ the}$ pore area , and V its volume.

• Interpretation of pore distribution:
- Short T2 $_($ small pores): Corresponds to water bound by capillary action (clays, microporous pores). This fluid cannot be extracted (not producible).
- Long T2 $_($ large pores): Corresponds to free and mobile fluids (displaceable water, light oil, or gas in macroporosity). This is the target zone for exploitation (sweet spots).

4. Synthetic NMR signature of reservoir fluids

Fluid	Time T1	Time T2	T1/T2 Ratio	Viscosity / Mobility
Open water	Long (~ 2-3 s)	Long (~ 2-3 s)	≈ 1	Low viscosity, very mobile
Bound water (clays)	Very short (< 10 ms)	Very short (< 10 ms)	≈ 1	Immobile (linked to the matrix)

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Oil light	Medium to Long	Medium to Long	≈ 1 to 2	Fluid, high commercial value
Heavy oil / Bitumen	Short	Extremely short	Very high (> 10)	Very viscous, quick to relax
Natural gas	Very Long (3-5 s)	Short (by broadcast)	Pupil	Very high diffusivity

Technical Note on Diffusion: In the presence of a magnetic field gradient, the thermal displacement of molecules (diffusion) causes an additional irreversible phase shift. This phenomenon considerably reduces the T2 of gas and light oil, providing an infallible criterion for distinguishing hydrocarbons from formation water.

5. Identifying "forgotten" reservoirs using RSS-NMR

RSS-NMR technology (which combines satellite *remote sensing imaging* , or *RSS* , and Nuclear Magnetic Resonance) makes it possible to highlight **forgotten** or bypassed *reservoirs* . *reservoirs*) by remotely mapping the magnetic signature of hydrogen atoms contained in underground fluids.

This approach overcomes the limitations of traditional seismic and conventional electrical logging to identify unexploited hydrocarbon pockets.

Here's how this method works in practice:

1. Direct fluid detection by resonance

Unlike traditional methods (such as resistivity) which deduce the presence of oil indirectly, NMR RSS-NMR technology **directly targets the hydrogen nuclei** of water, gas, and oil. By sending specific resonant electromagnetic waves, it excites these atoms remotely and measures their response signal.

2. The differentiation between free water and bound water

In so-called "complex" reservoirs (such as low-resistivity reservoirs), traditional tools often mistake oil for conductive salt water or clay. NMR solves this problem through the analysis of relaxation times (T_1 and T_2) : [

- **The water bound to the clays** has very small pores and separates very quickly (extremely short time T_2).
- **Mobile hydrocarbons** (the "forgotten" exploitable reservoirs) retain their signal for longer.
  This distinction makes it possible to identify productive areas where previous analyses concluded there were only sterile water layers.

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3. Independence from the rock (Lithology)

NMR provides a **measurement of total and effective porosity** that is completely independent of the rock type (whether sandstone, carbonate, or clay). By eliminating uncertainty related to the rock matrix, the RSS-NMR method accurately identifies the exact volume of mobile fluid available in neglected geological structures.

4. Remote Satellite Scanning (RSS)

The integration of satellite technology (RSS) makes it possible to project and capture these resonant variations on a large scale. It allows for the precise delimitation of the geometric contours and depth of hydrocarbon anomalies even before any drilling, which proves particularly profitable for revitalizing **mature,** already exploited fields by finding residual pockets within them.

6. A concrete example of low-resistivity reservoirs unlocked by this technology

A historical and emblematic example of a low resistivity reservoir unlocked by this approach is found in the **Berkine Basin in Algeria , particularly on the Gassi Touil** field complex , as well as in the deltaic geological layers of the **Gulf of Mexico** .

In these regions, massive oil-bearing areas were initially classified as "barren" (aquifers) by oil companies before Nuclear Magnetic Resonance (NMR) corrected the situation.

Here is how the situation actually unfolded on the ground:

The initial problem: The trap of glauconium and micropores

- **The classic data:** During the first drilling operations, electrical logging tools measured extremely low resistivity, often falling **below 1 to 2 Ohm·m** . According to the laws of classical physics (such as Archie's formula), such conductivity meant that the rock was saturated with more than 60% or 70% salt water. Engineers therefore **abandoned these areas** , believing they would only produce water.
- **The hidden geological reality:** The rock was actually a very fine sand containing glauconite *(* a conductive clay mineral) and a huge number of micropores. These micropores retained water by capillary action (bound water), creating an electrically conductive network on the surface, but **the core of the larger pores was filled with mobile and exploitable oil** .

NMR solution : Revealing the invisible oil

By applying NMR technology (and then its extension by surface scanning RSS-NMR), the operators analyzed the **T_2 distribution spectrum** of the fluids.

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The signal immediately revealed a dual-dynamic signature:

1. A very short T_2 peak (a few milliseconds), confirming that the water responsible for the low resistivity It was **motionless and trapped** in the clay.
2. T_2 peak , irrefutably proving the presence of a highly mobile **and light fluid** (hydrocarbons).

The concrete result

Thanks to this discovery, the zones were drilled. Contrary to the predictions of traditional electrical tools, the wells produced **hydrocarbons completely free of water** (*water-free production*). In the Berkine Basin , as in the "thin sands" of the Gulf of Mexico, this made it possible to redefine the reserves of mature fields and recover millions of barrels that had been literally "forgotten" during the first waves of exploration.

Another example related to complex carbonate reservoirs (Middle East)?

In the Middle East, where nearly 80% of oil production comes from carbonate sedimentary structures, the most famous case study is the **Shuaiba Formation** (found notably in the United Arab Emirates, Oman, and Qatar). [1 , 2]

This carbonate reservoir, of the chalky limestone type (*chalky limestone*) or containing pyrite, constitutes the perfect example of a **low resistivity (LRP) reservoir Pay)** unlocked thanks to the advances of the NMR . [1 , 2]

The geological trap: The bimodal structure of carbonates

Unlike the fine sands of Berkine , the complexity of Middle Eastern carbonates lies in the extreme heterogeneity of their pores. The Shuaiba Formation presents a network porous bimodal: [1]

- **very fine microporous matrix :** Created by compaction and geological diagenesis processes (micritization). These tiny pores trap a massive amount of salt water that is irreducible by capillary action. [1 , 2]
- **Interstitial macroporosity : Much** larger cavities or fractures, capable of accommodating and allowing the circulation of large quantities of oil. [1]

The failure of conventional tools:
Hypersaline water trapped in the interconnected microporosity provided an electrical highway for the current of traditional logging tools. Resistivity collapsed completely (often below **0.5 to 1 Ohm.m**). For Archie's mathematical models, the theoretical water saturation (Sw) approached 80 to 90%, leading to these areas being classified as mere aquifers with no commercial value. [1 , 2]

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NMR solution : Mapping pore size

By introducing NMR (and later RSS-NMR remote geophysical scanning to assess the extent of these structures), engineers were able to overcome the limitations imposed by the electrical properties of salt water. [1]

7. A concrete example of low-resistivity reservoirs unlocked by this technology

NMR directly measures the hydrogen signal from fluids and sorts it according to the size of the cavities where it is located:

T_2 signal in Shuaiba carbonates

Intensity | Bound water (Immobile) Mobile oil (Usable)

of | [===] [=======]

Signal | [=====] [=========]

| _____[=======]________[===========]____

+-->

0.1 1 10 100 1000 (ms)

^

NMR Carbonates cut -off (cut-off threshold at ~92 ms)

1. **The first peak (very short T_2 , < 92 ms):** This corresponded to still water confined in the micropores of the chalk. This water is trapped and will never leave the rock, so it does not interfere with production.
2. **The second peak (long T_2 , > 100 ms):** It corresponded to light hydrocarbon molecules lodged in exploitable macropores.

The result

By identifying that almost all the water was immobile (*bound water*), the NMR proved that the saturation of free and mobile water was actually minimal. The wells drilled and activated in these sections of Shuaiba produced **clean oil at high yields** , without any trace of water.

This discovery has made it possible to reassess upwards the reserves of giant fields in the Middle East and to exploit entire layers of limestone that were thought to be doomed by water.

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