

Polymer-Flood Produced-Water-Treatment Trials

R.S. Al-Maamari, Sultan Qaboos University; M. Sueyoshi, M. Tasaki, and K. Kojima, Shimizu Corporation; and K. Okamura, Tecnet

Summary

Polymer-enhanced-oil-recovery (EOR) operation has been implemented for the production of oil from difficult mature oil fields in Oman. The polymer used to sweep oil toward production wells in this EOR technique is resulting in the generation of polymer-flood produced water (PFPW) of increasing viscosity. Current methods of treating oilfield produced water must be reconsidered for the effective treatment of PFPW of such changing quality.

In a previous study, the use of polyaluminum chloride (PAC) was proposed for the coagulation of oil in produced water to be separated by flotation and filtration. As such, laboratory tests were conducted to evaluate the applicability of PAC and other chemicals for treatment of PFPW with higher viscosity than ordinary oilfield-produced water. These tests indicated clearly that aluminum sulfate (AS) was more effective for treatment of such higher-viscosity water.

A pilot plant developed during the earlier study was used to conduct coagulation/flocculation-, flotation-, filtration-, and adsorption-treatment trials for PFPW from an oil field at which polymer EOR was under way. For the final trial, the inlet PFPW viscosity was 1.4 cp at 40°C and oil concentration was greater than 200 mg/L AS was applied for the coagulation/flocculation and flotation stages, and was found to be effective in reducing oil concentration to 1 mg/L Filtration and adsorption stages resulted in further improvement of water quality. Most of the polymer used for EOR was believed to have been removed along with oil and suspended solids.

Introduction

Oman's main oil-production company, Petroleum Development Oman (PDO), produces roughly 8 m³ of water/m³ of oil, totaling 4.5 million B/D of water (Al-Manhal 2009). Much of this produced water is reinjected into the oil reservoirs for pressure maintenance, and some is used to generate steam for enhanced-oil-recovery (EOR) projects. Because all of Oman's production facilities are currently onshore and well inland of the coast, marine disposal is not an option for the remaining produced water.

Disposal to shallow aquifers was phased out in 2005 (Breuer and Al-Asmi 2010) to avoid any contamination of these aquifers and to preserve them for future use (Al-Manhal 2009). While reed plants have been used in recent years to treat large quantities of this produced water, in the case of lower-salinity brines (Al-Manhal 2010), much of the water is still disposed of into deep-lying aquifers, a costly and energy-intensive process because of the high

levels of pressure needed to pump the water down to a depth of approximately 2 km below the surface (Al-Manhal 2010). Some concerns also exist for deep-well disposal over the long run in terms of clogging of the reservoirs by oil and of increasing saturation pressure caused by the finite limit of water that can be absorbed by the aquifers (Al-Manhal 2009, 2010). As such, less-expensive and environmentally acceptable alternatives for produced water have been sought. In fact, PDO has been searching for ways to convert this liability into a water resource. Suitable treatment and use of produced water represents an attractive alternative to disposal. In terms of possible use of treated produced water, the relatively low salinity of the currently disposed water increases the deployment options of such water after treatment. In light of such need, the authors have been working to identify simple, highly efficient treatment systems for produced water in Oman through laboratory tests and treatment trials.

There is no single treatment technology suitable for all cases of produced water. Generally, produced water contains traces of dispersed and dissolved oil; heavy metals; boron; corrosive fluids, such as hydrogen sulfide and carbon dioxide; production chemicals; radioactive isotopes; formation minerals; and other solids (Fakhru'l-Razi et al. 2009; Al-Manhal 2003; Khatib and Verbeek 2002). Therefore, the selection of suitable treatment methods/technologies depends on the water characteristics and chemistry, as well as numerous other factors, including target treated-water quality on the basis of reuse/discharge plans, capital/operating costs, facility space constraints, treatment-unit mobility, durability/ease of operation and maintenance, and waste-stream-byproducts pre- or post-treatment requirements (Arthur et al. 2005).

There are various physical, chemical, and biological methods proposed for produced-water treatment. Available technologies have been described and compared in the literature (Fakhru'l-Razi et al. 2009; Arthur et al. 2005; CSM 2009; Kenawy and Kandil 1998; Plebon 2004). Primary-treatment equipment includes skim tanks, American Petroleum Institute-type separators, and plate-pack interceptors, which rely on simple and cost-effective gravity methods to separate free oil and coarse solids (large droplets/particles greater than 150 µm in diameter), mainly for recovering as much oil as possible rather than for treating water. Secondary-treatment techniques involve enhanced separation of dispersed oil and fine solids (small droplets/particles 20 to 150 µm in diameter) and include flotation (dissolved gas, induced gas) with and without coagulation (aluminum and iron salt, polymer), hydrocyclones, and centrifuges, generally reducing the dispersed-oil concentration to less than 40 mg/L Hydrocyclones have been reported to be able to handle finer solids (5 to 15 µm in diameter), reducing oil and grease levels to 10 mg/L Polishing- and tertiary-treatment technologies target emulsified oil and finer solids (smaller droplets/particles 5 to 20 µm in diameter) and dissolved oil (less than 5 µm in diameter), and include media filters (walnut shell, sand, anthracite), cartridge filters, membranes, adsorption (activated carbon), and biological treatment (reedbed), and reduce dispersed-oil concentration to less

than 5 to 10 mg/L (SPE 2011). Combinations of more than one method/technology may be used in series.

Primary-treatment equipment is standard throughout Oman. Secondary-treatment techniques, such as induced-gas flotation, gas-flotation tanks, and hydrocyclones, have also been used at some sites in Oman (Al-Manhal 2009), but performance results have not been reported publicly. Polishing- and tertiary-treatment technologies, such as walnut-shell filters, have also been used at some sites in Oman, but again, performance results have not been reported publicly. Reedbed treatment is also used, and the initial capacity of 45 000 m³/d (Breuer and Al-Asmi 2010) is being doubled (Oman Daily Observer 2012).

In a previous study (Al-Maamari et al. 2014), treatment trials of oilfield-produced water were carried out with a versatile, mobile pilot plant developed specifically for testing different-quality produced waters to different treatment levels. With the pilot plant, coagulation/flocculation, flotation, filtration, and adsorption processes could be tested separately or in series. Flotation with polyaluminum chloride coagulant and adsorption by activated carbon were two processes that were tested during the trials, and were not being used for produced-water treatment in Oman.

Since the previous study, polymer-EOR operation has been implemented for oil production from difficult, mature oil fields in Oman. The polymer used to sweep oil toward production wells in this EOR technique results in the generation of polymer-flood produced water (PFPW) of increasing viscosity. As such, current methods of treating ordinary oilfield-produced water must be reconsidered for the effective treatment of PFPW of such changing quality.

The focus of this study was the treatment of such PFPW from polymer-EOR operations. Three trials and laboratory testing were conducted for the treatment of PFPW from polymer-EOR operations. 20-m³ samples of PFPW were collected from the field for each of the trials, and a 40-L sample for the laboratory tests was also collected from the field on a separate occasion. The pilot plant used in the previous study was also used for these trials. As before, the pilot-plant design allowed for the testing of coagulation/flocculation, flotation, filtration, and adsorption processes in different combinations according to PFPW quality and at different levels of treatment. For these trials, the treatment process was adjusted to allow for testing additional processes such as aeration and a second coagulation/flocculation.

Experimental

Pilot-Plant Design. The design of the pilot plant is based on the chemical- and mechanical-treatment processes of coagulation/flocculation, flotation, and adsorption. The pilot plant is flexible, allowing for the testing of different combinations of these individual processes for the treatment of different types of water to different levels of oil concentration, according to need. For example, for marine disposal of such water, the secondary-treatment processes of coagulation, flocculation, and flotation might be sufficient. For irrigation reuse, the additional tertiary processes of filtration and adsorption might also be required. The combined-process design was based on the objective of lowering oil concentration in primary treated water of roughly 250 mg/L to approximately 0.5 mg/L. At this level of oil concentration, the treated produced water could be used as irrigation water (Sultanate of Oman 1993). The plant is compact to allow for transportation to conduct trials at different sites, and its capacity is 50 m³/d. Most of the descriptions in the remainder of this section were presented in Al-Maamari et al. (2014) and are repeated here for convenience.

Coagulation/flocculation was selected as the pretreatment to flotation to agglomerate small oil droplets and suspended solids into larger contaminant flocs (roughly 5 mm in diameter) to allow for more-efficient separation of contaminants from water and, consequently, smaller processing vessels. The pilot plant can be used to test a variety of coagulants/flocculants. Previously, a combina-

tion of polyaluminum chloride (PAC) and medium-strength anionic polymer (polyacrylamide, Takifloc A-103T) was used. The reasons for the selection of these chemicals were explained in Al-Maamari et al. (2014). Induced-gas flotation (IGF) was selected as an enhanced gravity-separation secondary-treatment technique that uses microbubbles to help separate/lift contaminants to the water surface for removal. Flotation was selected because of its lower cost relative to other secondary techniques, and IGF was selected over dissolved-air flotation because of its ease in operation, minimal equipment requirements, and small footprint. Nitrogen was selected as the flotation gas, for safety and maintenance issues related to corrosion and scaling.

Filtration was selected to remove any dispersed contaminants remaining in the water following flotation, and adsorption was selected to remove dissolved contaminants and any dispersed contaminants remaining in the water following filtration. While the pilot plant can be used to test a variety of filter media and adsorbents, anthracite and activated carbon were used during these trials because they were judged to be the most-cost-effective filtration and adsorption materials available.

Accordingly, the four main components of the plant are

- Two mixing tanks, volume=0.5 m³ each, operational capacity =0.4 m³ each
- Flotation tank, volume=0.8 m³, operational capacity=0.63 m³
- Filtration tower, volume=0.5 m³, operational capacity=0.4 m³
- Adsorption tower, volume=0.5 m³, operational capacity=0.4 m³

Additionally, there are holding tanks for raw water (RW), scum, and treated water, and there are smaller chemical tanks for preparation and dosing of the chemical solutions required for coagulation and flocculation of water contaminants.

Different pumps convey water through the treatment processes and also generate the microbubbles required for flotation. Mixers are used to prepare chemical solutions and to coagulate and flocculate contaminants in the water. A scraper removes separated oily scum from the surface of the water in the flotation tank. A pressure-swing-adsorption (PSA) nitrogen generator supplies nonexplosive gas for flotation.

The detailed pilot-plant system flow is shown in Fig. 1. RW is sent from the RW tank (1) by the submersible RW pump (1) to the mixing tanks (2&3). Coagulant solution [PAC/aluminum sulfate (AS)] is dosed from the coagulant tank (10) by the coagulant pump (8) to the coagulant-mixing tank, where RW and coagulant are mixed to coagulate contaminants. There are provisions to add a second chemical, if desired.

Coagulated water flows to the pressure pump (3), where nitrogen gas supplied from the PSA nitrogen generator (4) is injected into the pumphead to generate the microbubbles required for separation of contaminants by flotation. Polymer is dosed from the polymer tank (11) by the polymer pump (10) at the pump outlet to enlarge the flocs coagulated by PAC to allow for easier separation by flotation. A second pressure-pump system is available to increase system flow or as a spare.

From the pressure pump, coagulated/flocculated water enters the flotation tank (4), where nitrogen microbubbles separate the chemical/contaminant flocs, carrying them to the surface at which point they are removed by the scum scraper (16) and flow by gravity to the scum tank (12). Water treated by flotation flows to the adjoining flotation-treated-water tank (5).

Depending on the water level in the flotation-treated-water tank, the flotation-treated water is sent by the filtration pump (5) through the sand-filtration tower (6) and activated-carbon-adsorption tower (7) into the treated-water tank (8). Valves and piping exist to bypass both the filtration and adsorption towers or the adsorption tower only, according to the treatment processes being tested. Additionally, for cleaning of the filtration and adsorption towers, there is a backwashing pump (6).

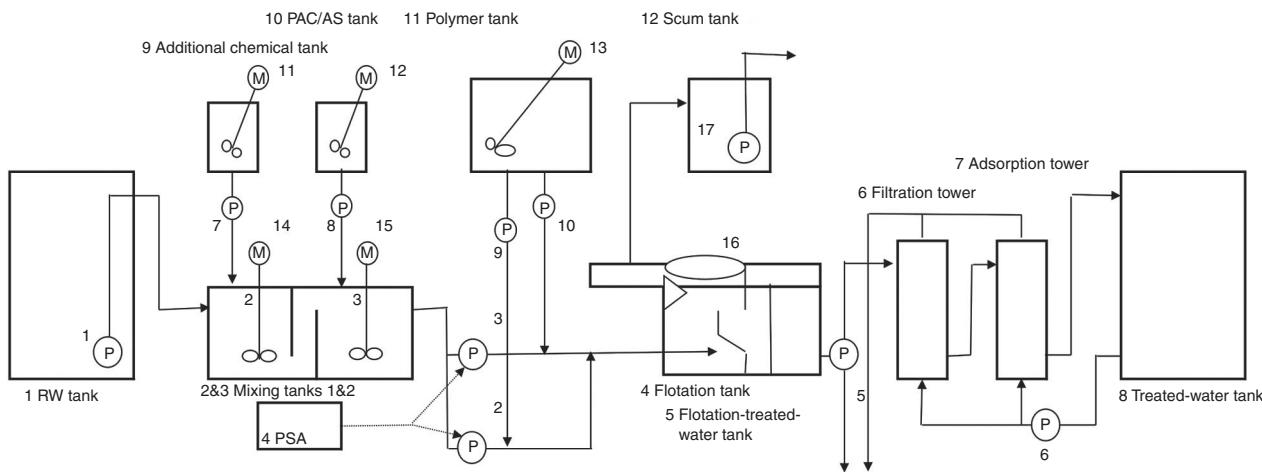


Fig. 1—Pilot-plant treatment-process-flow diagram.

Further to the earlier description of the pilot-plant process, chemical-dosing pumps are capable of supplying a concentration of 10 to 100 mg/L of coagulant and 0.2 to 5 mg/L of polymer to the water. These test ranges of chemical concentrations can be further increased by lowering the rate of water entering the plant and or increasing the concentration of the chemical solutions being added to the water. Maximum linear velocity for filtration is 5.2 m/h, and minimum space velocity for adsorption is 6.7/h. The filtration media used for these trials was anthracite instead of the sand used in the previous study. The adsorption media used for these trials was activated carbon (KURARAY COAL KW, Kuraray Chemical Company), which is the same as that used in the previous study.

As mentioned earlier, while the pilot plant was designed originally to test coagulation/flocculation-, flotation-, filtration-, and adsorption-treatment techniques, for these trials, the treatment system was adjusted to allow for the testing of additional processes such as aeration and a second coagulation/flocculation.

Trial Sampling and Analysis. For oil-in-water measurement, TD-500D fluorescence analysis was used after single extraction with *n*-hexane. The TD-500D analysis is a convenient method that can provide quick results on-site and can approximate the gravimetric method of oil and grease measurement [i.e., Environmental Protection Agency Method 1664 (EPA 1999), the designated regulatory method in the US]. Similar to such gravimetric methods, the TD-500D does not measure benzene, toluene, ethylbenzene, and xylene compounds that may be dissolved in water effectively. The TD-500D and such gravimetric methods measure the concentrations of less-volatile hydrocarbons that are more likely to be dispersed in water.

Turbidity was measured on-site with a Hanna Instruments Microprocessor Turbidity Meter HI93703 [up to 1,000 Formazin turbidity unit (FTU)]. Chemical oxygen demand was measured as oxygen demand by potassium permanganate consumed (*JIS K 102:2008*). Sulfides (S^{2-} , HS^-) were measured on-site by Gastec No. 211LL detector tubes for liquids. Additionally, viscosities were measured for polymer-flood produced-water (PFPW) samples with a BII viscometer, Type BLII (Toki Sangyo Company).

Water samples were collected from up to six different points, depending on the trial, as follows:

- RW inlet to the pilot plant
- After coagulation/flocculation and nitrogen flotation
- After aeration
- After second coagulation/flocculation
- After anthracite filtration
- After activated-carbon adsorption

Inlet-Water Characteristics. Because PFPW is expected to be of higher viscosity than ordinary produced water as a result of the presence of polymer used in enhanced-oil-recovery (EOR) operations, viscosity measurements were taken for each of the samples from the trials and laboratory tests. Measurements were taken at 60 rev/min (shear rate of 71.58 s^{-1}) and at a temperature of 40°C:

- Trial 1 sample from 20 m³ of PFPW: 0.69 cp
- Laboratory-testing sample from 40 L of PFPW: 1.88 cp
- Trial 2 sample from 20 m³ of PFPW: 0.74 cp
- Trial 3 sample from 20 m³ of PFPW: 1.40 cp

Additionally, viscosity measurements of solutions of distilled water, 0.44% sodium chloride (NaCl) (reservoir salinity), and EOR polymer FLOPAAM 3630 S (0 to 5000 mg/L) were carried out to gain a rough understanding of the viscosity of ordinary produced water without any polymer and of the quantity of polymer required to achieve a target viscosity of 16 cp, both at reservoir temperature of 46°C. Viscosity of distilled water and 0.44% NaCl solution without polymer at 46°C was 0.51 cp. The required polymer addition to distilled water and 0.44% NaCl solution to a target viscosity of 16 cp appeared to be more than 1000 mg/L (Fig. 2).

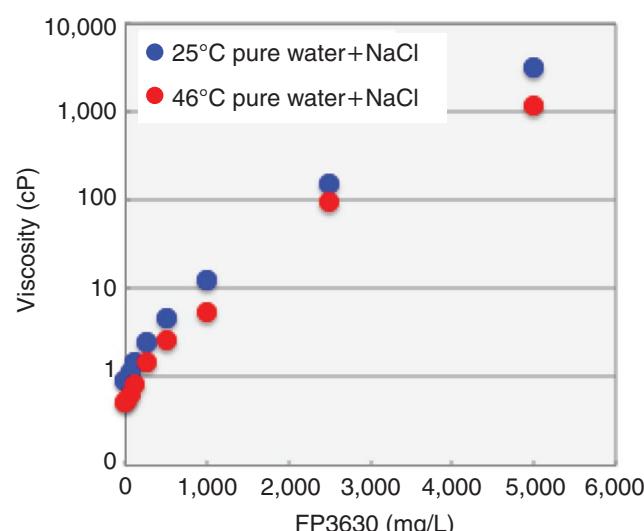


Fig. 2—Viscosity at room and reservoir temperatures vs. EOR polymer addition.

PAC (mg/L)	Turbidity		Oil	
	(FTU)	Removal (%)	(mg/L)	Removal (%)
0	58.0	—	91.2	—
50	47.2	18.6	46.4	49.1
100	42.5	26.7	39.7	56.5
150	30.7	47.1	23.5	74.2
200	30.5	47.4	21.2	76.8

Table 1—Trial 1 jar tests: Water quality vs. PAC addition. FTU = Formazin turbidity unit.

Compared with the viscosity reference value of solution without polymer of 0.51 cp and target viscosity of 16 cp, the viscosities of all four samples used for trials and laboratory testing were comparatively low (even though they were measured at a temperature of 40°C, which was 6°C lower than for the reference sample).

Results and Discussion

Three trials and several laboratory tests were conducted for this investigation for the treatment of polymer-flood produced water (PFPW). PFPW samples were delivered from the field in a 20-m³ tanker for each treatment trial. A 40-L sample was collected on a separate occasion for the laboratory tests.

The first PFPW-treatment trial was conducted with polyaluminum chloride (PAC) for coagulation of oil in produced water to be separated by flotation and filtration on the basis of the effectiveness of PAC in previous trials for ordinary produced-water treatment (Al-Maamari et al. 2014). Laboratory tests were then conducted to evaluate the applicability of PAC and other chemicals for treatment of PFPW of higher viscosity than ordinary oil-field-produced water. These tests indicated that aluminum sulfate (AS) would be more effective as a coagulant for the treatment of this water. Subsequently, the second PFPW-treatment trial was conducted with AS as the coagulant instead of PAC. However, because the PFPW tested during the second trial was of relatively low viscosity (closer to that of ordinary produced water), the difference in effectiveness of AS was not clear, and a third PFPW-treatment trial was conducted, again with AS instead of PAC.

The pilot plant was used for testing coagulation/flocculation-and flotation-treatment processes. Bench-scale equipment was used for aeration, second coagulation/flocculation, anthracite filtration, and activated-carbon adsorption-treatment processes in large part because of the limited volumes of water available for the trials.

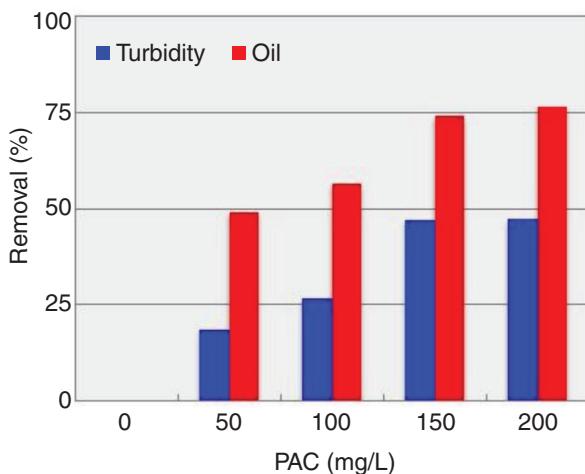


Fig. 4—Trial 1 jar tests: removal rates vs. PAC addition.

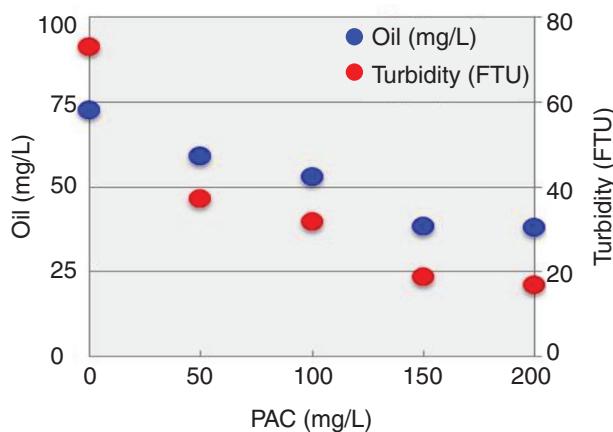


Fig. 3—Trial 1 jar tests: water quality vs. PAC addition. FTU=Formazin turbidity unit.

Trial 1. PAC was used as the coagulant for the previous treatment trials of ordinary produced water. On the basis of its effectiveness in these previous trials, PAC was proposed and used for the first PFPW trial to evaluate the effectiveness of PAC treatment.

20 m³ of PFPW was transported from the field. The viscosity of the water was much lower than expected (0.69 cp at 40°C). Initial jar tests indicated a suitable chemical-addition rate of 150 mg/L of PAC (and 2 mg/L of polymer) for the pilot trial (**Table 1** and **Figs. 3 and 4**). However, because a relatively high concentration of oil remained in the water from these initial jar tests, additional jar tests for a second PAC treatment were carried out with water pretreated with 150 mg/L of PAC. These additional jar tests indicated that a second PAC addition of 60 mg/L would be effective in reducing the oil-in-water (OIW) concentration to less than 5 mg/L (**Fig. 5**). As such, a second coagulation/flocculation treatment was added for the trial.

Two separate sets of jar tests were conducted to assess the effect of aeration on water quality. The first set of tests indicated that with preaeration, better water quality could be achieved with less PAC addition. For example, with 100 mg/L of PAC addition, preaeration resulted in an OIW concentration of less than 5 mg/L and turbidity in the range of 10 FTU (**Fig. 6**), compared with an OIW concentration of close to 20 mg/L and turbidity of approximately 30 FTU for results without such preaeration followed by a higher PAC-addition rate of 150 mg/L (**Fig. 3**). The second set of tests confirmed that aeration was effective for sulfide (S²⁻) stripping (even more so when combined with pH control) (**Fig. 7**). The S²⁻ concentration was reduced from close to 30 mg/L to nearly zero at aeration rates

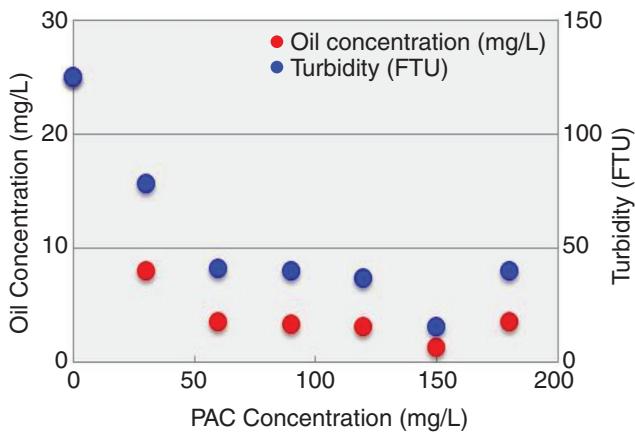


Fig. 5—Trial 1 jar tests: water quality vs. second PAC addition.

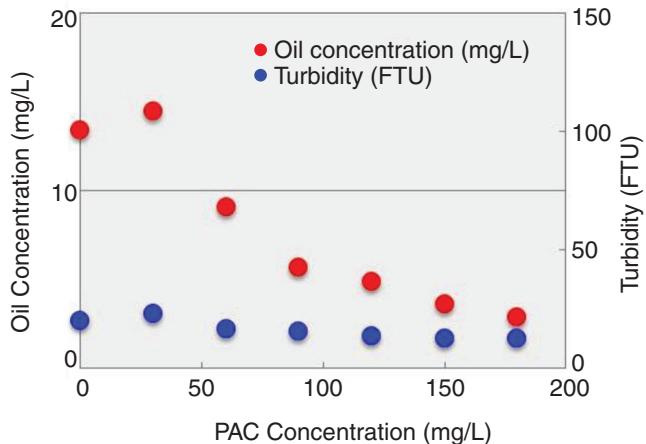


Fig. 6—Trial 1 jar tests: Water quality vs. PAC addition preceded by aeration.

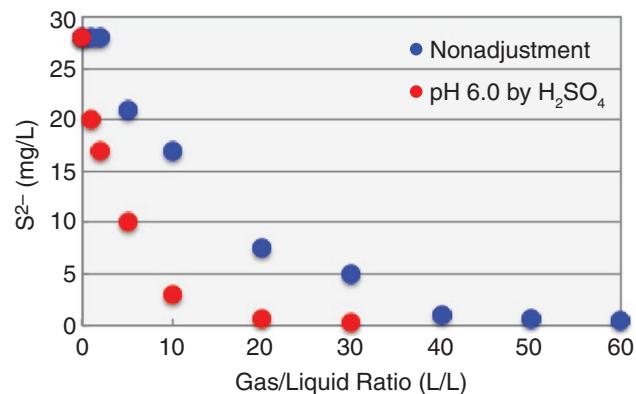


Fig. 7—Trial 1 jar tests: Sulfide removal vs. aeration rates with and without pH control.

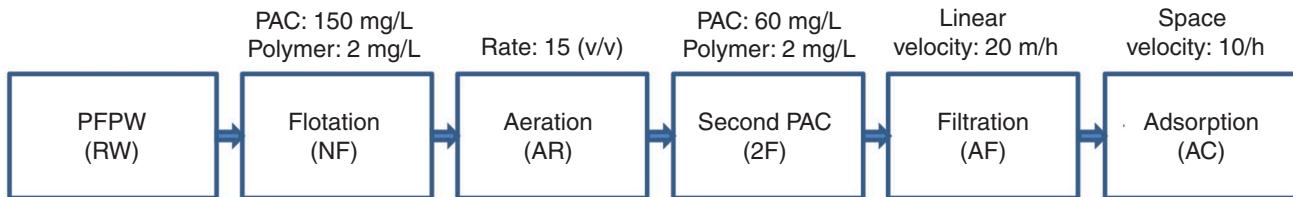


Fig. 8—Trial 1 treatment-process flow. RW=raw water; NF=nitrogen flotation, AR=aeration, 2F=second coagulation/flocculation, AF=anthracite filtration; AC=activated-carbon adsorption.

	RW	NF	AR	2F	AF	AC
Oil (mg/L)	78.9	44.0	12.3	4.4	3.0	0.7
Turbidity (FTU)	55.0	52.0	125.0	38.0	17.8	10.3
Sulfides (mg/L)	38.0	13.5	N.D.	N.D.	N.D.	N.D.

N.D. = Not detected.

Table 2—Trial 1 water quality after each stage of treatment.

greater than 40 (greater than 20 with pH control). On the basis of these results, the aeration process was also included for this trial (**Fig. 8**). While aeration would probably be more effective before the first coagulation/flocculation/flotation process, it was not possible to do so during this trial. Modification of the pilot-plant process is recommended in the future to test such preaeration.

Jar tests were also conducted to evaluate the performance of six alternative chemicals (including deoiler) as coagulant, but they were all evaluated to be either less effective or, in one case, less practical to use than PAC, and were not selected for testing in the trial. Additional jar tests were conducted to evaluate the performance of oxidants (hydrogen peroxide, sodium hypochlorite) for removal of S^{2-} , but they were not effective and also were not selected for testing in the trial.

During the trial, S^{2-} concentration was reduced from 38 to 13.5 mg/L after the coagulation/flocculation/flotation processes. As expected, the aeration step removed the remaining S^{2-} . The pilot-trial results indicated that OIW concentration in PFPW was reduced from 79 to 0.7 mg/L through coagulation/flocculation, flotation, aeration, second coagulation/flocculation, anthracite filtration, and activated-carbon adsorption (**Table 2** and **Fig. 9**).

Laboratory Tests. The 40-L sample of PFPW collected for the laboratory tests was of higher viscosity than previous trials (1.88 cp at 40°C). A different chemical, AS, was tested, and its performance was compared with that of PAC on the provided sample. Results

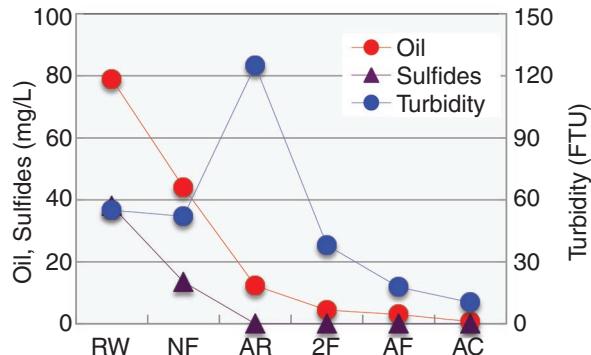


Fig. 9—Trial 1 water quality through different stages of treatment.

indicated that AS was more effective than PAC for treatment of this water, particularly at a 150-mg/L chemical-addition rate (**Fig. 10**).

Because the viscosity and oil concentrations in the provided PFPW sample were low, an additional 500 mg/L of enhanced-oil-recovery (EOR) polymer (3630 S) and additional oil (Japanese Heavy Oil A, equivalent to ISO No. 2 Fuel Oil—Diesel Fuel or Oil) were emulsified with the sample, resulting in a viscosity of 4.5 cp and an oil concentration of 2500 mg/L, and the sample was retested with AS and PAC. AS addition of 200 mg/L was effective in reducing the oil concentration in water (well below 0.5 mg/L), while PAC was ineffective. This reduction appeared to be related to the reduction in viscosity with the addition of AS (**Fig. 11**). Most of the polymer used for EOR was believed to have been removed along with oil and suspended solids.

Trial 2. On the basis of its effectiveness in laboratory tests, AS was proposed and used as the coagulant for the second PFPW-treatment trial to evaluate the effectiveness of AS treatment.

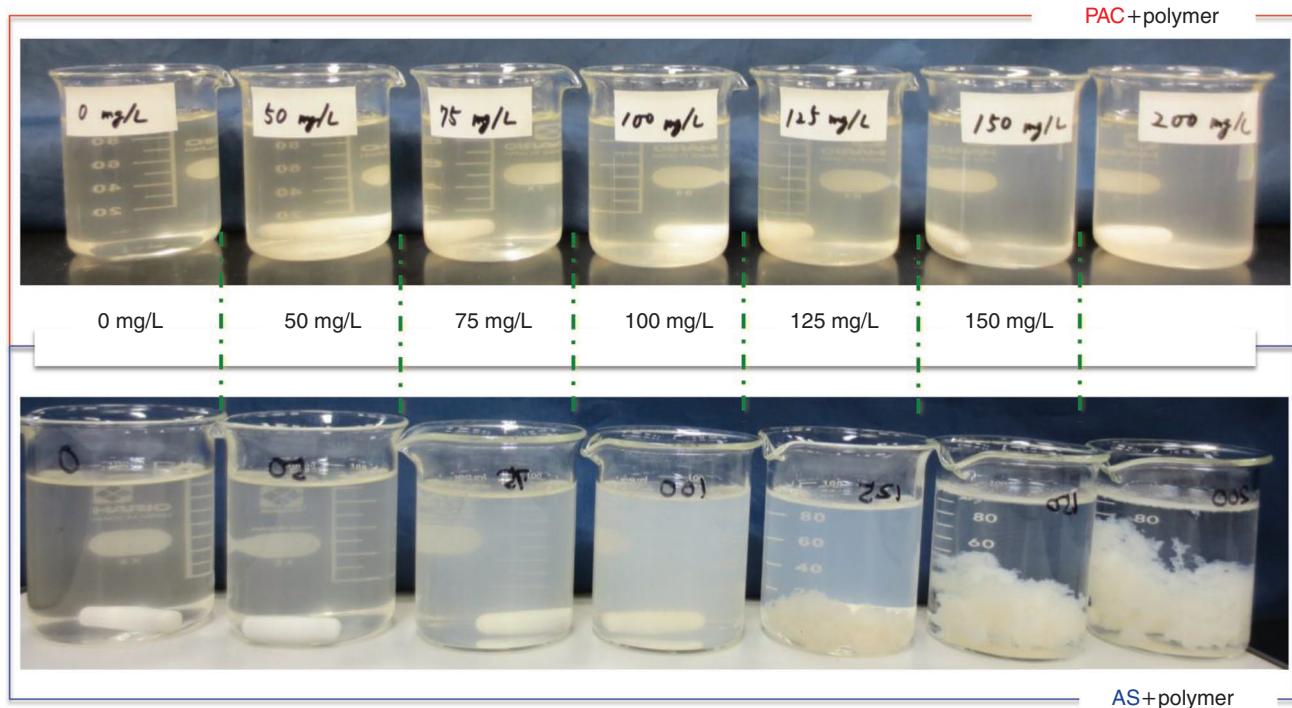


Fig. 10—Laboratory test: AS vs. PAC addition.

20 m³ of PFPW was again transported from the field by tanker. The viscosity of this water (0.74 cp at 40°C), while higher than that in the first trial (0.69 cp), was still considerably lower than that in the laboratory tests (1.88 cp). The effect of both AS and PAC was checked through jar tests. While PAC performed better in terms of turbidity at lower chemical additions (less than 500 mg/L), there was not much difference in terms of OIW concentration (**Table 3**

and **Fig. 12**). Because PAC was already used in the first PFPW trial, it was decided to use AS for this second trial.

Subsequent jar tests indicated a chemical-addition rate of 600 mg/L of AS (with 2 mg/L of polymer) for the pilot trial (**Table 4** and **Fig. 13**). However, because turbidity remained in the water, additional jar tests for a second coagulation treatment with AS or PAC were carried out with water that had been pretreated

	PFPW + 3630 S			PFPW + 3630 S + Fuel Oil A		
Chemical (mg/L)	None	PAC: 200 A-104T: 2	AS: 200 A-104T: 2	None	PAC: 200 A-104T: 2	AS: 200 A-104T: 2
Viscosity (cP)	4.49	4.23	0.64	4.52	4.37	0.65
Turbidity (FTU)	34.8	41.1	0.2	>1,000	>1,000	1.1
Oil (mg/L)	-	-	-	2453	2051	0.1

Fig. 11—Laboratory test: AS vs. PAC for PFPW+ERO polymer+oil.

AS or PAC Concentration (mg/L)	AS		PAC	
	Turbidity (FTU)	Oil (mg/L)	Turbidity (FTU)	Oil (mg/L)
0	29.6	25.7	29.6	25.7
50	40.6	—	26.3	—
100	42.2	—	22.6	—
150	40.9	—	23.6	—
200	53.5	—	22.5	—
250	53.0	—	19.8	—
300	47.6	—	17.3	—
350	27.5	—	5.0	—
400	22.6	0.7	3.9	1.3
500	N.D.	0.3	1.8	0.2
600	N.D.	0.2	2.2	0.2
700	N.D.	0.2	N.D.	0.1

N.D. = Not detected.

Table 3—Trial 2 jar tests: Water quality vs. AS/PAC addition.

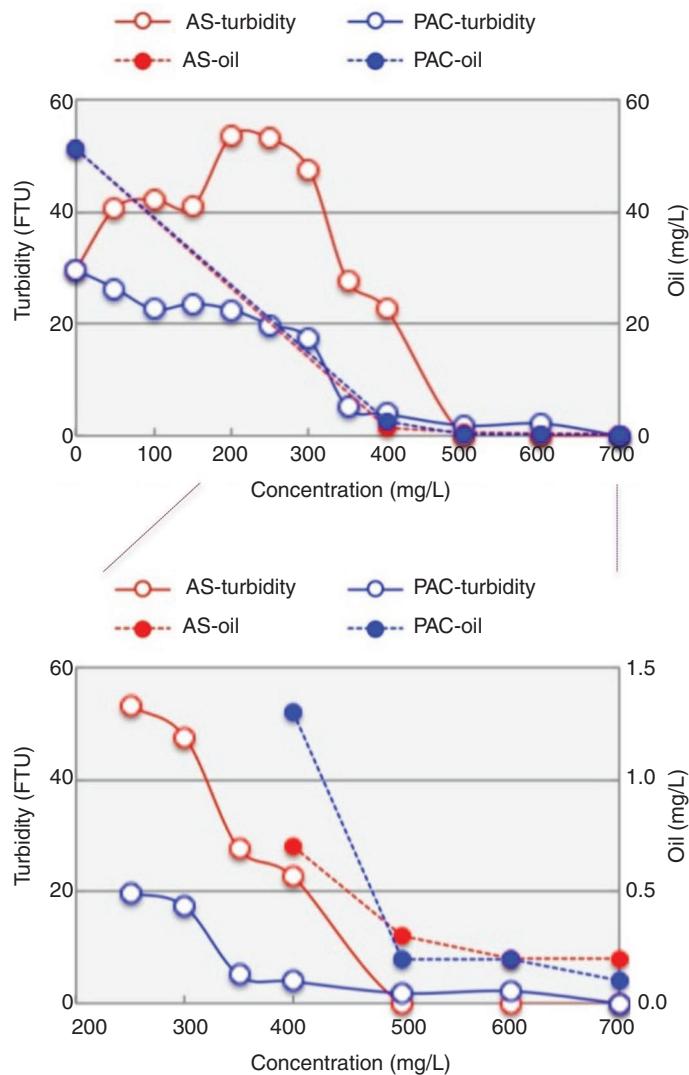
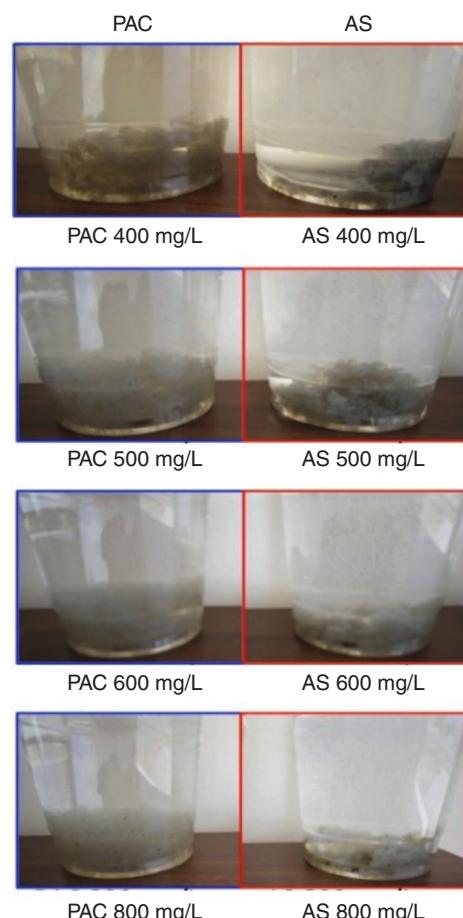


Fig. 12—Trial 2 jar tests: water quality vs. AS/PAC addition.

with 600 mg/L of AS. These additional jar tests indicated that a second AS addition of 10 mg/L would be effective in reducing turbidity to less than 3 FTU (PAC performance was similar) (**Table 5 and Fig. 14**). As such, a second coagulation/flocculation treatment with 10 mg/L of AS was added for the trial. The trial-treatment-process flow is shown in **Fig. 15**.

The pilot-trial results indicated that the OIW concentration in PFPW was reduced from 28.9 to 0.6 mg/L through a single coagulation/flocculation/floatation treatment only (**Table 6 and Fig. 16**).

Trial 3. 20 m³ of PFPW was again transported from the field by tanker. The viscosity of this water (1.40 cp at 40°C), while higher than for the water in the first and second trials (0.69 and 0.74 cp, respectively), was still lower than that used in the laboratory tests (1.88 cp). The OIW concentration was very high, greater than 200 mg/L. Again, the effect of both AS and PAC was checked through jar tests. At an addition rate from 600 mg/L upwards, AS appeared to perform better than PAC in terms of turbidity (**Fig. 17**). Again, AS was selected as the coagulant for this third trial. Subsequently, jar tests were conducted to determine the appropriate AS-addition rate for the trial, as well as the choice of flocculation polymer. These jar tests indicated a chemical-addition rate of 700 mg/L of AS with polymer A-103T (2 mg/L) for the pilot trial (**Table 7 and Figs. 18 and 19**).



AS (mg/L)	Turbidity (FTU)	Oil (mg/L)	pH
0	151	34.3	8.22
300	151	3.6	7.23
350	111	1.4	7.16
400	32.3	0.3	7.11
450	29.7	0.5	7.02
500	30.0	0.3	6.98
550	13.0	0.4	6.90
600	8.5	0.3	6.85
650	8.0	0.1	6.81
700	15.8	0.1	6.71

Table 4—Trial 2 jar tests: Water quality vs. AS addition.

However, because turbidity again remained in the water, additional jar tests for a second coagulation treatment with AS were carried out with water pretreated with 700 mg/L of AS. These additional jar tests indicated that a second AS addition of 90 mg/L (with 1 mg/L of polymer A-103T) would be effective in further reducing turbidity (**Fig. 20**). As such, a second coagulation/flocculation treatment of 90 mg/L of AS (with 1 mg/L of polymer A-103T) was added for the trial. Trial-treatment process flow is shown in **Fig. 21**.

Pilot-trial results indicated that the OIW concentration in PFPW was reduced from 210 to 1 mg/L through double coagulation/flocculation and flotation treatment alone (**Table 8** and **Fig. 22**). Filtration and adsorption stages resulted in further improvement of water quality.

Conclusions

A summary of results for the polymer-flood produced-water (PFPW) treatment trials follows:

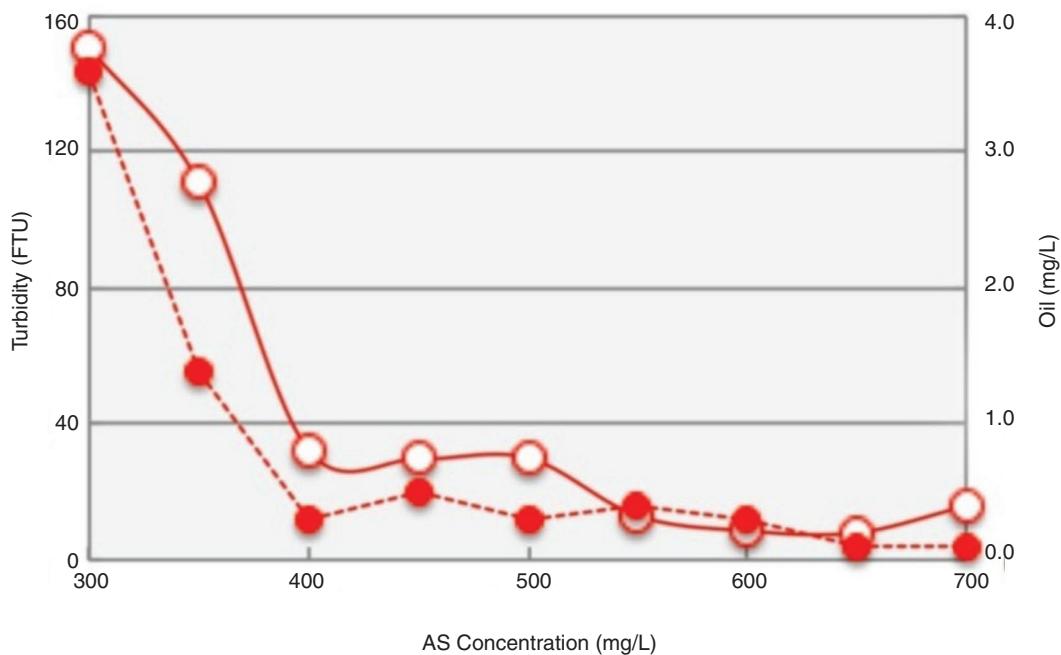
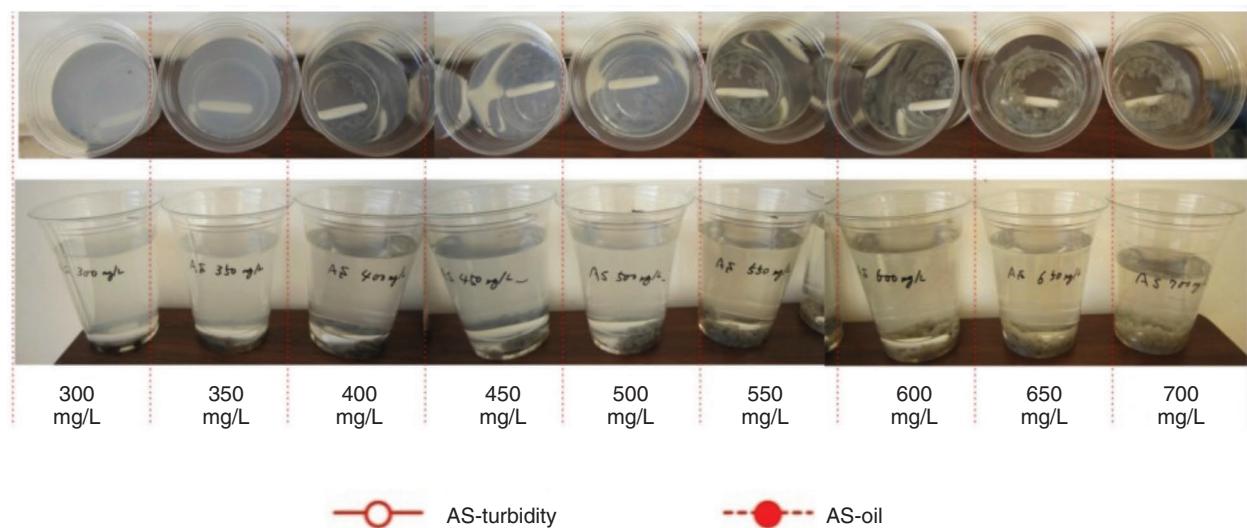


Fig. 13—Trial 2 jar tests: water quality vs. addition.

Turbidity (FTU)		
AS/PAC (mg/L)	PAC	AS
0	39.42	39.42
5	8.89	6.38
10	3.03	2.84
20	1.61	2.00

Table 5—Trial 2 jar tests: Turbidity vs. second AS/PAC addition.

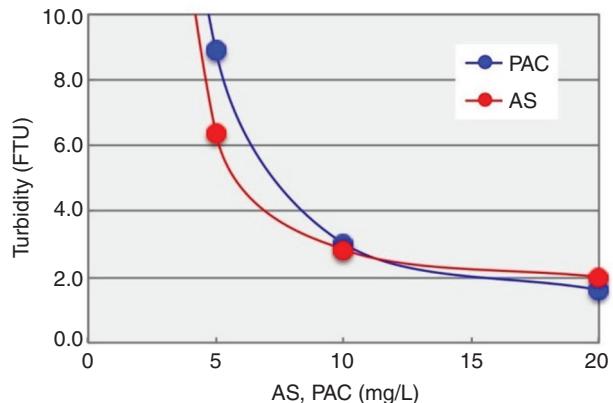


Fig. 14—Trial 2: Turbidity vs. second AS/PAC addition.

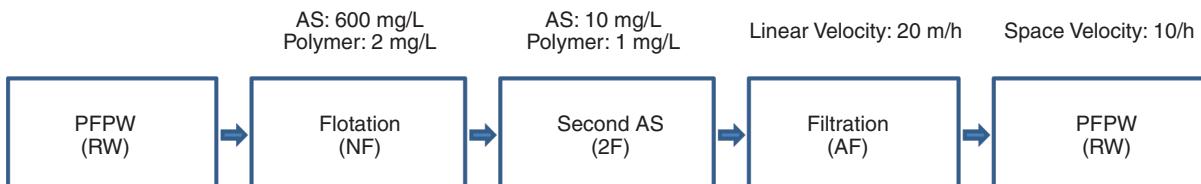


Fig. 15—Trial 2 treatment-process flow.

	RW	NF	2F	AF	AC
Turbidity (FTU)	47.83	1.45	N.D.	N.D.	N.D.
COD (mg/L)	120	20	20	20	4
Oil (mg/L)	28.9	0.6	0.3	0.1	N.D.
pH	8.18	7.32	7.30	7.31	8.35
Sulfides (mg/L)	0.6	N.D.	N.D.	N.D.	N.D.

N.D. = Not detected.

COD = Chemical oxygen demand.

Table 6—Trial 2 water quality after each stage of treatment.

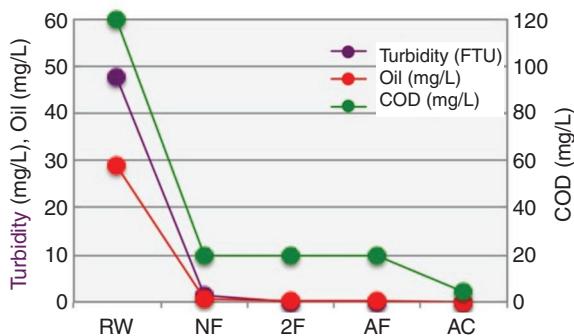


Fig. 16—Trial 2 water quality through different stages of treatment. COD=chemical oxygen demand.

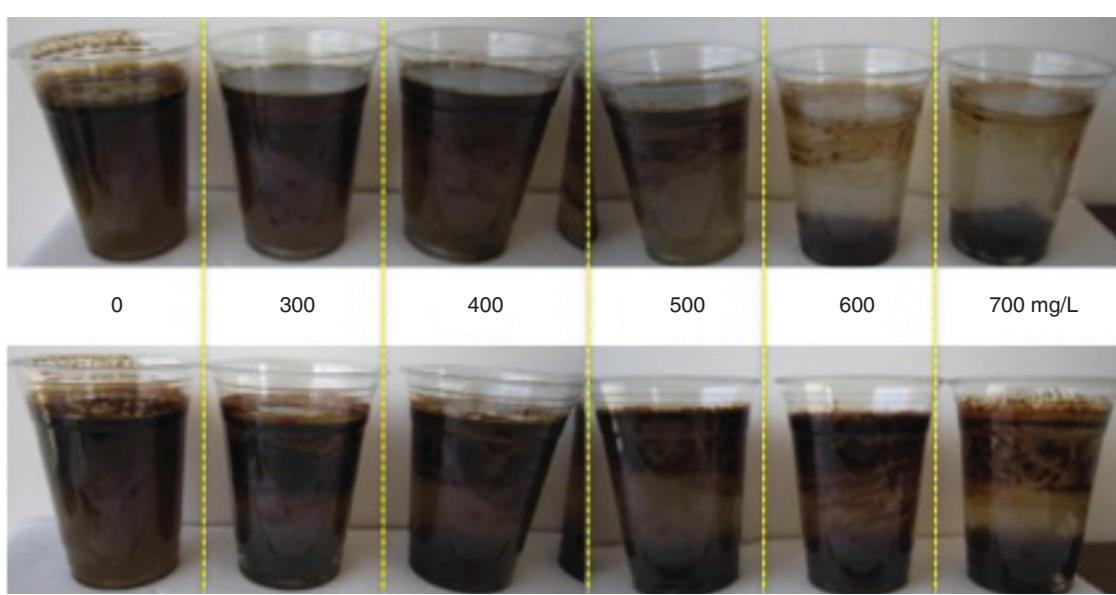


Fig. 17—Trial 3 jar tests: AS vs. PAC addition.

AS (mg/L)	Turbidity		Oil	
	A-104T (mg/L)	A-103T (mg/L)	A-104T (mg/L)	A-103T (mg/L)
0	342	395	158.5	183.1
500	151	138	19.0	14.3
550	128	117	18.2	4.1
600	132	99	6.2	9.0
650	84	82	2.5	5.3
700	40	36	1.5	1.2
750	52	66	1.8	2.8
800	121	55	9.3	1.5
850	78	55	7.1	1.9

Table 7—Trial 3 jar tests: Water quality vs. polymer type and AS addition.

- The viscosity of PFPW is only slightly higher than that of ordinary produced water from the same field.
- Coagulation with polyaluminum chloride (PAC) was not as effective for higher-viscosity PFPW compared with lower-viscosity ordinary produced water from the same field.
- Coagulation by aluminum sulfate (AS) was more effective in removing dispersed oil from higher-viscosity PFPW, the viscosity of which was higher than ordinary produced water from the same field.
- Double coagulation with AS was effective in reducing oil-in-water concentration in PFPW from 210 to 1 mg/L.
- Filtration and adsorption stages resulted in further improvement of water quality.
- Most of the polymer used for enhanced oil recovery was believed to have been removed along with oil and suspended solids.

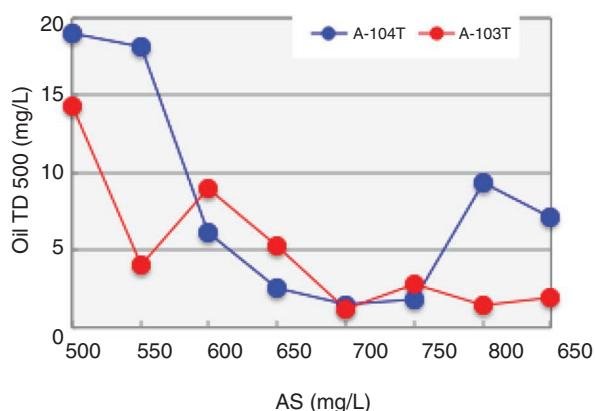
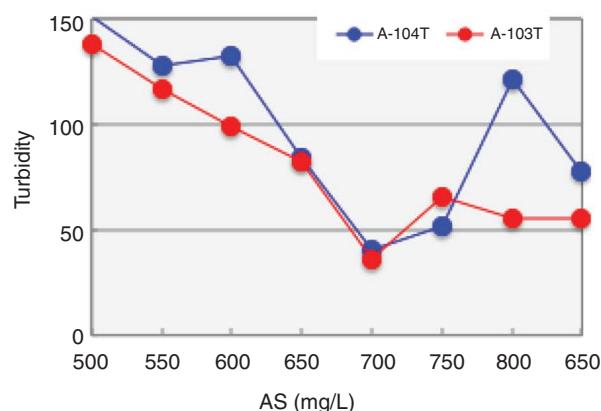


Fig. 18—Trial 3 jar tests: water quality vs. polymer type and AS addition.

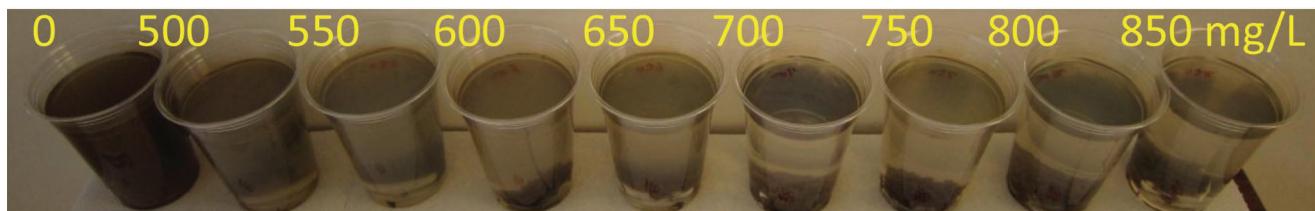


Fig. 19—Trial 3 jar tests: AS addition with polymer A-103T.

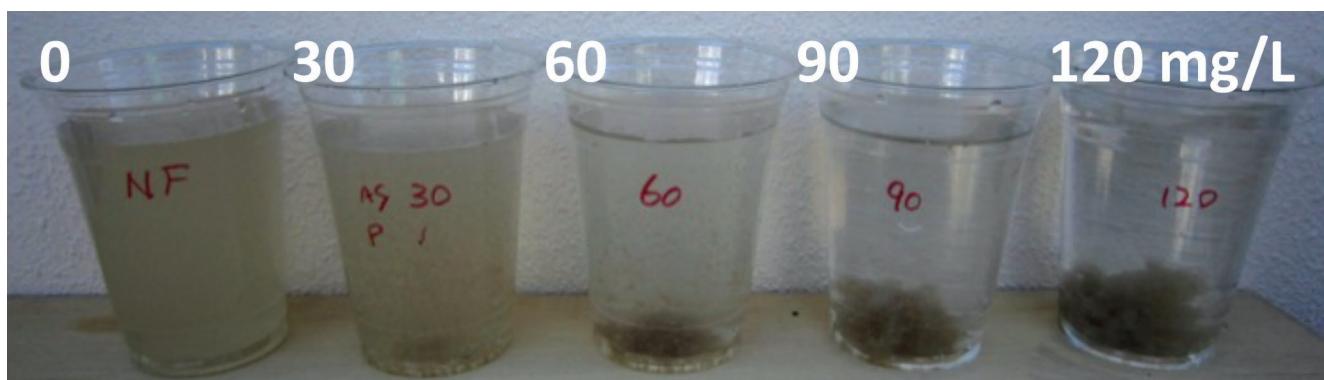


Fig. 20—Trial 3 jar tests: second AS addition.

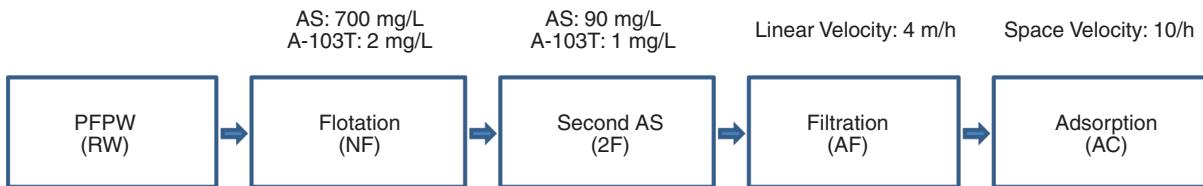


Fig. 21—Trial 3 treatment-process flow.

Stages	Turbidity (FTU)	Chemical Oxygen Demand (mg/L)	Oil (mg/L)
RW	355	200	209.7
NF	105	120	35.5
2F	35.6	120	1.0
AF	26.3	120	0.6
AC	24.8	5.0	0.2

Table 8—Trial 3 water quality after each stage of treatment.

Potential areas for additional work are

- Further investigation into the mechanism of AS performing better than PAC for treatment of PFPW.
- True potential for effective treatment of higher-viscosity PFPW, seen in laboratory tests, could not be tested because of the lower viscosity of the water that was delivered for the trials. As PFPW viscosity continues to increase and samples of such water become readily available, further tests are recommended, preferably on-site to eliminate changes that occur to water during transportation and to allow for longer periods of testing.
- Trials indicated that double coagulation/flocculation is effective for treating more-difficult produced water. Modification of the pilot unit to allow for easier testing of double coagulation/flocculation when required and further tests with the modified plant are recommended.
- Trials indicated that the aeration pretreatment for sulfide stripping could reduce the amount of chemical addition required and contribute toward the reduction of turbidity. Modification of the pilot unit to allow for easier testing of such pretreatment when required and further tests with the modified plant are recommended.

Acknowledgments

This study received generous support from Japan Cooperation Center, Petroleum, under the auspices of the Ministry of Economy, Trade & Industry, Japan. Logistical support was provided by Petroleum Development Oman.

References

- Al-Maamari, R.S., Sueyoshi, M., Tasaki, M. et al. 2014. Flotation, Filtration, and Adsorption: Pilot Trials for Oilfield Produced-Water Treatment. *Oil and Gas Facilities* **3** (2): 56–66. SPE-161289-PA. <http://dx.doi.org/10.2118/161289-PA>.
- Al-Manhal. 2003. Oil & water (produced-treatment and disposal). *PDO News* **3**: 12–13.
- Al-Manhal. 2009. Water, water, everywhere... *PDO News* **1**: 2–8.
- Al-Manhal. 2010. Reed beds: an environmentally-sound way to dispose of produced water. *PDO News* **2**: 14–15.
- Arthur, D.J., Langhus, B.G., and Patel, C. 2005. Technical summary of oil & gas produced water treatment technologies. Technical Report, ALL Consulting, LLC, Tulsa, Oklahoma.
- Breuer, R. and Al-Asmi, S.R. 2010. Nimir Water Treatment Project—Up Scaling a Reed Bed Trial to Industrial Scale Produced Water Treat-
- ment. Presented at the SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Rio de Janeiro, 12–14 April. SPE-126265-MS. <http://dx.doi.org/10.2118/126265-MS>.
- Colorado School of Mines (CSM). 2009. An Integrated Framework for Treatment and Management of Produced Water: Technical Assessment of Produced Water Treatment Technologies. RPSEA Project 07122-12, Colorado School of Mines, Golden, Colorado (November 2009).
- Environmental Protection Agency (EPA). 1999. Method 1664, Revision A: N-Hexane Extractable Material (HEM, Oil and Grease) and Silica Gel Treated N-Hexane Extractable Material (SGT-HEM; Non-polar Material by Extraction and Gravimetry. EPA-821-R-98-002, Office of Water, Washington, DC (February 1999).
- Fakhru'l-Razi, A., Pendashteh, A., Abdullah, L.C. et al. 2009. Review of technologies for oil and gas produced water treatment. *J. Hazard. Mater.* **170** (2–3): 530–551. <http://dx.doi.org/10.1016/j.jhazmat.2009.05.044>.
- JIS K 102:2008, Testing methods for industrial wastewater*. 2008. Tokyo, Japan: Japanese Standards Association.
- Kenawy, F.A. and Kandil, M.E. 1998. Comparative Evaluation Between a Modified CFP Separator and All Other Available Oil-Water Separation Techniques. Presented at the SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Caracas, Venezuela, 7–10 June. SPE-46817-MS. <http://dx.doi.org/10.2118/46817-MS>.
- Khatib, Z. and Verbeek, P. 2002. Water to Value - Produced Water Management for Sustainable Field Development of Mature and Green Fields. Presented at the SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Kuala Lumpur, 20–22 March. SPE-73853-MS. <http://dx.doi.org/10.2118/73853-MS>.
- Oman Daily Observer. 2012. Major boost to treated water. *Oman Daily Observer* **31** (177).
- Plebon, M.J. 2004. TORR - The Next Generation of Hydrocarbon Extraction From Water. *J Can Pet Technol* **43** (9): 15–18. PETSOC-04-09-TN1. <http://dx.doi.org/10.2118/04-09-tn1>.
- SPE. 2011. Challenges in Reusing Produced Water. *SPE Technology Updates*, 12 October 2011, <http://www.spe.org/tech/2011/10/challenges-in-reusing-produced-water/> (accessed 06 January 2013).

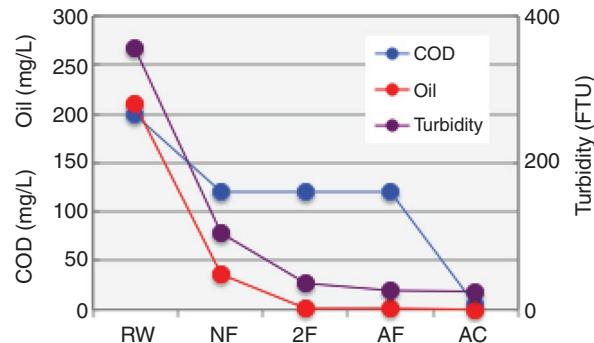


Fig. 22—Trial 3 water quality through different stages of treatment. COD=chemical oxygen demand.

Sultanate of Oman. 1993. *Ministerial Decision No. 145 of 1993 Issuing the Regulations on Wastewater Reuse and Discharge*. Oman: Ministry of Regional Municipalities and Environment.

Rashid Al-Maamari is an associate professor and head of the Petroleum and Chemical Engineering Department, Sultan Qaboos University. His research interests include enhanced oil recovery and treatment and use of oilfield-produced water. Al-Maamari holds a PhD degree in petroleum engineering from New Mexico Institute of Mining and Technology.

Mark Sueyoshi is a senior environmental researcher with Shimizu Corporation. He has more than 20 years of experience working with research organizations in Gulf Cooperation Council countries on environmental-engineering technical-cooperation projects related to the oil industry, specifically in the fields of produced-water treatment, groundwater treatment, and oily-sludge treatment.

Masaharu Tasaki is a senior research engineer with the Institute of Technology, Shimizu Corporation. He has more than 30 years of research experience as a specialist in the fields of microbial ecology, bio-/phytoremediation, and environmental manipulation.

Keisuke Kojima is a research engineer with the Institute of Technology, Shimizu Corporation. He has more than 10 years of research experience in the areas of urban water, environmental investigation, and chemical analysis. Kojima holds a PhD degree in urban engineering from the University of Tokyo.

Kazuo Okamura is a chief research engineer with TECNET Limited. Previously, he was with the Institute of Technology, Shimizu Corporation for more than 20 years. Having more than 40 years total of research and development experience, Okamura's areas of expertise include methane fermentation, activated sludge, groundwater treatment, produced-water treatment, bioremediation, slurry-reactor sludge treatment, and oil recovery from sludge.