

# Simulation of single well tracer tests for surfactant–polymer flooding

Peter X. Bu · Abdulkareem M. AlSofi ·  
Jim Liu · Lajos Benedek · Ming Han

Received: 19 May 2014 / Accepted: 13 October 2014 / Published online: 31 October 2014  
© The Author(s) 2014. This article is published with open access at Springerlink.com

**Abstract** A single well tracer test (SWTT) is a method to investigate the residual oil saturation near the wellbore. It presents an important tool to evaluate enhanced oil recovery (EOR) processes. For EOR evaluation, two SWTTs (one before and another after EOR application) can be used to estimate the reduction in  $S_{or}$  due to the application of an EOR process. The change in  $S_{or}$  is a measure of the incremental oil recovery of the applied EOR technology. In this work, we use University of Texas Chemical Flooding Simulator to guide the design of SWTTs that will be later run to evaluate chemical flooding potential. First, we perform thorough sensitivity simulations using an idealistic homogeneous model. Second, we perform simulations using a realistic model, which was generated based on the selected evaluation well (Well-X). In the sensitivity runs, we investigate the effects of various parameters such as partitioning coefficients, reaction rates, injection rates, injection volumes, and shut-in times. Based on the results, we provide recommendations for designing the SWTTs. Furthermore, simulations using the Well-X model suggest an incremental oil recovery factor of 14.7 % OOIP due to surfactant-polymer flooding. This is consistent with lab data and provides assurance to multi-well field applications. More importantly, those simulation results support the utility of SWTTs in evaluating chemical flooding potential. Based on the results, we expect to observe distinct back-production peaks, clear separation between the reactive and product tracers, and measurable variation in separation due to chemical EOR application that can be categorically analyzed.

**Keywords** Chemical flooding · EOR · Tracer · Single well · Simulation

## List of symbols

SWTT	Single well tracer test
EOR	Enhanced oil recovery
CEOR	Chemical enhanced oil recovery
OOIP	Original oil in place
ROS	Residual oil saturation
PV	Pore volume
$K$	Partition coefficient of reacting tracer
$\beta$	Retardation factor
$Q_r$	Cumulative produced volume of reacting tracer concentration arrival peak
$Q_p$	Cumulative produced volume of product tracer concentration arrival peak
$S_{oi}$	Initial oil saturation
$S_{or}$	Residual oil saturation
$h$	Target formation thickness (ft)
$T$	Reservoir temperature (°F)

## Introduction

A single well tracer test (SWTT) is a method for measuring residual oil saturation near the wellbore. It provides an efficient mean of confirming laboratory results at the well-scale and in situ (in the reservoir). This method is non-destructive (i.e., after the test, the formation is returned to its original condition). For this reason, multiple oil saturation measurements from a single well are feasible (Oyemade 2010).

The use of tracers for saturation measurement depends on chromatographic retardation of two tracers, one is

P. X. Bu · A. M. AlSofi (✉) · J. Liu · L. Benedek · M. Han  
Saudi Aramco, Dhahran, Saudi Arabia  
e-mail: abdulkarim.sofi@aramco.com

soluble in both water and oil and another only soluble in water. Thereby, when transported a given distance, the two tracers exhibit different times of flight (Tomich et al. 1973; Sheely 1982). In a single well application, one of those two tracers is generated in situ. This is done by injecting a reacting tracer, which is soluble in both water and oil. After the reacting tracer is pushed to the desired depth of investigation, the well is shut-in for few days to allow hydrolysis of the reacting tracer. Upon hydrolysis, this reacting tracer yields another (product) tracer that is only soluble in water (Cockin et al. 1998). In this way, before back production the two tracers are located at the same distance from the well. When the well is opened for production, the reacting tracer lags relative to the product tracer. This is due to the partitioning of the reacting tracer between the mobile aqueous phase and the stationary residual oleic phase (Haggerty and Schroth 1998). Thus, through monitoring effluent concentrations of the reacting and product tracers, the residual oil saturation can be determined from the time lag of the two peaks (Fig. 1).

An SWTT is typically performed in a production well with the following injection procedure:

- Water injection* to establish the water flooding residual oil saturation in the zone of investigation.
- Tracer injection* in which a water solution of the reacting tracer is injected. This solution typically includes two additional tracers: a cover tracer and a material balance tracer.
- Chase water injection* by which the reacting tracer is pushed to the desired depth of investigation. This

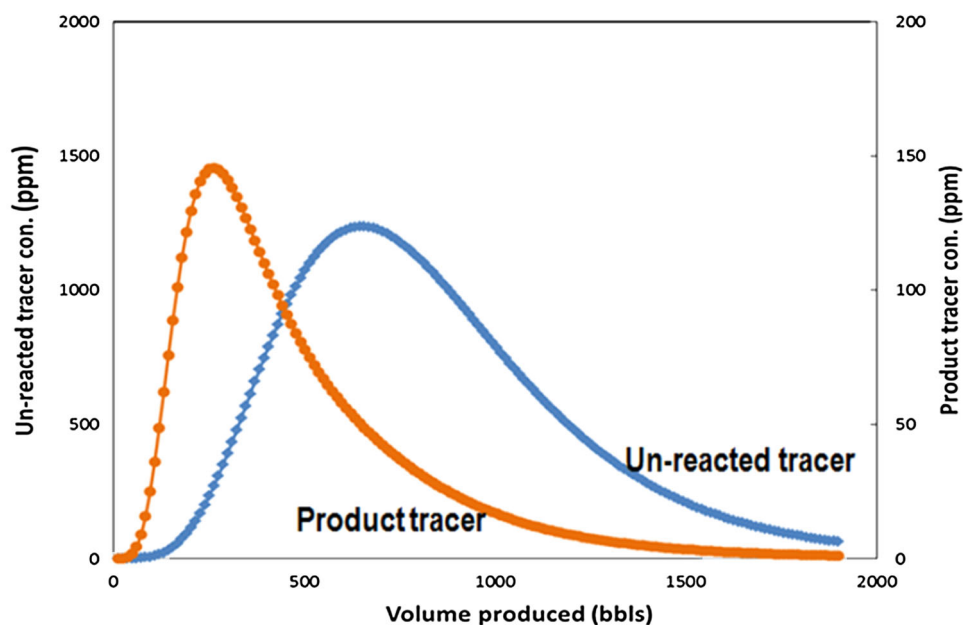
water solution will include the material balance tracer but not the cover tracer.

- Shut in* for two to seven to allow sufficient hydrolysis of the reacting tracer and hence detectable amounts of the product tracer and
- Back production and monitoring* for 1–3 days in which the produced liquid is sampled regularly to measure tracers' concentrations and establish their production profiles.

Clearly, an SWTT program involves many variables such as injection volumes and rates, shut-in time, and reacting tracer's concentration, reaction rate and partitioning coefficient. The design of a successful SWTT should consider the various variables in play in light of the inherent reservoir uncertainties especially those in residual oil saturation, heterogeneity, and dispersivity. An appropriate tracer in terms of reaction rate and partitioning coefficient needs to be used. More importantly, the program needs to allow sufficient injection volumes, and tracer back-production. Numerical simulation of SWTTs can guide the design of a successful SWTT.

In this paper, we present a simulation-based sensitivity study for the design of SWTTs. For this purpose, we use the University of Texas Chemical Flooding Simulator (UTCHEM) to investigate the effects of the various design parameters, tracer properties, and underlying uncertainties. UTCHEM was used because it has the capability of modeling a reactive partitioning tracer, as well as surfactant and polymer injection (Sheng 2011).

**Fig. 1** A Schematic single well tracer test back-production profiles



### The base SWTT simulation model

#### A radial grid

Initially, we tested both Cartesian and radial coordinate systems. We ran two simulation cases in both Cartesian and radial grids. The two cases had different gridblock sizes (Table 1). In the first case, refined cells of 1.5 ft were set around the wellbore, while in the second, larger cells of 3 ft were set around the wellbore. As expected, a Cartesian grid was not well suited for modeling a SWTT. A Cartesian grid substantially increases running time and additionally yields poor predictions. First, for models with equivalent volumes, the total number of cells in a Cartesian grid is 82 times greater than the number of cells in a radial grid. Consequently, a Cartesian grid required a much longer running time (two orders of magnitude higher than times spent using a radial grid, refer to Table 1). Second, in terms of the reactive and product tracers' profiles (Fig. 2), a big difference between the Cartesian and radial results was

evident. This is probably due to numerical dispersion and grid orientation effects.

#### Refined cells of 1 ft

For the radial grid, we performed preliminary simulations with varying gridblock refinements around the wellbore. Cells of 0.5, 1.0, 1.5, 2.0, and 3.0 ft ( $\Delta r$ ) were used. Figure 3 shows the simulation results in terms of the reactive and product tracers' profiles. As expected, due to lower numerical dispersion, higher peak concentrations are obtained with finer grids. However, in terms of the conventional SWTT interpretation which uses the reactive and product tracers' peaks to estimate residual oil saturations, an estimate of residual oil that is consistent with the simulation input value was obtained with refined cells of 1.0 ft.

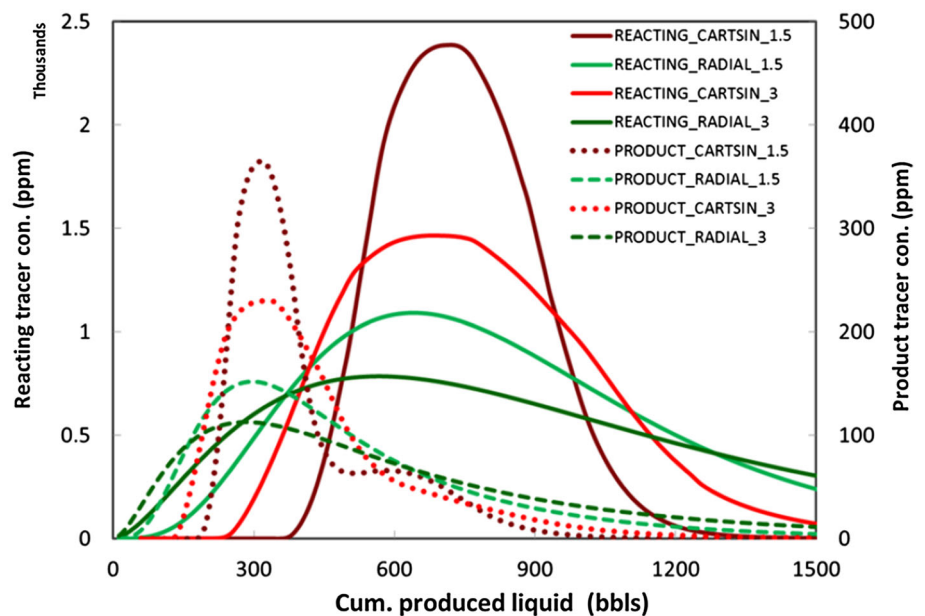
#### A 20 ft radius of investigation

Injection volume of a single well tracer test mainly depends on the tested interval thickness and the necessary investigation depth. However, large volumes take longer time for injection and back-flow. This can complicate the test results, and consequently increase the probability of failure. Smaller injection volumes yield more ideal shaped and easy to interpret profiles. The test size or volume to be injected is usually controlled by the production rate of the target well. The amount of water that can be produced in 1 day is a normal test volume, and 2 days production is considered as an upper limit (Deans and Carlisle 1988). For the given conceptual model, the investigation volume is

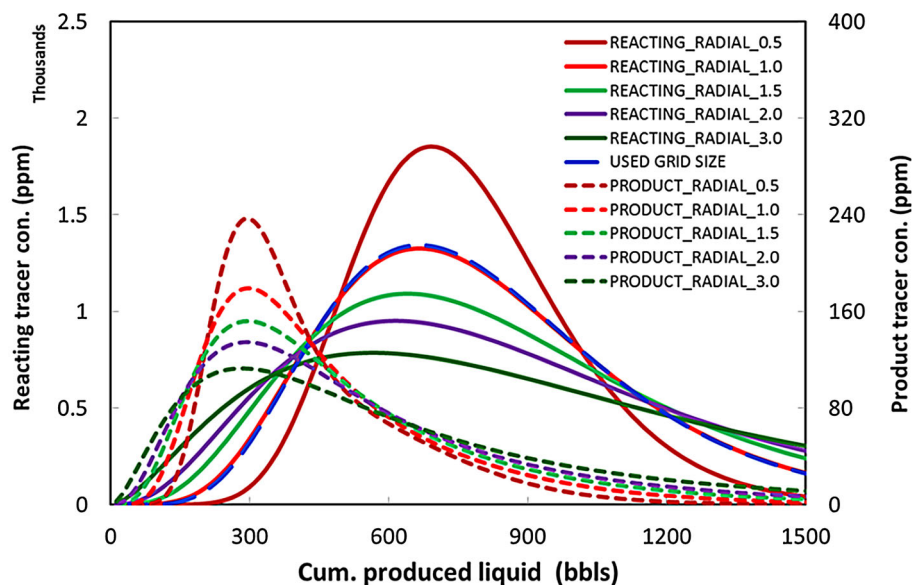
**Table 1** Details of cases under Cartesian and radial coordinate system

Grid	Cartesian		Radial	
	A	B	A	B
Number of cells	$91 \times 91 \times 15 = 124,215$		$100 \times 1 \times 15 = 1,500$	
Case	A	B	A	B
Refined cells size (ft)	1.5	3	1.5	3
Running time (s)	89,955	12,446	856	834

**Fig. 2** Coordinate system and grid refinement effects on simulated back-production profiles



**Fig. 3** Gridblock size effects on simulated back-production profiles



**Table 2** Input parameters for the base case

Parameter	Base case
Partition coefficient ( $K$ )	3
Injection time (day)	1
Reacting tracer volume (ft <sup>3</sup> )	650
Reacting tracer concentration (ppm)	10,000
Push bank volume (ft <sup>3</sup> )	3,700
Reaction rate (1/day)	0.05
Shut-in time (days)	2.5
Injection rate (ft <sup>3</sup> /D)	4,350
Production rate (ft <sup>3</sup> /D)	3,350

assumed to be 4,350 ft<sup>3</sup>, which is analogous to an investigation depth of 20 ft for an interval that is 15 ft thick.

#### The base model

Based on those preliminary results, a conceptual radial model with a radius of 5,245 ft and a thickness of 15 ft is used. 100 and 15 cells are used in the radial and vertical directions, respectively. The model is homogeneous with a porosity of 0.23 and a permeability of 600 mD. The remaining input parameters for the base model are shown in Table 2. In all simulations, unless otherwise stated, those base input parameters are used.

### SWTT sensitivity simulations and results

#### Reacting tracer concentration

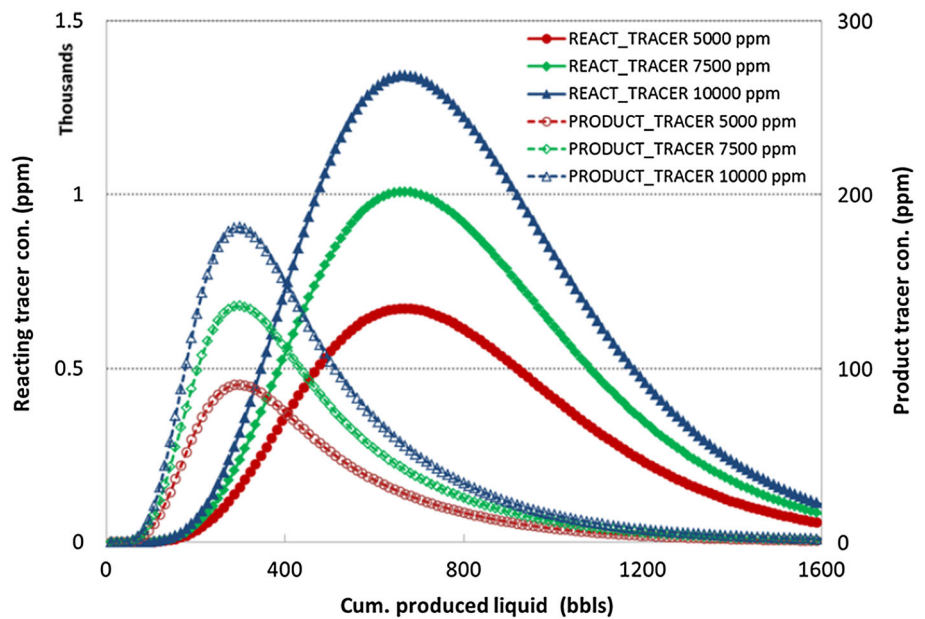
In a SWTT, the estimate of residual oil saturation depends on effluent concentrations of the reactive and product

tracers. The selection of the right injection concentration of the reactive tracer is thus important to generate a detectable amount of the product tracer and to avoid an overuse of the reactive tracer. To investigate the effects of reactive tracer injection concentration, three cases were simulated at concentrations of 5,000, 7,500, and 10,000 ppm. The results are shown in Fig. 4. At an injection concentration of 10,000 ppm, the product tracer concentration in the effluent is around 200 ppm. Therefore, an injection concentration of 10,000 ppm is recommended, which is close to SWTT data published in the literature (Table 3).

#### Partitioning coefficient

The partitioning coefficient ( $K$  value) defines the ratio of reactive tracer concentrations in the oil and water phases at equilibrium. It depends on the oil composition, injection water chemistry and reservoir temperature. A reactive tracer  $K$  value is measured in the laboratory through batch experiments and at multiple concentrations to ensure a relatively constant value over the range of concentrations expected through the test. A tracer that partitions strongly into the oil phase (i.e., large partitioning coefficient) would prolong the test duration. On the other hand, a tracer with a small partitioning coefficient makes discerning the differences in mean residence times difficult. It has been shown that errors can be minimized by appropriate selection of tracers based on their partitioning coefficient (Deans and Ghosh 1994; Shook and Ansley 2004). If the residual oil saturation is expected to be high, a tracer with a low  $K$  value can be selected and the test can be terminated earlier. If the residual oil saturation is low, a low  $K$  value tracer will not exhibit sufficient retardation for a unique estimate

**Fig. 4** Simulated back-production profiles for different injection concentration of the reacting tracer



**Table 3** Parameters from cases of other published paper

Case	h (ft)	EtAc		Push bank		Shut-in (days)	Salinity (ppm)	T (°F)	Reference
		Con.	(bbl)	Con.	(bbl)				
1	20	1.5 % V	550	0.5 % V	1,370	12	120,000	170	Tomich et al. (1973)
2	65.6	10,000	189	2,500	755	2.5	5,000	115	De Zwart et al. (2011)
3	160.7	9,000	1,000	2,400	4,044	4			De Zabala et al. (2011)
4	22	15,245	75	4,300	525	1.7	4,200	194	Hernandez et al. (2002)
5	32	9,000	135	1,700	570	4.5	200,000	100	Deans and Carlisle (1988)
6	45	7,000	135	12,700	550	5	43,000	234	Deans and Carlisle (1988)

of residual oil. The range of suitable  $K$  values has been suggested by Deans and Ghosh (1994)

$$\frac{0.5(1 - S_{or})}{S_{or}} \leq K \leq \frac{1.5(1 - S_{or})}{S_{or}} \tag{1}$$

and Shook and Ansley (2004)

$$\frac{0.2(1 - S_{or})}{S_{or}} < K < \frac{3(1 - S_{or})}{S_{or}} \tag{2}$$

For instance, with an expected  $S_{or}$  of 0.3, a suitable reactive tracer should have a partitioning coefficient between 1.2 and 3.5 based on Deans and Ghosh recommendation and between 0.5 and 7 based on Shook et al. recommendation.

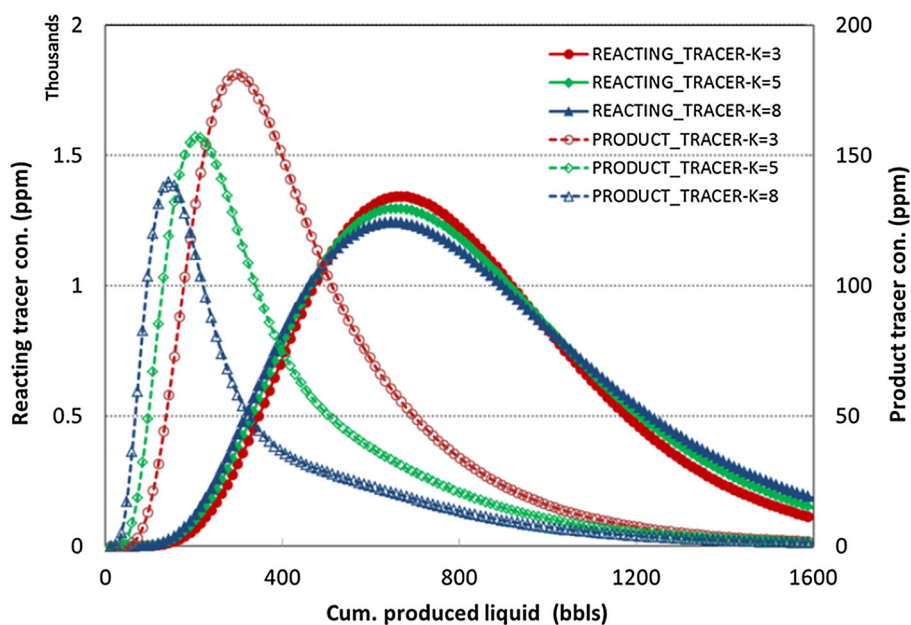
To investigate partitioning coefficient effects, five simulation cases were run with  $K$  values of 2, 3, 4, 5, and 8. Illustrative simulation results are shown in Fig. 5. First, the product tracer concentration decreases with an increasing partitioning coefficient. This is since with a higher partitioning coefficient a smaller amount of the reactive tracer is soluble in water and consequently, a smaller amount is

hydrolyzed to form the product tracer. Second, with an increasing partitioning coefficient, the separation distance (i.e., lag between the peak of the reacting and product tracers) increases. This is since a reacting tracer with a bigger partitioning have larger amounts soluble in the stationary oil phase, which results in an effective placement that is closer to the well.

#### Reaction rat

In a SWTT, the tracer reaction is a hydrolysis process (Wellington and Richardson 1994). A higher reaction rate leads to higher concentrations of the product tracer, and lower concentrations of the reacting tracer (Romero et al. 2012). If reaction rate is too high, much of the product tracer will be generated during the injection phase (rather than the shut-in phase), which affects the normal distribution of its back-production profile. On the other hand, a low reaction rate requires a longer reaction time (shut-in time) to form detectable concentrations of the product tracer.

**Fig. 5** Partitioning coefficient effects on simulated back-production profiles



To investigate reaction rate effects, we simulate five cases with different reaction rates of 0.005, 0.25, 0.05, 0.1, and  $1 \text{ day}^{-1}$ . Those reaction rates were selected based on the range of hydrolysis rates reported by Deans and Ghosh (1994). Illustrative simulation results were shown in Fig. 6a and b. When the reaction rate is higher than  $1.0 \text{ day}^{-1}$ , the reacting tracer concentration is too low and the product tracer concentration is too high. On the other hand, when the reaction rate is lower than  $0.005 \text{ day}^{-1}$ , the concentration of the product tracer is too low and difficult to monitor. For reaction rates between 0.025 and  $0.1 \text{ day}^{-1}$ , Fig. 6b, concentrations of both the product and reacting tracers are in the right range. In comparison to product tracer concentrations reported in the literature, it is reasonable to select a reacting tracer with reaction rates between 0.05 and  $0.1 \text{ day}^{-1}$ , for the target reservoir condition.

#### Shut-in time

Shut-in time is the period in which the reacting tracer is allowed to hydrolyze and form the product tracer. Five simulations were performed with different shut-in times of 1, 2, 2.5, 3, and 4 days. As expected, Fig. 7 shows that longer shut-in times lead to higher product tracer concentrations. In practice however, cross flow and dispersion (phenomena that are not accounted for in those five simulation runs) could disturb the residual oil saturation interpretation especially for a longer shut-in time. Therefore, and due to operational considerations, shut-in times should be reasonable. Based on the simulation results, a shut-in time between 2 and 3 days is sufficient to meet the

test requirement. Accordingly, the recommended shut-in time is 2.5 days.

#### Dispersivity

We simulate three cases with varying longitudinal dispersivities of 0, 0.5, and 1 ft. Figure 8 shows the simulation results. First, with an increasing longitudinal dispersivity, the peaks of both the reacting and product tracers shift to the left and the concentration profiles become more skewed. This can cause difficulties in interpretation of the SWTT results. Second, tracer concentrations decrease with an increasing longitudinal dispersivity.

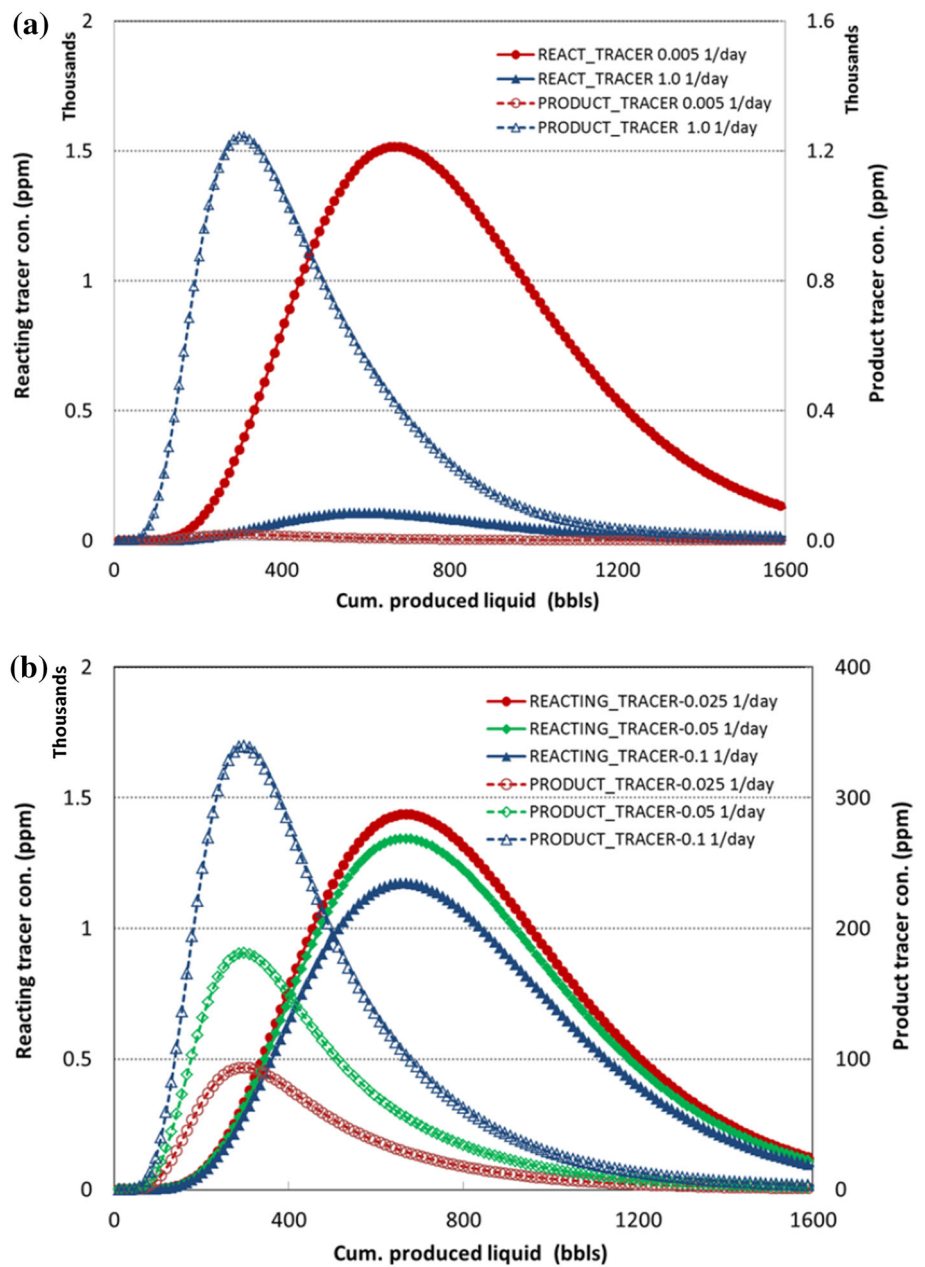
#### Residual oil saturation

The key task of a SWTT is to estimate the residual oil saturation. Cases were simulated to understand effects of different residual oil saturations. Residual saturations of 0.2, 0.28, and 0.35 were simulated and the associated relative permeability curves are shown in Fig. 9. Simulation results are shown in Fig. 10. The results indicate that with increasing residual oil saturation the peak of the product tracer shifts to the left, and consequently the separation distance (lag between the reacting and product tracer) increases. This is since a higher residual oil results in an effective placement that is closer to the well.

#### Shut-in time and reaction rate

There are close relationship between shut-in time and reaction rate. Low reaction rates need longer shut-in

**Fig. 6** Reaction rate effects on simulated back-production profiles



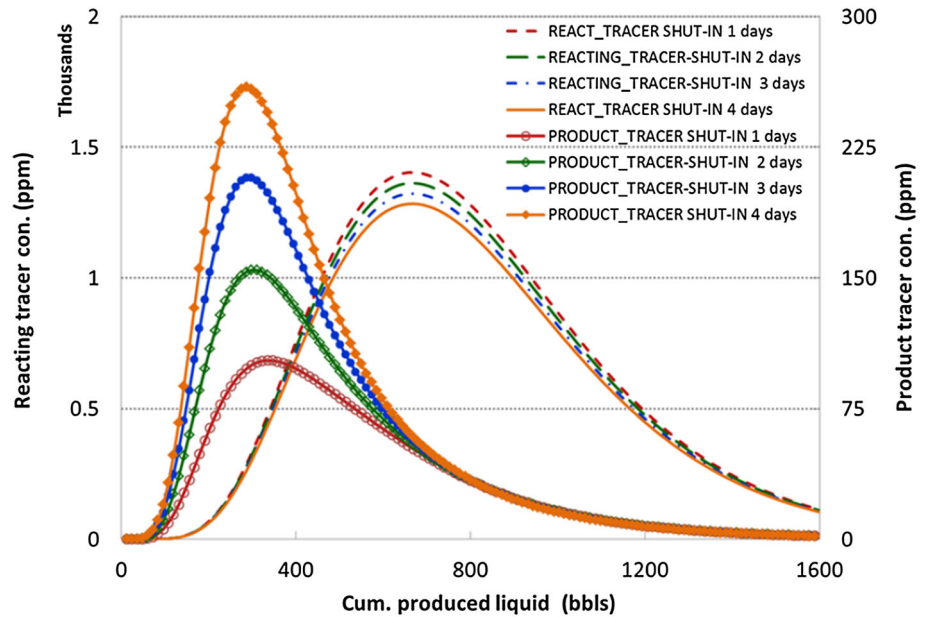
time. As such, additional simulation cases were run to better understand the relationship between shut-in time and reaction rate. The parameters used in those simulations are summarized in Table 4. In those three cases, reaction rate times shut-in time is kept at a constant value of 0.125. Figure 11 shows the simulated results. Despite using the same value of shut-in time multiplied by reaction rate, the concentration profiles for both tracers vary. The relation between reaction rate and shut-in time is not linear between them and the reaction rate has a larger effect on tracer concentrations than shut-in time.

Sensitivity-based recommendation

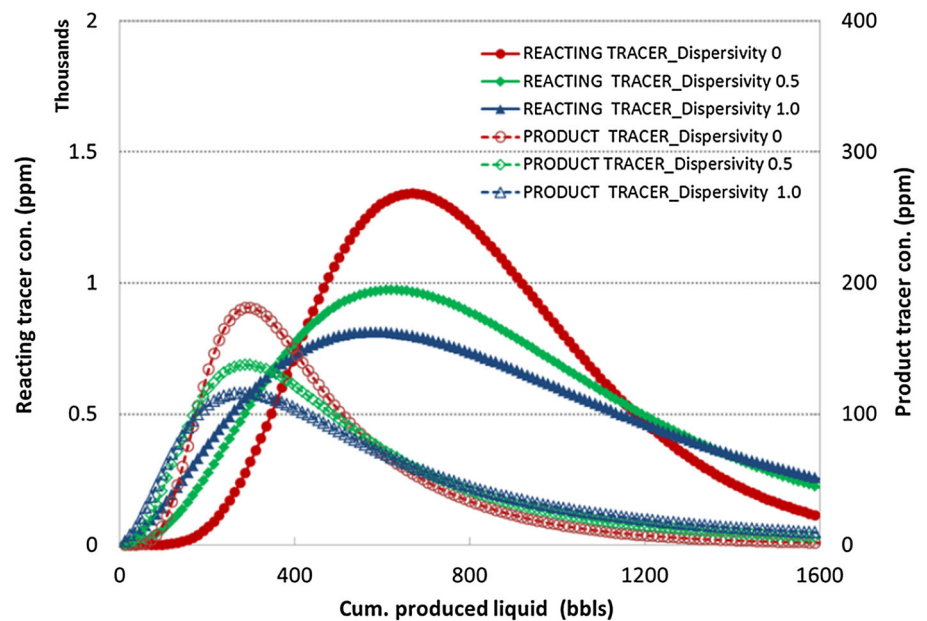
Based on the previously reported sensitivity simulations, the following values or ranges are recommended for designing the SWTT program.

- (a) A reactive tracer with a partitioning coefficient between 3 and 4 is desired.
- (b) A reactive tracer with a reaction rate ranging from 0.05 to 0.1 day<sup>-1</sup> is reasonable.
- (c) A reactive tracer concentration of 10,000 ppm is sufficient.
- (d) A shut-in time of 2.5 days is recommended.

**Fig. 7** Shut-in time effects on simulated back-production profiles



**Fig. 8** Longitudinal dispersivity effects on simulated back-production profiles



## Chemical EOR efficiency evaluation using a SWTT

### Candidate well

Well-X is a candidate well for chemical EOR efficiency evaluation using a SWTT. The perforation interval is 15 ft, which is a suitable thickness. Based on logging data, porosities along the wellbore vary from 0.16 to 0.31 with an average of 0.254. Furthermore, using previously established porosity–permeability transforms for the given reservoir, permeabilities along the wellbore vary from 5 to 1,137 mD with an average of 431 mD. Figure 12 shows

the porosity and permeability distribution in vertical direction. Few layers exhibit permeabilities that are high (higher than twice the average permeability).

### Operational program

Figure 13 summarizes the SWTT program for Well-X. Here, 1 PV represents the volume of investigation. The program includes two SWTTs before and after surfactant polymer flooding. In the surfactant polymer-flooding phase, 0.7 PV will be injected. In injection order, the chemical slug will consist of 0.1 PV of a conditioning



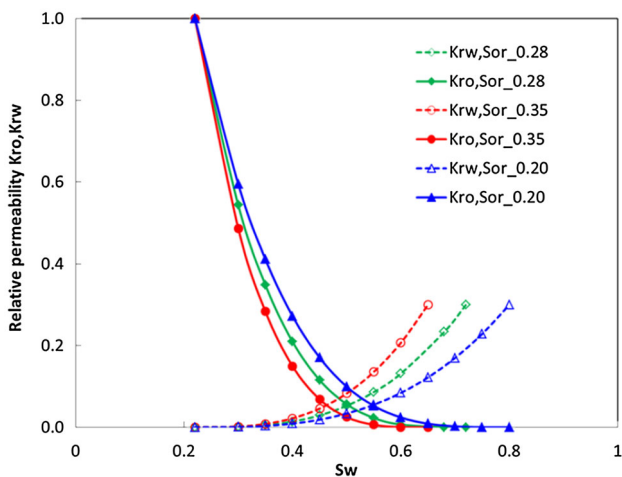


Fig. 9 Relative permeability realizations

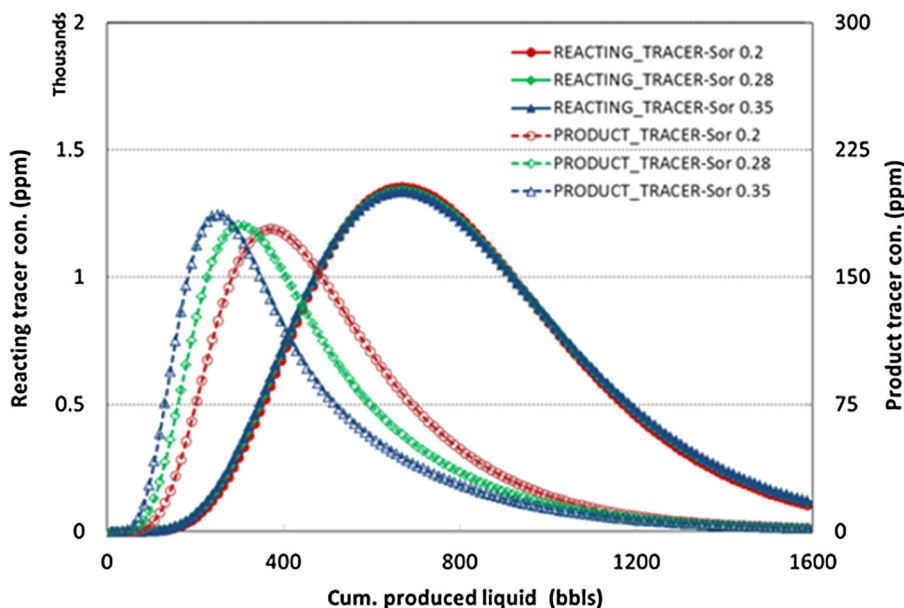
polymer slug, 0.4 PV of a sloppy surfactant-polymer slug, and 0.2 PV of a chase polymer slug. Concentrations of the polymer and surfactant are 2,000 ppm and 0.2 wt%, respectively. This chemical slug will be followed with chase water. At an injection rate of 1,600 bbls/day, which is equivalent to the volume of investigation (Table 5), the whole program will be completed in 1-month.

SWTT Interpretation

For actual results, analytical and/or numerical approaches can be used to interpret the SWTT back-production. Analytically, the residual oil is

$$S_{or} = \frac{\beta}{\beta + K} \tag{3}$$

Fig. 10 Residual saturation effects on simulated back-production profiles



where  $K$  is the partitioning coefficient of the reactive tracer, and  $\beta$  is the retardation factor estimated based on the tracers back-production peaks

$$\beta = \frac{Q_r}{Q_p} - 1 \tag{4}$$

where  $Q_r$  and  $Q_p$  are respectively the reactive and productive tracers' peak times in cumulative production volumes.

Simulation model

In previous simulations, we used a conceptual homogenous model. In reality, reservoirs are heterogeneous. In simulations of a SWTT, reservoir properties around the wellbore can be assumed to be homogeneous in the areal direction but not in the vertical direction. Variations in the vertical direction can lead to substantial variations in the distribution and saturations of the remaining oil. Therefore, capturing those vertical heterogeneities might be necessary to successfully simulate the SWTT. A simulation model for Well-X was set up based on those properties interpreted from log data (Fig. 12). As for the conceptual case, we use 100 cells in the areal direction with grid refinement around the wellbore. In the vertical direction, we use 50 cells (layers) to represent the permeability distribution along the wellbore. Figure 14 shows the permeability and porosity distributions in the model, which reasonably reflects the geological model (refer to Fig. 12).

Chemicals input parameters

Based on the previous sensitivity simulations, a reactive tracer with a reaction rate of 0.05 day<sup>-1</sup> and a partitioning

**Table 4** Input parameters for simulations investigating shut-in time and reaction rate co-effects

Parameter	Case-1	Case-2	Case-3
Reaction rate (1/day)	0.025	0.05	0.1
Shut-in time (days)	5	2.5	1.25

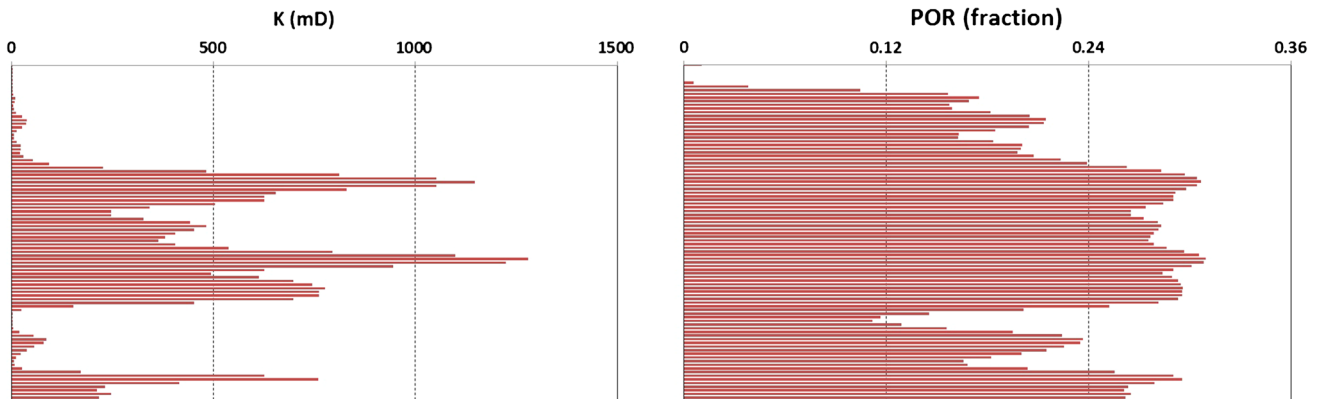
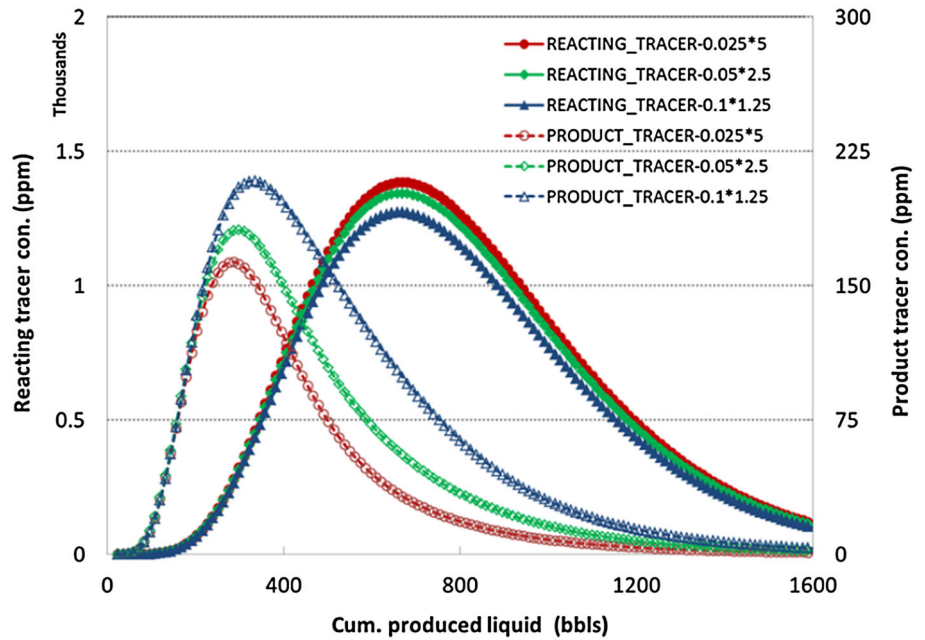
coefficient of 3 is used. The surfactant and polymer are selected based on previous laboratory screening and evaluation (Han et al. 2013). Input parameters, capturing the properties and effects of the selected surfactant and polymer, were previously generated (AlSofi et al. 2013) and used in this study. Those parameters were generated based

on laboratory measured properties of the selected surfactant and polymer and were further tuned through history matching a set of core flooding experiments.

Simulation results

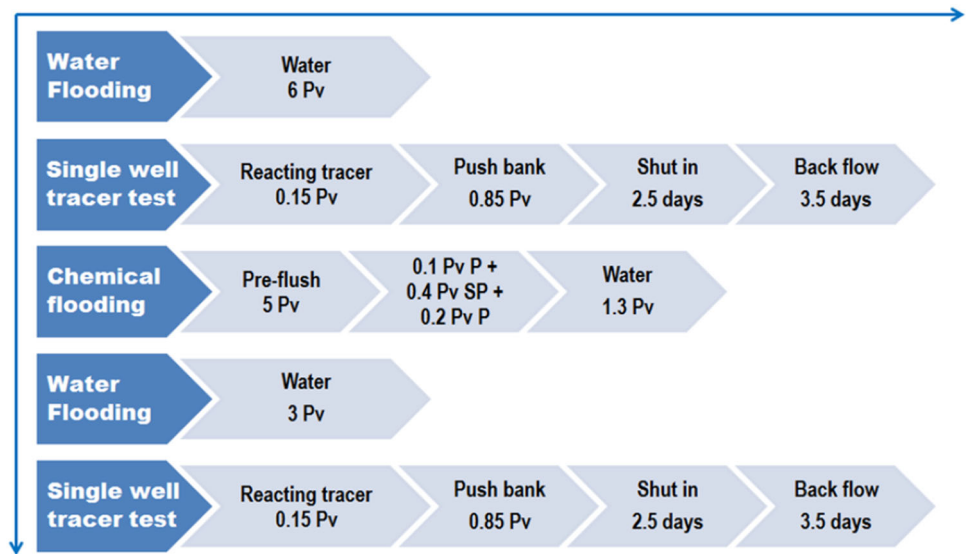
Figure 15 plots the simulated tracers’ back-production before and after chemical flooding. From such results, estimates of the remaining oil saturations can be obtained. Based on Fig. 15, back-production results (Table 6), and Eqs. , the residual oil saturations are estimated to be 0.326 and 0.211 before and after chemical flooding, respectively. Those estimates are close to the residual oil saturations of the inputted relative permeability sets. Finally, the

**Fig. 11** Reaction rate and shut-in time co-effects on simulated back-production profiles



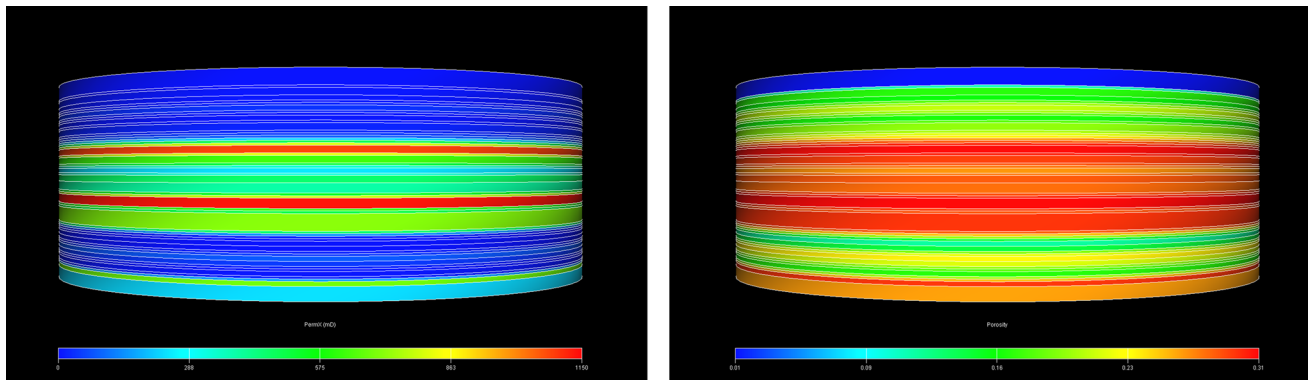
**Fig. 12** Well-X permeability and porosity logs

**Fig. 13** Operational schedule for Well-X chemical flooding efficiency mini-pilot



**Table 5** Operational parameters for Well-X SWTTs

Reacting tracer concentration (ppm)	Volume of investigation (ft <sup>3</sup> )	Injection rate (ft <sup>3</sup> )	Production rate (ft <sup>3</sup> )	Reaction rate (day <sup>-1</sup> )	Partition coefficient	Shut-in time (days)
10,000	8,992	8,992	7,194	0.05	3	2.5



**Fig. 14** Well-X SWTTs simulation model

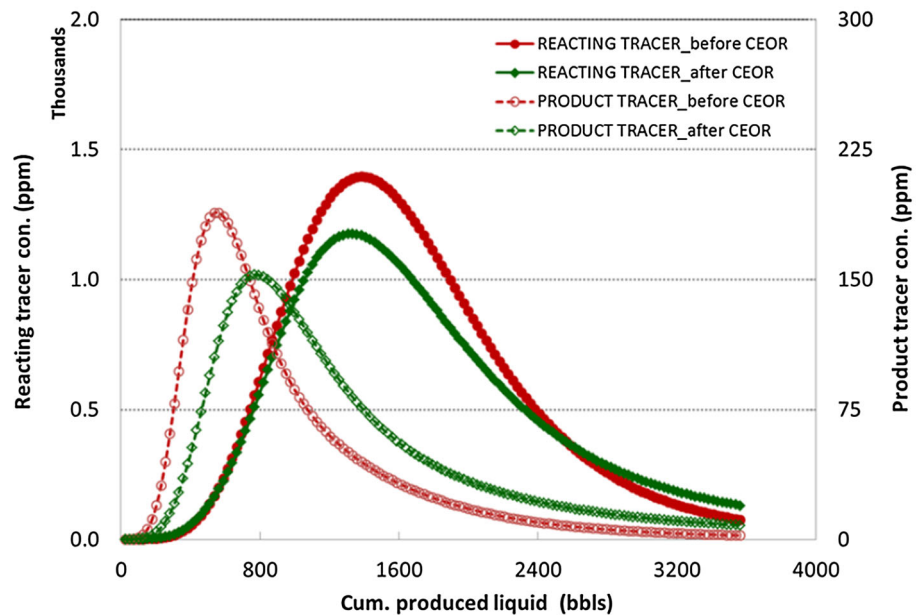
difference in remaining oil estimates measures the efficiency of the chemical flood. Based on an initial oil saturation of 0.78, chemical flooding results in an incremental recovery of 14.7 % OOIP within the SWTT investigation volume.

**Conclusions**

We use UTCHEM to guide the design of SWTTs that will be later run to evaluate chemical flooding potential. First, we perform thorough sensitivity simulations using an idealistic homogeneous model. Second, we perform

simulations using a realistic model, which was generated based on the selected evaluation well. Based on the sensitivity simulations, we provide recommendations for designing the SWTTs program. (1) A reactive tracer with a partitioning coefficient between 3 and 4 and a reaction rate between 0.05 and 0.1 day<sup>-1</sup> is desired. (2) A reactive tracer concentration of 10,000 ppm is sufficient. (3) A shut-in time of 2.5–3 days is recommended. Additionally, based on the literature (4) an injection volume that is equivalent to daily production (5) an injection rate that is equivalent to the average daily production rate, and (6) a tracer slug around 15 % of the total injected volume are recommended. Furthermore, the realistic simulation results,

**Fig. 15** Simulated back-production profiles before and after chemical flooding



**Table 6** Simulation-based peak concentrations and their corresponding peak times

SWTT no.	Reacting tracer		Product tracer	
	Peak concentration (ppm)	Corresponding cum. produced liquid (bbl)	Peak concentration (ppm)	Corresponding cum. produced liquid (bbl)
1	188.5	564.2	1,395.4	1,385
2	152.7	739.4	1,175.1	1,333.7

confirm the further reduction in residual oil saturation due to chemical flooding. An incremental oil recovery of 14.7 % OOIP is expected due to the application of chemical flooding, which is consistent with our previous core-flooding results. Moreover, those simulation results support the utility of SWTTs in evaluating chemical flooding potential. We expect to observe distinct back-production peaks, separation, and variation due to chemical flooding that can be categorically analyzed.

**Acknowledgments** The authors would like to thank the Saudi Aramco/EXPEC Advanced Research Center for their permission to publish this paper.

**Open Access** This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and the source are credited.

## References

- AlSofi AM, Liu J, Han M (2013) Numerical simulation of surfactant-polymer coreflooding experiments for carbonates. *J Petrol Sci Eng* 111:184–196
- Cockin AP, Malcolm LT, McGuire PL (1998) Design, implementation and simulation analysis of a single-well chemical tracer test to measure the residual oil saturation to a hydrocarbon miscible gas at Prudhoe Bay. In: SPE 48951 presented at the SPE annual technical conference and exhibition, Orleans, 27–30 Sept 1998
- De Zabala E, Parekh B, Solis H, Choudhary M, Armentrout L, Carlisle C (2011) Application of single well chemical tracer tests to determine residual oil saturation in deepwater turbidite reservoirs. In: SPE 147099 presented at the SPE annual technical conference and exhibition, 30 Oct–2 Nov, Denver
- De Zwart AH, Stoll WM, Boerrigter PM, van Batenburg DW, Al Harthy SSA (2011) Numerical interpretation of single well chemical tracer tests for asp injection. In: SPE 141557 presented at the SPE Middle East oil and gas show and conference, 25–28 Sept, Manama
- Deans HA, Carlisle C (1988) Single-well chemical tracer test handbook, 2nd edn. Chemical Tracers Inc, Laramie
- Deans HA, Ghosh R (1994) pH and reaction rate changes during single-well chemical tracer tests. In: SPE/DOE 27801 presented at the SPE/DOE 9th symposium on improved oil recovery, Tulsa
- Haggerty R, Schroth MH (1998) Simplified method of “push-pull” test data analysis for determining in situ reaction rate coefficient. *Groundwater* 36(2):314–324
- Han M, AlSofi AM, Fuseni A, Zhou X, Hassan S (2013) Development of chemical EOR formulations for a high temperature and high salinity carbonate reservoir. In: IPTC 17084 presented at 6th international petroleum technology conference, Mar 26–28, 2013, Beijing
- Hernandez C, Chacon L, Anselmi L, Angulo R, Manrique E, Romero E, de Audemard N, Carlisle C (2002) Single well chemical tracer

- test to determine asp injection efficiency at Lagomar VLA-6/9/21 area, C4 member, Lake Maracaibo, Venezuela. In: SPE 75122 presented at the SPE/DOE improved oil recovery symposium, 13–17 Apr, Tulsa
- Oyemade SN (2010) Alkaline-surfactant-polymer flood: single well chemical tracer tests-design, implementation and performance. In: SPE 130042 presented at the SPE EOR conference at oil & gas west Asia, Muscat
- Romero C, Agenet N, Lesage AN, Cassou G (2012) single-well chemical tracer test experience in the Gulf of Guinea to determine residual oil saturation. In: IPTC 14560 presented at international petroleum technology conference, 7–9 Feb, Bangkok
- Sheely CQ, Baldwin DE (1982) Single-well tracer tests for evaluating chemical enhanced oil recovery processes. *J Pet Tech*, Aug; pp 1887–1896
- Sheng JJ (2011) Modern chemical enhanced oil recovery theory and practice, Chap 2. Gulf Professional Press, Houston
- Shook GM, Ansley SL (2004) Tracers and tracer testing: design, implementation, and interpretation methods. In: INEEL/EXT-03-01466 Idaho National Engineering and Environmental Laboratory Bechtel BWXT, Idaho
- Tomich JF, Dalton Jr RL, Deans HA, Shallenberger LK (1973) Single well tracer method to measure residual oil saturation. *J Pet Tech*, Feb; pp 211–218 Trans., AIME, 255
- Wellington SL, Richardson EA (1994) Redesigned ester single-well tracer test that incorporates ph-driven hydrolysis rate changes. *SPE Reserv Eng* 9(4):233–239