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Organic Oil Recovery - Resident Microbial Enhanced Production Pilot in Bahrain

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Abstract

Tatweer Petroleum has been involved in a Pilot study to determine the efficacy of Organic Oil Recovery (OOR), a unique form of microbial enhanced oil recovery as a means of maximising oil recovery from its Rubble reservoir within the Awali field.

OOR harnesses microbial life already present in an oil-bearing reservoir to improve oil recovery through changes in interfacial tensions, which in the case of Rubble will increase the heavy oil's mobility and improve recovery rates and reservoir wettability. These changes could increase recoverable reserves and extend field life through improved oil recovery with negligible topsides modifications. The Pilot injection is implemented by injecting a specific nutrient blend directly at the wellhead with ordinary pumping equipment. The well is then shut-in for an incubation period and thereafter returned to production.

In Tatweer Petroleum's Awali field the Rubble reservoir is one of the shallowest oil reservoirs in the Bahrain and the first oil discovery in the Gulf Cooperation Council (GCC) region. The reservoir can be found at depths of around 1400 – 1900 ft. During initial laboratory testing of the Rubble target wells the reservoir showed a diverse and abundant resident ecology which has been proven capable of undergoing the necessary characteristic changes to facilitate enhanced production from the target wells. The Pilot test on one of these wells, called Well (A) within this paper, took place in July 2020 and due to this process, the ecology of this well showed these same changes in characteristics in the reservoir along with an associated oil response. The full method of implementation of the Pilot test will also be discussed in detail and will include any challenges and/or successes in this area. The initial state ecology reports of Well (A) are demonstrated and compared to that of post-Pilot test ecology. We also present the production figures for the well prior to and post the Pilot implementation. A correlation will be demonstrated between changes in ecology and an increase in production.

Reservoir Summary

The Awali field contains multiple stacked oil & gas reservoirs within a faulted north-south trending anticline. It is assumed that all reservoirs are charged from the same deep source or sources via sequential vertical migration during periods of tectonic compression that generated and reactivated faults. Although similarly sourced, the crude properties gradually change with depth. Dry and wet gas filled the deep Khuff formation whereas highly viscous crude and bitumen charged the Aruma formation at 500 feet depth.

In the Mishrif formation (locally know as Rubble) underlying the Aruma, the oil properties vary laterally across the structure. It is estimated that only 10% of Original Oil in Place (OOIP) to be light oil (20 to 30 API) mainly concentrated in the east and northeast flank of the reservoir, whereas the remaining 90% is classified as heavy oil (below 18 API). The gravity significantly decreases heading south until it reaches 12 API with viscosities reaching 400 cP. The current average reservoir pressure is estimated around 300 psia (initially 600 – 700 psia) and temperature is ~120° F. The initial solution GOR is 28 scf/bbl and bubble point pressure is 316 psia. Water salinity is around 80,000 to 100,000 ppm NaCl.

The Rubble reservoir has been historically considered as secondary target for higher potential deeper reservoirs, as wellbores were salvaged from underlying formations to Rubble. When Tatweer Petroleum was founded in 2009, a dedicated development plan was put together with the aim of further developing the Rubble formation. The plan includes an intense drilling program in the east and northeast flank. Additionally, a gas injection pilot has been planned and executed to provide a pressure support program in the depleted fault blocks. In order to exploit the majority of the OOIP which is classified as heavy oil, several thermal pilot pads have been drilled and executed since 2011 in different areas of the formation. Cyclic steam stimulation (CSS) has worked well in the selected areas of Rubble, recovering potentially 10% of the OOIP within the pilot area. As CSS recoveries in similar reservoirs typically only reach 15% OOIP, alternative methods (including non-thermal) with higher potential recovery are being considered.

In Bahrain the late Cretaceous Mishrif formation is known as the (Rubble) limestone. Its name reflects its abuse by extensive erosion, karsting, faulting and fracturing. Two dominant fault sets exist, both associated with Late Cretaceous regional compressional events. NNE-SSW relaying faults dominant the axis of the anticline, whereas later NW-SE trending strike-slip wrench faults cut across the field, but most prominent on the structural flanks. Both fault sets extend below the Rubble, passing through the underlying LS2 and Ostracod formations.

Fractures are associated with both faults sets. However, the NNE-SSW fractures include regional joints and thus form the overwhelming majority. Based on core and wellbore image logs, most joints are bed bound, however larger fault associated fracture swarms appear to locally breach the basal thin shale and argillaceous beds that separate Rubble from the underlying Ostracod formation. Faults and fractures were generated during uplift. Erosion and karsting of Rubble formation due to percolating meteoric water the fault and fractures walls are etched and irregular while their apertures are widened. Furthermore, due to the strike-slip stress regime and current Zagros regional compression, many Rubble fractures and some bedding planes are critically stressed and propped open.

Well (A), was chosen for initial sampling and microbial screening. The Rubble field map showing the position of Well (A) is shown in Figure 1. Following laboratory analysis this well was selected for a production well Pilot of the Organic Oil Recovery (OOR) technology. The production history of Well (A) is shown in Figure 2.

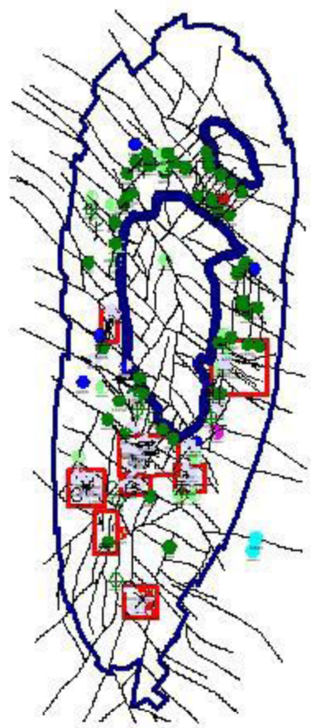

Figure 1—Rubble field map showing the location of all wells.

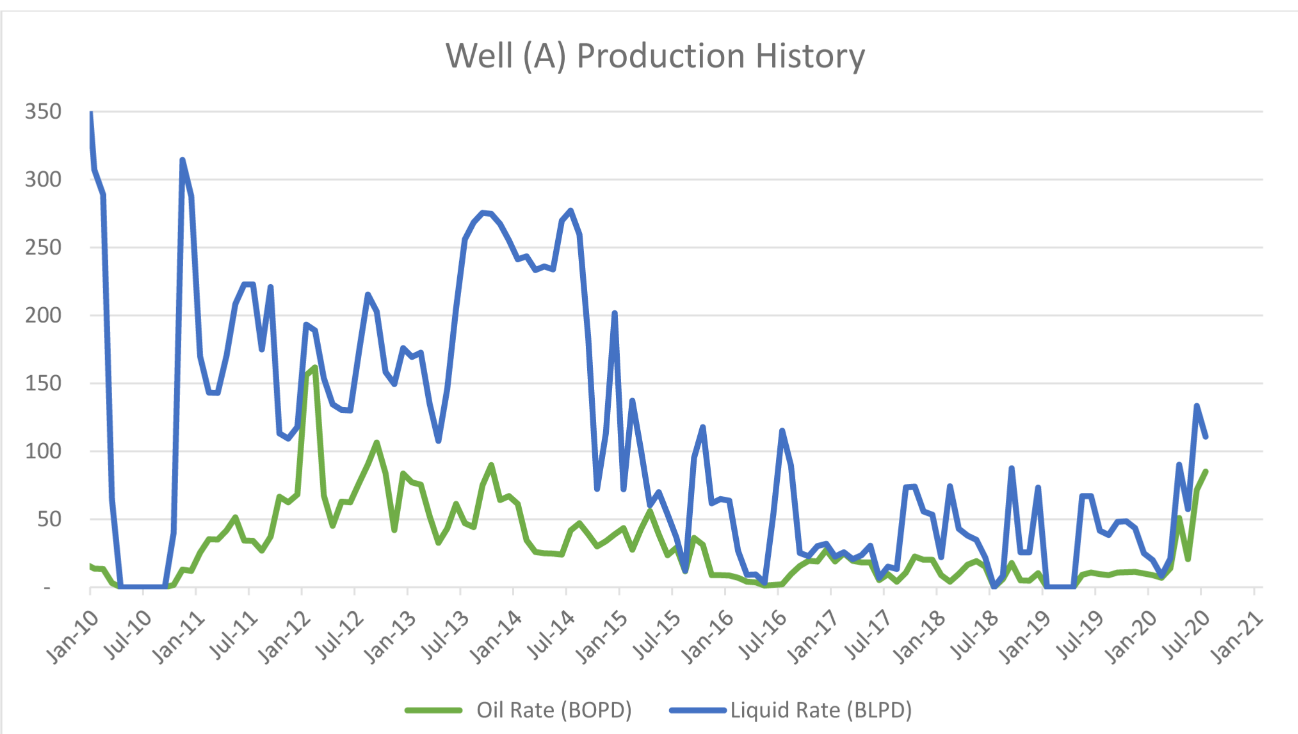

Figure 2—Well (A) Production History (2010 – 2020).

Prior to the Pilot implementation Well (A) short term production forecast was defined by Tatweer. This forecast was important to ensure that a clear conclusion could be drawn on the production impact of the OOR Pilot. Ideally the well should be producing in a stable manner prior to the OOR Pilot.

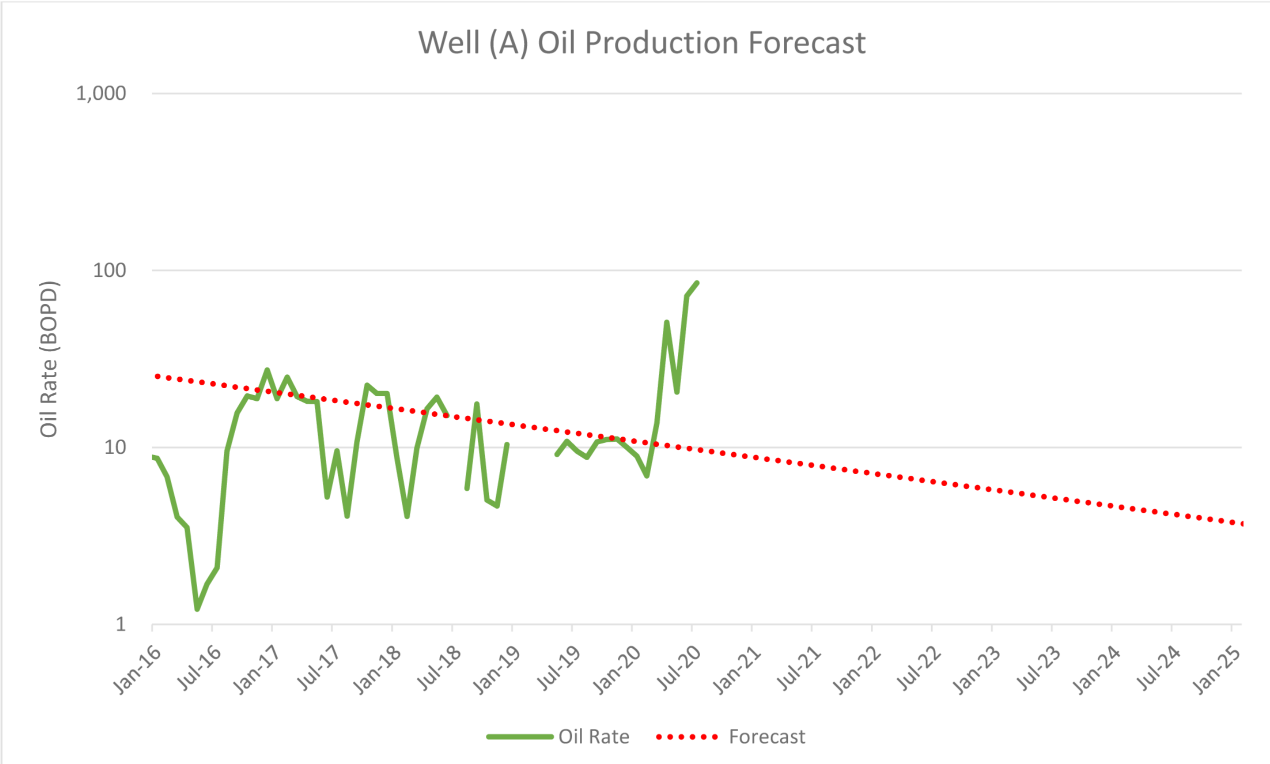

Figure 3—Well (A) short term forecast without an OOR Pilot treatment.

Field Screening & Initial Laboratory Work

Initial OOR technology screening of Tatweer Petroleum's Rubble field was completed in Q2 2019. Reservoir and well technical details were reviewed against OOR's defined technical criteria to determine the suitability of the reservoir for the technology application. Parameters such as oil gravity, reservoir temperature, water salinity, water pH and reservoir permeability were closely considered. A summary of the main parameters aligned to the OOR guidance criteria is detailed below in Table 1.

Table 1—Summary of Rubble screening criteria.

Screening criteria	Rubble Reservoir	OOR technical criteria
Oil Gravity (API)	18	12 – 42
Produced Water pH	7.3	6 - 8
Reservoir Temperature (ºC)	48	<105
Produced Water Salinity (TDS)	60,000	<215,000
Reservoir Permeability (mD)	3.5	> 1

Following positive field screening results a produced water sample was collected from the wellhead of Well (A), and received at the laboratory in Monrovia, California, on August 6th, 2019. For each well to be sampled successfully 2 litres of produced water is required to be collected and sealed in four (4) 500 ml bottles. An example is shown in Figure 4.

COMPANY:	TATWEER PETROLEUM	
FIELD:	RUBBLE	
LOCATION:	BAHRAIN (LAND)	
WELL NUMBER:	A	
DATE:	6/08/19	
TIME:	07:05	
TEMPERATURE AT TIME OF SAMPLE:	40 °C	°F
TEMPERATURE AT TIME OF BOTTLING:	36 °C	°F
pH:		
LAB WORK ORDER NUMBER:	LHUNTIT190223	

Figure 4—Well (A) sample bottles.

Upon arrival at the Titan laboratory two (2) bottles of each well sample were sent to a separate genomics laboratory for DNA and RNA sequencing analysis to identify the microbial ecology present.

Within the laboratory spin and stains were completed on samples from the remaining two (2) bottles to assess whether living microbes were present. After the spin and stain the remaining fluid was taken through a thermal reactivation process by raising the temperature from 20 ˚C measured on arrival gradually over time for 3 to 4 days until the sample reached the minimum reservoir temperature of 42 ˚C. One bottle was carefully agitated in case any microbes had settled out and then individual samples were taken from this fluid to fill a number of tubes. Each of these tubes contained different OOR Process nutrient combinations and concentrations as well as 1 tube containing only sampled produced water as a control.

The top of each tube was flushed with 100 % nitrogen to exclude as much oxygen as possible. These tubes were then incubated at 45 Celsius and in a dry and dark incubator. Every 3 to 4 days the tubes were examined for any growth (usually seen as a gradual increase in turbidity or opacity). A little growth was observed after 3 weeks in the samples at 45 Celsius and a little more after 4 weeks of incubation. At this point samples were taken from the tubes which exhibited this growth, smeared on slides, fixed, and then stained by the Grams differential method with slight variations due to the expected types of microbes. After staining and drying the slides were then examined under a high-power digital imaging microscope for abundance, type and morphology of microbes present and thereafter representative images were taken for documentation and later use for comparison post any Pilot Test (In-Situ Microbial Response Analysis (ISMRA)).

In Table 2, growth results are shown from Well (A) which demonstrate the microbial ecology present, and that it can grow in more than one nutrient combination. These results are needed to support progression of the Pilot test in the field.

Table 2—Growth observations in full work up tubes.

Reservoir Name:	Rubble		
Well Number:	Well (A)		
Incubation Details:	Incubated at 43 - 45°C		
Notes on Entire Set: (Smells, Sediments, Colours)	Tubes had a slight amount of cloudiness at the beginning and very little colour and almost no oil		
Tube	**Contents**	**Tube Observations**	
		06-09-2019	04-10-2019
1	No Nutrients	Very slightly cloudy	Very slightly cloudy
2	1mL control Bacteria	N/A	-
3	1X Nutrients	Slightly cloudy	Slightly cloudy
4	0.1X Nutrients	Very slightly cloudy	Very lightly cloudy
5	2X Nutrients	Slightly cloudy	Moderately cloudy
6	No Alpha	Slightly cloudy	Lightly cloudy
7	No Beta and Alpha	Slightly cloudy	Lightly cloudy
8	No Zeta and Alpha	Slightly cloudy	Lightly cloudy
9	No Zeta	Slightly cloudy	Lightly cloudy
10	No Beta	Slightly cloudy	Lightly cloudy
The designations in Greek letters in the above table stand for various components of the nutrient recipe that are excluded in that test tube.			

Staining performed on 13-10-2019

Slide	**Slide Observations**
1	+
2	N/A
3	+ to ++
4	+
5	++ to +++
6	+
7	+
8	+
9	+
10	+

+ means a few microbes, + to ++ means few to more than a few and ++ to ++ means some to many microbes. Numbers will go from 100 per ml to more than 10,000,000 per ml.

Imaging Studies on samples from Well (A)

In addition to the number of microbes, the type and the morphology were also reviewed. In the partial image in Figure 5 below, an image of the microbes found in the produced water sample is shown that was labelled Tube 1 – Control, no nutrient supplementation.

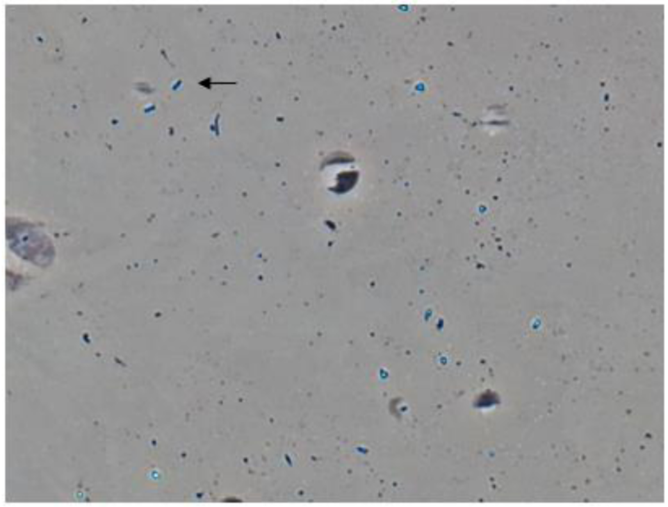

Figure 5—High resolution microscopy image of Tube 1 - Control sample (partial image) shows very few microbes present mostly of rod type and mostly gram positive. The arrow points to examples of the microbes.

Of the other tubes, some growth was observed as shown within the partial image in Figure 6 below.

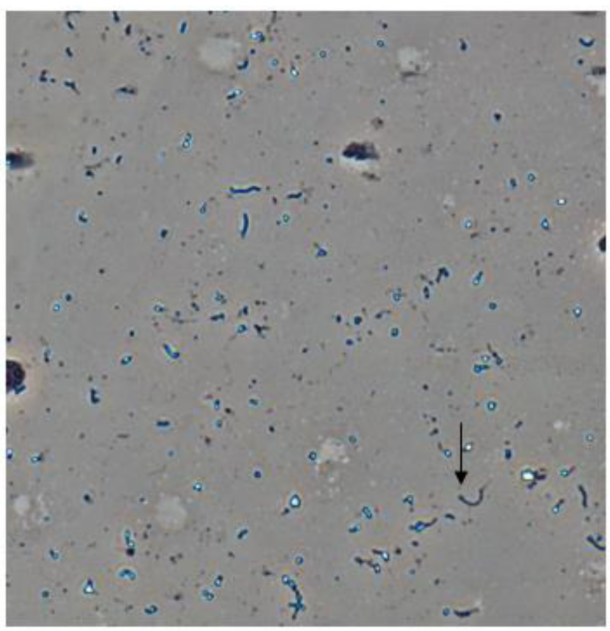

Figure 6—Stained sample from a Tube 5 containing a typical OOR nutrient combination (partial image). There has been an increase in microbe number with some exhibiting morphological changes associated with the activation that denotes a positive result. The arrow indicates rods now in groups known as "chains".

The microbe concentration increased by several times in some tubes and is typical of a positive response. Growth in the laboratory strongly indicates there were living extremophiles present in the samples collected from the well that grew at around 45 ˚C and have been activated and stimulated to grow in the laboratory study.

As well as the growth and microscope imaging studies the diversity of the microbes present in the produced water is examined by a metagenomic study to identify the metabolic traits and microbe families present. We give a simplified example of the results of this analysis for Well (A) sample below.

Genetic Analysis for Well (A) Sample

Archaeal and Bacterial populations of each sample were analysed in parallel by 16s metagenomic sequencing, using MiSeq platform. This approach robustly detects both bacteria and archaea.

The metagenomic analysis showed Rubble Well (A) Produced Water had 9.79E+07 microbes per ml. The Genetic analysis was successful and showed a diverse collection of microbes, many typical of oil field reservoirs.

The Well (A) sample data is shown in Figure 7 below. This shows a significant presence of Thermophilic microbes that can respond to the OOR Process, as well as the presence of Sulfidogens. There is sufficient diversity for the OOR Process to have a significant effect.

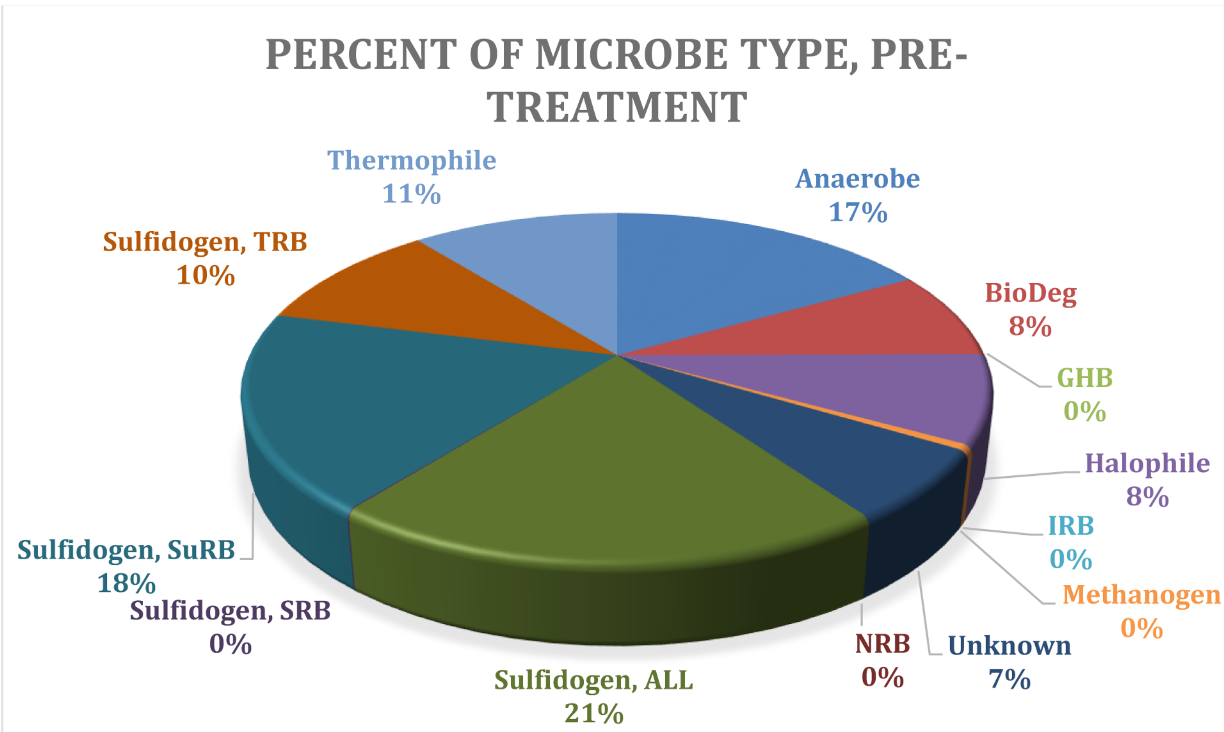

Figure 7—Shows the overall genetic traits present in the analysis of produced water sample from Well (A) performed by metagenomic analysis.

Field Application

Following successful laboratory analysis and microbial evidence which showed that resident microbiology within Well (A), could be activated by OOR nutrient, a Pilot test was initiated within Well (A) in August 2020. The Pilot is typically applied in a single producing well to test a relatively small volume of the nutrient formulation created from the initial laboratory work described in the previous section. In the case of Rubble, there is no waterflooding or water injection program within this field and any subsequent treatments will also progress directly through producing wells.

Rigging Up, Treatment Preparation & Mixing

A closed line hard piping system was constructed next to Well (A) by Schlumberger making use of a pumping truck to allow for the frac tank filled with 'sweet' injection water to be suitably connected to Well

(A). The line was connected directly to the wellhead to allow for the pumping of the treatment into the well via the casing in the form a classic ‘bullheading’ operation. This system ensured that water and nutrient mix could be safely and compliantly introduced to the producing well.

One, 200 litre drum of concentrated nutrient and 100 barrels (15,900 litres) of ‘sweet’ injection quality water was supplied to the well site prior to injection, with the water being stored in a contained 500-barrel (79,500 litres) frac tank.

A pre-injection produced water sample was collected on the 27th July from Well (A)'s wellhead prior to it being shut-in before treatment. The nutrient was then introduced into the frac tank and mixed thoroughly with the 100 barrels (15,900 litres) of injection quality ‘sweet’ water which was already contained in the tank. This was achieved by connecting both the inlet and outlet ports on the tank to the pump truck and thereafter circulating the nutrient/water mixture for 15 minutes to ensure the fluids were thoroughly mixed and homogeneous.

To ensure that there was no contamination from any residual chemicals or other fluids or particulates, prior to any mixing or pumping the tank and all flow lines were flushed with clean fresh water.

Treatment Pumping

On the 1st August 2020 the 101 barrels (16,000 litres) of diluted nutrient was injected directly at the wellhead between the casing and tubing at a rate of 1 bpm for the first 30 minutes and thereafter increased to 2 bpm until the treatment pumping was complete. The injection rates were monitored in real time with the help of specialised software connected digitally to the pumping truck. The total injection time for the treatment was approximately 65 minutes. During the entire duration of pumping the main treatment pressure within the well did not exceed 400 psi. This was below the maximum stated pressure limits of 1200 psi set by Tatweer Petroleum. The maximum pressure is set to ensure safety of the well and prevent any damage to the formation.

First Over Displacement – Post Treatment

To ensure that the nutrients injected are pushed out of the wellbore into the formation, the first of two over displacements of injection quality ‘sweet’ water was applied. This injection consisted of 25 barrels (4,000 litres) pumped at a rate of 2 bpm. This injection equated to 150 % of the tubing volume and took approximately 12 minutes to complete with the maximum pressure within the well not exceeding 1200 psi. After the injection was complete all lines were bled down and removed from the wellhead, and the well was shut-in for a period of 11 days.

Second Over Displacement - Post Treatment

To allow for the increased and activated population of resident microbiology to be pushed further out from the wellbore, a second over displacement of injection quality ‘sweet’ water was initiated on 11th August. The well was rigged up and prepared as described earlier, after which the 50 barrel (8,000 litres) second over displacement was pumped at a rate of 2 bpm for 25 minutes. After the injection was complete all lines were bled down and Well (A) was shut-in for a period of 10 further days. A typical shut-in period for a Pilot test is 10 days total (7 days + 3 days), however due to the heavy nature of the oil and the complexity of the Rubble reservoir it was decided to increase the well shut-in period to 21 days. It was believed that the extra incubation time would increase the stimulated ecology's ability to break down the heavy oil for effective recovery. The extra displacement has proven to result in higher populations of activated microbes being present for a longer period when compared to treatments with a single displacement.

Well Restart

After the 21-day shut-in period was completed the well was brought back onto production on the 22nd August. To help minimise the expected effect to the resident downhole ecology of bringing a well back into full service quickly, flow was gradually increased through production choking. The production choking schedule followed is outlined within Table 3 below.

Table 3—Return well to production choking schedule.

Date	Production Choke
22nd August 2020	25%
23rd August 2020	50%
24th August 2020	100%

Post-Pilot Microbial/Production Response

To understand the microbial response from the Pilot, water samples were taken daily, weekly, and then monthly thereafter. The sampling schedule completed on Well (A) is outlined within Table 4 below, with each ‘sample’ consisting of four (4) × 500ml bottles of produced water from Well (A).

Table 4—Post Pilot produced water sampling schedule.

Date	Sample # & Day from Injection
27th July 2020	Sample #1 – Pre-treatment sample
22nd Aug	Sample #2 – 90 mins after restart
22nd Aug	Sample #3 – 3 hours after restart
23rd Aug	Sample #4 – 25 hours after restart
24th Aug	Sample #5
25th Aug	Sample #6
/	n/a
/	n/a
3rd Sep	Sample #8
10th Sep	Sample #9
17th Sep	Sample #10
21st Oct	Sample #11
24th Nov	Sample #12

Each sample was analysed in the Titan laboratory where the microbe content was assessed both for abundance and evidence of activation using a staining and imaging technique and a limited growth analysis to ensure the microbes were living. Figure 8 shows an example of an image from Sample #2 (90 minutes after well restart).

The laboratory image outlined in Figure 8 indicates that there were numerous microbes present, numbering approximately 37.125 million per ml within Sample #2, while Figure 9 shows approximately 31.875 million microbes per ml present for Sample #5. When comparing these post treatment microbial populations against the pre-treatment sample population of 9.125 million microbes per ml it can clearly be see that there has been a significant increase in the microbial population resulting from the treatment process.

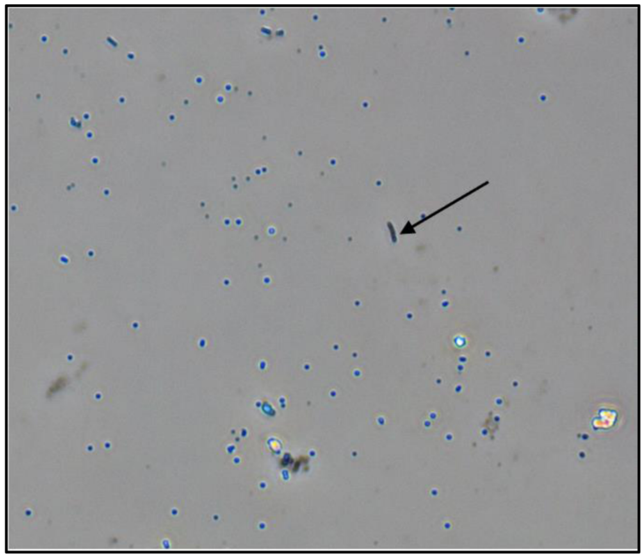

Figure 8—Image from Sample #2 staining showing activated microbes. The arrow points to a short chain of rod-shaped microbes. There are numerous microbes of both cocci and rod varieties present.

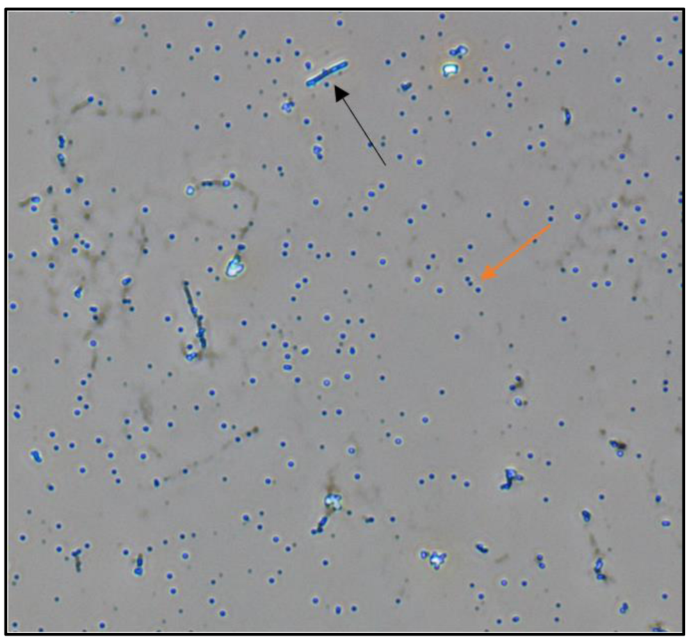

Figure 9—Image from Sample #4, 2 days after well re-start, showing an increased number of microbes present and changes in morphology. Microbes in chains (black arrow for example of rods and orange arrow for cocci) indicate activation of the microbes by the Titan nutrient mixes.

In Table 5 on the following page, an estimate of the microbes per ml in each sample is given to provide an overview of how the OOR Process has worked over time, post-Pilot injection. The microbial populations from each post-Pilot sample were calculated by using the microns per pixel of the laboratory microscope images extrapolated from the known volume of liquid placed on the slide, aligned to the area over which the fluid is spread. The resulting number is accurate as regards the slide but may vary by up to a magnitude in the actual sample due to the small volume taken. The sample itself taken from the well is also small in comparison to the total water produced from the well each day. Nevertheless, if microbes in the millions are found post OOR treatment, it is a strong indication that the OOR Process has taken effect.

Table 5—Post-Pilot produced water microbial populations (from slide counts).

Sample #	Notes / Observations for Well (A)			
Sample #1 Pre-treatment	Notes: None			
	Microbe Count in Field	146	Microbe Count/ ml	9,125,000
Sample #2	Average Microbe Count in field: 310 Average Microbe Count / ml: 19,374,833			
	Microbe Count in Field – Figure 10	594	Microbe Count/ ml	37,125,000
Sample #3	Notes: None			
	Microbe Count in Field	575	Microbe Count/ ml	35,625,000
Sample #4	Notes: None			
	Microbe Count in Field	615	Microbe Count/ ml	38,437,500
Sample #5	Notes: None			
	Microbe Count in Field	510	Microbe Count/ ml	31,875,000
Sample #6	Notes: Did not receive sample due to lack of water – oil cut almost 100%			
	Microbe Count in Field	/	Microbe Count/ ml	/
Sample #7	Notes: Did not receive sample due to lack of water – oil cut almost 100%			
	Microbe Count in Field	/	Microbe Count/ ml	/
Sample #8	Notes: None			
	Microbe Count in Field	348	Microbe Count/ ml	21,750,000
Sample #9	Notes: Average Microbe Count in field: 62.3 Average Microbe Count / ml: 3,895,833.33			
	Microbe Count in Field – Image#1	55	Microbe Count/ ml	3,437,500
	Microbe Count in Field – Image#2	75	Microbe Count/ ml	4,687,500
	Microbe Count in Field – Image#3	57	Microbe Count/ ml	3,562,500

The pre-treatment sample taken had approximately 9.125 million microbes per ml. This population was similar to the numbers measured within the original produced water samples taken in August 2019 to determine if this well was suitable for the OOR Process. This can therefore be considered a reliable baseline for Well (A).

All the samples taken after the Pilot test treatment and shut-in period, except for sample #8 had more microbes per ml than the pre-treatment sample. The presence of microbes increased with time for the first few samples and then began to drop off for a few days followed by a further increase in microbes towards the end of the sample period being reviewed. This is very typical of the OOR response. The nature of the sampling process provides a moment in time of the reservoir ecology and thus should be seen as indicative of real time changes.

In addition to the population increase there was also a clear increase in microbes which indicated a response to the OOR Process, where the nature or the microbe changes from being Hydrophilic to being Hydrophobic through nutrient limitation. The maximum number of microbes seen in this series was more than 20-fold higher than the pre-treatment sample. The post treatment samples had a majority of microbes that had morphological changes consistent with the activation to the Hydrophobic form.

When post treatment samples are received, as well as staining and imaging, some of the samples are put back in nutrients to determine what percent are still alive and capable of growth, and if they are still activated by the OOR Process. If available, a genomic analysis is also performed (this was not available for these samples due to Covid-19 causing shortages of ingredients used in the analysis). Tubes were set up for growth from Samples #3, #8 and #9 using no nutrient addition and two concentrations of the nutrient mix used in the well treatments and incubated at the Bottom Hole Temperature (BHT). After one week the control had very little sign of growth and both concentrations had very clear growth. This confirms that living microbes were present in the samples taken at the well head and that they grow at the nominal BHT.

Samples were taken from these tubes and stained and imaged to demonstrate the growth and diversity of the microbes present in the well sample. In Figure 10 below, we show an example of the stained and imaged microbes from one nutrient concentration.

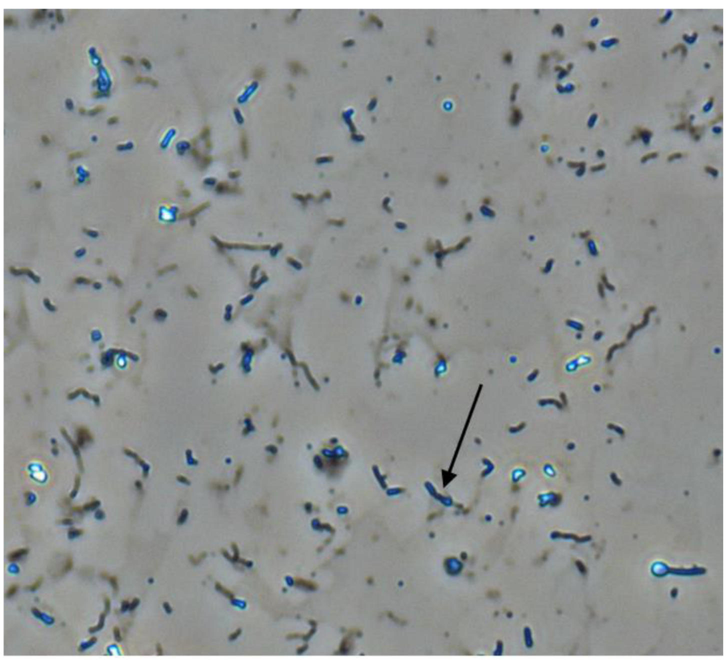

Figure 10—Image of stained microbes from Tube 3, a low concentration of the nutrient recipe. The arrow points to chain of rods. There are many short chains and many rods and some cocci.

Following Well (A)'s production re-start on the 22nd August, a program of well testing was completed. Well tests on Tatweer Petroleum's Awali field are undertaken by third party service companies and are completed through connecting each individual well to a mobile test separator. Fifteen (15) individual well tests of the same duration of 6 hours were completed at planned intervals and the results are shown in Table 6 below. The first well test took place on the 23rd August 2020, one day after the well was re-started.

Table 6—Well (A) - Well Tests pre and post treatment.

Test date	Duration	Water Cut	Oil	Water	Liquid. Rate
	(Hr)	(%)	(bpd)	(bpd)	(bpd)
2/2/2018	6 hour	94.95	5	94	99
11/3/2018	6 hour	56.1	18	23	41
16/5/2018	6 hour	30.55	25	11	36
3/9/2018	6 hour	81.13	20	86	106
3/10/2018	6 hour	80.77	5	21	26
24/11/2018	6 hour	82.22	8	37	45
1/12/2018	6 hour	82.22	8	37	45
4/12/2018	6 hour	83.33	11	55	66
8/12/2018	6 hour	84.52	13	71	84
20/6/2019	6 hour	75.47	13	40	53
17/01/2020	6 hour	62.85	13	22	35
27/03/2020	6 hour	40.59	60	41	101
23/05/2020	6 hour	99.19	1	123	124
12/06/2020	6 hour	15.85	138	26	164
20/07/2020	6 hour	30.95	58	26	84
1/08/2020	*Pilot Nutrient Injection*				
22/08/2020	*Well re-start*				
23/08/2020	6 hour	99.47	0.74	138.75	139.49
04/09/2020	6 hour	13.2	152.11	23.12	175.23
07/09/2020	6 hour	38.58	99.48	62.48	161.96
10/09/2020	6 hour	40.35	114.9	77.72	192.62
13/09/2020	6 hour	45.64	102.95	86.42	189.37
16/09/2020	6 hour	36.01	127.35	71.66	199.01
21/09/2020	6 hour	8.06	223.93	19.63	243.56
24/09/2020	6 hour	38.17	160.09	98.84	258.93
25/09/2020	6 hour	50.04	114.81	115	229.81
13/10/2020	6 hour	63.01	87.76	149.48	237.24
19/10/2020	6 hour	55.72	105.88	133.24	239.12
25/10/2020	6 hour	38.84	168.02	106.72	274.74
29/10/2020	6 hour	35.83	200.21	111.79	312
13/11/2020	6 hour	76.32	56.67	182.66	239.33
19/11/2020	6 hour	91.64	9.84	107.84	117.68
25/11/2020	6 hour	99.32	1.6	232.94	234.54
01/12/2020	6 hour	42.83	134.08	100.46	234.54
07/12/2020	6 hour	50.4	121.68	123.66	245.34
13/12/2020	6 hour	65.61	152	290	442
14/12/2020	6 hour	65.60	130	248	378
19/12/2020	6 hour	64.74	140	257	397
27/12/2020	6 hour	64.92	147	272	419
26/01/2021	6 hour	65.44	122	231	353

The first well test completed on the 4th September measured on average an oil production rate of 152.11 BOPD with a total liquid rate of 175.23 BPD. This oil rate was the highest tested rate since 2009 and similarly the well's water cut from the first well test was measured at 13.2 %, which again was one of the lowest tested within a period of over 10 years.

Analysing the post treatment well test numbers against the pre-treatment forecast, as seen in Figure 11 on the following page, it can be interpreted as showing a response in the production due to the OOR Pilot injection. This response continued for more than 3 months from well re-start. Similarly, the well test water cut of the fluid showed significant change following OOR treatment. When these numbers are considered against the laboratory results, particularly the microbial population outlined within Table 5, they point to a correlation between the production and microbial response.

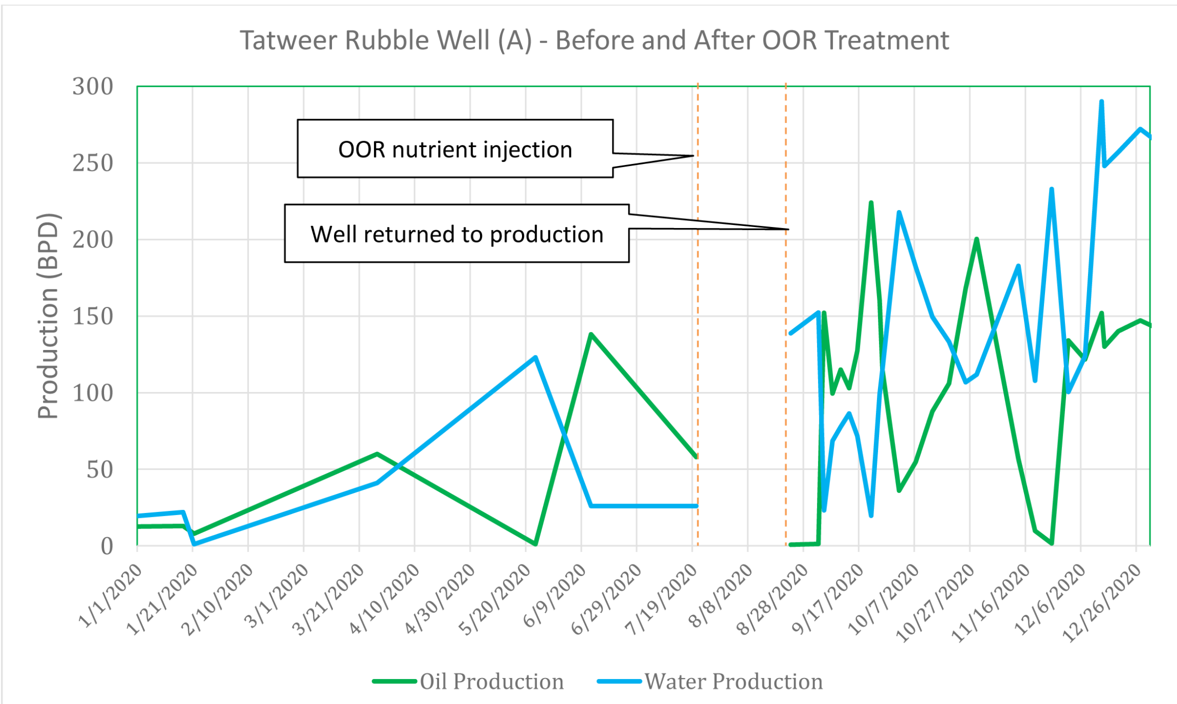

Figure 11—Comparison of OOR Pilot treatment production results against the pre-treatment forecast for Well (A).

The increase and peak microbial populations coincided with the increasing numbers of activated microbes seen in the samples over the first two weeks. Given that the oil production is still above baseline beyond the last scheduled well test, monitoring of both the production and microbial response has continued.

A continuous steam injection program has been ongoing in the vicinity of Well (A) since Q3 2020. The steam injection well is located approximately 800m away from producer Well (A). The microbial analysis of the post-Pilot produced water does not support the theory of a direct steam injection impact on Well (A) production, as the microbes sampled and analysed were still growing at the original BHT. Additionally, there is no indication that analysed reservoir microbes were being killed off by higher temperature steam condensate from the steam injection program. It is worth noting that the well temperature seems to be around 45C which is fairly cool and not indicative of heat, at least, reaching this reservoir area from the nearby steam injection.

Nevertheless, the significant increase in the total liquid production post treatment (Table 6) can only be explained by the change in reservoir dynamics, whereby the steam injection, which is likely to have turned to hot water quickly upon injection, introduced a pressure support mechanism. Moreover, the water salinity analysis post treatment on the producer showed lower figures compared to the average water salinity across the Rubble formation, which suggests a fresh water source has been introduced as result of the ongoing steam injection.

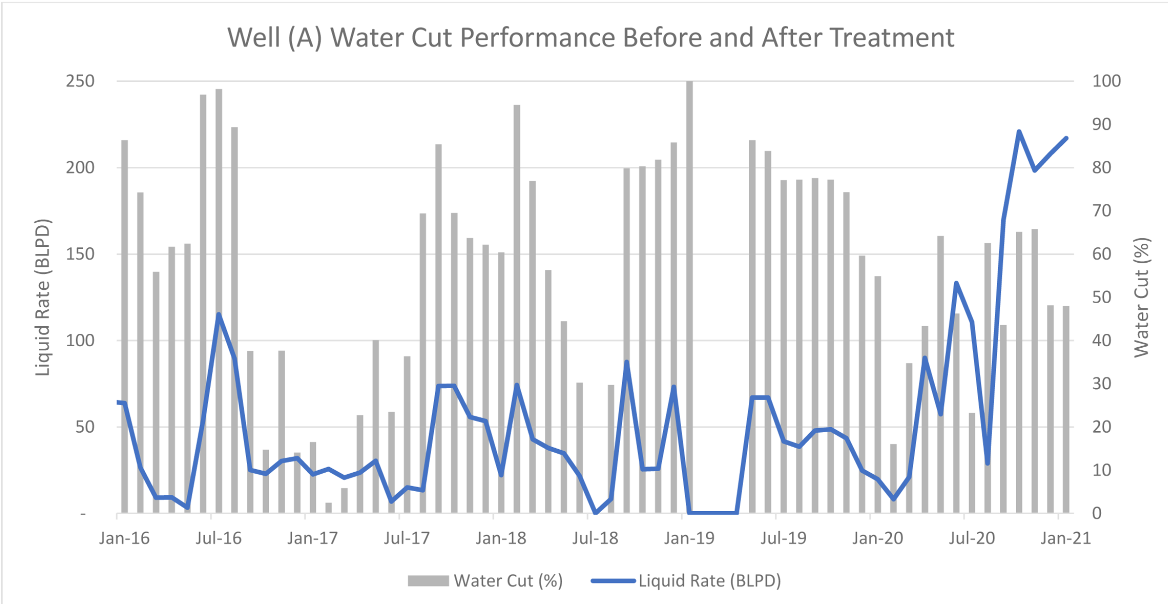

Figure 12—Well (A) well test water cut comparison.

In summary, the combined effect of the organic oil recovery treatment with the introduction of a pressure support mechanism in such a tight, highly fractured, and low-pressure reservoir is likely to have been a major factor to the success of the Pilot.

Conclusions/Discussion

During the initial laboratory testing of Well (A) the reservoir showed a diverse and abundant resident ecology which was deemed capable of undertaking the necessary characteristic changes to facilitate enhanced oil production. With the presence of energy in the reservoir, through the application of a pressure support program, the Pilot test results have proven both a strong microbial and production response, which demonstrates that Organic Oil Recovery technology has been successfully applied to a heavy oil producing carbonate field in Bahrain. A strong correlation between the microbial and production responses has been implied through the mapping of microbial population growth and microbial nutrient limitation against the measured production response.

With the presence of the energy in the reservoir, whether it is natural (i.e. active water aquifer) or provided through an artificial pressure support program (i.e. waterflood or steam flood), OOR has proven to release additional trapped oil with a relatively small contact area in heavy oil. This opens new opportunities to take advantage of existing heavy oil fields to recover trapped oil which would not normally be produced and left in ground at the end of the field's life. In fields where steam flooding or water flooding can be applied the use of OOR technology could be considered to further enhance oil production in heavy oil reservoirs.

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