# INTERWELL TRACER TECHNIQUE – AN EFFECTIVE TOOL TO ASSIST OIL RECOVERY

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In secondary or tertiary oil recovery, water, gas or solvent is injected into the reservoir to maintain the reservoir pressure and displace oil toward the producers. By injection of tracer in the injection fluids and observation of tracer appearance in the producers the interwell community as well as residual oil saturation in the swept zone can be determined. This information is of importance to improve the reservoir description to reduce the technological risk and useful to optimize the oil recovery.

This paper presents the review of applications of the interwell tracer techniques in the oil field.

**Keywords:** *interwell tracer test, tracer, residual oil saturation, oil field, reservoir, permeability, transit time, oil recovery, miscibility, secondary recovery, tertiary recovery.*

# ĐÁNH DẤU LIÊN GIẾNG – MỘT CÔNG CỤ ĐẮC LỰC PHỤC VỤ KHAI THÁC DẦU KHÍ

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**Tóm tắt**

Trong các giai đoạn khai thác thứ cấp và tam cấp, nước, khí hay dung môi được bơm vào mỏ để duy trì áp lực mỏ và đẩy dầu về giếng khai thác. Bằng cách pha chất đánh dấu vào dòng lưu chất bơm và lấy mẫu phân tích sự xuất hiện của chất đánh dấu tại các giếng khai thác, kỹ thuật đánh dấu liên giếng cho các thông tin về tính liên thông giữa các giếng bơm và khai khác cũng như độ bão hòa dầu trong vùng quét của lưu chất. Đó là những thông tin quan trọng để cải thiện mô hình mỏ giúp giảm thiểu những rủi ro và góp phần tối ưu hóa công nghệ khai thác.
Bài báo trình bày tổng quan về những ứng dụng của kỹ thuật đánh dấu liên giếng kèm theo những ví dụ minh họa ứng dụng trên thực tế.

**Từ khóa:** *Kỹ thuật đánh dấu liên giếng, chất đánh dấu, độ bão hòa dầu, giếng bơm ép, giếng khai thác, mỏ dầu, độ thấm, thời gian di chuyển, độ rỗng, tính hòa trộn.*

## 1. INTRODUCTION

Tracer test is a well-known technique to study the flow dynamics and transport media. In the last decades it has been greatly enhanced and is used in many earth science applications in hydrology, aquifers, mining, oil reservoirs, geothermal fields, pollutants dispersion, atmospheric circulation, oceanology, geology, etc. [1].

Interwell tracer tests have been used in the petroleum reservoir since the 1950s with the initial applications to prove qualitatively communication between the well pair [1]. In the last decades, the benefit of tracer tests has been further recognized that make interwell tracers commonly used in both secondary and tertiary oil recoveries.

In oil reservoir, by directly tracing reservoir fluid movement, tracer tests constitute an important and decisive technique in providing fundamental information on the fluid transport, formation properties, fluid saturation and offering solid elements in validating reservoir models.

The method of interwell tracer test consists in the injection at the injection well of a slug of a chemical compound or isotopic tagged compound, which is carried by the injection fluid following the flow trajectories and is later observed at other downstream sites (production or observation wells), normally at very low concentrations. The tracer breakthrough curve in form of tracer concentration observed at the sampling well along the time elapsed since tracer injection provides therefore information on the transit time of injection fluid from injection well to the production wells, the well to well connection, the flow pattern, the swept volume, communication channel characteristics, and the porous media properties [2].

In interwell study tracers are classified into passive (non-partitioning) and partitioning. The passive tracer is used in tracing only one phase like HTO is ideal passive tracer to follow injected water which does not partition into other phases such as formation rock, gas or hydrocarbon phase; while partitioning tracer like isopropanol or butanol can partition into both oil and water phases. If two or three partitioning tracers are injected simultaneously into the injection well the miscibility of fluid injection and residual oil saturation in the zone between two wells can be determined.

Although several methods exist to obtain precise information for reservoir description purposes, such as 4D seismic and pressure testing, tracers have proven a very useful and efficient experimental tool in complex reservoirs where data are difficult to obtain with other techniques [2, 3, 4, 5]. In principle, tracer is used to follow the injected fluid in oil recovery that make tracer advantageous as the only method that allows investigation of the flow under reservoir. With the development of chemical tracers in the 1990s, the applications of interwell tracer test have become more widespread in oil production [6]. These tests are increasingly used in the design of enhanced oil recovery methods to follow the flow though the reservoir, control breakthroughs [7, 8, 9] and select the most appropriate wells for enhanced oil recovery projects [10].

## 2. INTERWELL WATER TRACER TEST

In secondary and tertiary oil recovery, waterflooding and water-based floods are the most widely used methods. Through marking the injected water by a small amount of water soluble tracer, the injected water can be distinguished from the formation water, or from different injection sources. Therefore, the interwell water tracers are applied in the reservoir for many reasons and in a variety of circumstances. They can be a powerful tool for describing the reservoir, investigating unexpected anomalies in flow, or verifying suspected geological barriers or flow channels and to measure residual oil saturation Sor in the late stage of water flooding. They can also be used in a test section of the field before expanding the flood, or to monitor the actual flow pattern in EOR pilot tests.

### 2.1. Tracers

In interwell water tracer test the suitable small amount of water soluble tracer is added to the injected fluids to follow the fluids under reservoir condition. The tracer can be radioactive isotopes (radiotracer) or chemical compounds (chemical tracer) provided it meets the criteria such as faithfully following the path and velocity of the fluid with which it is injected, no existing in the formation water or injected water, no or insignificant absorption in the formation rock, thermal stability and reasonable cost. In nature the radiotracer and chemical tracer are of the same function to follow injected fluid, just different in the method of detection. However, the radiotracer was commonly used in the field in the last decades owing to simplicity and high sensitivity in analysis. Recently, the modern technologies allow detecting chemical compounds at ultralow concentration such as GC/ECD, GC/MS or LC/MS that gives chemical tracer more common employment. The commonly used compounds as the interwell water tracer are listed in the Table 1 below.

Table 1. Commonly used water tracers for interwell study in petroleum reservoir

| Tracer compounds | Description | Comments |
|---|---|---|
| HTO (Tritiated water) | Radioisotope Tritium H-3 (T) is tagged in the water molecule. H-3 is radioisotope emits beta radiation of energy 18.3 keV, half-life is 12.3 years. Tritium is analyzed by Liquid Scintillation Counter | HTO is considered as the ideal tracer for water tracing. It has been used most widely in the past for petroleum reservoir study. HTO is used as the reference of other compounds potential for water tracing. |
| Alcohol tagged H-3 or C-14 | Radioisotope Tritium H-3 or Carbon-14 is tagged in the alcohol molecule such as methanol or ethanol. C-14 half-life is 5730 years, emits beta radiation of energy 156 keV. C-14 is analyzed by Liquid Scintillation Counter. | Radioisotope tagged alcohol is good tracer for water tracing. However, H-3 should be tagged in the C-bond. Ethanol can be attacked by the microbes. |
| Benzoic Acid tagged H-3 or C-14 | Radioisotope Tritium H-3 or Carbon-14 is tagged in the benzoic acid molecule. | Radioisotope tagged benzoic acid is good tracer for water tracing. However, H-3 should be tagged in the C-bond. |
| Fluorinated Benzoic Acids (FBA) | FBAs are analyzed by GC/ECD. Detection limit ~ ppb. | Chemical tracers for water tracing. Applicable in high temperature reservoir (>$90^0$C). |

The tracer amount to be injected to the injection well is estimated based on the assumption of total dilution volume of the flooding pattern and the minimum detection limit. In practice, the amount of radiotracer can be milicuries to curies in radioactivity and of chemical tracer can be kilograms in weight.

## 2.2. Field implementation

Generally, the field implementation of tracer test includes injection of tracer and sampling. Tracer solution is injected directly into the well head of the injection well or the flowline of water injection system to the well head. It is not required to shut down the well during injection of tracer. The arrangement of tracer injection is illustrated in Figure 1.

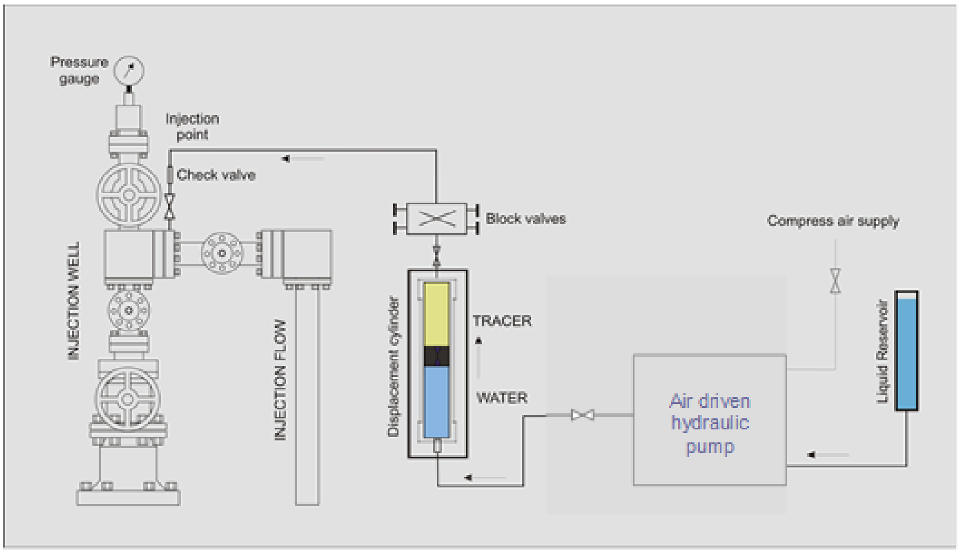



Figure 1. An arrangement of tracer injection at the well head (*Source: CANTI*)

Produced water samples are collected at the well head of production well for analysis of tracer in monitoring tracer appearance. The sampling frequency is normally as high as few samples a day during the first weeks after injection of tracer and will reduced to few samples a month in the next months. In case of the water cut is as low as less than 10% the Well Head Sampler installed in the well head can be used for direct extraction of water from produced fluid (Figure 2).

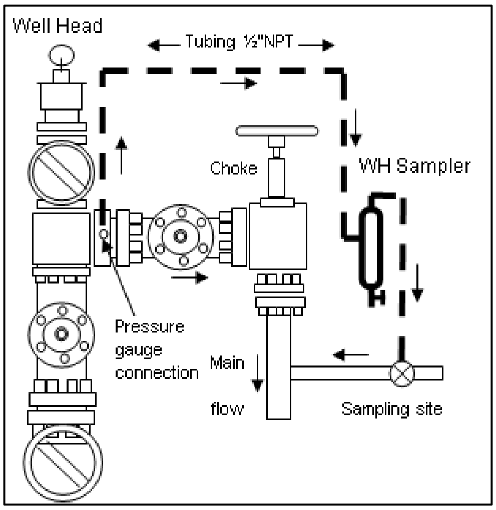



Figure 2. The Well Head Sampler installed at the well head for extraction of water from produced fluids (*Source: CANTI*)

## 2.3. Tracer analysis

Initially, only some of collected samples need to be analyzed until tracer breakthrough is found. Once breakthrough is detected, all samples are counted to define tracer response curve.

Water sample firstly is cleaned out to remove solid particles, oil before being analyzed.

In general, since the concentration of tracer in the produced water is in the ultra-low level that it is impossible to directly analyze, the proper procedures for enrichment of tracer concentration are needed. The radioactive tracers are analyzed in Liquid Scintillation Counter for beta counting or Gamma Spectrometer for gamma counting, while the chemical tracers such as FBAs are analyzed by GC/MS or

GC/ECD. Figure 3 introduces the photo of Tracer Analytical Laboratory of CANTI.

Figure 3. A corner of Sample Treatment Lab (left) and Analytical Instruments GC/ECD and GC/MS (right) at CANTI campus.

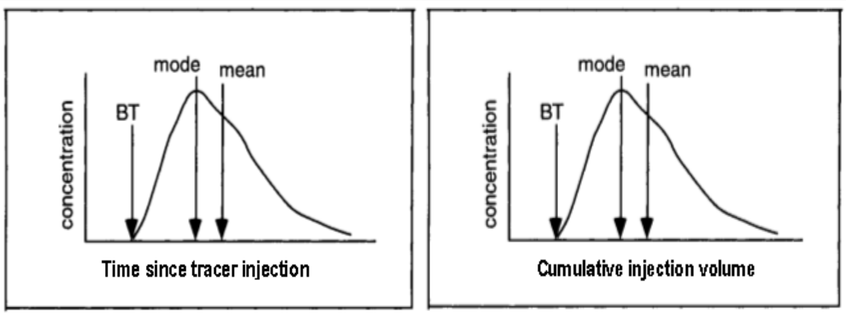
## 2.4. Tracer data interpretation

The tracer response in the observed production well can be expressed as the breakthrough curve which is the tracer time response C(t) as tracer concentration vs. time elapsed since injection of tracer. The time response of a tracer pulse input implies residence time distribution of injected fluid (water or gas or solvent) traced, [11]. This expression helps correlating tracer breakthrough with other field data such as volumetric response vs. injected fluid and produced fluid [12].

In a tracer response curve three landmarks are commonly defined (Figure 4). The breakthrough BT is the time tracer concentration found higher than detection limit that implies the fastest portion of tracer. The expression of tracer response vs. cumulative injection volume implies the volumetric sweep. And the recovered amount of tracer is expressed by tracer response vs. cumulative produced fluid.

In order to gather the valuable information of the swept formation zone and fluid flow from the tracer response, three interpretation methods can be applied. They are moment analysis, analytical modelling and numerical simulation [13, 2, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23 and many others].

Figure 4. Tracer time response C(t) (left) and volumetric response C(Vi) – tracer concentration vs. cumulative injection volume (right).




The main benefits when the interwell tracer test is deployed in the field would be improvement of reservoir description including validation of reservoir model, investigation of flooding performance and measurement of residual oil saturation.

*Case Studies 1- Characterization of fracture*

MR is the fractured basement reservoir characterized by high fractured heterogeneity that makes a lot of uncertainty in reservoir modeling. It is confirmed by the geologist that in this kind of reservoir the hydrocarbon and fluids are contained in the fracture network. The interwell tracers were implemented to gain the experimental data of function of faults and fractures and well to well connectivity for improvement of reservoir model and reservoir description [24]. The injectors and according tracers are Wells 301 (TR3), 306 (TR1) and 307 (TR2). The producers for sampling are 14, 21, 201, 206, 303, 305, 308, 309, 310 and 314.

After 420 days of monitoring, tracer breakthrough was found as below (Figure 5, left):

Injector 307 – Well 305: Tracer TR2, Breakthrough time 262 days

Injector 301 – Well 314: Tracer TR3, Breakthrough time 133 days

Well 14: Tracer TR3, Breakthrough time 378 days

Well 308: Tracer TR3, Breakthrough time 366 days

Injector 306: No tracer found during 420 days of observation that was also an evidence of poor performance of this well.

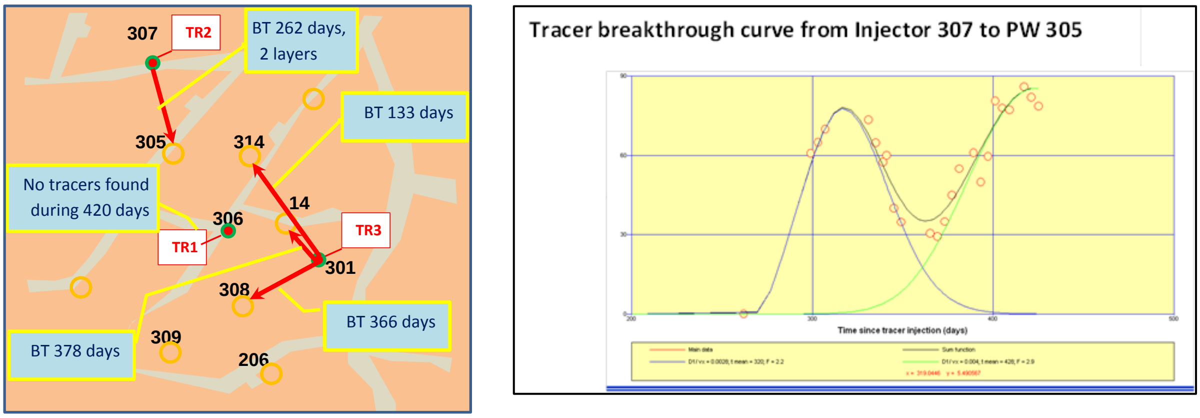



Figure 5. Tracer injection and monitoring in MR Reservoir. The map shows well arrangement and tracer breakthroughs from the injectors (left) and example of tracer interpretation (right).

Tracer breakthrough data were interpreted for interwell connectivity by using moment method after matching the experimental data by tracer transport equation. The parameters of interwell connectivity including the number of conductive conduits, mean transit time, mean velocity, permeability and swept volume of each conduit connecting two wells were obtained by interpretation. Figure 5, right, gives example of interpretation of tracer breakthrough curve showing 2 connecting conduits between Wells 307 and 305. The total swept volume from Well 307 to Well 305 was determined as 1,000 $m^3$, the permeability in range from 30 to 50 mD. The TR3 tracer responses from injector 301 broke

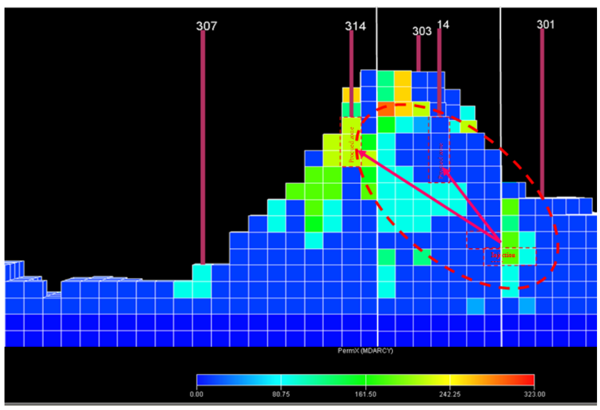


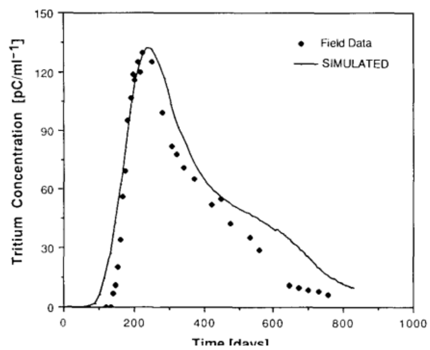

Figure 6. Tracer from Injector 301 broke through in Well 14 and 314 that provided experimental evidence of connectivity to improve reservoir model [24, 25].

through in Well 14 and 314 provided the evidence of connection over the fractures that is helpful to improve the reservoir model (Figure 6) [25, 26].

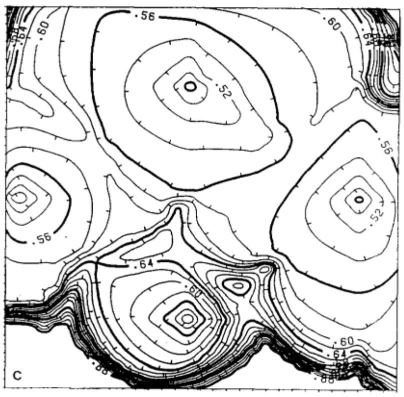
*Case study 2 - Multiple-well, multiple tracer project*

A multiple-well (4 injectors), multiple-tracer (7 tracers) project has been successfully implemented using a comprehensive three-dimensional, chemical flood, compositional simulator UTCHEM developed at the University of Texas [27]. The study illustrates the potential of accurate reservoir simulation to be used as a tool to incorporate various field data for reservoir description purposes. Both areal and vertical variations of permeability and oil saturation were determined as well as both longitudinal and transverse dispersivities.

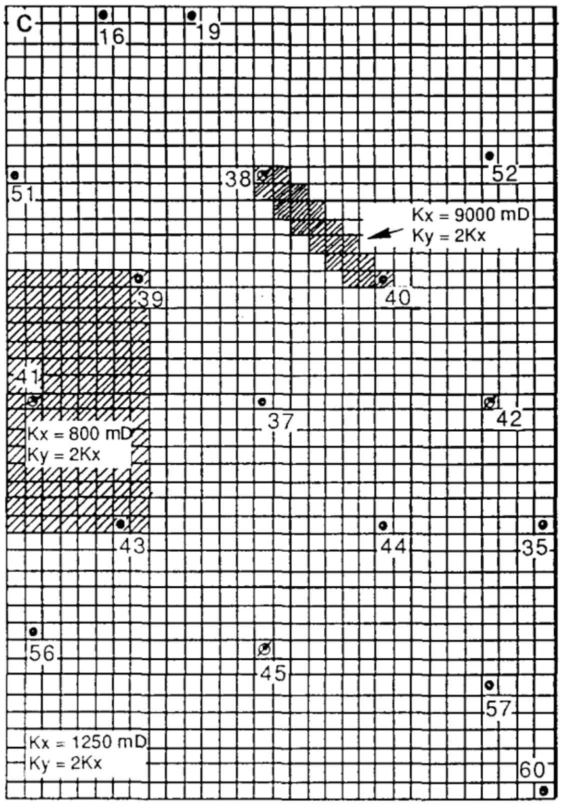
The study clearly demonstrates the advantages and practicality of the use of a compositional chemical simulator, based upon accurate, higher-order finite differences and extremely fast vector processing, to do field scale interwell tracer analysis quantitatively. The results modeled the area of high permeability (900 mD), the number of layers and mapping Sor in the reservoir (Figure 7).




Simulation of tracer curve at Well 39




Oil saturation distribution in layer 3




Areal permeability variation in layer 3 in nal final match

Figure 7. Examples of results of the multiple well, multiple tracer project [25].

*Case study 3 - Interwell Tracer Test for validation of secondary recovery pilot*

The water flooding pilot in MM reservoir (Kuwait) was designed as the five-spot injection pattern based on the geological data of homogeneity. The IWTT was conducted to gain the experimental data of connectivity and flow trend to validate the design [28].

Injectors (Tracer): X-210

Producers for sampling:  X-201, X-129, X-128 and X-126 (Figure 8).

After 11 months of monitoring, tracer breakthrough curves were obtained in form of tracer concentration vs. time since tracer injection. The radial standard analytical model was applied to match the experimental data that allows decomposing the breakthrough curve into the elementary peaks. Each peak represents one conductive layer. The moment method was then used to calculate the parameters of connectivity of the interwell zones. Table 2 below gives example of tracer data interpretation in calculation of the connectivity between X-210 to X-126 in which two layers F1 and F2 were found.

Conclusions: Interwell Tracer Test was applied in MM reservoir to validate the pilot of five-spot pattern of water flooding. The tracer data and interpretation showed that water was mainly moving to Wells X-126 (west) and X-129 (east). No tracers found in X-128 (south). A very small tracer breakthrough was found in X-201 (north). The connectivity between well pairs was also calculated based on the radial standard model. The tracer has provided the experimental evidence that there is good connectivity in the west and the east direction and very poor and even no connectivity to the south and to the north. The suitable flooding pattern should be three-spot or direct line model in this area.

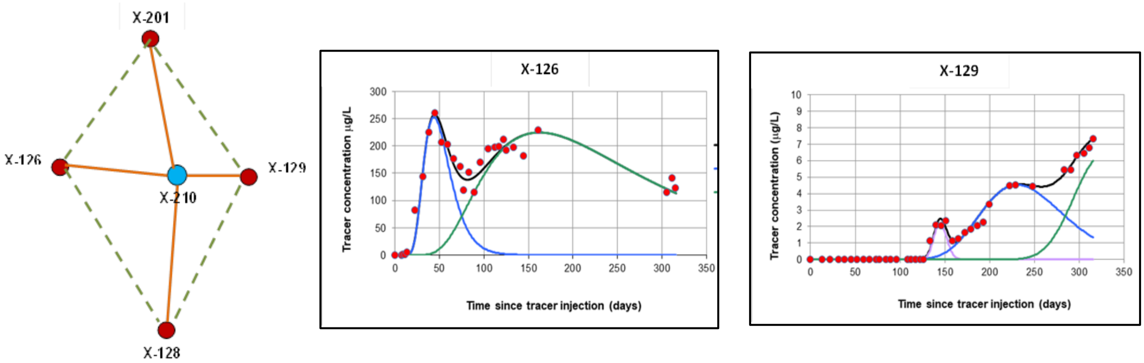



Figure 8. Five-spot water flooding pilot in MM reservoir. The injector X-210 was designed to distribute water to 4 surrounding production wells X201, X-129, X-128 and X-126. Tracers were found in X-126 and X-129. The moment and analytic interpretations gave the number of layers connecting wells as following: two layers between X-210 and X-126; three layers between X-210 and X-129.

Table 2. An illustration of connectivity parameters determined by interpretation of tracer data for Well X-210 and X-126.

| Parameter | Total | F1 (Layer 1) | F2 (Layer 2) |
|---|---|---|---|
| Breakthrough (days) | 9 | 9 | 31 |
| Mean time (days) | 179 | 52 | 189 |
| D/vx* | - | 0.058 | 0.19 |
| Peak time (days) | 45 | 44 | 162 |
| Maximum velocity (m/day) | 78 | 78 | 23 |
| Mean velocity (m/day) | 3.55 | 13.5 | 3.63 |
| Water recovery (%) | 10.3 | 1.95 | 8.48 |
| Average permeability (mD) | | 1417 | 390 |
| Swept volume (bbls) | | 33,321 | 144,865 |

*D/vx is dimensionless dispersion parameter, where D is dispersion coefficient, v is the mean pore velocity and x is the injection to observation distance.

## 3. INTERWELL GAS TRACER TEST

Gas flooding is also the method used in secondary and tertiary oil recovery. In secondary recovery, the associated gas separated from produced oil is commonly used to inject into the gas cap or inject in the pattern to maintain the formation pressure to form a miscible bank to push oil toward to the producers. In tertiary recovery of enhanced oil recovery (EOR), the gas is used in water alternative gas (WAG) injection, gravity assisted gas drainage (GAGD) or in form of solvent mixture of $CO_2$ injected into the formation in the miscible injection process [2].

In 1990s, the common gas tracers for interwell test are the radioactive gas such as Kr-85, tritiated methane, ethane or butane and the chemical such as $SF_6$, Kr, Ne and He [2]. Recently, the emerging chemical gas tracers have been developed such as Perfluorocarbons (PFCs). The modern analytical procedures in GC/ECD or GC/MS allow detecting PFCs in the air samples at ultralow level as $10^{-15}$ l/l [30]. Because the injected gas is a mixture of different molecular components, each with their individual values on diffusion and partition coefficients, so no single gas tracer is an ideal tracer for the injected gas. Because of difference of partitioning coefficient the gas tracer will retard after the mean linear velocity of injected gas. Therefore, in the case to meet the objective of investigation of well to well connection, only one gas tracer can be used for injection. But to give more quantitative information such as interwell connectivity, residual oil saturation, miscibility, it is necessary to use at least two tracers having different partitioning coefficient $K_d$ in oil phase [29].

In general, there are up to 15 derivatives of PFCs can be used as the interwell tracers which are very insoluble in water phase therefore they are confined to oil phase. As mentioned above, because two tracers are selected to inject in the injector for assessment of immiscibility, sweep efficiency and residual oil saturation Sor, it is necessary to measure the partitioning coefficient $K_d$ in reservoir condition of each tracer for interpretation [2, 31, 32, 33].

*Case study – Gas tracer for determination of Sor in WAG injection*

Interwell partitioning tracer technique was applied to determine Residual Oil Saturation Sor in the pilot of EOR of WAG injection in fractured MD reservoir [33, 34].

Injected simultaneously into the Injector BX-3 were three tracers TR1, TR2 and TR3 which are of different partitioning coefficients Kd. TR1 and TR2 are the main tracers while TR3 is the new compound for testing.

Samples were collected in the well head of the Producers AX-7, AX-11, AX-9-2 and AX-9 (Figure 9a). During 600 days, tracers TR1 and TR2 were found in AX-9 and AX-7 while TR3 was not detected.

In AX-7, TR1 and TR2 broke through almost simultaneously (Figure 9b); no significant retardation even the partitioning coefficient of two tracers is different (11.0 and 17.0 respectively). It seems miscible of injected gas with oil under reservoir condition. Because of no retardation in tracer breakthrough, Sor between BX-3 and AX-7 was not able to calculate.

In AX-9, the retardation time of TR1 and TR2 breakthroughs was determined for each peak, Peak 1 and Peak 2 by the moment method (Figure 9c,d). By using retardation factor and partitioning coefficient determined in the laboratory, the values of Sor for each layer F1 and F2 connecting BX-3 and AX-9 were determined as 9.9 % and 35.4 %, respectively. Those numbers are in range of the values estimated by other methods.

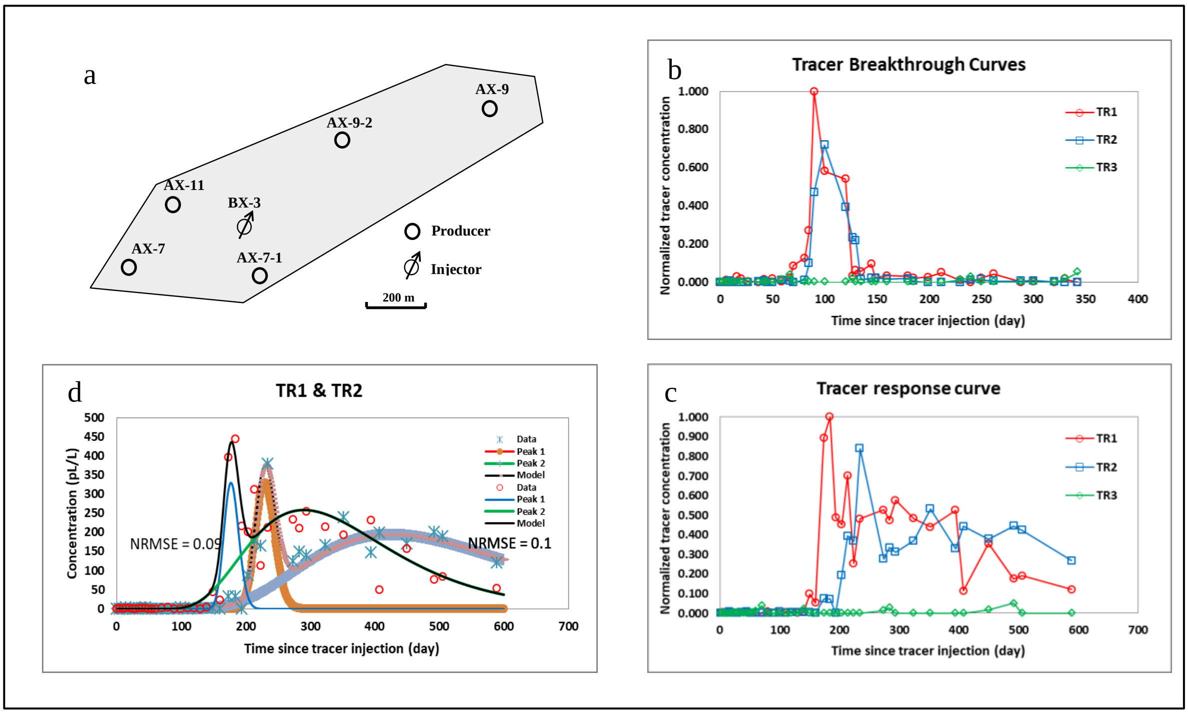



Figure 9. a- Well arrangement map. b, c- Tracer TR1 and TR2 response curves in well AX-7 and well AX-9, respectively; tracer TR3 was not detected. d- Matching of tracer response curve in AX-9 by using analytical model for further moment interpretation of heterogeneity and calculation of Sor.

## 4. CONCLUSIONS

The paper reviews the common applications of water and gas tracers in interwell study in oil reservoir. The case studies illustrated a number of useful data and information that the interwell tracer tests can bring to the reservoir management such as well to well connectivity, injection fluids distribution, trend flow and estimation of residual oil saturation. This information obtained exclusively by tracers is helpful for improving reservoir characterization, assessment of a flooding design or an EOR program.

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