# Tracer data to assess transport directions, flow and sweep efficiency and remaining oil saturation in hydrocarbon reservoirs

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Inter-well tracer testing is proven as an efficient reservoir surveillance technology and has been used extensively worldwide the last 2-3 decades. Most of the interwell chemical tracer technology in use today was developed by the Institute for energy technology (IFE) located at Kjeller outside Oslo. IFE also developed an extensive tracer service based on the tracer technology research. This service vas commercialized in 2013 through Restrack. Restrack delivers a full portfolio of integrated tracer services, based on IFE's research. The portfolio include inter-well gas & water tracing, single well tracer tests (SWCTT) and partitioning inter-well tracer tests (PITT). The tracer service is provided to international and national oil companies world-wide.

Tracers for oil or gas reservoirs must fulfil several important characteristics. They must be thermally, chemically and biologically stable under reservoir conditions and not adsorb on rock surfaces. In addition, suited tracers must be unique in the reservoir environment, have excellent analytical sensitivity and be environmentally acceptable. Typical chemical tracers are fluorinated benzoic acids for water (Galdiga and Greibrokk, 1998), or perfluorocarbons for gas (Dugstad et al., 1992; Kleven et al., 1996).

Tracers follow reservoir fluids and therefore reflect reservoir flow dynamics. An obvious, and important information provided by tracer data is mass transport connectivity. Further interpretation, using so-called residence time distribution (RTD) analysis will give the allocation of injection fluids in offset producers as well as quantitative information on sweep volumes and flow heterogeneity (conduits and thief-zones).

Partitioning inter-well tracer testing (PITT) has recently been field-proven for inter-well applications (Viig et al. 2012; Hartvig et al., 2015) as a reliable tool to monitor the relative flow of oil and water and to measure remaining or residual oil saturation (Sor). Tested in both carbonate and sandstone reservoirs, new PITT tracers and methodologies provide a unique tool to measure oil saturations on a field-scale. Comparing PITT tracer results to results obtained using the well-known push-and-pull single well chemical tracer test (SWCTT), show that PITT results agree very well with SWCTT results. This enables saturation assessment on field-wide scale, with a significantly reduced production interference.

**Field example 1: Verification of water flow in Snorre by tracers and 4-D seismic.**

To understand sand layer communication and to what degree the faults act as barriers or not, a significant tracer program (with more than 50 individual injections) has been executed at Snorre. The tracer program started early in 1993, about ½ year after production start, and still continues today.

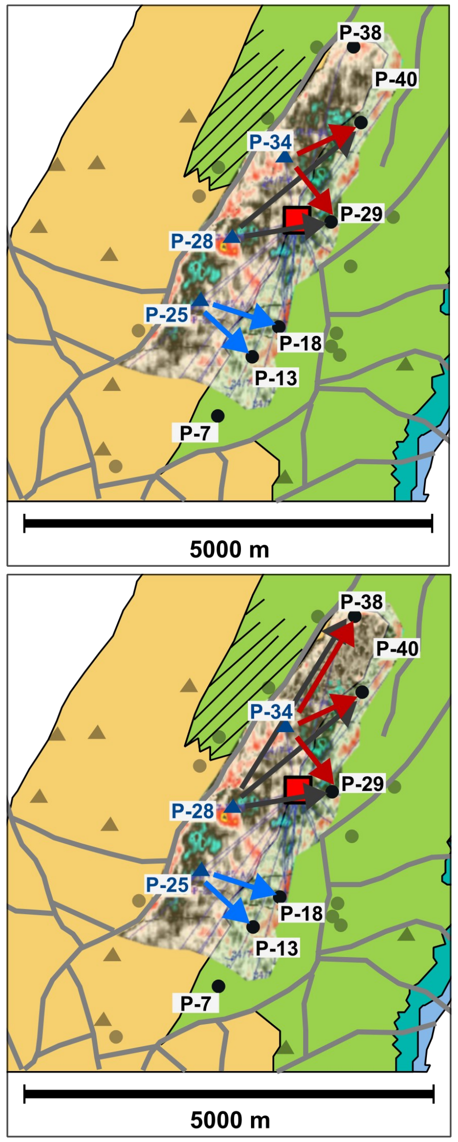


*Figure 1. Map of Snorre with CFB. The seismic image shows dimming effects interpreted from the difference between the two first seismic surveys at Snorre (upper figure) and the two subsequent seismic surveys (lower figure). The black represents strong dimming and indicate the water front. Tracer breakthrough (indicated by arrows) correspond well with the fronts from the dimming.*



In the Snorre field, 4-D seismic surveys and corresponding interpretation show clear dimming (seismic amplitude decrease) as oil is substituted by water (cf. Figure 1). These surveys were performed after five years of production (Figure 1, upper) and after an additional four years of production (Figure 1, lower). The dark colour in Figure 1 corresponds to reservoir areas where oil has been substituted by water.

Comparing with the 4-D seismic data the tracer data are in excellent agreement with the water front inferred from the seismic study. In addition, the tracers add significant information, revealing that the water in the P-38/P-40 area originates from two sources, namely P-34 and P-28.

**Field example 2: Quantification of flow and sweep efficiency from tracer data.**

To monitor a polymer EOR project in the Wintershall operated Bockstedt field, located onshore Germany, a tracer campaign was executed. A tracer deployed in injector B-83 was monitored in the offset producers B-81 and B-56 (cf. the Bockstedt pilot area illustrated in Figure 2. To assess the sweep volume, the flow allocation from the injector towards individual producers and to quantify the heterogeneity of the flow, residence time distribution analysis was used. This is a systematic methodology to infer information about the reservoir flow dynamics and to quantify the nature of the fluid flow in the reservoir. Briefly, the distribution of residence times for a tracer mass is given as the product of production rate and tracer concentration:

$$\varepsilon(t) = C(t) \cdot Q_p(t) / M$$

The temporal moments for each well *j*

$$m_0 = \int_{-\infty}^{+\infty} \varepsilon_j(\tau) d\tau,$$

$$m_1 = \int_{-\infty}^{+\infty} t \cdot \varepsilon_j(\tau) d\tau, ...$$

of this distribution can be used to calculate the fraction produced tracer mass in each producer ($M_0 = m_0$) as well as the average residence time ($\langle T \rangle = m_1/m_0$). The swept pore volume is given from the average residence time and the injection rate by $V_s = Q_i \langle T \rangle$. Further, the partial integrals of the two first moments, denoted flow capacity

$$(F(t) = \int_0^t E(\tau) d\tau / m_0)$$

and storage capacity ,

$$\Phi(t) = \int_0^t E(\tau) d\tau / m_1$$

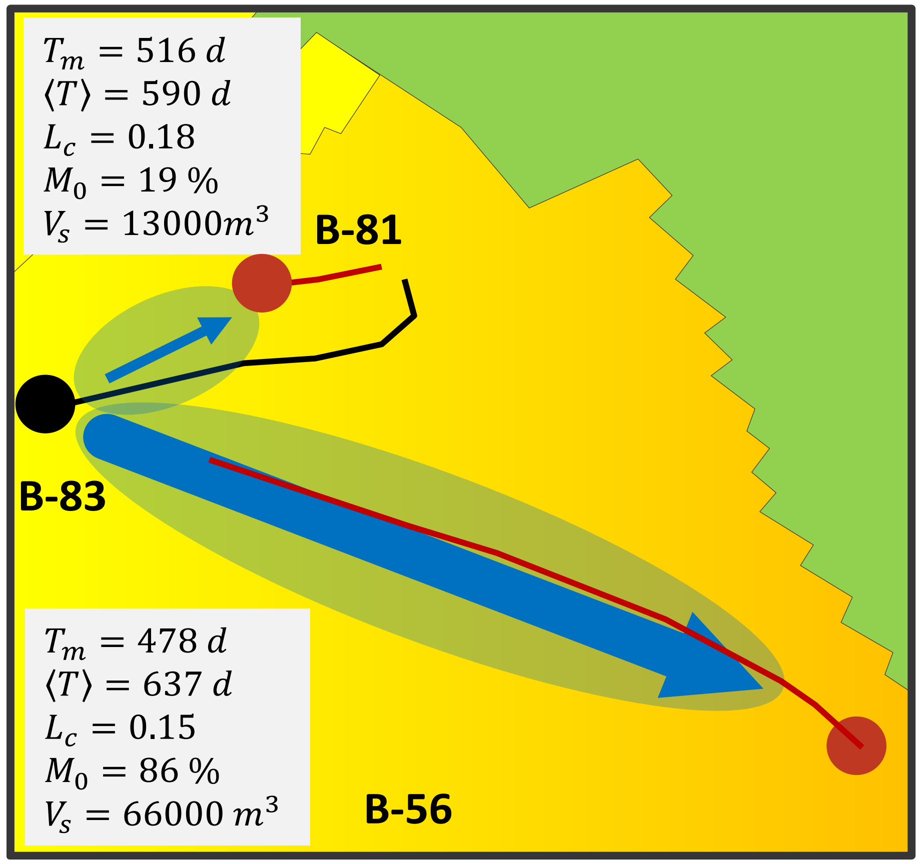


*Figure 2. Map of Bockstedt pilot area investigated using tracers. The fraction of produced over injected tracer mass (Mo) is given by the arrow widths and the magnitude of the sweep volume (Vs) is indicated by the area of the ellipses in the figure. The most common (the mode Tm) and the average (‹T›) residence times are also given – in addition to the estimated heterogeneity index (Lorentz coefficient Lc) for the flow.*

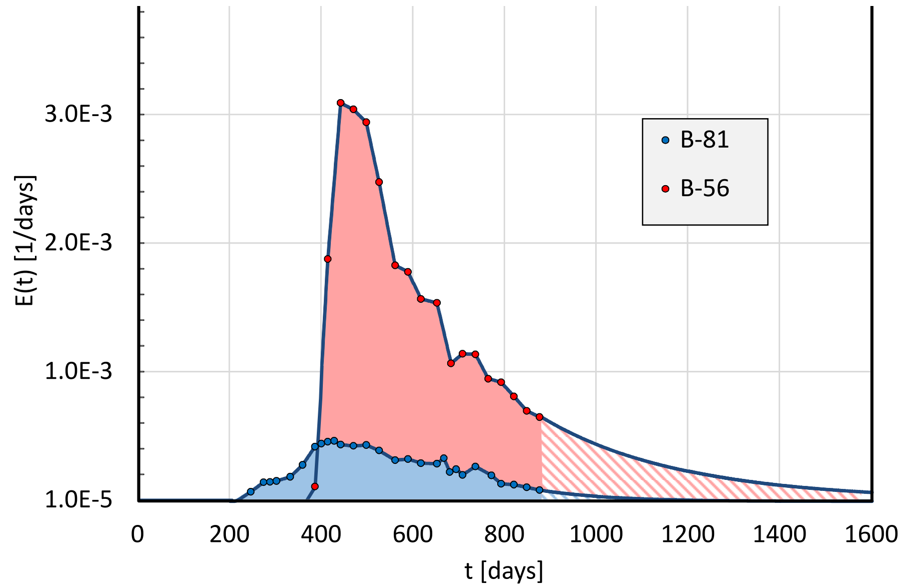


*Figure 3. Tracer response in Bockstedt wells B-81 and B-56. The shaded regions above 860 days are extrapolations of the data. Individual measurements are given as points.*

can be used to calculate the so-called Lorentz coefficient ($L_c$) that is a measure of how heterogeneous the flow is. $L_c$, ranges from 0 for completely homogeneous flow to 1 for completely heterogeneous flow.

From the fraction of produced over injected tracer mass (zeroth moment of the residence time distribution) about 1/5 of the water injected in B-83 in travel towards B-81. These fractions correspond to the area under the tracer curves in Figure 3.

The sweep volumes can be compared to the physical pore volume and used to assess the sweep efficiency. A good sweep manifests itself with a relatively small. From sweep volumes and $L_c$ in the pilot area in Bocksted, we can conclude that the area between the injector and both the producers is well swept, in agreement with the fact that the reservoir is a relatively homogeneous sandstone reservoir.

**Field example 3: Quantification of remaining oil saturation using partitioning tracers.**

The partitioning inter-well tracer test (PITT) is a non-intrusive low-cost test that can provide measurement of oil saturation in the region between injectors and producers in an oilfield. Lack of stable partitioning tracers has previously limited the application of PITTs in petroleum reservoirs. A recent field test in the Total operated Lagrave oil field proved the stability and reliability of six new partitioning tracers at reservoir conditions.

In PITTs remaining oil saturation is given by:

$$S_0 = \frac{T_p - T_w}{T_p + T_w(K-1)}$$

Where $T_p$ and $T_w$ are retention times for the partitioning and water tracers, respectively, and $K=C_0/C_w$ is the oil/water partition coefficient. Based on retention times the six new tracers yielded $S_0 = 24 \pm 1\%$ . This result was later verified and corresponds very well to saturation measurements on core samples.

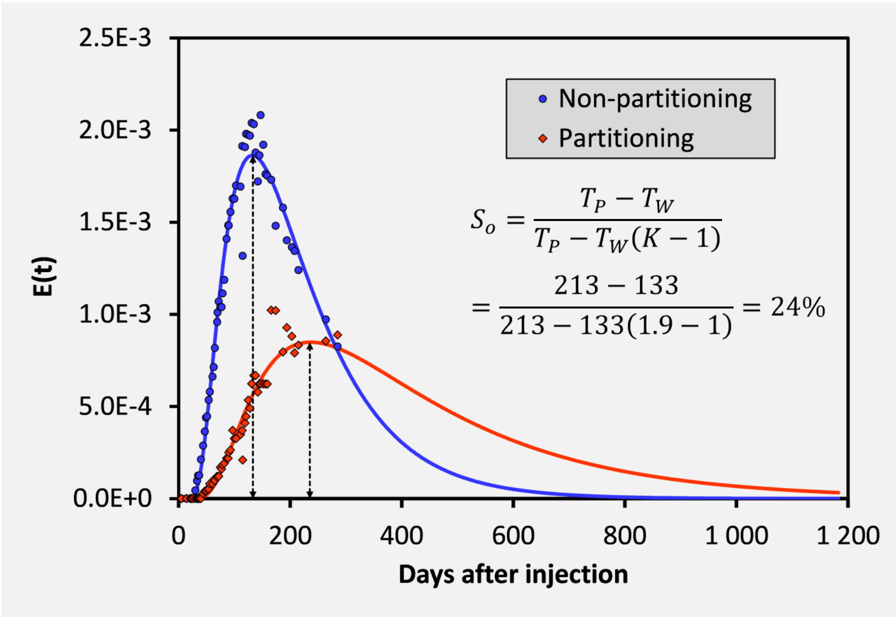


*Figure 4. Tracer response of partitioning and non-partitioning tracers in Lagrave well LAV-1. The difference in arrival times and the partitioning coefficient K yields a saturation of 24% between injector and producer.*

Useful links

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# Produced Water Sand Management

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The amount of produced water increases as an oil field matures. While the worldwide average for water cut is around 75%, for some reservoirs it may increase to 98%. Managing the increasing volume of produced water is one of the main challenges the petroleum industry is dealing with today. With increasing environmental regulations, more and more produced water is being reinjected.

PWRI (produced water reinjection) typically leads to a decrease in operational cost, an increase in hydrocarbon recovery and a decrease in surface disposal of water. But like all other operations, reinjection of produced water poses some challenges. According to SPE, 70% of oil fields produce sand, or other types of sediments. The removal of solids from the water, prior to reinjection, is a key operation operators have to deal with. Presence of solids in reinjection water can result in injectivity decline (blocked pores), failure of water injection pumps and shut downs. Excessive amount of solids cause serious damage to the rotary equipment (PWRI pumps), valves as well as the system pipe work. Consequentially, water injection would be unsustainable with frequent equipment failures.

According to BP, damage to the produced water reinjection system, caused by solids present in reinjection water, is the main source of production deferrals on ETAP (Eastern Trough Area Project)*. On ETAP solids erode pumps, isolation and choke valves resulting in 1 mmbbls/yr in deferred production, £2M maintenance costs and a demand of 600 POB per year. According to BP, with the water cut (WC) and gas oil ratio (GOR) increasing, and reservoir depleting, the risk of deferrals and integrity failures is also likely to accelerate making solids management one of the main issues to be addressed.

From an economic perspective, effective sand management in produced water – whether it is reinjection, discharged, or processed water – means more efficient operations, less downtime and decreased maintenance costs. Avoiding solids in the produced water system helps minimize injectivity loss over time and maintain PWRI pumps utilization. In order to eliminate failure of water injection pumps due to entrained solids, minimize erosion on piping and down time it is important to implement an effective sand management strategy.

The FourPhase surface solids removal system, called QuadFlow, is designed for permanent installation with focus on minimal logistical impact, and with emphasis on safe and quick installation. QuadFlow is a cost efficient and effective tool for protecting your top side equipment from unwanted solids and eliminating damage to PWRI pumps that can result in costly downtime. The QuadFlow uses next generation cyclone technology that has a proven solids separation efficiency of 99.8% for particles ≥ 20micron.

With space being a premium on many offshore installations the QuadFlow unit is designed to be compact – measuring 2.0 x 2.5 meter footprint. In addition to market leading solids removal technology, FourPhase has a solutions driven team of experts with more than a hundred years of combined experience – FourPhase is a trusted expert in solids management.

Contact us for more information on how our solids removal system can help solve solids challenges related to produced water reinjection.

**Sand Management on ETAP: A multi-discipline approach, 6th European Sand Management Forum 26th March 2014