011 LABORATORY AND FIELD MEASUREMENTS OF RESIDUAL OIL SATURATION FROM GAS INJECTION AT THE OSEBERG FIELD

ARNE SKAUGE, JAN INGOLF KRISTIANSEN and SIGMUND SØGNESAND
Norsk Hydro ASA, 5020 Bergen, Norway

Abstract

Updip gas injection has been the main drive mechanism in the oil production from the Oseberg Field since the start of production in December 1988. The oil field is located in the North Sea area, and is one of the larger oil reservoirs. The paper summarizes the available data giving information about the residual oil saturation after gas injection, and show how log interpretations have been applied for monitoring of the gas displacement process.

Both core analysis and field measurements have been used in the analysis of the remaining oil saturation (ROS) after gas injection. Core analysis, well logs, and single-well transient tests have been used to estimate the efficiency of the gas injection. Long core gas injection, centrifuge oil drainage experiments, and single well gas tracer tests have confirmed a residual oil saturation of less than 10 saturation units in the Tarbert formation of Oseberg. The sponge core showed ROS to gas, in the range of 5 - 20 saturation units. The overall summary of available data has concluded a microscopic displacement efficiency by gas injection leaving a residual oil saturation of 10 saturation units.

The cased hole log, Pulsed Neutron Capture tools (PNC) also called TDT-P log (Thermal Decay Time) has been extensively used to monitor the gas frontal advancement already from the start of the oil production. We have also attempted to estimate the residual oil saturations from TDT-P logs. These data have shown systematically higher ROS values than other methods. The paper also discusses the calculation of saturations from TDT and compares the results to the other measurements.

Introduction

Oseberg is a high permeability sandstone reservoir belonging to the Middle Jurassic Brent Group. The field reservoir geology[1] and production monitoring[1-3] have been described in earlier presentations. The oil field is developed primarily by full scale gas injection supplemented by water injection in some reservoir units. Re-cycling of produced gas, and gas imported from the Troll field is used for pressure support. Production monitoring and reservoir monitoring[1-3] have confirmed gravity stable gas front evolution. The expected ultimate recovery is about 60 per cent of the original oil in place. Oil production was started late 1988, and by mid-1997 about 65 per cent of the estimated reserves have been produced.

Residual Oil Saturation Determination Techniques

Remaining oil saturation (ROS) can be calculated from many different return signal from well tests; resistivity logs, pulsed neutron capture (PNC) logs, single well tracer tests, nuclear magnetic logs (NML), carbon/oxygen (C/O) logs, and electromagnetic propagation tool (EPT). All log determined ROS are porosity average oil saturation, while the single well tracer test gives a permeability weighted average. The different methods have been compared for waterflood ROS determination[4]. The ROS from single well tracer tests is expected to give lower ROS due to high displacement efficiency in the more permeable fractions of the reservoir.

In addition, core analysis is a direct measurement of ROS in the laboratory by long core gas injection or by centrifuge capillary pressure and relative permeability measurements. Pressure cores have been applied to preserve the core at bottomhole pressure until the core fluids can be immobilized by freezing. Sponge coring uses a sponge-sleeve made of a porous oil-wet polyurethane material to collect the oil bleeding from the core. By use of mass balance the total oil volume present can be calculated.

Laboratory measurements of gas displacement efficiency.
Laboratory gas injections are usually unsteady state displacements, and determines the oil mobilization after some pore volume of injected fluid. The oil left behind is often referred to as residual oil saturation, but should rather be named remaining oil saturation. The reason is mainly because the core flood could continue to produce oil at a low fractional flow. Laboratory core floods are more dominated by capillary forces that may lead to high remaining oil saturation compared to the "true" residual oil saturation. To reduce the influence of capillary end-effects often long cores have been used in the laboratory core flood experiments. The statistical accuracy of gas - oil core flood measurements and comparison of different experimental methods have been discussed in a recent paper[5]. The efficiency of the gravity stable gas injection may depend on the pore structure of the rock. Gas ROS data from different flow units of the Oseberg field have therefore been compared from series of gas drainage centrifuge experiments.

Field methods for measurement of gas displacement efficiency
The ROS from single well tracer tests is expected to give lower ROS due to high displacement efficiency in the more permeable fractions of the reservoir. Sponge coring is another field method that has been applied with the objective to determine oil saturation. In addition, field measurements have been compared to the more traditionally laboratory core analysis using long core gas injection and / or centrifuge gas drainage experiments.

Several wells have served as observation wells in time periods before they were set into production. Iso-saturation maps have been calculated to describe and illustrate the sweep efficiency of the gravity stabilized gas injection. Especially have the TDT-P logs in deviated production wells acted as precursors for the gas front movement towards the horizontal wells located low on the structure. The use of gas front monitoring has been applied to balance the offtake from different zones of the reservoir. Other applications of the TDT-P logs have been to estimate the extent of gas cones at the production wells, and evaluate to what extent the gas saturation is reduced during shut-in.

Results and discussion

After the discovery of the Oseberg Field a large number of core flood experiments have been performed to evaluate the residual oil saturation both after water- and gas-injection. The experiments indicated that even an equilibrium gas injection in Oseberg was more favourable than a waterflood. Any compositional exchanges between a dry injection gas and the reservoir oil would increase the oil recovery further.

Laboratory measurements
An example of centrifuge core plug experiments is given by four Tarbert cores from 30/9-B32. The cores had permeabilities of about 2 Darcy. The residual oil saturations by drainage in centrifuge at 3000 rpm were close to zero (0.5-1.4 saturation units (s.u.)). Due to these surpricingly low oil saturations, all cores were subjected to solvent extraction. The oil saturations after extraction were still very low (1.5-3 s.u.) The interfacial tension between oil and gas in the ambient centrifuge experiments is considerable higher than the interfacial forces in the reservoir. Centrifuge experiments represent a lower limit of residual oil saturation after a gas flood.

Several different long core experiments have been performed using different types of injection gas. Due to liquid hold-up from end effects, the long core experiments are the most representative. The hold-up of oil due to capillary end effects is a laboratory artefact, where the measured S_{org} is higher than the reservoir value. The residual oil saturation has been calculated from history match simulations of experiments and extrapolation to a final endpoint has been defined by a relative permeability cut-off value. Injecting a non-equilibrium gas will shrink the oil, and the therefore reduce the residual oil saturation. The ROS is therefore dependent of the process used to achieve the ROS. Injecting of dry gas will strip the bypassed oil of intermediates. This stripping effect has been calculated to be 40% of the residual oil saturation in the laboratory core floods. The average residual oil saturation from the long core dry gas injection was reported to be (5.5-8 s.u.).

If the residual oil saturation after mass transfer is 6 s.u., the shrinkage effect was 40%, the residual oil saturation where no mass transfer has occurred was 10 s.u.. This leads to a residual oil saturation where no mass transfer has occurred to be 10 s.u.. The oil relative permeability curves from the long core experiments are shown in Figure 1.

Summary of the gas injection residual oil saturation shows variation in the range of 1 and 15 s.u., with an average residual oil saturation from long core experiments of about 10 s.u., for the Tarbert formation. Additional oil production from compositional effect is expected to bring the ultimate residual oil saturation below the measured ROS. The fewer experiments have been performed on the Oseberg-, Etive-, and Ness formation, but the data indicate a somewhat higher remaining oil.

Sponge core test was performed in the lower part of Gamma Tarbert, well 30/9-B32. The results showed that very little oil was trapped in the sponge. One conclusion from an internal summary note was that the flooded zone seems to be at true residual, however, the oil saturation seems to increase with depth indicating that still a saturation change with time is expected. ROS confirmed approximately 15 -20 s.u.. Sponge core results may indicate better than expected drainage of the bottom part of LT-3 and efficient drainage of LT-2. ROS had to be corrected for formation volume factor. The ROS distribution with depth and ROS compared to change in permeability are included in Figure 2.

Single-Well Gas Tracer Test, B-03

Single-well tracer tests[6-8] to determine waterflood residual oil saturation have been applied in Oseberg in the single-well tracer test on the Tarbert formation of well, B12A. A similar concept was designed to determine Sor after gas injection into the ORE formation of well, B03. This well has earlier been an observation well in ORE, and the TDT-P log data had shown that the gas contact was below the bottom perforations. Dimethylcarbonate (DMC) was injected into the gas stream, during soak-in the DMC will hydrolyse to form methanol and carbondioxide. The difference in return-time for the three tracers determines both the water and oil saturations. For details about this novel single-well tracer test method we refer to recent paper[9].

The material balance tracer showed delayed return at backproduction, possible due to liquid hold-up near the well or non-symmetrical inflow/outflow. The production profile of SF_6 show two peaks, which can be explained by non-symmetrical flow pattern. The water saturation is low ($Sw < 10$ s.u.) when calculated from comparing backproduction of DMC and the hydrolysis reaction products, methanol.

The single-well gas tracer tests can not be modelled by a constant oil and water saturation in each radial layer. The tracer tests have been history matched under the assumption of a gradient in the liquid saturation with distance or a three-layer approach with non-symmetric inflow/outflow.

The injected main tracer, DMC (dimethylcarbonate), is delayed in all tests and there were several problems in interpretation of the results. However, the remaining oil in the gas contacted zone is estimated to be low and less than 10 s.u.. The main tests using radioactive tagged CO_2, show DMC and CO_2 peaks at close to the same position in time, giving a history match with ROS less than 10 s.u. Tracer production profiles are included in Figure 3.

Residual oil calculations from TDT-P log data.
TDT-P monitoring data from the wells 30/9-B-03, -07, -08 and 30/6-C25 have been quantitatively analysed with the purpose to determine TDT-derived residual oil saturation after gas flooding. The Oseberg formation has been the main target, but Lower Ness has also been evaluated in well 30/9-B03. The basic data consisted of 22 runs in 30/9-B03, and 14 runs in total for the other wells. Data interpretation is based on timely change of measured formation capture cross sections are exclusively caused by gas replacing oil. TDT derived ROS depends only on initial water saturation, porosity, difference of the capture cross section of oil and gas and finally the change of measured capture formation cross section.

Generally, the TDT-P logs produce consistent and precise readings and the uncertainty of TDT evaluated ROS is about +/- 5 s.u. This number is based on the repeatability of the individual reference curve combined with the precision of the CPI-data. The monitoring curves show very good description of the gas frontal movement, Figure 4, detected by a substantial decrease of the formation capture cross section. The analysis shows that after the gas front has passed, the measured formation capture cross section do not change with time. This indicates that within the actual limits of accuracy and the monitored time span, no additional drainage occurs after the gas front has passed. The analysis infers oil saturations average of about 35 s.u. For the three wells that are non-gas injectors in the Oseberg formation, while the oil saturation in well 30/9-B-07 that is an active gas injector in the Oseberg formation is substantially lower, ROS of about 20 s.u., Figure 5.

Reservoir monitoring by TDT-P logs
The TDT-P logs have been a useful source for reservoir monitoring. The gas front movement has been detected in many wells. The average gas front movement has been 5 cm/day TVD, as shown in Figure 6. The TDT results are used for production planning. The production rates have been adjusted to assure an even and stable gas front in Oseberg. TDT data from some wells indicates that the gas front in Etive and Lower Ness is behind the gas front in the Oseberg formation. The low permeable Rannoch serve as a flow barrier between Etive and Oseberg.

Conclusions

- Residual oil saturation estimated from laboratory measurements agree with estimates obtained from field test measurements.

- Long core gas injection, centrifuge oil drainage experiments, and single well gas tracer tests in B-03 ORE formation) all confirm an estimate for residual oil saturation of less than 10 s.u. in Oseberg. The sponge core in 30/9-B32 (Tarbert) showed residual oil saturation to gas in the range of 15 - 20 %PV.

- Log measurements of residual oil saturations calculated from TDT-P log data show systematically higher ROS in the range of 30-35 s.u., inconsistent with all other measurements. However, TDT-P logs have proved of great value for monitoring of the gas frontal movement.

- Gas front monitoring has indicated stable gas front evolution at high oil production rates from the main reservoirs.

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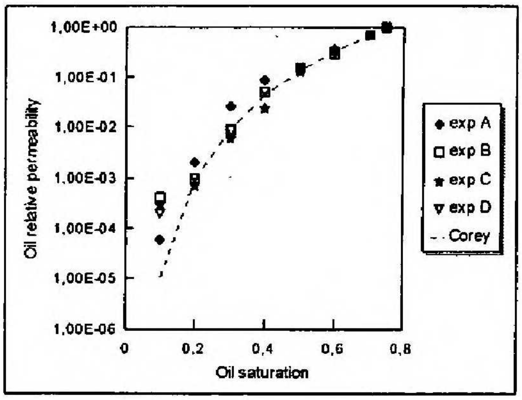

Figure 1. Oil relative permeability from long core gas injection

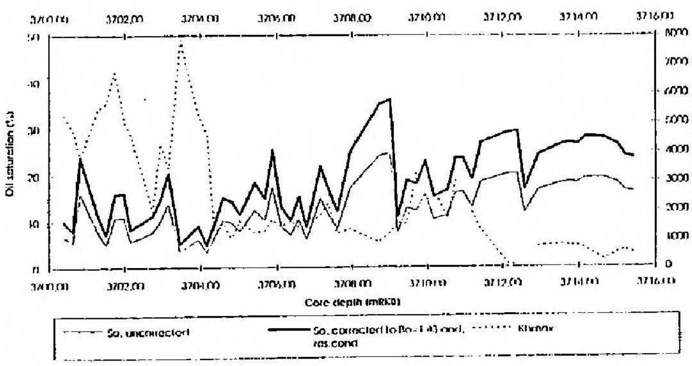

Figure 2. Sponge core analysis of residual oil saturation, well 30/9-B32

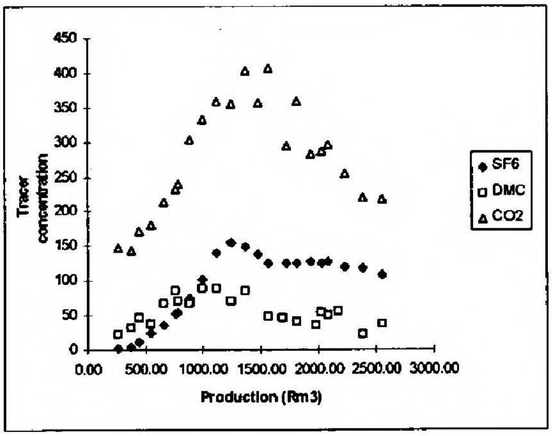

Figure 3. Tracer production profiles for DMC, and CO_2 from single well tracer test, 30/9-B03

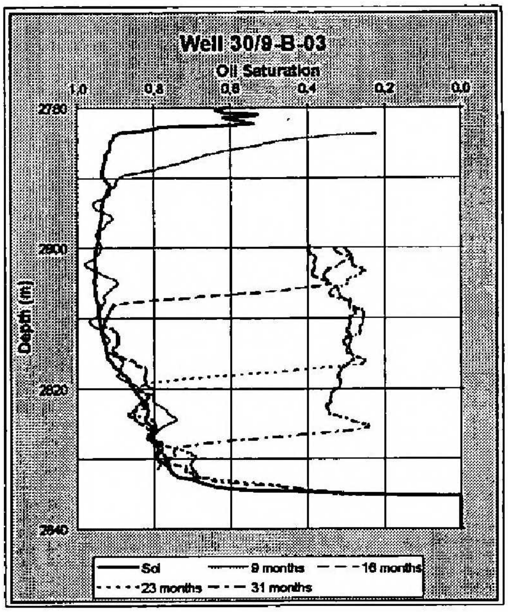

Figure 4. Oil saturation versus depth, well 30/9-B03

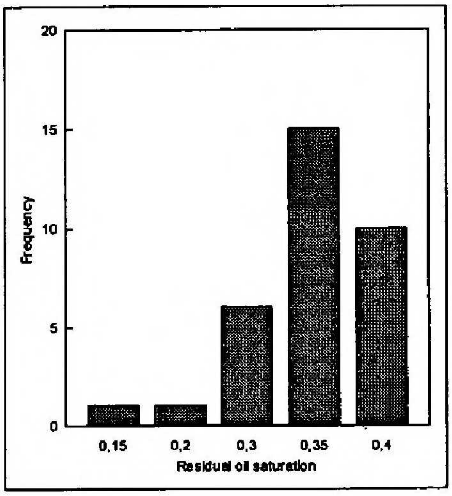

Figure 5. Variation of residual oil saturation TDT analysis

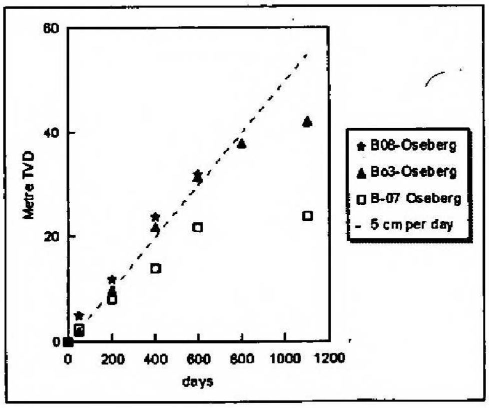

Figure 6. Gas front intervals for movement from four TDT logged wells