



A Commercial Scale Xanthan Polymer Flood Project in a High Salinity, Low Viscosity Oil Reservoir in North Germany

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Abstract

A commercial scale polymer pilot project is performed in cooperation between Preussag and BEB in Germany and Statoil in Norway.

The Vorhop-Knesebeck petroleum reservoir is about 1200 m deep. The reservoir rock is a consolidated sandstone with a porosity of 27 % and an average permeability of $1 \mu\text{m}^2$. Reservoir temperature is 56 °C and the viscosity of the oil under reservoir conditions is 4 mPa s. The salinity of the reservoir brine, which is also used as injection- and mixing water for the polymer, is 220 g/l TDS.

Though the recovery by water flooding is already high, an additional recovery by polymer flooding of about 8% of the original oil in place is expected.

A numerical reservoir simulation was performed to find the optimum production and injection scheme. Production in the confined structure is from two wells. A polymer slug of 0.4 PV will be injected into two wells.

About 80 tons of xanthan will be needed. The xanthan is produced by Statoil in a 30 m³ pilot fermentor. The production process of the xanthan was optimized according to the needs in the field.

Polymer injection started in December 1989. No injectivity problems were encountered during polymer injection. A response to polymer injection was observed in one well after about 5 months of polymer injection and in another well after one year.

1. Introduction

Both companies, Statoil and Preussag, have in the past done laboratory work and research on the subject of polymer flooding. Though the conditions in the oil fields operated by both companies are somewhat different, the ideas about the mechanics of polymer flooding and how an EOR-polymer should look like have shown to be very similar in Statoil and Preussag.

Statoil has developed know-how in biotechnology and built a pilot plant for the production of xanthan. The idea behind this strategy was to be independent in technology and in the markets that are dominated by the current producers of xanthan, which is mainly used in food industry.

Preussag was planning polymer flooding in its oil fields, which are already producing at very high water cuts. A technical successful pilot project had been performed in the Eddesse-Nord oil field. On the basis of results from this pilot another project was planned for the Vorhop-Knesebeck field.

At that time, when oil prices were still low, no polymer product was available on the market at prices that allowed to perform this project economically.

So Statoil and Preussag joined together. Statoil provided the polymer and Preussag, together with its partner BEB, the oil field. For Statoil this project gave the opportunity to test its xanthan in a field case, and to perform a pilot test at costs that are much lower than for a pilot test in the North Sea. For Preussag this cooperation allowed to continue the activities in polymer flooding.

The project is performed in the upper layer of the Dogger- β sandstone of the block "H3a" of the Vorhop-Knesebeck oil field. This part of the reservoir is separated from all the other parts of the oil field by faults and comprises 4 wells. The total pore volume is approximately $430\,000\text{ m}^3$. It is intended to flood a slug of polymer of 40 % of the pore volume with xanthan at a concentration of 500 - 600 ppm, which gives a viscosity of the polymer solution of 4 mPa s under reservoir conditions, which is the same as the oil viscosity.

The project is divided into two phases:

Phase I: Injection of polymer solution into one well, which was used before for water injection, at a rate of $120\text{ m}^3/\text{d}$. The injection time will be about 22 months until a clear response is seen in the nearest production well. The necessary amount of polymer was estimated to be 48 000 kg of active material or $1\,370\text{ m}^3$ of fermentation broth.

Phase II: Injection of polymer solution into two wells at a rate of $160\text{ m}^3/\text{d}$ for about 17 months. The necessary amount of polymer is estimated to be 50 000 kg of active matter or about $1\,430\text{ m}^3$ of fermentation broth.

The xanthan is delivered to the field as a broth of a concentration of 3.5 %. The project started in December 1990.

2. Reservoir engineering

2.1 Reservoir description and production history

Block "H3a upper layer" comprising the wells VK8, VK45, VK48, and VKH3a was developed in 1959 with well VK8. Since the 8th of May 1982 well VK45 is producing from this unit and since 22nd of December 1982 well VK48.

Due to production in well VK8 the pressure decreased in this unit within 4 years from 13 MPa to the bubble point pressure of 1.5 MPa. After that the production mechanism was solution gas drive and the reservoir pressure stayed constant at the bubble point. This shows that the unit is an undersaturated, confined reservoir.

Since April 1984 the most up dip well VK48 was produced with a steadily decreasing production rate and since August 1984 GOR was increasing.

From October 1984 until March 1985 production was maintained by pressure relief in the casing. After this had been stopped, casing pressure was increasing and the fluid level was decreasing, so that production was no longer possible since March 1985.

To restart production well H3 was drilled in October 1986 for water injection. This well did

not reach the structure at the desired position, but was landing on the other side of a fault in the neighbour block. So this well was deviated to well H3a which found the reservoir at the location as shown in Fig. 1.

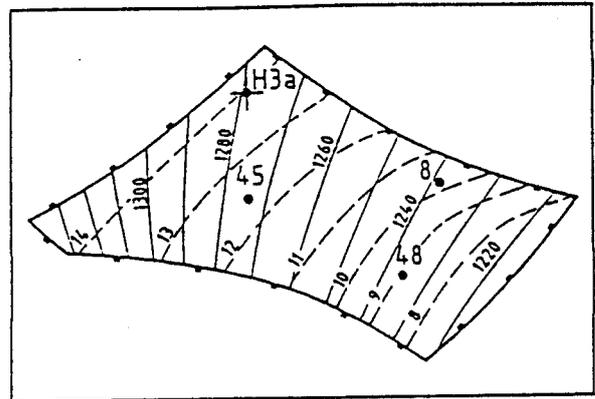


Fig. 1: Structure map of block H3a,
— depth in m, --- thickness in m

Water injection into well VKH3a was started in February 1987. The reservoir pressure increased very quickly. The production could be started again in July 1987 from well VK48 and VK45 and production from well VK8 could be increased.

2.2 Geological situation

Block "H3a upper layer" is confined in the South and in the East by sealing faults, but there is a small communication with the lower layer of the block in the North and also, what was found by numerical reservoir simulation, with the block in the East. As long as there is no big pressure difference between these blocks the fluid flow across the faults is very small.

The reservoir block "H3a upper layer (wells VK8/45/48/H3a)" and the reservoir block "wells VK20/36/44b" in the North are from the reservoir geological point of view one hydrodynamical closed unit. This is the reason why both blocks have to be considered in the numerical reservoir simulation.

2.3 Reservoir parameters

The reservoir parameters relevant for the polymer flood project are summarized in Table 1.

In Figure 2 the log sequence of the upper layer in well VK48 is given together with the results of the core analysis. This figure shows that the upper layer may be divided into two smaller layers. Permeability varies from about 1000 - 5000 mD in the upper part to about 500 mD in the lower part.

Table 1: Reservoir parameters polymer project
Vorhop Knesebeck block H3a

Depth	1250	m
Area	145 000	m ²
Thickness	8 - 14	m
Porosity	27	%
Pore volume	430 000	m ³
init. water sat.	14	%
OOIP	370 000	Res. m ³
Form. volume factor	1.04	
Form. temperature	56	°C
Oil viscosity	4	mPa s
Oil density	860	kg/m ³
Salinity of form. water	210	kg/m ³
Permeability	1000	mD

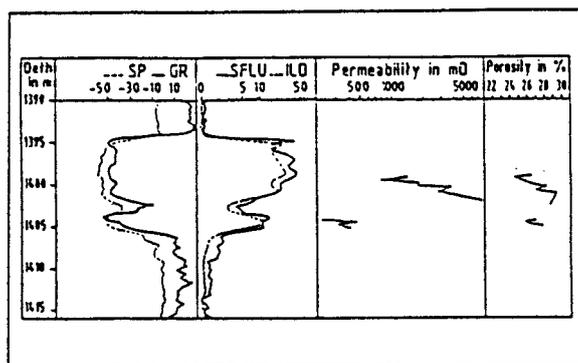


Fig. 2: Log and core data from well VK48

The mineralogy is given in Table 2. Though the sand is relatively clean, there is still a significant amount of clay minerals, feldspar and dolomite.

Table 2: Mineralogy of reservoir rock

Quartz	86	%
Muskovite Illite	1	%
Kaolinite	2	%
K-Feldspar	7	%
Heavy Minerals	1	%
Dolomite	3	%

3. Numerical reservoir simulation

A first reservoir simulation study was performed in 1986. The purpose of this study was to determine the potential for water flooding in block "H3a upper layer" and to find the optimum location for an injection well.

Based on this study prediction runs for polymer flooding were done in 1988 [1]. These runs showed that there was a potential of an incremental oil recovery of about 8 % of the

original oil in place which was about 29 000 m³ or 24 000 t.

When this first simulation study was done the water cut in wells VK8 and VK48 was still zero, so that a correct description of the reservoir and prediction of water cuts was not yet possible.

The first simulation study was updated in January 1990. The grid model was adjusted according to a new geological view, which was developed in 1988 in a geological study comprising the whole field. The main outcome of this study for block "H3a" was that the block was bigger in the south west part as was assumed in the first study.

The main task in this study was to match again the pressure behavior in the reservoir. It was found that there must be a small communication in the south west part across the fault with well VK49. A small amount of gas migrated over this fault and led to an increase in GOR in well VK49.

A map of the structure as used in this simulation is shown in Fig. 3.

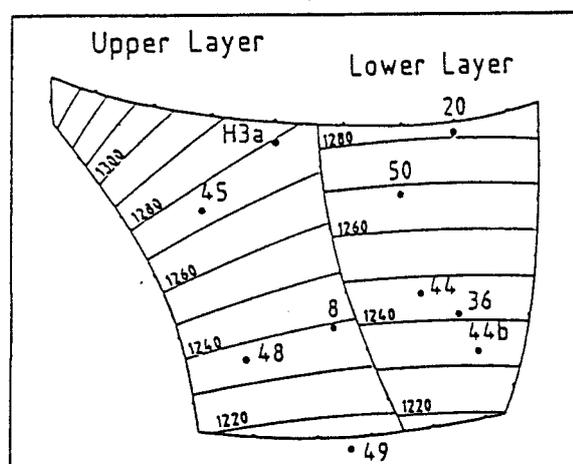


Fig. 3: Structure map as used in reservoir simulation

The first and second simulation studies were performed using the SURE simulator. In the third study the ECLIPSE simulation model was used, which is also used by Statoil.

The main task in this study was to match the water cut development in the different wells correctly. This could be achieved by adjusting absolute and relative permeabilities. The model was still 2-dimensional.

The polymer predictions using this model were not as promising as in the first two models. How far these changes can be explained by the change of the simulation program has to be investigated in the future. This will be done by

simulating laboratory polymer flood experiments. Further a 3-dimensional model will be set up.

The results of this simulation with respect to water cut development in the different wells are shown in Figures 4 - 6. These figures also show the measured water cuts in the field. The field measurements indicate a response to polymer flooding much earlier than predicted by the model.

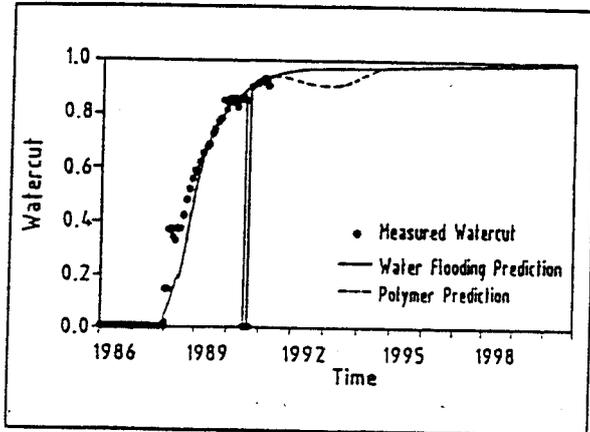


Fig. 4: Water cut well VK8

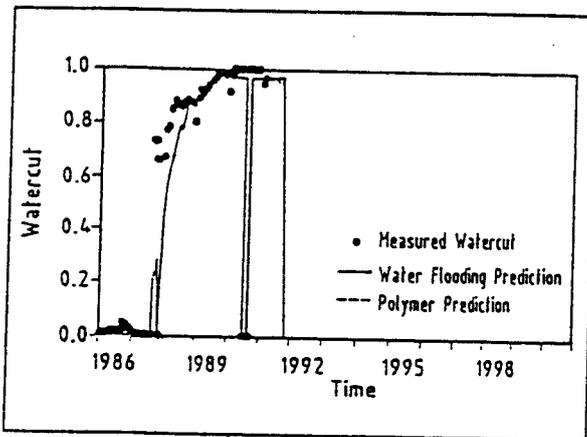


Fig. 5: Water cut well VK45, 3rd simulation

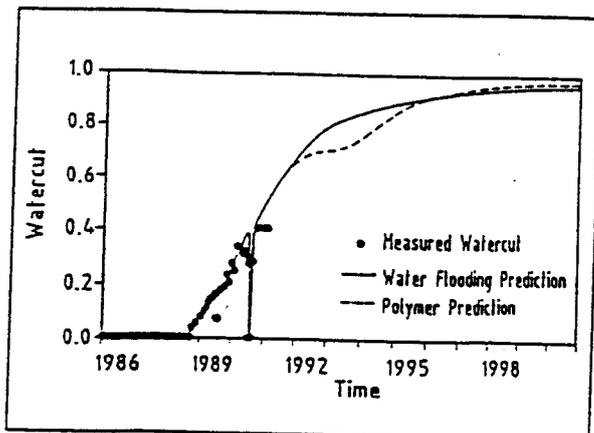


Fig. 6: Water cut well VK48

4. Polymer

4.1 Polymer screening

A polymer screening for this project was performed at Preussag during the planning phase of this project [2]. Independently Statoil came to similar results how an EOR-xanthan should look like [3].

Based on these results it was relatively easy to agree in a testing and quality assurance procedure for the polymer.

4.2 Xanthan fermentation

4.2.1 Introduction

Through this Statoil/Preussag joint field project, a situation came up where the xanthan based polymer system developed by Statoil could be tested in a realistic scale. The development program for this EOR-xanthan was initiated in 1985 and was finalized in 1989 when the production process was scaled up to fermentors of 30 m³ at Statoil's biotechnology centre Biosentrum. An initial test sample of 20 m³ was tested by Preussag in June 1989 and its quality was found to be acceptable.

4.2.2. Xanthan production process

4.2.2.1 Basic fermentation of biopolymers

Xanthan constitutes the major fermented biopolymer and is used extensively in the food-, chemical- and oil industry. It is normally produced through a fermentation process where the bacteria *xanthomonas campestris* is the production organism. A typical industrial production fermentor has a working volume around 100 m³ and the product obtained at a concentration of around 2 % can be precipitated with alcohol, dried and sold as dry powder. The limiting factors in this type of fermentation process are:

- mixing efficiency of broth
- O₂ transfer from air to liquid
- heat transfer from fermentation broth

The gradual increase in viscosity of the broth reduces normal transfer and mixing efficiency found in non viscous liquids.

4.4.2.2 The Statoil - EOR - xanthan process

As mentioned above, Statoil started the development programme of the xanthan process in 1985. The product used in this project is produced at Biosentrum in a fermentor of 30 m³ and is transported directly to Vorhop-Knesebeck after having gone through quality testing. It is important to note that the product does not require any down stream treatment before

injection. Major criteria for qualifying this EOR-xanthan product have been:

- selection of proper production organism
- identification of growth media, composition and product quality relations
- determination of fermentation parameters
- scale up of process to 30 m³
- determination of product quality related to changes in production conditions

4.2.2.3 Important production parameters

The idea that the Statoil xanthan product could be used without any pretreatment has been the overall goal for the optimization of the production process. The fermentation equipment at Biosentrum is specially designed for viscous fermentation broth. This reflects the overall geometry of fermentors as well as the design of the aeration- and mixing system. In addition, the different fermentors of increasing size have identical geometry which makes the Biosentrum ideal for scale up of the fermentation processes. To optimize the product quality as well as productivity of the process, the following production parameters are of importance:

- length of fermentation time in seed and production fermentation (Fig. 7)
- control of pH profile in fermentation
- optimal CO₂/O₂ ratio
- initial concentrations of sugar as a carbon source and its influence on final xanthan concentration
- ideal ratio between inorganic and organic nitrogen source

The process is still being developed and it is intended to improve the process further, especially concerning productivity.

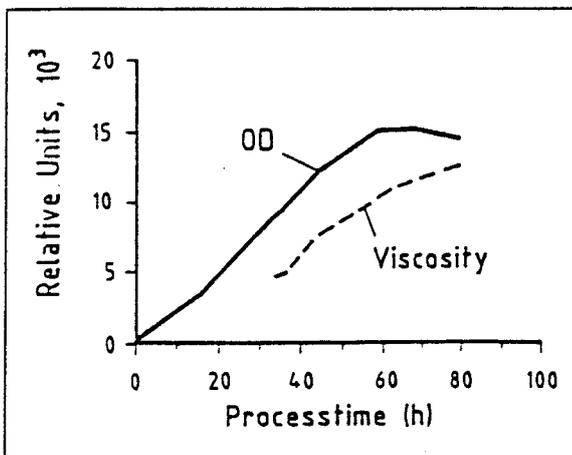


Fig. 7: Cellular growth (OD units at 540 nm) and broth viscosity (cP) during a typical large scale fermentation of xanthan.

4.2.3. Quality testing

Following fermentation in the production fermentor, the product is transferred to a storage tank where it is kept while quality testing which is performed on 1 litre samples sent to Preussag and the Production Laboratory at Statoil.

As predicted, we do see variation from batch to batch as to final concentrations of xanthan as well as filterability/intrinsic viscosity. The reason(s) for these variations is hard to explain, the best guess being that the bacteria see a slightly different surrounding from batch to batch in terms of nutrients, O₂, pH and temperature.

4.2.4. Delivery programme

Since January, 1990, approximately three containers of 23 m³ has been sent monthly from Stavanger to Vorhop-Knesebeck.

4.2.5 Experience obtained

The project so far has shown that large scale xanthan fermentation may lead to batch dependent variations. Such variations can be hard to explain, and therefore, quality testing has to be an integrated part of all future polymer projects. Consequently, before starting any new full scale field projects, one has to ensure that the polymer supplier really can deliver the right EOR quality regularly. This can best be done by an extensive evaluation of possible producers at an early stage of the project. Important quality criteria will be quality of product, skill of personell and regularity in production.

5. Field operations

A decision to continue with Phase 2 will be taken on the basis of results from Phase 1.

Table 3: Project schedule in phase I:

Injection into well H3a	
Injection rate	120 m ³ /d
Time	22 months
Polymer concentration	0.5 kg/m ³
Polymer consumption	40 000 kg active material
	1 140 m ³ Xanthan broth

5.1 Water quality and water treatment

The reservoir brine from the oil treatment plant is used as mixing water for the polymer. The water is not filtered or treated otherwise to remove solids. The water quality is continuously monitored at the oil treatment station and before polymer mixing using the HYDROGUARD system [4].

Before the polymer is mixed to the water formaldehyde, citric acid and hydrochloric acid

are added to the injection stream. The citric acid is used to sequester divalent iron and thus prevent gelation of the xanthan. Formaldehyde is used as biocide at a concentration of 1000 ppm. The hydrochloric acid lowers the pH from about 6 to 5. This improves injectability of the water, reduces microbial activity and makes polymer mixing easier.

5.2 Polymer logistics, transportation and storage

The polymer is produced at the Statoil Biocenter in Stavanger. The xanthan broth is coming from the fermentor at a concentration of about 3 % active material.

As the investment for further concentration of the polymer broth is very high the polymer is shipped at this concentration to Germany.

The polymer is shipped in 23 m³ tank containers from Stavanger to Hamburg. These containers are then transported to the field, where the polymer is drawn directly from the containers and mixed with the injection water.

It has turned out that continuous supply of the polymer in the field is sometimes not possible, because of problems in transportation and storage capacity. For this reason an additional 40 m³ storage tank was mounted in the field to avoid breaks in injection.

5.3 Polymer mixing

A flow scheme of the polymer mixing is shown in Fig. 8 and 9. Fig. 8 shows the water stream coming in an 8 km long pipeline from the oil treatment plant.

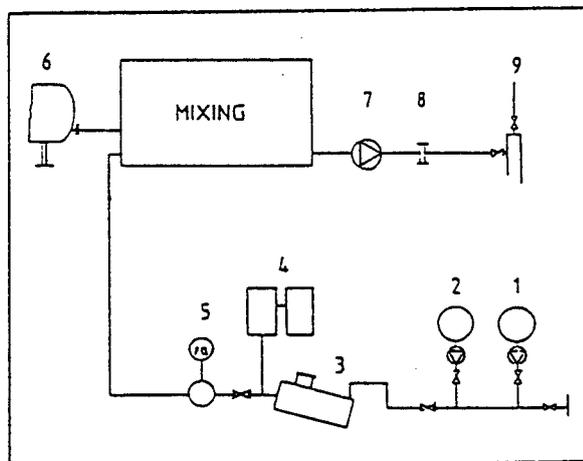


Fig. 8: Polymer mixing - pipe line system
1) HCl and citric acid 2) Biocide 3) Oil separator 4) Hydroguard 5) Flow meter 6) Polymer storage 7) Injection pump 8) Shear plate 9) Injection well

Before this water is mixed with polymer hydrochloric acid, formaldehyde and citric acid are added. Small amounts of oil that are still

present in the water and have accumulated in the pipe line are separated in a small 1 m³ separator.

The polymer mixing is shown in detail in Fig. 9. The xanthan broth is drawn from the tank container or the storage tank using 3 inch stainless steel pipes, so that the high viscous xanthan broth is still flowing under hydrostatic pressure and about 0.2 bars nitrogen pressure, which is applied to the tank containers.

Before the broth is metered by a special metering pump to the water stream it is pressed through a 20 μm filter. This shearing improves the mixing and dilution of the polymer in the high salinity brine. After mixing with the water the polymer solution has a concentration of 500 - 600 ppm of active xanthan. This solution is sheared in a dynamic mixer, and then transported to the injection pump. Behind the injection pump a shear plate is mounted in the flow line to further improve the quality of the polymer solution.

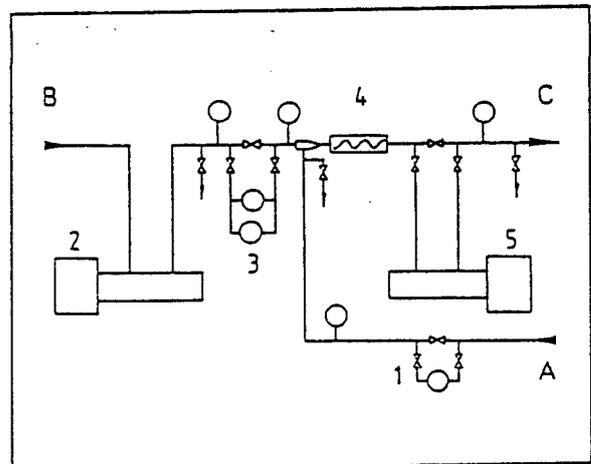


Fig. 9: Polymer mixing - mixing container
A) Incoming water stream B) Xanthan broth stream C) Polymer solution stream
1) Water filter 2) Polymer metering pump 3) Shear filtration 4) Static mixer 5) Dynamic shearing

5.4 Preparation of injection well

The injectivity of the injection well H3a was not good enough for the polymer injection. A flow meter log (PLT) showed that only the upper two meters of the perforation were taking the injection water. So the whole sand zone was reperforated using a 5 inch perforation gun with deep penetration shots.

Before this reperforation the injection well head pressure was about 70 bars. Directly after the reperforation the injection pressure was only about 6 bars. The pressure then rose within 20 days to 18 bars where it remained stable.

This pressure behavior shows very good the capillary effects that occur when water is

imbibed into an oil saturated zone in a water wet sandstone, as it is also observed in core flood experiments.

Besides the reperforation no other stimulation was necessary to improve and maintain the injectivity of the well also for the polymer injection period.

6. Results

6.1 Water quality

The water quality ratio measured during the first 6 months of operation is shown in Fig. 10. The criterion for a suitable water quality was a water quality ratio below 50 ppm/mD. Fig. 10 shows that this was the case during most of the time. When water quality became too bad for longer time periods (< 24 h) the injection was interrupted.

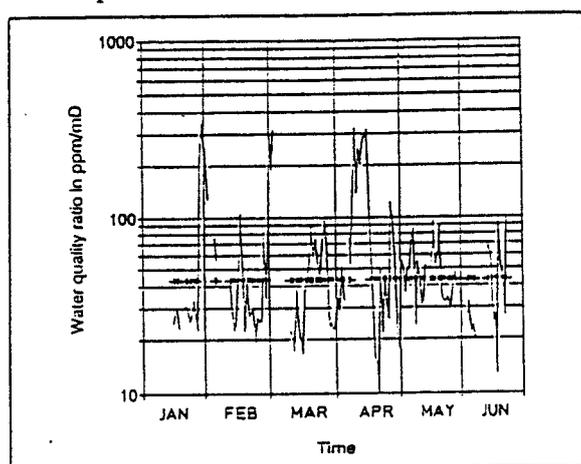


Fig. 10: Water quality ratio of injection water

6.2 Quality of different xanthan batches

The results of the xanthan quality testing are given in Table 4. The concentration of active xanthan in the broth is listed together with the pyruvate content and the concentration that is necessary to give a viscosity of 4 mPa s under reservoir conditions. The pressure increase Δp in a flood test and the residual resistance factor RRF are measured according to [2]. This table shows that 6 batches did not fulfil the quality requirements and had to be dumped. Four batches produced in summer 1990 had to be rejected. After the reason for the insufficient injectability was found a constant good quality xanthan was produced.

Table 4: Xanthan quality during first year of operation

Batch	Act. %	Pyrv. %	Conc. ppm	Δp %	RRF	Rem.
XC21	3.28	4.06	565	11	1.23	
XC22	3.20	4.35	450	22	1.81	
XC26	4.04	4.88	480	14	1.24	
XC31	2.55	4.65	530	14	1.67	
XC32	3.17	4.47	470	958	60.00	dmpd
XC33	3.24	4.06	530	11	1.40	
XC37	3.22	4.71	400	8	1.30	
XC39	2.92	4.14		469	16.2	dmpd
XC40	3.10	4.76	420	9	1.65	
XC42	3.20	4.48	430	14	1.44	
XC43	3.10	4.75	405	37	1.07	
XC44	2.91	5.00	390	9	1.47	
XC45	2.90	4.68	640	342	8.67	dmpd
XC46	2.70	4.54	425	144	5.77	dmpd
XC48	2.36	4.67	430	121	4.36	dmpd
XC51	2.65		500	1633	50.00	dmpd
XC52	2.59		400	29	1.71	
XC53	2.85		505	22	1.87	
XC54	2.79		500	9	1.50	
XC55	2.75		510	8	1.30	
XC56	2.97		540	25	2.20	
XC57	2.89		535	28	2.14	
XC58	3.09		540	22	2.07	
XC59	2.90		475	10	1.57	

6.3 Injection performance

The injection performance can be seen in Fig. 11 and 12. Fig. 11 shows the increase in well head pressure of the injection well H3a during the first days after start of polymer injection. The pressure of 20 bars during water injection was taken as zero, so that this figure only shows the pressure increase due to the higher viscosity. The figure shows measured and calculated values.

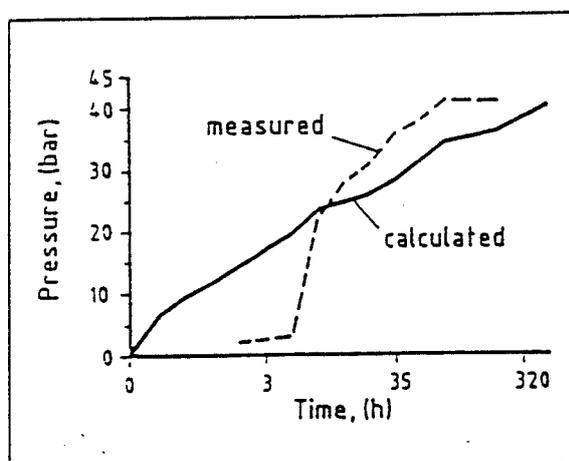


Fig 11: Calculated and measured increase in well head injection pressure

It can be seen that the pressure increased very quickly within 35 hours by about 40 bars and reached a stable value after about three days.

This pressure increase was calculated by assuming a water permeability of 180 mD and a viscosity of 10 mPa s. The permeability corresponds to the permeability to water at residual oil saturation, the viscosity to a temperature of about 20 °C. The temperature around the injection well was cooled down by the injection water, which has a surface temperature of about 15 °C. Fig. 11 shows that the calculated values fit rather good with the measured data.

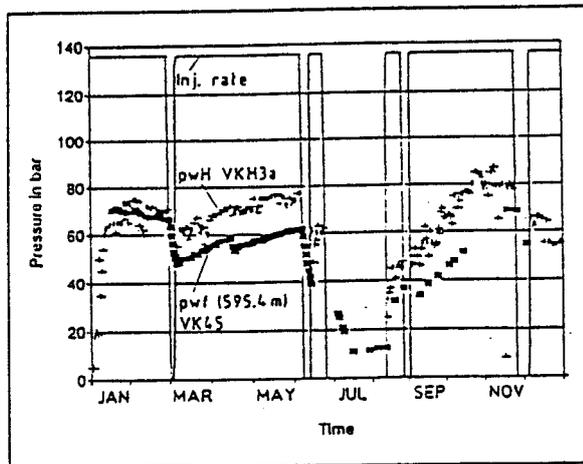


Fig. 12: Injection pressure development of well H3a during first year of injection.

The long term development of the injection pressure is shown in Fig. 12. Together with the well head pressure the reservoir pressure is shown as measured in well VK 45. From this plot it can easily be seen, that after the injection pressure had reached the stable value as described before no further increase occurred. Variations in injection pressure follow variations in reservoir pressure.

6.4 Recovery

As may be seen in Fig. 4 and 5 the beginning of a decrease in water cut is expected in wells 8 and 45 in the middle of 1991.

In well 8 as well as in well 48 a stabilisation and even a decrease in water cut is observed about 3 months after start of injection. This may be explained by a change in pressure distribution in the reservoir which causes flow of oil in parts of the reservoir where it was immobile during water flooding.

Since the beginning of 1990 only pure water without any oil was produced in well VK 45. This shows that the actual values of water cut in the field are higher than predicted by the simulator for water cuts above 95 %. This means that a long production period with high water cuts as it was predicted before will not occur.

On the other side a clear response to polymer flooding in this well was observed in January 1991. The water cut decreased to values of 93 - 95 %.

The further water cut development of this well will be important for the appraisal of phase I of the project.

Water samples are regularly taken from all of the wells and will be analysed for formaldehyde and xanthan.

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