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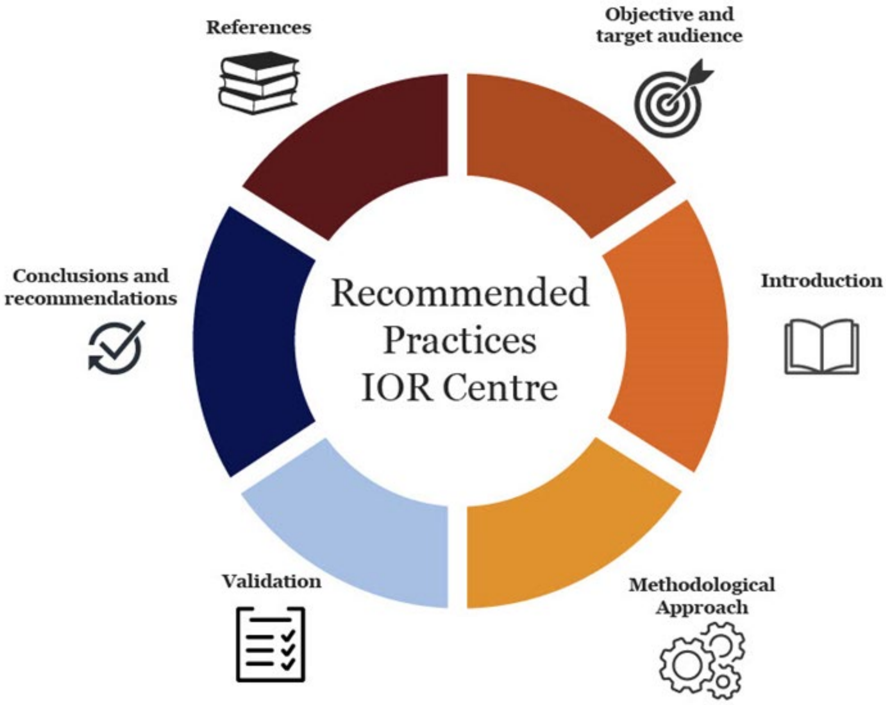

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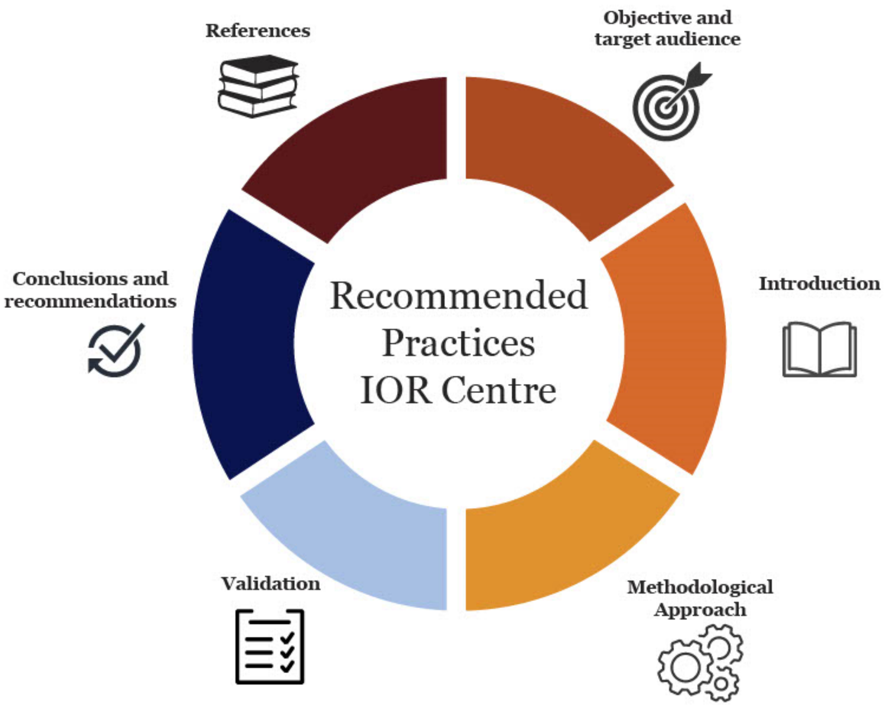

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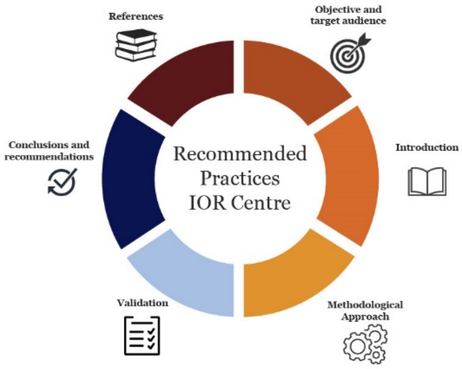
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Objective and target audience

A partitioning inter-well tracer test (PITT) determines the residual (or even remaining) oil saturation (S_{OR}) in the flooded region between well-pairs. This type of tracer test can be used to identify improved oil recovery (IOR) targets, evaluate IOR projects, evaluate enhanced oil recovery (EOR) methods, and improve reservoir description for efficient hydrocarbon production. Thus, the main objective of the work with inter-well oil/water partitioning tracers developed within the framework of the IOR Centre is to provide tools and methodologies to improve reservoir description for efficient management of resources.

The present report aims to provide insight to its users on the deployment of tracer technology in the inter- well region of water-flooded reservoirs to determine S_{OR}. In turn, this parameter can be used as basis to evaluate the efficiency of several oil-production related operations. It will explain workflows, expertise, and tools needed as well as the importance of the information obtained, and methods to obtain it.

This report is directed towards operators, primarily to reservoir engineers and reservoir managers, and service companies, particularly those already engaged on the deployment of tracer technology or those who aim to begin this activity. R&D personnel working in both operators and service companies may also benefit from the contents of the present report.

Introduction

Environmental concerns combined with societal and technological issues are driving a change in the traditional way to produce hydrocarbons, particularly on the Norwegian continental shelf (NCS) where the peak oil production was reached in the early 2000s and has been declining ever since (NPD, 2021). The future production of oil & gas will rely increasingly on IOR projects and EOR methods (IEA, 2021; Muggeridge et al., 2014). The efficient deployment of such methods requires a thorough understanding of the reservoir, thus the need for reservoir characterization technologies. The PITT determines SOR in the swept volumes between injector/producer well pairs. SOR is a very important parameter for the identification of targets, design and evaluation of IOR projects. Even though the PITT was introduced in 1971 (Cooke, 1971) few tests were successfully performed to date, largely due to the time this test takes (a few months), and to the poor selection of the tracers used (Silva et al., 2018; Tang, 1992). Viig et al. (2013) presented a successful PITT performed on the Lagrave field in France using new PITT tracers specifically selected for such an application. The same tracers were again successfully used in the Bockstedt field in Germany (Hartvig et al., 2015), and on a carbonate land-based reservoir of undisclosed location (Sanni et al., 2018). Within the scope of the IOR Centre, a systematic methodology for the development of new oil/water partitioning tracers, which was also applied, was presented (Silva, 2021). The large-scale deployment of PITT can provide critical information to improve efficient and profitable recovery of hydrocarbons by complementing the understanding of the reservoir. The recommended use of the tracers developed within the scope of the IOR Centre is a “standard” PITT, which typically consists of:

Selection of qualified tracer (s) to be used

A correct selection of the tracers to be used can be done by combining a “laboratory screening” of the production water (to ensure that the compound is not present in advance) with the analysis of production and reservoir data (to estimate breakthrough times and the total amount of tracer (s) needed for the test) (Dugstad et al., 2013). This should be done individually for every well-pair to be studied.

Definition of a plan to monitor tracer production

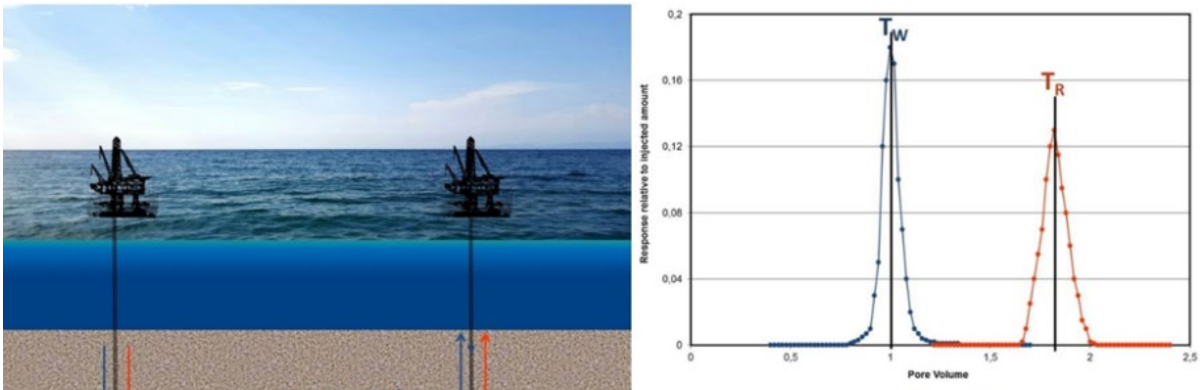
Based on the expected breakthrough times for the tracers, a plan to collect and analyze samples of produced water is defined. This plan is typically done with the same information (production and reservoir data to estimate breakthrough times and the total amount of tracer needed for the test) used on the previous point and should contemplate a sufficiently large number of samples to obtain complete production curves, while reducing as much as possible their numbers to ensure cost efficiency.

Simultaneous pulse injection of the passive (s) and partitioning tracer (s)

A concentrated solution containing the total amount of tracers is prepared in the same aqueous matrix. This solution is then injected together with the injected water as a pulse. When the injected tracers encounter hydrocarbons, the partitioning tracer will establish an equilibrium distribution between the water-contactable oil and the mobile aqueous phase. This leads to a lag in production of the partitioning tracer relatively to a passive one (that travels exclusively with the water). This lag is dependent on (proportional to) the amount of hydrocarbons present along the travelled path. The quotient between the equilibrium concentration of the tracer in the hydrocarbon and aqueous phases is the partition coefficient (K) of the tracer. K is primarily dependent on the salinity of the aqueous phase, composition of the hydrocarbon phase and temperature of the system (Silva et al., 2021). For a given system, the value of K is constant and independent of the initial concentration of the tracer or which of the two phases it was originally present in. For a field test, the K values of the partitioning tracers to be deployed are determined upfront in the laboratory using samples of real produced oil and water from the field to be tested. The measurements of K are performed under the relevant conditions of temperature.

Analysis of the tracers and building of the production curves

The produced water samples are collected accordingly to the monitoring plan and the tracer concentration determined in the laboratory. Results are then plotted against time or produced volume, and the differences in time (or volume) of arrival of the tracers should be notable. Fig. 1 illustrates the general principle of the PITT and an idealized production curve.



$$S_{OR} = \frac{T_R - T_W}{T_R + T_W(K-1)}$$

Fig 1. Illustration of the principle of a PITT. When traveling through a hydrocarbon bearing medium, the phase-partitioning tracer (orange dots) is delayed relatively to the passive water tracer (blue dots). S_{OR} between injector/producer well pairs can be determined from the tracer production curves

The equation in Fig. 1 allows to calculate S_{OR}. In this equation, T_R is the residence time of the partitioning tracer, T_W the residence time of the water tracer and K is simply the oil/water partition coefficient of the partitioning tracer.

Determination of S_{OR} from the tracer production curves

Residence time distribution analysis (RTD) allows to determine the residence times for the tracers (T_R and T_W). For this, the water production data during the whole time of the test is required. When calculating S_{OR}, T_R and T_W typically correspond to the first moment of the tracer, however, (Tang, 1995) demonstrated that accurate values of S_{OR} can be determined from any "same tracer mass recovery landmarks". In order words, the time of arrival of the tracers corresponding to the same produced amounts relatively to the total injected ones.
In a water-flooded reservoir, a PITT should be deployed when the production water-cut (≥ 90%) suggests that the remaining hydrocarbons are effectively stagnant in relation to the injected fluids (Serres-Piole et al., 2012). Thus, the PITT can be used to evaluate the sweep efficiency, identify IOR/EOR targets, evaluate IOR projects and EOR methods, and better characterize fluid circulation.

Methodological Approach

We identified two main drawbacks to field implementation of PITTs: i) the lack of a systematic approach to qualify new oil/water partitioning tracers for the inter-well region of water flooded oil reservoirs; ii) the small number of such tracers, developed specifically for this application ("designed" to ensure the maximum accuracy possible). Thus, we aimed for the development and application of a systematic methodology to qualify such compounds. All the scientific and technical details are available elsewhere (Silva, 2021), however the methodology consists of the following main steps:

Selection of the new tracer candidates

The selection of new tracer candidates is based on the requirements of the application combined with key physico-chemical properties of the chemical compounds. Water solubility properties, octanol/water partitioning (real or estimated data is available for virtually every molecule), the existence of features that confer stability to molecules (i.e. chemical resonance), etc, are some of the key features for this step.

Evaluation of long-time thermal stability and interactions with rock materials

Long-time static stability experiments are performed in relevant conditions of temperature and salinity, as well as in the presence of typical sedimentary rock materials. The objective is to ensure that the tracer candidates are stable and do not exhibit any significant interactions with rocks (reversible or irreversible adsorption, chemical reactions with or surfactant-like flow on the surface). A PITT can take several months of even years (depending on the interwell volume available and injection flowrates) and the tracers used most remain thermally and chemically stable under reservoir conditions and be "blind" to other reservoir components than hydrocarbons.

Development of analytical methods for the stable compounds in real production waters

When the tracer candidates exhibit sufficient stability, it is crucial that they are analyzable in real production waters in the lowest possible concentration. This directly impacts the feasibility of the test, both in terms of cost and logistics. The same magnitude in differences of limits of quantification of the tracers is directly reflected in the total amount of tracers needed for the test. For example, if the quantification limit of a tracer is reduced from 2 mg/L to 2 µg/L, then 1.000 X less tracer will be needed to perform the same test.

Characterization of the K-value

As mentioned before, for a given system, K is constant. However, K is primarily dependent on temperature, oil composition, and ionic strength of the aqueous phase. If any of these parameters vary significantly along the path between injector and producer, then it is important to understand also how K varies, to ensure the accuracy of the SOR values determined by the PITT.

Evaluation of the dynamic flooding properties of the chemically and thermally stable candidates

Experiments are necessary to verify that: i) inside a porous medium, in the absence of hydrocarbons, the PITT tracer candidates flow together with the water and no significant deviations are observed; ii) that the tracers yield accurate S_{OR} results in a lab-scale PITT performed in a controlled setting (vs reference partitioning tracers in a bench-top experiment).

Field (or large-scale flooding) trial

The complete qualification of new tracers is only concluded at this step. The compounds developed by the work within the IOR Centre, where only tested on the laboratory scale.

Validation

The PITT does not require any validation per se. It is a well-known and developed test, used also in environmental sciences (Jin et al., 1995), introduced to the oil industry in 1971 (Cooke, 1971) and further expanded and improved several times, i.e. (Deans, 1978; Shook et al., 2009; Tang, 1992; Tang, 1995). Nevertheless, the quality of the PITT starts with the quality of the tracers it is based upon. Thus, any new inter-well tracer (both passive and phase-partitioning) should be properly qualified and validated before use. The final validation of the new tracer (s) must be done in large scale flooding experiment, preferably on a natural sedimentary basin, against "reference" tracers. These are tracers that have been proven on the field and are now routinely used when tests are deployed. As an example of such oil/water partitioning tracers, the ones introduced by Viig et al. (2013) are available. Thus, new PITT tracers can be developed, qualified, and validated on the laboratory scale as described by (Silva, 2021). This will minimize the risk of unsuccessful and costly field trials. The new PITT tracers can then be used on a field trial together with the "reference" ones and the relative results produced by each of them used as basis for their validation. In principle, this requires the participation of at least one operator and one service company, that would also co-finance the project.

Conclusion and recommendations

The paradigm of oil production on the NCS has changed. There are clear political signs about severe limitations to the prospection and development of new resources, as well as the pressing need to reach carbon neutral production of hydrocarbons from existing fields. At the same time, the production of hydrocarbons is still needed to satisfy global demand (IEA, 2021) and the oil recovery rate on the NCS by the end of production is in average around 50% (NPD, 2021). Additionally, many oilfields on the NCS are mature or rapidly reaching maturity and significant reserves are still underground. The profitable, efficient, and carbon neutral production of the oil remaining on the NCS will depend to a very large extent on the use of new methods and techniques of production. These will translate on an increasing number of IOR projects and EOR methods. The design of such projects requires the best possible description of the reservoir. Knowing how much oil is left in the swept volumes between injectors and producers is a key parameter to understand the reservoir. PITTs can contribute to provide this information. Thus, the deployment of more PITTs will contribute to ensure the efficient deployment of IOR projects, thus helping to ensure profitability and sustainability of oil production on the NCS.

Knowledge gaps

The PITT was introduced to the oil industry in 1971 and plenty of work to improve the deployment and interpretation of this test was done over the years as well as the establishment of systematic method to obtain new oil/water partitioning tracers. However, very little work has been done focusing on the fundamentals of the PITT. The PITT relies on two fundamental assumptions: i) when a hydrocarbon and an aqueous phase become in contact, the equilibrium distribution of the partitioning tracer between both happens instantaneously. This translates into local equilibria conditions along the whole swept volume of the interwell region. This is verified in small-scale laboratory experiments with very homogeneous porous matrices, however it is unclear that it can be safely extrapolated for the field scale; ii) the ratio volume of oil contactable by water/area of oil contactable by water is not considered in the PITT. Further studies are needed to understand border conditions where the two basic assumptions behind the PITT breakdown.

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