Analysis, Interpretation, and Design of Inter-Well Tracer Tests in Naturally Fractured Reservoirs

Aymen A. Alramadhan*, Ufuk Kilicaslan, David S. Scheckter

Harold Vance Department of Petroleum Engineering, Texas A&M University, College Station, Texas, USA

*aymen.alramadhan@pe.tamu.edu; ufuk.kilicaslan@pe.tamu.edu; david.scheckter@pe.tamu.edu

Abstract

In order to understand the complex fracture network that controls water movement in a developed area within Spraberry Trend in West Texas and to better manage the on-going waterflood performance, a field scale inter-well tracer test was implemented. This test presents the largest inter-well tracer test in naturally fractured reservoir reported in the industry and includes the injection of 13 different tracers and sampling of 110 producers in an area covering 6533 acres.

This inter-well tracer test generated a total of 598 tracer responses from 52 out of the 110 sampled producers. Tracer responses showed a wide range of velocities from 14 ft/day to ultra-high velocities exceeding 10,000 ft/day with same-day tracer breakthrough. Re-injection of produced water has caused the tracers to be re-injected and added an additional challenge to diagnose and distinguish tracer responses affected by water recycling. This paper investigated analytical, numerical, and inversion modeling approaches in order to categorize, history match, and connect tracer responses with water-cut responses with the objective to construct multiple fracture realizations based entirely on water-cut and tracers’ profiles. In addition, the research highlighted best practices in the design of inter-well tracer tests in naturally fractured reservoirs through lessons learned from this test.

Results indicated that tracer responses could be categorized based on statistical analysis of tracer recoveries with each category showing distinguishing behavior in tracers’ movement and breakthrough time. In addition, it showed that tracer and water-cut responses in the lease are dominantly controlled by the fracture system revealing minimum information about the matrix system. Numerical simulation studies showed limitations in dual porosity formulation/solvers to model tracer velocities exceeding 2200 ft/day. Inversion modeling using Gradzone Analysis showed that east and north-west of the developed area have significantly lower pore volume compared to south-west.

Keywords

Inter-well Tracer Test; Tracer Response; Fractures Characterization; Naturally Fractured Reservoirs

Introduction

The successful implementation of tracer tests in the areas of petroleum reservoirs and groundwater fields over the years has made those types of tests very reliable tool for reservoir description and characterization. Unlike pressure transient tests which provide a low resolution description of the reservoir by averaging reservoir properties over the bulk drainage volume, tracer tests have the ability to capture small scale features making it suitable for a more detailed and a higher resolution reservoir description. In secondary and enhanced oil recovery projects, the degree of success of economically recovering the remaining oil requires a robust understanding of fluid migration paths and recovery mechanism in the reservoir.

The majority of inter-well tracer tests have the main objective of assessing connectivity and direct communication between injectors and producers. Other important objectives of inter-well tracer tests include: identifying flow anisotropy in the reservoir, evaluating sweep efficiency, identifying flow barriers, characterizing areal reservoir heterogeneity, assessing reservoir layering, estimating fluid velocities, and determining offending injector(s) in case of channeling. Once any or all of these objectives are met, the reservoir engineer will be able to design and implement more efficient sweep improvement strategies [1,2,3].

2168-5517/15/02 097-26, © 2015 DEStech Publications, Inc.
doi: 10.12783/jpsr.2015.0402.05
When a pulse of injected tracer reaches the production well, the produced concentration will be a distributed tracer response curve. This is due to water movement in the reservoir through a distribution of flow paths and different flow rates within each path. A typical tracer response curve will show at least four distinctive landmarks as shown in Figure 1: breakthrough time, maximum concentration produced, variance of response, and mean of the distribution. Sweep efficiency is typically described in term of breakthrough time when it is plotted as a function of cumulative water injection rate. In a one dimensional homogenous system, breakthrough is a measure of the swept pore volume by injected water. In two or three dimensional heterogeneous system, breakthrough represents a measure of the swept volume by only the highest conductive path between injector and producer. A nearly instantaneous tracer breakthrough is an indication of fracturing. An early breakthrough with a sharp response is an indication of water channeling through a high permeability and thin stringer. A late breakthrough is an indication of poor communication or low transmissibility path between injector and producer \(^{(10)}\).

The peak tracer concentration produced represents the mode of the tracer’s velocities distribution while the variance of tracer distribution curve is dependent on local variation in flow velocity and/or on longitudinal dispersion. The mean of tracer distribution represents the mean volume of water injected\(^{(12,7)}\).

Several researchers showed that multiple peaks in a tracer response can be extremely informative for reservoir description. Abbaszadah \(^{(6,5)}\) showed that multiple peaks have strong correlation with the minimum number of layers to match the tracer response. In addition, he indicated that if multiple peaks are observed to be close in location to each other, it is an indication of substantial interference between layers contributing to tracer flow. Datta-Gupta et al. \(^{(39)}\) showed that multiple peaks in a tracer response could be interpreted in term of correlated and uncorrelated heterogeneity that reduce vertical and areal sweep efficiencies.

A thorough survey of the literature of large-scale interwell tracer tests in naturally fractured reservoirs is presented in Table 1 \(^{(20,21,22,23)}\). The survey indicated that most of the tests were qualitative in nature and the general conclusion was they were used only in a qualitative manner to assess injector-producer connectivity without taking advantage of other information carried within a full tracer response curve. The numerical simulation from Spraberry Trend Area as reported by Scheckter et al. indicated that extremely high fracture permeability (several darcies) was required to history match tracer breakthrough and magnitude \(^{(20)}\). The ensuing dual porosity simulation thus demonstrated the tremendous contrast between high fracture permeability and low average matrix permeability (less than 1 md) in the area as determined by extensive core data. Case study highlighted in this paper within Spraberry Trend Area in West Texas presents the largest inter-well tracer test in naturally fractured reservoir reported in the industry and includes the injection of 13 different tracers and sampling of 110 producers in an area covering 6533 acres. This inter-well tracer test generated a total of 598 tracer responses from 52 out of the 110 sampled producers. Case study presented in this paper is included in Table 1 for comparison purposes.

![FIGURE 1: EXAMPLE OF A TYPICAL TRACER RESPONSE](image-url)
### Background of Spraberry Trend

The Spraberry Trend Area in West Texas was considered to be the largest oil field in the world at the time of its discovery in 1949 with 8-10 billion barrels of original oil in place. Spraberry is composed of naturally fractured, low permeability siltstone which makes it problematic for both primary production and waterflooding. Based on primary recovery, its original recovery factor was projected to be less than 10%. This low anticipated recovery was the main drive to initiate waterflooding projects in several areas of Spraberry in late 1950s. Unexpectedly, waterflooding projects in Spraberry showed very limited success where areas subjected to more than 40 years of waterflooding showed less than 15% oil recovery. Reasons for the low waterflooding recovery are still not fully understood. Several hypotheses were developed to explain the wide-scale poor performance waterflooding. Those include: low matrix permeability and extensive fracturing, incorrect well pattern alignment, fracture mineralization, lack of pattern confinement and injection well density, low effective permeability to oil, and stress-sensitive fracture conductivity.

### Inter-well Tracer Test in the Developed Area within Spraberry Trend

#### Production History & Tracer Project Description

The developed area within Spraberry Trend was first put on production in mid of 1951. The oil production was dry for about 22 years until the first water breakthrough occurred in early 1973. Early water production data shows complex water-cut behavior indicating the presence of a complex fracture system. Example of such water-cut behavior is shown in Figure 2. Water injection in this lease started in January 1983 after around 32 years of primary depletion with one power water injector. Additional injector was introduced in 1990 and three more were introduced in late 2001/early 2002. Lease performance plots from July 1951 until March 2012 are shown in Figures 3 and 4.

In 2010, a decision was made to develop a large area of Spraberry using 11 inverted 9-spot patterns. In order to effectively manage the pattern water flood area as well as the area outside the pattern, 13 different non-reactive water tracers were injected through 13 injectors and 110 producers were water sampled. Objectives of this inter-well tracer test are to understand complex water movement in the reservoir, to assess injector-producer connectivity, and to understand sweep and fractures heterogeneity. The tracer test lasted for 114 days from start of first tracer injection in April 25, 2011 until the analysis of the last water sample in August 17, 2011.

#### Table 1: Comparison of Large-Scale Inter-Well Tracer Tests in Naturally Fractured Reservoirs

<table>
<thead>
<tr>
<th>Author</th>
<th>Field, location</th>
<th>Tagged injectors</th>
<th>Sampled producers</th>
<th>Number of Tracer Responses</th>
<th>Study Approach</th>
<th>Study Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitzberg et. al.</td>
<td>North West Fault Block, Prudhoe Bay, Alaska</td>
<td>22</td>
<td>53</td>
<td>&gt; 46</td>
<td>Qualitative</td>
<td>1992</td>
</tr>
<tr>
<td>McConnell et. al.</td>
<td>A Devonian Lower Nisku dolomite formation, Alberta, Canada</td>
<td>5</td>
<td>20</td>
<td>20</td>
<td>Qualitative</td>
<td>2002</td>
</tr>
<tr>
<td>Schechter, D.S. et. al.</td>
<td>Spraberry Trend, O’Daniel Unit, West Texas</td>
<td>6</td>
<td>29</td>
<td>45</td>
<td>Numerical Simulation</td>
<td>2002</td>
</tr>
<tr>
<td>Husain Zaberi et. al.</td>
<td>A giant carbonate oil field, Saudi Arabia</td>
<td>5</td>
<td>65</td>
<td>7</td>
<td>Analytical</td>
<td>2008</td>
</tr>
<tr>
<td>Alramadhan et. al</td>
<td>Spraberry Trend, West Texas</td>
<td>13</td>
<td>110</td>
<td>598</td>
<td>Analytical, statistical and numerical</td>
<td>2013</td>
</tr>
</tbody>
</table>
breakthrough was observed from the same day of tracer injection, and a total of 598 tracer elution curves were detected from 52 out of the 110 sampled wells. Tracer injection and sampling locations are shown in Figure 5. It should be noted that rose diagram in Figure 5 was built using core and dynamic data from nearby leases and the blue ellipses reflects areas where lease operator believe it is swept by injected water.

![Figure 2: Example of Early Complex Water-Cut Behaviour Observed Within Area Understudy](image1)

![Figure 3: Lease Oil and Water Production Rates and Lease Water-Cut with Time.](image2)
Anlysis, Interpretation, and Design of Inter-Well Tracer Tests in Naturally Fractured Reservoirs

**FIGURE 4: LEASE WATER INJECTION PERFORMANCE VERSUS TIME**

**FIGURE 5: TRACER SAMPLING & INJECTION LOCATIONS WITH FRACTURE ORIENTATION ROSE DIAGRAM. IN THIS TRACER INJECTION PROJECT, 13 INJECTORS WERE TAGGED WITH TRACERS, 110 PRODUCERS WERE SAMPLED AND A TOTAL OF 598 TRACER RESPONSES WERE OBTAINED BY END OF PROJECT.**
Effect of Water Recycling

In the test area, the produced water from all wells flows through surface pipelines to a re-injection facility. The re-injection of produced water has also caused the tracers to be re-injected and to affect the results of the tracer test. Measurement of tracers’ concentration at re-injecting facility has been made and reported as part of the test.

Analytical Tracer Interpretation Techniques

Analytical tracer interpretation techniques are any type of interpretation that does not require building and running numerical simulation models. This includes analyzing tracers responses using Method of Moments (MOM), searching for data patterns in tracer or water-cut responses, analyzing distributions of tracer recovered, tracer velocities, and tracers’ breakthrough time, assessing layering from multiple peaks in tracers’ responses, mapping observations, and making links between tracers responses and wells’ or lease performance.

Methods of Moment

Net swept volume calculations using moment analysis require three basic entries: produced tracer concentration, water production and injection rates during tracer production \(^{(7)}\). This is done for each injector-producer pair where tracer production is detected. In order to map directions of maximum swept volumes, all volumes were normalized by dividing by the maximum value. Figure 6 shows distribution of lease-wide net swept volumes (normalized). The full field distribution of normalized net swept volume appears to be very close to a normal distribution. This is most likely a reflection of the distribution of fracture properties within tracer-flow area which are the main drive of the sweep. Connecting wells that showed high swept volumes (normalized swept volumes ≥ 0.50) consistently show four major flow features oriented N76°E. These major flow features highlighted in green in Figure 7 were detected by 10 out of the 13 tagged injectors. For these 10 injectors to be widely spaced covering a large area of the lease and consistently detecting these four flow features, it is an indication that these flow features are inter-connected and governs the majority of injected water movement in the tracer test area. Honoring high swept volumes from Method of Moments and knowledge of fracture orientation from nearby areas, inter-connectivity could be explained by NE-SW fractures connecting each of 10 injectors with these four major flow features.

![Image](image.png)

**FIGURE 6:** DISTRIBUTION OF NET SWEPT VOLUMES FROM METHODS OF MOMENTS WAS FOUND TO BE CLOSE TO A NORMAL DISTRIBUTION. IT’S BELIEVED THAT THIS IS REFLECTIVE OF THE DISTRIBUTION OF FRACTURE PROPERTIES THAT CONTROLS WATER MOVEMENT WITHIN AREA UNDERSTUDY
Tracers Recoveries: Statistical Analysis & Categorizing Responses

Although the injection system was tagged with tracers, overall recovery was poor with none of the 13 injected tracers showing more than 10% recovery. Such low tracers’ recoveries are not expected in a reservoir where highly conductive fractures are believed to be the main drive for the high water-cut observed in the lease. The main reason for such poor tracers’ recoveries, as next sections will show, is that the developed area receives substantial water influx from injection activities in neighboring leases causing it to be excessively diluted. A summary of total tracer recovered for each of the 13 tracer is shown in Figure 8. Distribution of tracer recoveries for the 598 tracer responses obtained in this study is shown in Figure 9. As shown in Figure 9, majority of tracer responses in this inter-well tracer test exhibit less than 0.01% tracer recovery (52.2% of tracer responses). These responses show similarities in term of excessive dilution and non-peakng trend which suggest that they could be studied as one category. The next interval from 0.01-0.1% shows a different frequency trend compared to tracers with < 0.01% recovery. Similarities in the number of tracer responses observed within this interval suggest that these three intervals could be combined into one category. In a similar manner, tracer responses with recoveries between 0.1-0.5% as well as tracer responses with recovery higher than 0.5% could be combined into two additional categories. Although the last two categories still show low tracer recoveries, they are expected to be containing the maximum useful information about tagged water movement in developed area.
FIGURE 8: RECOVERIES IN PERCENTAGE OF EACH OF THE 13 INJECTED TRACERS. ALTHOUGH TRACERS TRAVELLED IN ULTRA-HIGH VELOCITY, NONE OF THEM EXCEEDED 10% RECOVERY. SIGNIFICANT PART OF THIS RESEARCH WAS DIRECTED TO EXPLAIN QUICK BREAKTHROUGH-LOW RECOVERY PHENOMENA.

FIGURE 9: HISTOGRAM OF RECOVERIES FROM ALL TRACERS’ RESPONSES (COLOURS REPRESENT 4 DIFFERENT RESPONSE CATEGORIES). LOW TRACER RECOVERY GROUPS HIGHLIGHTED IN YELLOW AND ORANGE SHOWED ANOMALIES IN TRACER RESPONSES REFLECTED THAT THEY WERE AFFECTED BY WATER RECYCLING. THIS RESEARCH CONCLUDED THAT MEDIUM TO HIGH TRACER RECOVERY GROUPS HIGHLIGHTED IN GREEN AND PURPLE SHOULD BE THE ONE TO BE USED IN CHARACTERIZATION AND RESERVOIR MANAGEMENT.

**Linking Tracers Recoveries to Wells’ Water Performance**

To illustrate quantitatively the significance of tracers in explaining wells’ water performance, one inverted nine spot pattern is taken as a case study (Figure 10). Enclosed in this pattern area one of the unique tracer responses
where the pair “X1011- X1003” showed the highest tracer concentration produced in this inter-well tracer test. In addition, this pattern showed a total of 77 responses obtained from 7 out of its 8 producers. Tracer responses in this pattern are in the range of 0.001-2.1% which covers the four tracer recovery categories defined earlier. In this case study, water production from each well in the pattern is decomposed into two components: tagged water rate and untagged water rate. The tagged water rate is the water being contributed by all of the tracer-tagged injectors and is calculated by simply multiplying tracer recovery of each injector with its injection rate. The untagged water rate is the water rate of the well after removing the water flowing from tagged injectors. This is used to analyze the significance of tracers in explaining wells water production.

This inverted nine spot pattern highlights several aspects of the tracer test area. First, tracer recovered explains only 8% on average of pattern water production which raises a question about where the injected water is going. Second, water-cuts of producers in the pattern are high raising a question about the source of the water produced. Third, for a field where water injection rates are in the range of 120-390 bbls/day, tracer recoveries < 0.1% reflect infinitesimally small water movement of a fraction of a barrel. Modeling this scale of volumes is irrelevant and does not fit the purpose of this study. Thus, these tracer responses will not be mapped or simulated and more focus will be put on responses with tracer recoveries of “0.1-0.5%” and “0.5%+”. Forth, preferential path for tracers in the developed area is in the NE-SW and E-W direction reflecting major fracture system carrying injected water in this direction. Tracer movement through an N-S or NW-SE direction does exist but it is rare. Fifth, pattern producers located on the E-W fracture system show strong connection with 9 out of the 12 tagged injectors outside the pattern. This was indicated by moderate tracer recoveries and it reflects a complex and inter-connected fracture network where far injectors as well as nearby injectors have a direct impact on pattern performance. The nature of this fracture network will be investigated in more depth in next sections when tracers from all other producers are mapped.

**Patterns in Tracers Responses**

**Tracers’ Velocities**

A histogram of all tracer velocities of this inter-well tracer test is shown in Figure 11. The distribution covers a wide range from zero velocities to ultra-high velocities of 13,288 ft/day with majority of observations lying in the lower
velocities interval. For responses unaffected by water recycling, velocity distribution is very close to a tri-modal normal distribution (Figure 12). The three normal distributions most likely reflect three sets of fracture systems each with different mean connectivity and fracture pore volume. This distribution can be an effective tool for future fracture characterization studies as it provides an estimate of number of active fracture sets as well as average properties for each. Basis for selecting tracer responses unaffected by water recycling is discussed in detail in next section.

FIGURE 11: THREE TRENDS OBSERVED IN DISTRIBUTION OF TRACERS' VELOCITIES. THE DISTRIBUTION COVERS A WIDE RANGE FROM ZERO VELOCITIES TO ULTRA-HIGH VELOCITIES OF 13,288 FT/DAY WITH MAJORITY OF OBSERVATIONS LYING IN THE LOWER VELOCITIES INTERVAL.

FIGURE 12: TRI-MODAL DISTRIBUTION OF TRACERS' VELOCITIES OBSERVED WITHIN RESPONSES WITH 0.1-0.5% RECOVERY. THE THREE NORMAL DISTRIBUTIONS MOST LIKELY REFLECT THREE SETS OF FrACTURE SYSTEMS EACH WITH DIFFERENT MEAN CONNECTIVITY AND FrACTURE PORE VOLUME. THESE DISTRIBUTIONS CAN BE AN EFFECTIVE TOOL FOR FUTURE FrACTURE CHARACTERIZATION STUDIES AS IT PROVIDES AN ESTIMATE OF NUMBER OF ACTIVE FrACTURE SETS AS WELL AS AVERAGE PROPERTIES FOR EACH.
Tracers’ Breakthrough Time

The global distribution of tracer breakthrough time is shown in Figure 13. It shows that majority of tracer responses were obtained in the first two weeks of the project (64% of tracer responses). In addition, it shows a systematic discontinuity starting from the third week of the test and continues in a cyclic manner. This study showed that this cyclic behavior is only seen for tracer responses with both anomalies and very low recovery (<0.1%). It was concluded that this behavior is associated with water recycling. As a result, only tracer responses obtained during the first two weeks of the test were used for fracture characterization as those are less affected by water recycling.

![Graph showing tracer breakthrough time distribution.]

FIGURE 13: DISTRIBUTION OF TRACERS’ BREAKTHROUGH TIME SHOWS THAT MAJORITY OF TRACER RESPONSES WERE OBTAINED IN THE FIRST TWO WEEKS OF THE PROJECT (64% OF TRACER RESPONSES). IN ADDITION, IT SHOWS A SYSTEMATIC DISCONTINUITY STARTING FROM THE THIRD WEEK OF THE TEST AND CONTINUES IN A CYCLIC MANNER. THIS RESEARCH SHOWED THAT TRACERS RESPONSES OBTAINED WITHIN THIS INTERVAL WERE A RESULT OF WATER RECYCLING.

Single Peak & Multi-Peak Responses

Multiple peaks in a tracer response reflect the degree of layering in the reservoir system. To evaluate how many layers are needed to explain tagged water movement within the developed area of Spraberry Trend, the number of peaks for all early tracer responses occurring during the first two weeks of the tracer test is evaluated and shown in Table 2 below. In summary, majority of tracer responses show single peak tracer response (87.3% of total early responses). Thus, movement of tagged water from a given injector to a given producer could be explained most of the time by using a single layer model. Dual peaks and triple peaks tracer responses present only 11.4% and 1.3% of total early responses, respectively. These less frequent responses could be explained by two and three layers models. Table 3 shows that number of peaks in a tracer response shows a strong correlation with tracer recovery indicating that as tracer recovery increases, the higher resolution the tracer response provides about the layering of the system.

<table>
<thead>
<tr>
<th>No of peaks</th>
<th>Frequency</th>
<th>Relative Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>329</td>
<td>87.3%</td>
</tr>
<tr>
<td>2</td>
<td>43</td>
<td>11.4%</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>1.3%</td>
</tr>
</tbody>
</table>
TABLE 3: PEAKING IN TRACERS RESPONSES LINKED TO TRACER RECOVERY CATEGORY

<table>
<thead>
<tr>
<th>Tracer Recovery</th>
<th># of peaks</th>
<th>Frequency</th>
<th>Relative Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.01%</td>
<td>1</td>
<td>119</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.01-0.1%</td>
<td>1</td>
<td>158</td>
<td>94.6%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>9</td>
<td>5.4%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.1%-0.5%</td>
<td>1</td>
<td>47</td>
<td>63.6%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>25</td>
<td>33.7%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2</td>
<td>2.7%</td>
</tr>
<tr>
<td>0.5%+</td>
<td>1</td>
<td>5</td>
<td>29.4%</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>9</td>
<td>52.9%</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3</td>
<td>17.6%</td>
</tr>
</tbody>
</table>

**Mapping Tracers Recoveries**

Mapping tracers recoveries highlighted two types of tracers movement in the reservoir: simple tracers movement and complex tracers movement. The simple tracers movement is indicated by high tracers recoveries and is limited to the vicinity of the injector’s wellbore in the E-W and NE-SW direction. On the other hand, the complex tracers movement was indicated by moderate tracers recoveries and it highlighted the flow of injected water outside the 11 patterns injection area. In addition, it highlighted the complex inter-connectivity between pattern injectors and pattern producers. Simple tacers movement indicated by high tracer recoveries is shown in Figure 14 while complex tracers movement indicted by moderate tacers recoveries is shown in Figure 15.

**FIGURE 14:** MAPPING FRACTURE NETWORK BY INTEGRATING ALL HIGH TRACER SHOWS. THIS FRACTURE NETWORK IS CONFINED WITHIN PATTERN INJECTION AREA
Developed Area Production Performance

Overall analysis of production performance highlights several aspects of this development area. First, lease water production closely follows the lease water injection indicating a poor waterflooding performance. Second, dry production wells covering almost entire development area are shifted to very high water-cuts in the range of 70-85% almost simultaneously in three months between July-September 2002. Third, nature of injected water breakthrough in this lease occurs simultaneously. This was observed from water breakthrough of 7 wells in 1973 and 44 wells in 2002. Fourth, no dry production is observed in development area after the global water breakthrough in 2002. Recent inverted 9-spot patterns introduced in 2010 show high initial water-cut and poor injection performance raising questions about the contribution of the water injected and the source of water produced.

A Highlight on Dry Production History

The analysis of water production rate of the groups of wells that exhibited simultaneous water breakthrough in 1973 and 2002 shows three key findings: first, the simultaneous early water breakthroughs without any active injection system in 1973 support the hypothesis of the presence of an external water source feeding the developed area. Second, two out of four active injectors during 2002 are responsible for majority of the group water production rate. This is evidenced by the match obtained between group water production rate and sum of wells injection rates (Figure 16). Third, when developed area was subjected to water injection shutdown for 8 months from late 2004 to mid of 2005, an abnormal increase in water-cut of several producers was observed. This abnormal increase in watercut was attributed to water influx to development area from an external water source.
Construction of Simulation Models

Multiple sectors and full-field simulation models were built in order to run sensitivities and to model different water-cut and tracer responses observed in the developed area. Cases investigated are summarized in Table 4 below. In general, objectives of building simulation models include:

1. Assessing flow path characteristics by matching tracer breakthrough and peak concentration through high resolution simulation models.
2. Assessing dilution and initial saturation uncertainty
3. Using pseudo wells to model loss of tracer & injected water outside study area.
4. Assessing average reservoir properties capable of explaining wells’ performance

**TABLE 4: SUMMARY OF SIMULATION CASE STUDIES INVESTIGATED IN THIS STUDY**

<table>
<thead>
<tr>
<th>Case</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Study I</td>
<td>Matching abnormal tracers velocities</td>
</tr>
<tr>
<td>Case Study II</td>
<td>Modeling Tracer Flow outside Pattern Injection Area</td>
</tr>
<tr>
<td>Case Study III</td>
<td>Modeling moderate and relatively high tracer responses within development area</td>
</tr>
<tr>
<td>Case Study IV</td>
<td>Modeling Simultaneous field-wide water breakthrough observed in year 2002</td>
</tr>
<tr>
<td>Case Study V</td>
<td>Full Field Simulation Model to capture water and tracers movement</td>
</tr>
</tbody>
</table>

**Case Study I: Matching Abnormal Tracers Velocities**

Tracer flow between the well pair ‘S1012 – R-18’ exhibited unique tracer response. Tracer traveled with a velocity of 8,900 ft / day toward well ‘R-18’ which exist outside patterns injection area. Tracer appeared 1 day after tracer injection with the first water sampled. Although breakthrough was fast, the tracer response exhibited excessive dilution showing tracer recovery of 0.3%. The tracer response and the locations of the two wells are shown Figure 17.

As sensitivities showed that tracer breakthrough time is primarily driven by fracture pore volume, Figure 18 below shows the linear relation observed while attempting to match tracer breakthrough time by changing (ϕ h). The slope of the line remains constant as long as the drawdown between the two wells remains unchanged. This linear
relation obtained through large number of simulation runs indicates that a breakthrough of 1 day is not mathematically possible using fracture properties alone. This supports the hypothesis of the presence of an external water source flowing to the developed area which creates both higher tracer velocities and excessive dilution. This phenomenon is modeled by introducing a pseudo injector and a pseudo producer acting 1000 feet away from development area to create a high drawdown across it. Figure 19 shows how the linear relation between \((\phi_f \cdot h)\) product and tracer breakthrough time changes under different influx conditions. Due to numerical limitations, the maximum achievable tracer velocity was 2,225 ft / day which represents only 25% of the actual velocity observed.

**FIGURE 17:** RESPONSE OF TRACER TRAVELLED OUTSIDE PATTERN INJECTION AREA WITH ABNORMAL VELOCITY OF 8900 FT/DAY (1 DAY BREAKTHROUGH). THIS RESPONSE IS STUDIED IN DEPTH IN SIMULATION CASE STUDY #1

**FIGURE 18:** LINEAR RELATION OBSERVED BETWEEN TRACER BREAKTHROUGH TIME AND \((\phi_f \cdot h)\) DURING MATCHING TRACER RESPONSES.
Case Study II: Modeling Tracer Flow outside Pattern Injection Area

Matching moderate tracer velocities in the range of 669 – 853 ft/day was achievable by modifying \((\phi F_H)\) product as mentioned in the previous case. Peak concentration was matched by modifying concentration injected to account for dilution caused by water flow from nearby injectors. Figure 20 shows the example of a tracer response match between the pair ‘S2114 - R18’ using a fracture porosity-thickness product of 0.006. Assuming a fracture porosity of 0.5%, these tracers reflect movement in highly stratified and fractured thin layers with 0.6-1 ft extending for vast distances outside tracer study area.
Case Study III: Modeling Moderate and Relatively High Tracer Responses within Development Area

In a similar manner to case study II, tracer responses were matched by modifying \((\phi \cdot h)\) product of the layer and by accounting for dilution from nearby wells. Both moderate and relatively high recovery tracer responses reflect movement of tagged water in highly stratified and fractured thin layers. Moderate tracer recoveries reflect movement of tagged water in a layer with \((\phi \cdot h)\) product in the range of 0.5 to 1.0x10⁻³ ft. On the other hand, tracer responses with relatively high recovery reflect movement of tagged water in a relatively thicker layer with \((\phi \cdot h)\) product in the range of 0.85 to 3.0x10⁻³ ft. Example of tracer match is shown in Figure 21.

![Figure 21](image)

**FIGURE 21** (SIMULATION CASE STUDY #3): TRACER RESPONSE MATCH FOR WELL PAIR ‘S1202 – S1809’ WITH MAP SHOWING THEIR LOCATIONS. TRACER MATCH PROVIDES A SOLUTION OF THE PRODUCT OF \((\phi \cdot H)\) BETWEEN THE PAIR OF INJECTOR AND PRODUCER.

Case Study IV: Modeling Simultaneous Field-wide Water Breakthrough

A simulation model was built with the objective to match the simultaneous field-wide water breakthrough and the water production performance of 44 producers from 2002-2009. Two approaches to model the problem were followed: first approach is to model wells performance using initially dry simulation model (initial saturation = Swir). Second approach is to model wells performance using initially wet simulation model (initial saturation > Swir).

The first approach has the advantage of capturing the early dry production of all wells. It showed some success in matching the water breakthrough time but did not show an acceptable water-cut match. Figure 22 below shows the best obtainable match for total water production rate using the first approach. It indicates that to achieve such quick water breakthrough, the pore volume of the system has to be very small in the range of \((\phi h)\) product of 0.75 or below.

The second approach has more flexibility to model water performance after breakthrough. It showed a remarkable success in matching the water production performance but leaves the early dry oil production period unexplained. Figure 23 shows multiple matches of development area water production and water-cut, respectively. The multiple matches indicate two important findings: first, water performance is dominantly driven by average water saturation in the matrix-fracture system. Second, the reservoir has a moderate matrix pore volume system of \((\phi h)\) product of 1.65. Different combinations of matrix porosity and thickness with the same product yield identical solution.
**Case Study V: Full Field Simulation Model**

A full field simulation model was built in order to model simultaneously the 13 tracers injected as well as performances of all producers and injectors in development area. The selection of full field boundary was done with precaution as tracer results showed interaction and ultra-high velocity gradients between tracer study area and surrounding. A selection of full field area should enclose all nearby water injection activity to capture history.
of early water movement in the lease. The boundary for the full field model chosen for this study is shown in Figure 24 below and it includes 23 injectors and 195 producers. The overall objectives of full field simulation model include:

1. Assess average reservoir properties capable of explaining wells’ performance.
2. Investigate the modeling of 13 different tracers simultaneously using a full field simulation model.
3. Investigate well interference through fracture system and its effect on tracer solution.

Attempts to study tracer responses using full field simulation model have not been successful. The main reason behind such unsuccess is the extreme sensitivity of tracer solution to size of gridcells and to any convergence problem encountered by simulator. Due to this extreme sensitivity of tracer solution, a decision was made to use the full field model only to match water-cut responses.

Sensitivity runs showed that water-cut response is driven dominantly by three parameters: initial water saturation of matrix-fracture system, thickness, and matrix porosity. While initial saturation could be inferred from initial water-cut of the well, average matrix porosity and thickness of the lease is estimated by trial and error. A matrix porosity-thickness product of 1.65 was found to match performance of several wells covering large area of the lease.

![Figure 24: Boundary of Full Field Simulation Model Selected for the Study](image)

**Inversion Modeling Approaches**

The process of history matching where parameters controlling reservoir performance is modified until an acceptable match is achieved between simulated response and observed performance data is a process that has been performed traditionally by trial and error. With the advancement of computational capabilities and optimization approaches, new tools were developed to assist the reservoir engineer in such a process \((179)\). These tools define an objective function based on the difference between observed data and simulated responses, and use gradient-based optimization techniques to minimize the objective function \((199)\). In this study, the objectives of inversion modeling can be summarized as follows:

1. Invert water-cut responses to predict fracture properties governing flow in reservoir.
2. Create multi-layer heterogeneous models through simultaneous or sequential inversion of water-cut responses.
3. Investigate applications of inversion modeling in naturally fractured reservoirs.

**Methodology**

Bissell (1980) proposed a “Gradzone Analysis” method which uses gradient information to guide reservoir engineer in choosing reservoir parameters to modify. This method is based on spectral analysis of the second derivative of the objective function (Hessian Matrix). Hessian Matrix is constructed using a quadratic approximation of the objective function near a minimum. In general, Gradzone Analysis is a procedure for selecting zones in a reservoir model to apply a common multiplier to a particular reservoir property for all grid cells within a zone. Typically, the reservoir property is pore volume (e.g. porosity) or transmissibility (e.g. permeability). Two case studies are presented in this paper which are summarized in Table 5.

<table>
<thead>
<tr>
<th>Case</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Study I</td>
<td>Modeling Simultaneous field-wide water breakthrough observed in year 2002</td>
</tr>
<tr>
<td>Case Study II</td>
<td>Inverting water-cut performance of a tracer-confined Pattern</td>
</tr>
</tbody>
</table>

**Case Study I: Modeling Simultaneous Field-wide Water Breakthrough**

Earlier in this paper, the simultaneous water breakthrough of 44 wells in 2002 was studied both analytically and by constructing simulation models. This case could also be investigated by the use of inversion modeling as linking produced water with only three active injectors simplifies the problem. Observed water-cut data from the 44 wells were given equal weights and the property chosen to be inverted was the pore volume of the fracture/matrix system. Sensitivity of solution to inversion design was investigated by changing number of simulation layers, number of Gradzones, number of sampling cells, and which property to invert. The optimum solution was obtained by sequentially inverting a two-layer model which showed a reduction of the objective function by 17% compared to 2.3% for a single layer model. Figure 25 shows the final match of group water performance of the wells compared to pre-inversion solution and one-layer inversion solution. Figure 26 shows pore volume heterogeneity for the two layers after sequential inversion.

![Figure 25](image-url)
Case Study II: Inverting Water-cut Performance of a Pattern

A high resolution sector model was built for one inverted 9 spot pattern that showed confined and moderate concentration tracer responses. For the objective function, observed water-cut data from three key wells were given equal weights and the property chosen to be inverted was the pore volume of the system. Figure 27 below shows the locations of the three key wells used in the objective function. Investigating different inversion designs under variable initial water saturation, the optimum solution was obtained by inverting a one-layer model which showed a reduction of the objective function by 13.3%. Figures 28 and 29 show the model heterogeneity and wells’ performance before and after inversion.
FIGURE 27 (INVERSION CASE STUDY #2): PATTERN USED FOR WATERCUT INVERSION

FIGURE 28 (INVERSION CASE STUDY #2): MATRIX / FRACTURE PORE VOLUME AFTER WATERCUT INVERSION OF A TRACER-CONFINED PATTERN. INVERSION RESULTS SHOW THAT MAJORITY OF PORE VOLUMES WITHIN PATTERN ARE CONCENTRATED AROUND THREE KEY PRODUCERS. THIS EXPLAINS THE CONFINEMENT OF THE TRACER USED IN THIS CASE STUDY.
Design Aspects of Inter-well Tracer Test

Lessons learned from this inter-well tracer test could be summarized as follows:

1. Volume of injected tracers used was excessively large. Only 18% of the volumes used were required to capture and characterize the complex fracture network in the field. Using a combination of low detection limit and excessive tracer volume was the main reason of creating high number of excessively diluted responses that added no value to characterization process.

2. Sampling of water produced should start from same day of tracer injection in order to avoid missing breakthrough time of ultra-high velocity tracers.

3. Sampling of water produced for tracer concentration measurements should have been terminated by the second week when majority of tracers responses turned to be intermittent and excessively diluted. This could have saved 87.7% of operating time without effecting test interpretation.

Conclusions

The research presented in this paper could be workflowed into three key phases: analytical interpretation, numerical modeling, and inversion modeling phase. Analytical interpretation phase was successfully used to achieve several key objectives: first, to build a robust pre-simulation understanding of preferential water movement directions within pattern area under study. Second, it was used as a data mining exercise to classify which group of tracer responses carries the most useful information in characterizing and managing the lease. Third, it helped to identify tracer responses highly affected by water recycling. Fourth, it identified a common direction where injected water is leaving the inverted 9-spot pattern development area to outside the lease.

For numerical simulation phase: first, it was used to investigate tracer flow formulation in dual porosity media to identify what reservoir characterization information is carried within a tracer response. Second, it was used to test limitations of dual porosity formulation to model ultra high velocities tracers. Third, it was used to test modeling 13 different tracers simultaneously in a full-field case.

For inversion modeling phase, an attempt was made to test capabilities of dual porosity inversion packages on a pattern level where tracers showed confined injection as well as on a field level to capture the nature of simultaneous water breakthrough observed in the field.

Conclusions based on the research findings could be summarized as follows:

1. Maximum sweep directions obtained from Methods of Moments indicate the presence of four major interconnected flow features oriented N76°E governing water movement in the field.
2. Poor overall tracer recovery with none of the 13 injected tracer recovered by more than 9%.
3. Tracers recovered explain no more than 10% by average of patterns’ water production
4. Tracers responses could be categorized into four groups based on the distribution of tracer recovery for all tracers’ responses.
5. Studying patterns of tracer responses based on tracer recovery highlights several aspects:
   a. Tracer responses with less than 0.01% recovery are highly affected by water recycling. As tracer recovery of the tracer response increases, the water recycling effect decreases.
   b. Velocity distribution of responses unaffected by water-recycling shows a tri-modal normal distribution. These distributions could serve as a powerful tool for future fracture characterization studies to estimate average properties of each set of fracture.
   c. Number of peaks in a tracer response correlates strongly with tracer recovery. This indicates that a higher recovery tracer response captures more the layering between a pair of injector and producer.
6. The development area within Spraberry Trend receives water influx from an external water source. This is supported by the following observations:
   a. The extensive instantaneous dilution and the abnormal tracer velocity of 8,900 ft/day for a tracer travelled across the lease outside pattern injection area.
   b. The absence of a mathematical solution using dual porosity formulation to describe a tracer velocity of 8900 ft/day based on fracture properties alone.
7. Breakthrough time of tracer responses provides a solution for (h/f) of the fracture layer. Peaks of tracer responses are highly affected by dilution and are not a reliable measure of any fracture property.
8. All investigations carried through numerical simulation modeling highlighted that the lease of dynamic response is dominantly governed by fractures revealing minimum information about the matrix system. Such very weak fracture-matrix communication is most likely caused by high degree of fracture mineralization.
9. Majority of pattern injectors, 6 out of 11, show that part of the injected water flow outside the development area toward east. Although tracers indicate small volumes, these volumes could be underestimated by excessive tracer dilution
10. Inversion modeling results show that north-east and west side of the lease have very low pore volume compared to the south-east. North-east and west side of lease have 2% and 35% of the pore volume existing in the north-east, respectively.

ACKNOWLEDGMENT

The authors would like to express their gratitude to Dr. David S. Schechter for his continuous support and encouragement to publish this work and for Harold Vance Department of Petroleum Engineering at Texas A&M University for all resources that made this work where it is today.

REFERENCES


Aymen A. Alramadhan is Reservoir Engineer working for Saudi Aramco since 2008. He is an active member of multi-disciplinary team managing offshore fields at Saudi Aramco. As Petroleum Engineer, Aymen worked as petro physicist, reservoir simulation, and well testing engineer on various giant oil fields owned by the company.

In 2008, he received his B.Sc. degree in Petroleum Engineering from King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia and in 2013, Aymen received his M.Sc. degree in Petroleum Engineering from Texas A&M University, College Station, U.S.

Ufuk Kilicaslan is a Reservoir Engineer working for Turkish Petroleum Corporation (TPAO), national oil company of the Republic of Turkey in Ankara. He actively involves in developing reservoir models for overseas exploration blocks and ongoing international projects of the company.

He received his bachelor’s degree of science in Petroleum and Natural Gas Engineering from Middle East Technical University, Ankara, Turkey in 2010. After getting scholarship from TPAO, he received his M.Sc. degree of Petroleum Engineering from Texas A&M University, College Station, U.S., in 2013.
David S. Schechter is Aghorn Energy Career Development Professor and Associate Professor of Petroleum Engineering at Texas A&M University, College Station, Texas. His research interests are Spraberry Trend Area, geological and petrophysical analysis, wettability determination and imbibition experiments, numerical modelling and reservoir simulation, and CO2 flooding and gas injection.

He received his B.Sc. degree in Chemical Engineering from The University of Texas at Austin, Austin, U.S. in 1988 and his Ph.D. degree in Physical Chemistry from Bristol University, England in 1988. He headed the Naturally Fractured Reservoir Characterization/Engineering group at the New Mexico Institute of Mining and Technology for 7 years. He has been involved in an extensive reservoir characterization effort in the naturally fractured Spraberry Trend Area which has involved geological, petrophysical, logging interpretation, core-flooding and simulation studies. He also spent five years at the Petroleum Engineering Department at Stanford University as a Post-Doctoral Research Associate and Assistant Professor.