Treating Reinjected Oilfield Brine By Microbial Clarification

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Summary

Rising water volumes and processing costs in the oil field have spurred OMV to look for alternatives to traditional water processing. Despite an elaborate central multistep water-treating system, increasing injection pressures, water fouling in the pipelines, and reservoir souring were noticed. In a five-year program involving field measurements, laboratory experiments, the construction of a pilot facility, and test injections, a new strategy was adopted. The central water-conditioning plant (WCP) has been revamped. Instead of biocide addition, removal of organic nutrients by a biological clarification step now produces a clear, well injectable, and stable injection water.

Introduction

Increasing awareness of environmental problems has made produced-water disposal a critical topic. Water flooding has become common practice for pressure maintenance, recovery of unswept oil, and as a basis for enhanced recovery methods.[1] Consequently, the amount of literature covering different aspects of water handling, treatment, analysis, and reinjection is growing rapidly; more specifically, the topic of formation plugging has been dealt with in a number of papers.[2–5] Nevertheless, there is still no unambiguous universal method to assess injection-water quality. In fact, very different practical aspects related to composition, solids content, stability, compatibility with formation/formation fluids, and microbiological contamination must be combined to define a parameter like injectivity. Hence, uncertainty about what to measure and the required treatment prevails and theories predicting injector half-lives from quality criteria have not gained general acceptance.[6,7] Some authors have used and recommend on-site core testing.[8,9] The contribution of bacterial activity to injectivity problems, although discussed early, has been emphasized more recently.[10–14] It was understood that because bacterial growth occurs over days and weeks, short-time filtration tests might be inadequate for characterization.

OMV has been operating a water distribution and injection system for more than 30 years. It is currently processing the better part of 10^7 m^3/year of brine through the conditioning plant at Schönkirchen, some 30 km northeast of Vienna, Austria. The pipeline network totals approximately 80 km of tubulars of various sizes and flow velocities; the volume of produced water is still increasing **(Fig. 1).**

Status of Water Conditioning

Brine and live oil flow from most fields through pipes to separation facilities where the production is monitored. To keep corrosion at bay, the main lines of the distribution system are made from reinforced cement. The different water streams illustrated in **Fig. 2** include surface water runoff and waste water. **Fig. 3** depicts the water streams entering the conditioning plant where they are passed through a flotation pool (2), a basin for flocculation by Fe^{+++} (3), and two sedimentation units running in parallel (4 and 5), before filtration through sand beds (6 and 7). Every hour, 1000 m^3 of processed brine leave the plant to injection or disposal wells. Oil is recovered from the floating sludge and injected into transport flow lines to the refinery. Solids are regularly removed from the pools and deposited at a dump. **Table 1** shows the composition of the water and some other parameters related to contamination.

Specifications

Water exiting the WCP must meet the specifications in **Table 2.**

Formerly, yearly analyses checked these parameters and the concentrations of the ionic species in solution. The frequency of backflushing necessary to regenerate the sand filters in the WCP provides some control over the filtration quality of the water. Another indication is the performance of a diatomaceous earth filter located at injectors in the Hochleiten field 20 km away. Very little information was available before increasing awareness of the problem prompted a comprehensive analysis program in 1993.

These specifications were set somewhat arbitrarily a long time ago, and while a better water quality clearly benefits the reservoirs, the question of how much effort the treatment really needs remained open. Because the water is not just disposed of but also used for pressure maintenance, the degree of conditioning could have been sized to the requirements of the flooded reservoir. However, because of logistical problems (need for separate tubular systems), this approach was rejected from the beginning, and an "overall" quality specification was defined.

Performance and Problems

The system has been working satisfactorily most of the time, but increasing demands and rising costs are a permanent incentive to look for alternative solutions:

- The separation of the solids from oil sludge once performed by a filter press needing a cake-building additive is accomplished now through a three-phase centrifuge (Tricanter). This reduces the volume of solids dramatically and recovers more oil.
- Tests with a flotation unit instead of sedimentation pools have not led to an improvement and were discontinued.
- Over the years, numerous flocculating agents and biocides have undergone testing to increase efficiency and to reduce costs.

However, some problems appeared that seemed intractable by conventional wisdom.

- Low-permeability formations in the tens of millidarcies range as well as EOR projects needed a better water quality, otherwise injectivity would be lost instantly.
- In all but the most permeable, fractured formations, injection pressure rose continuously. Increased pressure means higher energy expenses but transgressing the frac pressure could compromise the integrity of the formation and modify the flooding pattern. Acid stimulation could restore the injectivity temporarily, but the effectiveness of the treatments seemed to decline progressively. In the end, acidizing was given up altogether, allowing injection to proceed at the maximum allowable pressure until the injector was shut down and another well converted to injection.
- In spite of permanently switched biocides, development of bacteria in the whole system was out of control. **Fig. 4** shows H_2S concentrations increased along the flooding system. Pigged lines yielded a black, foul-smelling sludge attributed to the buildup of biofilms.
- Temporary stops caused by power disruptions mobilized huge volumes of suspended material upon restoration of flow in the lines. Filters plugged and had to be cleaned. At irregular intervals, sand filters in the WCP would need flushing back after half the normal water volume, resulting in double downtime and accumulation of untreated water. In severe cases, this could shut down production.
- Finally, a polymer pilot failed because of microbiological degradation of the xanthan.

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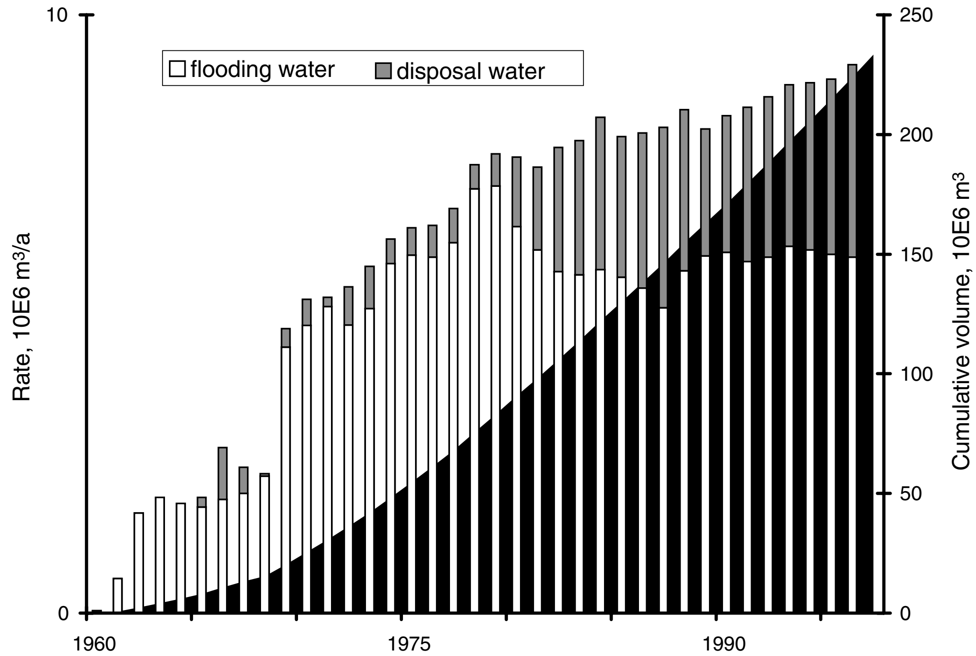

Fig. 1—Water injection in the Matzen field.

From that moment on, it was clear to everyone that a new approach to water treatment was required because too many risks were incurred in the existing process. A multiclient study on reservoir souring evaluated the whole system, confirming the increasing levels of hydrogen sulfide and the inadequacy of biocide application.[15]

Water Quality Parameters

Assessment of the water quality is still at the center of the problem. Basically, a better injectivity is required. Many theories have been developed to predict injectivity, but most of them rely on laboratory filtration tests with synthetic filtration media and stored-water samples. Because the water is unstable and precipitates upon standing, we thought that the best experience could be gained from on-line measurements on core plugs at rates comparable to the sandface in the wells.

However, these tests are lengthy to conduct and other quantities, indirectly related but more easily measurable, were determined to reflect the trend. It is impractical to conduct on-line filtration measurements, although a field apparatus has been developed and was introduced recently.[4]

Analysis of Water Quality Parameters at the WCP. The function of the WCP was monitored by analysis of the following parameters: TOC, COD, solids content, Fe^{++}, SO_4^{--}, S^{--}, free oxygen, and oil content. Detailed results have been presented;[16] only the main observations are reviewed here.

- Flotation and filtration separate oil to an average level of 5 mg/L.
- Less than 15 mg/L of solids is found at the outlet of the WCP.
- Reduction of sulfate (from 35 to 20 mg/L) to sulfide takes place in the WCP, the oxygen being reduced and further depleted in the transport lines. Hence, the system is partly aerobic at best, but mostly anaerobic.
- Water samples exposed to air display color changes, finally producing a milky haziness. Filterability of the water is low despite a fair performance in removing suspended particles.
- Active bacteria can be found in the whole system in spite of biocide addition.

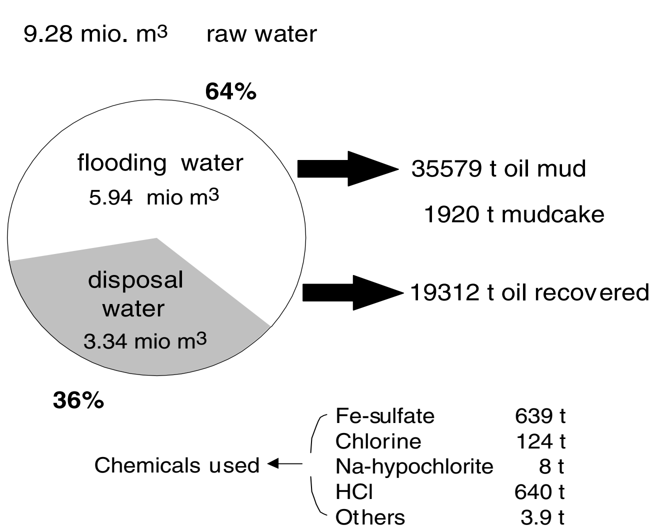

Fig. 2—Product streams in the WCP.

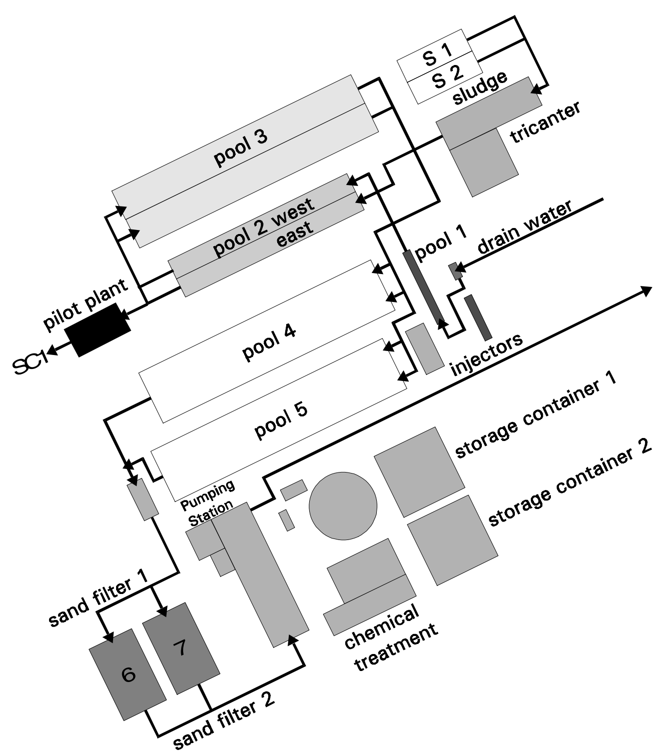

Fig. 3—Schoenkirchen WCP schematic.

TABLE 1—WATER COMPOSITION	
Contamination Parameters	mg/L
Total dissolved solids	22,200
Cl^-	12,500
SO_4^{--}	20
P (total)	0.04
NH_4^+	65
Hydrocarbons (HC)	6
Total organic carbon (TOC)	90
Dissolved organic carbon (DOC)	75
Chemical oxygen demand (COD)	300
Biological oxygen demand (BOD)	25

Microbiological Approach

After mounting evidence that biofouling, not suspended solids or incompatibility with the formation, was the main source of injectivity problems and that biocides could not control it, a new three-step philosophy was adopted.

1. Stop biocide addition.
2. Control bacteria by deprivation—i.e., substitute $FeSO_4$ flocculent with $FeCl_3$; improve the flotation step to remove suspended oil; and reduce dissolved carbon by microbiological water clarification.
3. Verify effectiveness of adopted measures by performance analysis.

It was important that the changes could take place in the existing WCP without new treatment ponds or additional filter units. Hence, a study was undertaken to assess the feasibility of the process, optimize parameters in a lab apparatus, build and install a field pilot including a flotation unit, and conduct injectivity tests on a test well.

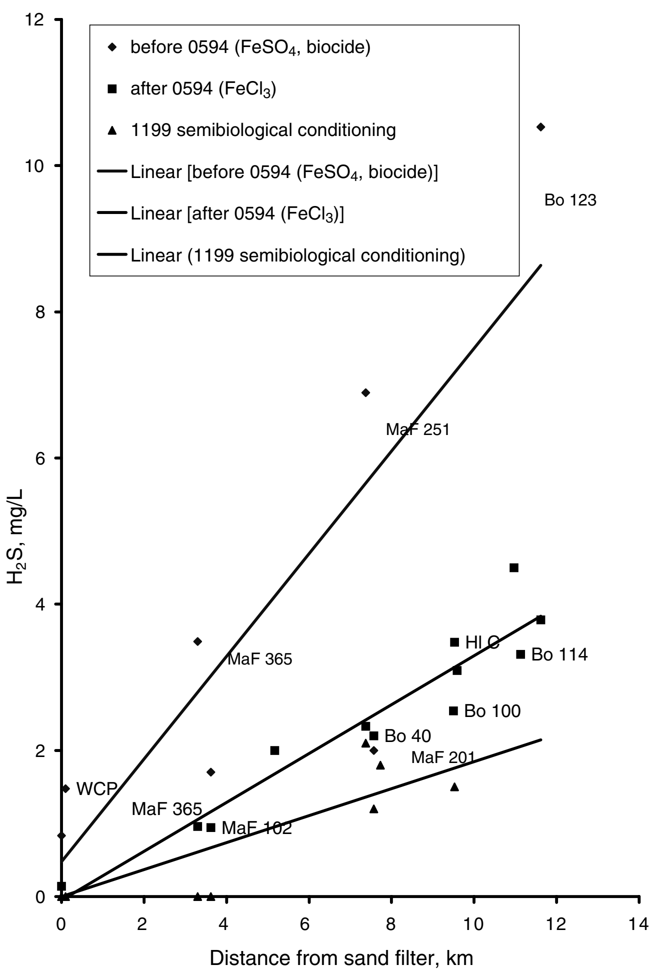

Fig. 4—Hydrogen sulfide at injector wellheads.

TABLE 2—SPECIFICATIONS FOR WATER EXITING THE WCP	
Parameter	Quantity
Solids < 8 μ	<10 ppm
Dispersed oil	<5 ppm
pH	<7.2 – 7.3

Elimination of Oil and Biodegradable Carbon. A schematic of the laboratory test apparatus is given in **Fig. 5.** Water from the outlet of Pool 3 is passed into an aeration tank; there, phosphoric acid is added and compressed air bubbled through nozzles at the bottom. The suspension flows over to a sedimentation container where the sludge is separated and recycled to the first tank. Then the liquid phase passes over to a second sedimentation unit.

Before starting the process, oil-degrading bacteria have to be seeded and adapted to the salinity and type of feed. Sludge from a communal water-treating facility was used to initiate the growth of biomass as charted in **Fig. 6.**

After several weeks of operation and optimization, it became clear that more than 90% of BOD could be eliminated routinely in the first step, making a second treatment cycle unnecessary **(Fig. 7).** The stability of the outflowing water was tested by contacting the runoff with iron nails in a glass tube. While the control brine turned black very fast resulting from production of hydrogen sulfide, no reducing activity could be detected in the biologically treated water, even after several months. TOC, COD, and redox potential likely remained essentially unchanged in contrast to normal water. This gave us the confidence to proceed to the next stage, the design of a pilot clarification plant.

The pilot plant was built during 1995 and put into operation in September. It consisted of two parallel, one-step trains fed by a common floatation unit as illustrated in **Fig. 8.** Processed water leaving the sedimentation tanks filtered through a sand-bed.

Control Parameters

Solids. Solids were determined by filtration through 0.45, 3, and 8 μ filters. Because the last step of the process is also an in-depth filtration, one would expect at least the same performance as by conventional treatment.

Turbidity. Although not a quantitative parameter ascertaining good filterability, turbidity was monitored also because it reflects the quantity of colloidal-suspended material. It is known from communal clarification plants that the presence of ciliate bacteria contributes to clear water because they consume the cells and debris left over from the aeration step. Various strains of halo-tolerant bacteria were tested for their resistance to oilfield brine; only one type could survive the conditions in the pilot plant.

Optimization of Processing Parameters

Input Oil Concentration. Too much oil can lead to overloading of the flocs, increasing buoyancy and promoting loss of oil-laden biomass, which, in turn, may plug the sand filter. With too little oil, proper flocs cannot form. It is possible to adjust the oil concentration

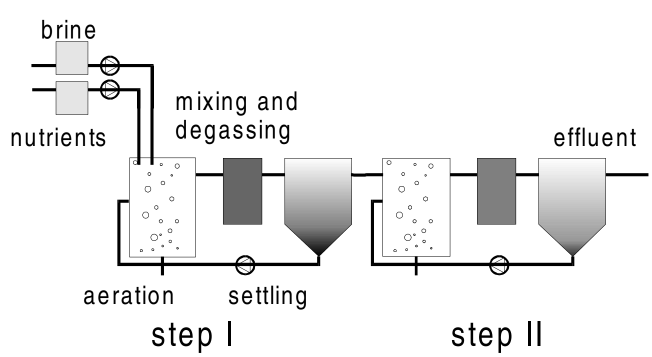

Fig. 5—Laboratory rig for development of biological water treatment.

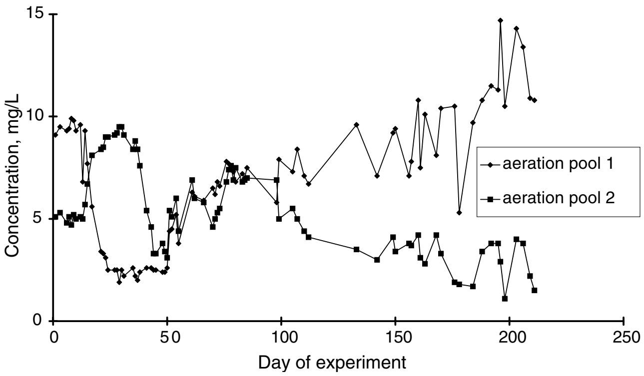

Fig. 6—Suspended organic material in laboratory rig.

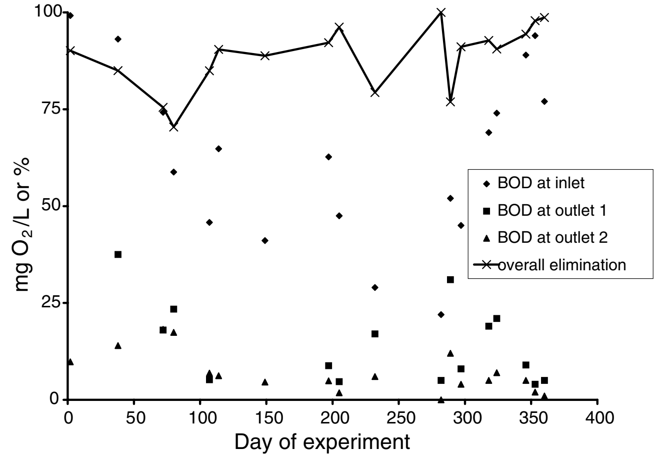

Fig. 7—Performance of laboratory test apparatus.

by regulating airflow in the floatation unit and changing the ratio between the primary and secondary water streams. Hence, a well-tuned oil separation unit is extremely important for a satisfactory performance of the biological step.

Templates. One option for increasing the throughput is to provide floating material to which the oil-degrading cells can attach themselves. Talcum, cellulose fibers, and later, anthracite were added, promoting sedimentation of the flocks. In contrast to anthracite, talcum was only adsorbed and not truly incorporated into the flock. Cellulose, which at first looked promising, had to be added continuously because it tended to disappear from the system in a very short time; a better solution consisted of imparting a positive charge to the talcum particles, thereby electrostatically binding the flocks to it.

Sludge Turnover. It was found that the increase of biomass over time in the system was not matched by a comparable reduction of free hydrocarbons. Hence, the efficiency decreased because other bacterial strains began to prevail. To help in selecting fast oil metabolizers, surplus sludge was removed at shorter intervals (weekly).

Filtration Sand Quality. From the outset, fluvial sand from the river March was used, the same sand quality as in the WCP. It has a very broad grain size distribution from 0.1 to 20 mm. Upon substitution by sized, commercial filter sands, filter life expectancy began to increase markedly up to 24 hours. Sieved sands with the exclusion limits 1–4, 1–2, and 1.25–0.75 mm were tested. **Fig. 9** shows a reduction in median size combined with a sharper distribution resulted in higher solids retention together with a threefold increase in filter plugging time compared to the natural sand. A final attempt to build a two-layered filter bed with sand and coarse anthracite failed owing to insufficient separation time during the backflushing step.

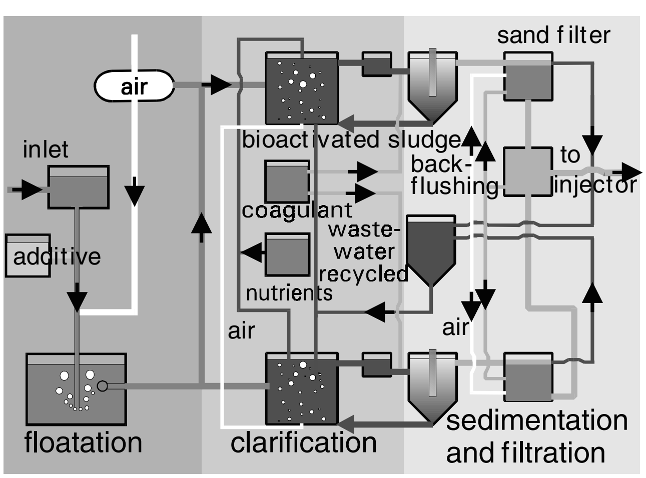

Fig. 8—Schematic of pilot plant.

Performance Evaluation

Process Parameters. To measure the efficiency of the process, the following parameters were monitored: HC, COD, and BOD. **Fig. 10** shows that the elimination curves for HC and COD do not necessarily run in parallel. Obviously, the most interesting quantity is the BOD because it corresponds to the organic load available for metabolization. The high percentage of reduction as illustrated in **Fig. 11** therefore translates into a hostile environment for bacteria and is reassuring.

Injection Models. The primary purpose of the biological processing is to increase water injectivity. Filtration tests are considered to give the best measure of quality improvement. Only a short-term comparison can be made from conventional membrane filtration tests. **Fig. 12** shows the plot of the filtration volumes of normal and biologically treated water vs. the root of time, according to Barkman and Davidson.[7]

Core filtration tests provide a more realistic way for evaluating filterability. It has been contended in the literature that calculations based on membrane tests tend to give much shorter injector half lives than are experienced in reality. Hence, a filtration rig with a Bentheim sandstone core (initial air permeability 2.10^{-12} m^2) and a pump injecting water at a constant rate of 1 dm^3/h were set up on site. The pressures were monitored until they reached 100 bar, which is the usual wellhead pressure when an injector has either to be stimulated or to be switched off. The tests typically lasted a few months with the longest one lasting just under a year. Results for a series of tests performed using synthetic brine, normal brine, and biologically treated brine are shown in **Fig. 13.** For better comparison, the curves' abscissa are given in absolute throughput volumes, because most plugging takes place at the inlet sandface and scaling in pore volume units distorts the curves. In spite of some scattering, it is obvious that the cores flooded with biologically treated water typically last three to four times longer than with conventional water. In some instances, a pressure port in the middle of the core was installed. In the first weeks, the pressure differentials

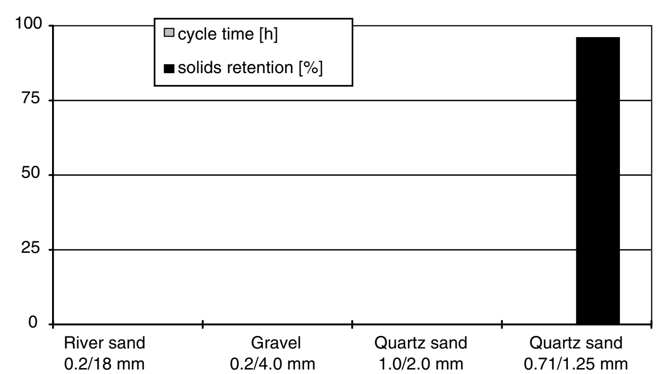

Fig. 9—Filtering efficiency of sand batches.

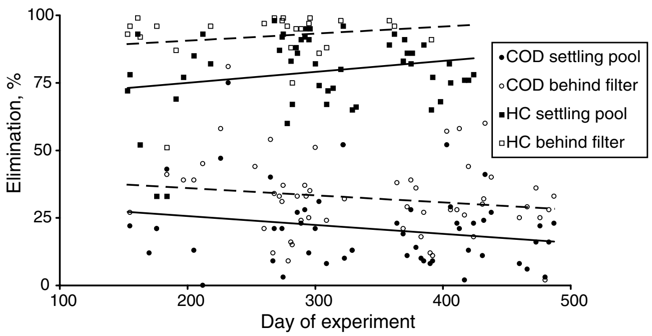

Fig. 10—Elimination of COD and HC in pilot plant.

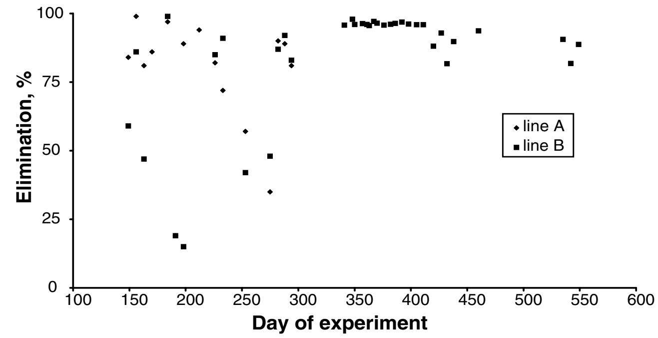

Fig. 11—Elimination of BOD in pilot plant.

over the in- and outlet segments were comparable; later, only the inlet pressure rose steeply. This reflects that the damage concentrated in the first 4 cm of the core. After the test, the samples were taken out of the apparatus, split apart, and further examined by scanning electron microscopy (SEM). Other samples served for stimulation experiments. In contrast to most other situations, here the reaction of various stimulating agents can be tested with the original plugging material in place. It helped develop a special treatment for water injectors that is now applied field-wide.

Field Test. Together with the decision to establish a pilot clarification plant, it was decided to test the produced water in an injection well. Well SC-1 located near the WCP was selected because it had a good injection record with the appropriate volumes. A pressure fall-off test was made that displayed a permeability of $0.275.10^{-12}$ m^2 in a net interval of 4 m with a skin of 44. The pressure history of the injector is shown in **Fig. 14.** Contrary to the general increasing trend, the wellhead pressure remained flat until mid-1994, when it began to decline. The pressure reduction is a consequence of substituting $FeSO_4$ by $FeCl_3$ as flocculent because of a diminished load of sulfate and is also apparent in other injectors. When injection at the SC-1 was switched from conventional to biologically treated water in August 1996, another pressure drop was anticipated from experience gained with core tests. At that time, pressure had begun to rise again; unfortunately, no definite trend reversal was noticed. Finally, the well was stimulated in February 1997 to obtain a new bottom line by getting rid of the plugging material in the tubing and perforations. After that, wellhead pressure stayed below atmospheric. With the dismantling of the pilot plant in May 1998, injection of conventional water has resumed, triggering a steep pressure increase.

While the lack of response seems disappointing, it means only that better quality water is not able to restore lost injectivity of a formation. As a basis for comparison, Well MaC-1 injects into the same horizon and also has 4 m net interval but handles 50% more volume. It was stimulated by the same procedure, but injection of conventional water started immediately afterwards. **Fig. 15** shows that after only 7 months, the pressure also began to rise, but much less dramatically. While the shorter pressure-free period is in line with cleaner water, the pressure trend runs contrary. It appears that despite all efforts to reproduce relevant parameters, the complex field reality yet eludes experimental definition.

Future Work

Results were deemed promising enough to start a revamp of the WCP. Substantial savings already had been made by discontinuing the addition of biocide (U.S. $500,000/year) and capitalizing on less energy needed for injection simply by substituting chloride for sulfate (U.S. $300,000 since 1995). At the same time, H_2S contents at the injector wellheads decreased by a factor of 3 even with-

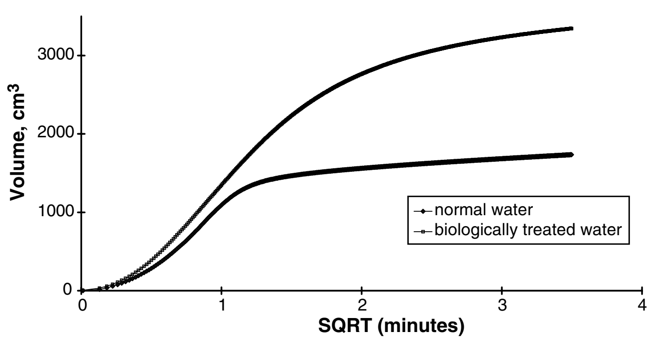

Fig. 12—Membrane filtration tests.

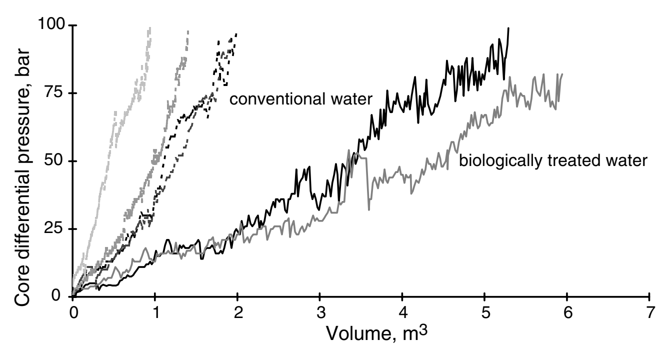

Fig. 13—On-line core-flooding tests.

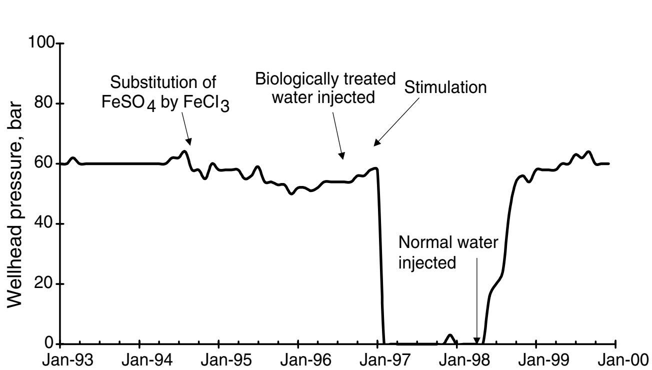

Fig. 14—Pressure history of well SC-1.

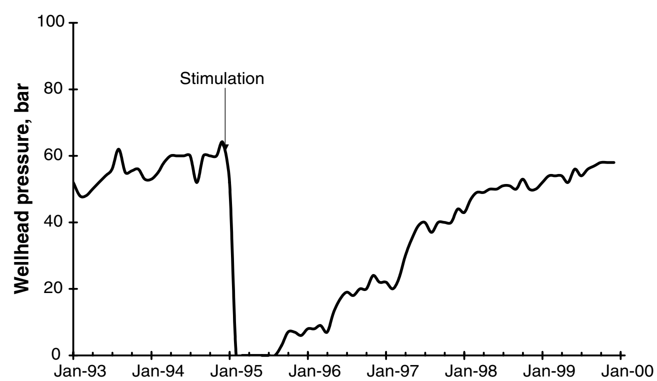

Fig. 15—Pressure history of comparison well MaC-1.

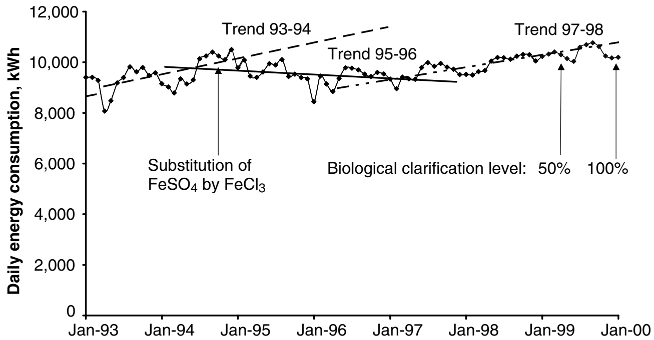

Fig. 16—Daily energy consumption by continuous injectors.

out addition of biocide (Fig.4). Water treatment costs are now approximately 12 cts/bbl.

Fig. 16 shows the wellhead pressures of all injectors that have been working continuously without interfering influences from workovers, stimulations, etc. The initially increasing pressure trend stopped with the reduction in sulfate, but is on the rise again since 1997. It is still too early to comment on the effect of the microbiological treatment, especially because the conversion to the new technology created some unexpected treatment problems resulting in periodic water quality fluctuations. However, we are confident that after a more thorough cleaning of flooding lines and a series of injector stimulations, a new database will substantiate the obtained improvements.

Conclusions

1. Laboratory tests have demonstrated that biological brine clarification produces stable, inert water.
2. A pilot plant delivering biologically processed water to a test injection well has been successfully in operation for more than 1.5 years.
3. In long-time core-injection tests, only one-third of the pressure rise with conventional brine has been obtained.
4. Because of the potential for cost reduction, the whole water processing system has been converted to the new technology.
5. The focus is now on increasing treatment efficiency and monitoring the pressure response in the field.

Acknowledgments

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