Integrated Field and Core Data Analysis of Residual Oil Saturation Measurements from ASP Flooding Candidate Sandstone Reservoir in North Kuwait

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Abstract. An Alkaline Surfactant Polymer multi-well pilot is planned for a giant sandstone reservoir in North Kuwait. The main reservoir segments have good oil recovery, therefore, the determination of immobile residual oil saturation to water flooding is one of the key input parameters to assess the commercial viability of ASP field development concept. Integrated field and core data analysis were conducted to determine water flooding base line residual oil saturation.

Log derived oil saturation estimates from the Pilot 7 drilled wells show relatively uniform and low remaining oil saturation. Additionally, one of the pilot wells was successfully cored with water based-mud Liquid Trapper technology. Integrated analysis of Liquid Trapper and Dean Stark native core oil data were reported earlier. New carefully designed and analyzed restored-wettability core flooding experiments were integrated with existing data. The results showed remarkable consistency with the low oil saturation range estimates observed from the open hole electrical logs and from a Single Well Chemical Tracer Test (SWCTT) in a nearby well.

We report on the importance of designing and executing careful SCAL program to characterize restored wettability state cores through performing standard relative permeability and residual oil saturation measurements. Selected representative plugs were cleaned and dried post Dean Stark analysis to initialize the samples at target initial oil saturation and to restore the wettability after aging. Combination of Amott spontaneous imbibition, multi-rate steady state and multi-speed centrifuge were conducted on core plugs from the same formation from two fields. Improved design and monitoring of the experiments resulted on high quality data from which it was possible to extract consistent set of relative permeability curves and residual oil saturation. Additionally, oil de-saturation measurements were conducted to assess the minimum capillary number at which residual oil can be mobilized. Residual oil saturation estimates from the restored wettability state plugs were found consistent with the findings from native Liquid Trapper cores, open hole logs, and SWCTT data analysis.

This integrated data gathering activities and related analysis manifest the value of information from integrated data sources are different reservoir scales. The results enable a robust base line definition of the maximum performance of water flooding to narrow the range of ASP EOR oil volume targets – the first step to assess the commercial viability of ASP field development concept.

1 Introduction

Zubair (ZU) formation is one of the key sandstone oil bearing reservoirs in North Kuwait (NK) fields. ZU formation is very thick and has multiple stacked oil producing reservoirs. Raudhatain Zubair oil field (RAZU) is one of the largest NK fields in which ZU formation includes four main clastic reservoirs: The Upper Zubair Shale, Upper Zubair Sand (UZSD), Middle Zubair Sand and the Lower Zubair Sand each with different fluid and rock properties [1]. UZSD has the best rock quality where the permeability of key producing zones is more than 1000 mD [2] and therefore it is the most prolific oil producing zone. UZSD was mainly developed through water drive from natural aquifer support and limited water injection.

UZSD reservoir channels are deeper than 9000 ft, at high initial reservoir temperature (~ 90°C), and initial reservoir

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pressure of 4600 psi. RAZU PVT properties are variable across the thick oil column. However, The UZSD reservoir key most oil productive channels have light (API Gravity 30-32) and low viscosity (0.5-1.0 cP) oil. furthermore, some of the reservoir channels sub-layers are characterized by poor mobility tar-mat zones [3].

RAZU is subject to ongoing short to medium terms field re-development opportunities with primary focus on infill drilling and improved water flooding activities [4]. Additionally, one of the best reservoir quality channels of UZSD, is chosen as the target of an Alkaline Surfactant Polymer (ASP) EOR Pilot [2] to maximize oil recovery post water flooding. The pilot is located about ~500 m away from the reference case oil water contact. The pilot layers and area of interest are subjected to adequate favorable natural aquifer support which resulted in a historical high oil recovery compared to other channels or reservoir units. Historical oil producers in this channel reached high water cut before they have been zone-transferred to other more oil productive layers that were of less priority in the past development schemes.

The 70 ft sand within the ASP pilot zone of interest has relatively homogenous permeability profile parallel to the bidding planes and therefore current remaining oil saturation are expected to be close to residual oil saturation and vertically uninform. The bottom of this channel has immobile high oil saturation attributed to high viscous tar-mat [3] and is excluded from the zone of interest for ASP piloting.

In a typical ASP EOR development opportunities of light oil reservoirs, the size of the prize incremental oil volume is primarily driven by the extent of mobilizing residual oil saturation. The lower the remaining oil or residual oil saturations, the more challenging the feasibility of the development concept is. In the case of RAZU and away from the favorable geological properties, it has unfavorable harsh reservoir conditions. The reservoir is at high temperature (>90°C), high formation brine salinity (~250,000 ppm), and very high divalent ions concentration (~20000 ppm) representing one of the key technical, operational, and cost challenges to any ASP development concept [2]. Therefore, in addition to mitigating the above-mentioned complexities attributed to reservoir conditions, determination of remaining and residual oil saturations of the target reservoir segments is key input to the feasibility of upscaling the planned ASP pilot results to commercial field scale development [5,6].

The objective of this paper is to expand on an earlier publication dedicated to integrated analysis to map remaining and residual oil saturation from different field scale and laboratory measurements [5]. We highlight the importance of designing and executing careful SCAL program to characterize restored-wettability state cores through performing standard relative permeability and residual oil saturation measurements. Improved design and monitoring of the experiments resulted on high quality data from which it was possible to extract consistent set of relative permeability curves and residual oil saturation from 2 different ZU reservoirs. Additionally, oil de-saturation measurements were conducted to assess the minimum capillary number at which residual oil saturation can be mobilized.

2 FIELD SCALE SATURATION

In preparation for the planned ASP pilot, 7 wells were drilled within ~95 m inverted five spot pattern as shown in Figure 1. From each well, typical conventional open- hole logs were recorded. Of most interest for the purpose of this paper, are the porosity and electrical saturation logs. Porosity logs show homogenous uniform sands in zone of interest and saturation logs showing relatively vertically uniform low remaining oil saturation [5]. Two of the pilot oil producers and the observation well were cored for reservoir characterization and logs calibration purposes. In parallel, a single well chemical tracer test was conducted in a representative nearby well in which the remaining oil saturation to water flooding was estimated at 0.24 ± 0.02 [7].

One of the cored pilot wells, Liquid Trapper technology [8] was deployed. Selected plugs were subject to Dean Stark analysis to estimate in-situ remaining oil saturation [5]. The saturation estimates from all available data sources, open hole logs, SWCTT, and Dean Stark were integrated together showing remarkable consistency of the estimated remaining oil saturation within ± 0.05 reasonable uncertainty range [5].

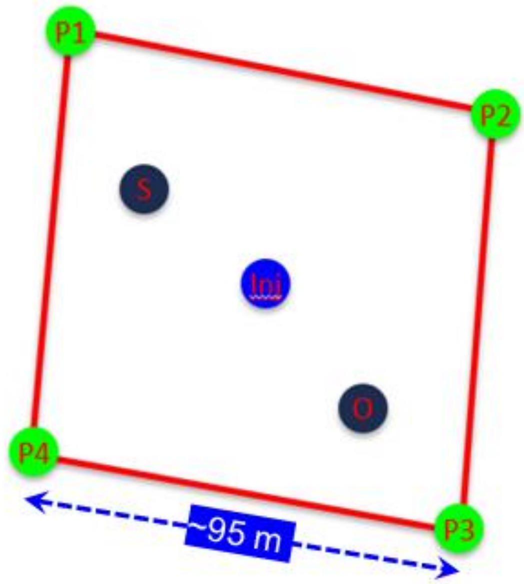

Fig. 1. Schematic of planned RAZU ASP pilot inverted 5-spot configuration, 4 oil producers (P1, P2, P3, P4), central injector (Inj), sampling (S), and observation (O) wells.

In the next section, the published data gathering and analysis [5] is expanded by including additional core flooding experiments. The results cover one of the pilot cored wells (O) and analogue well from Zubair formation in a nearby analogue field after wettability restoration.

3 RESTORED WETTABILITY CORE FLOODING EXPERIMENTS

3.1 RAZU ASP Pilot Observation Well

The pilot zone of interest was cored using Liquid Trapper technology to primarily estimate in-situ remaining oil saturation [5]. In the next sections, experiments on selected plugs post Dean Stark analysis will be discussed.

3.1.1 Plugs selection and preparation

A subset of the plugs that were used for Dean Stark analysis [5] were saturated with synthetic formation brine and their water permeability is measured. The plugs were brought to irreducible water saturation by 150 psi air-brine porous plate method. Dead crude oil is used to displace air from the samples in preparation of the wettability restoration process at reservoir pressure and temperature conditions. Samples were aged for 3 weeks. The 1.5-inch plugs basic properties are shown in table 1.

Table 1. Selected RAZU plugs basic properties

Sample ID	Porosity	Kw	Swi	Ko@Swi	Experiment
	fraction	mD		mD	
1	0.25	2672	0.05	2061	Steady State
2	0.22	1090	0.05	808	Steady State
11	0.23	1302	0.04	911	Steady State
3	0.22	1035	0.04	752	Centrifuge
9	0.23	1236	0.04	947	Centrifuge
12	0.23	1339	0.05	1034	Centrifuge

Trim ends from the 3 selected for centrifuge experiments, were prepared for mercury injection capillary pressure (MICP). Data show uniform pore size distribution and similar capillary pressure for the mobile saturation range as shown in Figure 2. MICP show is consistent with all other data sources confirming dominant homogenous high-quality rock >1000 mD for the Pilot zone of interest.

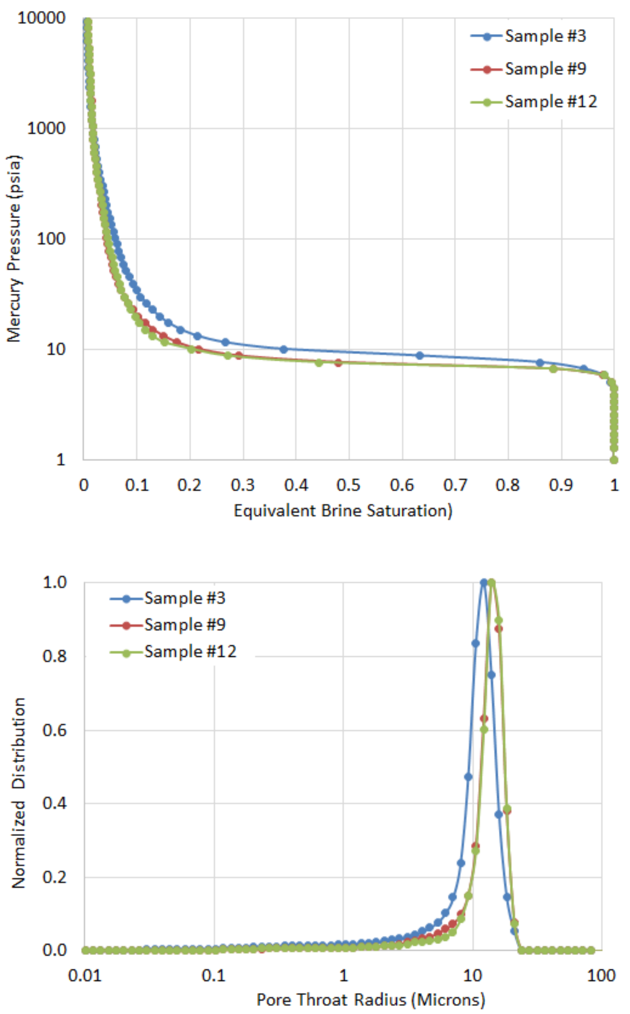

Fig. 2. Measured mercury injection capillary pressure from the 3 samples, upper panel, and pore throat size distribution, lower panel.

3.1.2 Steady state core flooding experiments

Three core plugs were selected for steady-state experiment after initialization and aging from Table 1. The injection rates and water fractional flow were designed carefully to cover the full range of oil and water relative permeabilities at reservoir equivalent stress conditions. The base total injection rate was set to 60 ml/hour and increase to 120 and 240 ml/hour at the final 100% water fractional flow to suppress capillary end effects. High quality pressure difference and X-ray saturation profiles, after many hours of steady state flow conditions, along the plugs were obtained from the three experiments. The calculated relative permeability curves and residual oil saturation from the 3 samples were comparable using simple analytical solution method as shown in Figure 2. Results show residual oil saturation at the end of bump floods in the range of 0.1-0.14. The end point relative permeability of water at residual oil saturation is ~0.4.

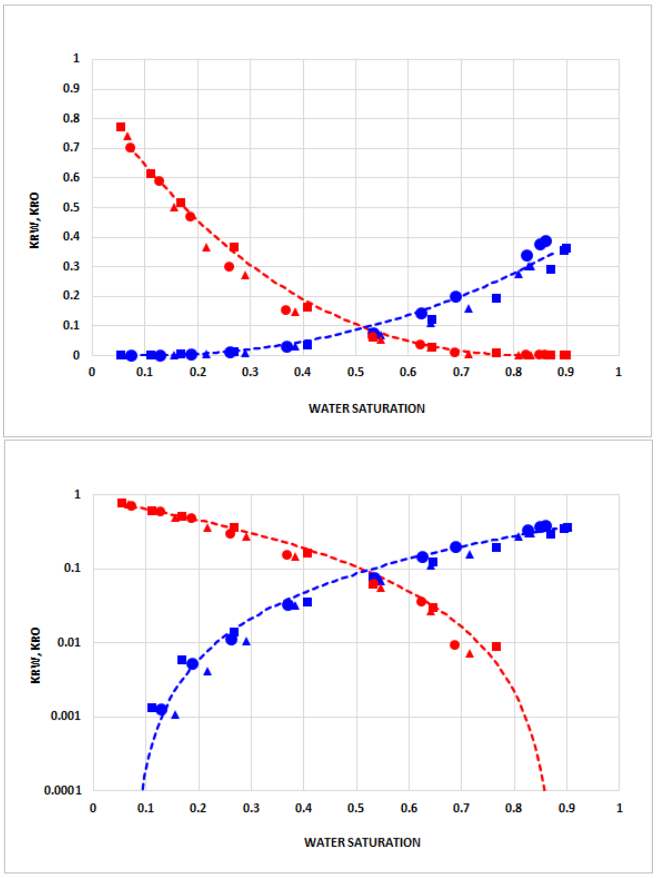

Fig. 3. Calculated oil and water relative permeability from the 3 steady state experiments (symbols) and simple Corey data fitting (dashed lines).

3.1.3 Multi-speed imbibition and secondary drainage centrifuge

Additional three plugs were selected for Amott spontaneous imbibition and multi-speed imbibition and secondary drainage centrifuge experiments at a temperature of 160 F. Amott static imbibition showed no oil production for 14 days, suggesting a non-water wet system. At the end of the imbibition experiments, the Hassler-Brunner calculated end oil face saturation [9] is in the range of 0.12-0.16 which is in a similar range obtained from the steady state experiments as shown in Figure 3 and Figure 4. However, the end point relative permeability at residual oil saturation was (0.5-0.6) was higher compared to 0.4 from steady state experiments. At the end of the first imbibition cycle, Amott static (secondary) drainage show no water production for 14 days. Multi-speed secondary drainage reached remaining water saturation 0.12-0.2 at 42 psi maximum end face capillary pressure [9].

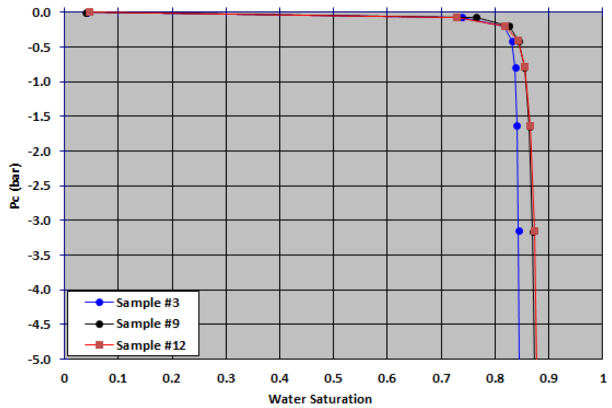

Fig. 4. Calculated imbibition capillary pressure from the 3 multi-speed experiments using Hassler Brunner analytical solution [8] from production data.

3.1.4 Secondary imbibition cycle

To improve the understanding of the performance of a surfactant polymer formulation that was under evaluation, a secondary imbibition experiment at elevated rotational speeds was conducted to assess the critical capillary and bond numbers at which de-saturation occur. The dimensionless bond number (N_b) is defined as:

$$N_b = \Delta\rho * g * K/\sigma \qquad (1)$$

Where $\Delta\rho$ is the density difference between oil and water, g is the centrifuge gravitational acceleration, K is the brine permeability, and σ is the interfacial tension between oil and water. The dimensionless capillary number (N_c) is defined as:

$$N_c = \mu * \upsilon/\sigma \qquad (2)$$

Where μ is the injectant viscosity and υ is the velocity of injected phase. Using the measured σ of 28 mN/m, the maximum bond number reached for practical centrifuge speeds reached up to 1.9E-3 without observing any sharp desaturation effects as shown in Figure 5. Ignoring any cyclic hysteresis effects, the end face residual oil saturation for the 3 sample is within the same range obtained from the first imbibition cycle.

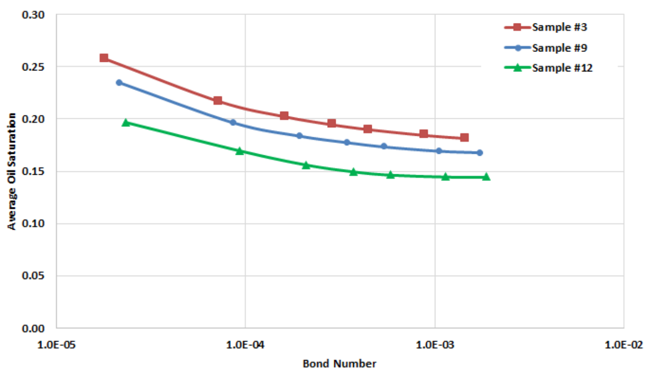

Fig. 5. Average oil saturation as a function of the calculated bond number for the 3 samples during the secondary imbibition experiment.

3.2 Residual Oil Saturation Measurements From Analogue Nearby Reservoir

From a nearby Zubair formation reservoir 8 plugs were selected for restored-wettability state experiments as shown in Table 2. The plugs have lower porosity and water permeability range compared to better quality RAZU core plugs. Formation brine salinity, reservoir temperature and API gravity are on similar range as for RAZU. Multi-rate relative permeability steady-state and multi-speed centrifuge experiments were carefully designed to reach residual oil saturation, using similar protocols of RAZU experiments above. The basic total injection rate was 30 ml/hour and additional 2 pump rates 60 and 120 ml/hour were used at the end of last fractional flow to suppress capillary end effects. The fit for purpose design and regular quality control of raw data resulted in high quality data from which it was possible to extract a narrow range of residual oil saturation between 0.13 and 0.19 as shown in Table 2. No attempt is made to relate end point saturation or relative permeability to porosity or permeability.

Static Amott experiments show negligible spontaneous imbibition suggesting non-water-wet system. At the end of forced imbibition, calculated Hassler-Brunner end face oil saturation is as low as 0.13 as shown in Table 2.

Table 2. Selected RAZU analogue reservoir plugs basic properties

Sample ID	Porosity	Kw	Swi	Ko@Swi	Sor	Experiment
	fraction	mD		mD		
22	0.18	266	0.09	228	0.19	Steady State
38	0.17	197	0.11	178	0.17	Steady State
42	0.18	599	0.06	500	0.18	Steady State
66	0.20	647	0.06	541	0.15	Steady State
23	0.20	506	0.10	381	0.13	Centrifuge
37	0.17	184	0.08	149	0.13	Centrifuge
41	0.18	371	0.12	228	0.13	Centrifuge
65	0.20	626	0.08	475	0.14	Centrifuge

4 DISCUSSION

In earlier publication [5], estimated oil saturation from open hole logs of the pilot wells were integrated with Dean Stark analysis on cores and fluids samples collected from Liquid Trapper coring job. It was shown that oil saturation estimated from field core data analysis, open hole oil saturation logs in the aquifer flooded zone are remarkably consistent as shown in Figure 6. However, water saturation estimated from Dean Stark analysis is lower than in-situ water saturation as a result of inherited workflow limitations, invasion by water-based mud and water loss during core processing [5].

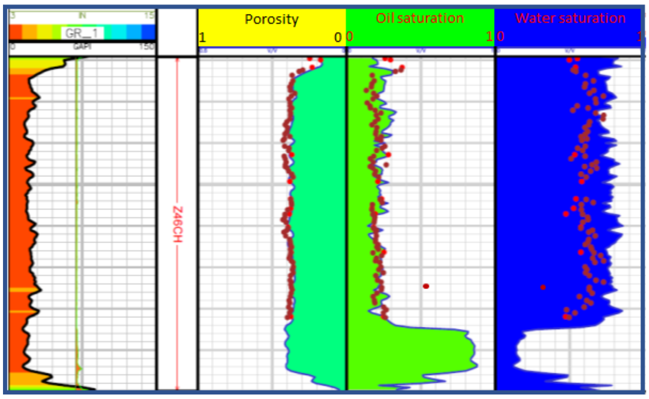

Fig. 6. Open hole logs showing gamma ray, porosity, estimated oil saturation and estimated water saturations. The dotted points are core porosity, estimated remaining oil saturation and estimated water saturation in the 2nd, 3rd, and 4th panels respectively [5].

The above restored-state wettability SCAL experiments on 6 RAZU core plugs were integrated with multi-scale remaining oil saturation data published earlier [5]. Figure 7 shows all the data collected to estimate the base line remaining oil saturation before ASP injection. Most of the data points taken from different sources and different scales are within 0.20 ± 0.05 bounds. However, the more homogeneous plugs centrifuge and steady experiments show residual oil saturation even lower than 0.2. This suggests oil saturation data from sources reported earlier [5] that are higher than 0.2 represent remaining oil rather true residual oil saturation.

Detailed simulation modeling of both the core flooding experiments and history matching of the pilot region could have helped narrow the range of oil saturation uncertainty. However, narrowing the range down to ± 0.05 from simple basic data and analytical analysis is significant fit for purpose achievement to estimate the upper limit of remaining oil targets before ASP injection. It is expected that in the coming weeks, 4 of the pilot oil producers and central injector will be opened for production to establish water injection base line before ASP injection. Measurement of the each well water cut and production logs profile along the target interval will be the ultimate step to close the loop of remaining oil saturation determination in the pilot zone of interest.

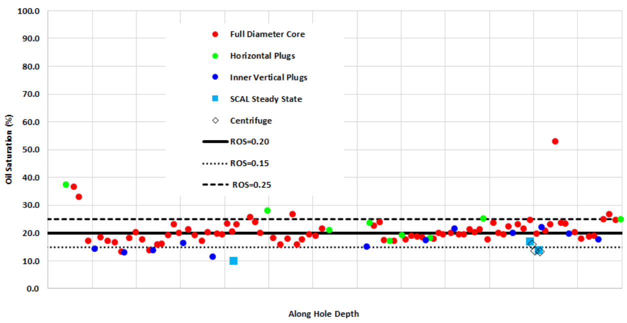

Fig. 7. Average oil saturation as a function of the calculated bond number for the 3 samples during the secondary imbibition experiment.

The RAZU centrifuge experiments reveal that an equivalent capillary number or a bond number higher than 1.9E-3 is needed for the onset of de-saturation effects. This would require reduction of interfacial tension to lower than 2E-3 mN/m at 1 ft/day water frontal velocity.

Adding the core flooding results from another nearby analogue reservoir, strengthens the case of findings that residual oil saturation for RAZU and similar reservoirs is lower than 0.20. This would enable using this data as analogue for other Zubair reservoirs across North Kuwait for both water flooding and assessment of EOR potential.

In summary, data in Figures 6 and 7 covering all sources (open hole logs, Dean Stark analysis, and restored wettability experiments) suggest narrow range of low oil saturation for baseline water flooding before ASP injection. The high oil saturation values such as 0.24 ± 0.02 from SWCTT [7] represent remaining oil saturation while lower values from SCAL experiments represent true residual oil saturation.

The above results have profound impact on the field re-development options. It shows that improved water flooding and infill drilling opportunities have the potential to extend the life of the field for many years to come [4]. Additionally, the anticipated reduced remaining oil targets make it more challenging to realize commercial applications of complex surfactant based EOR development concepts [6] given reported residual oil saturation after ASP formulation injection is 0.06 ± 0.05 [7].

5 CONCLUSIONS

Extensive data gathering campaign as part of preparation of RAZU ASP pilot resulted narrowing the uncertainties of both the remaining oil and residual oil saturation in the pilot zone of interest. The following conclusions can be drawn from this work:

- Integration and reconciliation of all data sources is essential exercise to bridge the gap between measurements at different length scales and time windows.
- Remaining oil saturation estimates are reduced to a narrow fit for purpose range 0.20 ± 0.05 based on sound basic data analysis without the need for complex simulations.
- Residual oil saturation is confirmed to be lower than 0.2 based on carefully designed SCAL experiments and reconcilable with the findings from native core Dean Stark data analysis
- Oil de-saturation measurements were conducted to assess the minimum capillary number at which residual oil can be mobilized show that interfacial tension less than 2E-3 mN/m is required to achieve residual oil saturation reduction
- High quality SCAL (data established the reservoir rock is not water wet and excellent set of oil and water relative permeability curves were obtained.

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