Enhanced gas recovery testing in the K12-B reservoir by CO_2 injection, a reservoir engineering study

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Abstract
Gaz de France Production Netherlands B.V. (GPN) is producing natural gas from the Dutch North Sea continental shelf. As one of the players in the Dutch gas supply market, GPN supports the idea of injecting CO2 into depleted gas fields in order to reduce CO_2 emissions into the atmosphere.

The gas produced at one of GPN's platforms, the K12-B platform, contains a relatively high proportion of CO_2. This CO_2 used to be separated from the produced natural gas and released into the atmosphere. The K12-B reservoir is located at a depth of some 3800 metres; with a hydrostatic pressure regime and a formation temperature of 132°C. Preliminary investigations indicated that it would be relatively easy to re-inject this CO_2 back into the reservoir. Hence GPN's K12-B platform offered a good opportunity to test CO_2 injection at large depths. Deployment of a CO_2-injection demonstration facility at the K12-B platform has increased our understanding of the benefits and drawbacks of this technique.

This paper reports on the results of phase 2 of the ORC project - Offshore Re-injection of CO_2. It covers the findings of the CO_2 re-injection test into a gas-producing compartment of the K12-B reservoir. At the end of 2005 there was no clear evidence of measurable improvement in the gas-production performance of the tested compartment. Continuing injection is needed to increase the EGR potential of CO_2 injection. Further study is needed and GPN has committed itself to continue the injection test in 2006.

Keywords: CO_2, Enhanced Gas Recovery, Gas field

Introduction
GPN's Offshore Re-injection of CO_2 (ORC) project is partly funded by the Dutch CRUST subsidy. The ORC project aims at investigating the feasibility of CO_2 injection and storage in depleted natural gas fields with the objective to develop a permanent CO_2 injection facility in the short term. The nearly depleted K12-B gas reservoir, which was produced via the K12-B platform in the North Sea, was chosen as demonstration site for the ORC project. The ORC project consists of several phases. This paper reports Test 2 of Phase 2. In this test CO_2 is injected into a nearly depleted reservoir compartment with two gas-production wells (K12-B1 and K12-B5) and one CO_2-injection well (K12-B6). During this implementation test, about 30,000 Nm^3/day CO_2 is re-injected; this equals about 20,000 tonnes per year.

The K12-B Gas Field
The K12-B gas field is located in the Dutch sector of the North Sea, some 150 km north-west of Amsterdam (Figure 1). Since 1985, GPN has been producing gas from this field from the Upper Slochteren Member (Rotliegend).

The K12-B structure was discovered in 1981 by the K12-6 exploration well. Surface facilities were put in place in 1985 and drilling of the initial development wells started the same year. Well K12-B8 was drilled in 1997 into the structure's northernmost fault block. That block turned out to be undrained and K12-B8 was the last development well of the K12-B structure. Currently, four wells are still producing gas from the K12-B reservoir: K12-B1, -B2, -B5 and -B7. It is expected that these wells will continue to produce gas until mid 2006 [4]. By that time the reservoir is expected to be fully depleted.

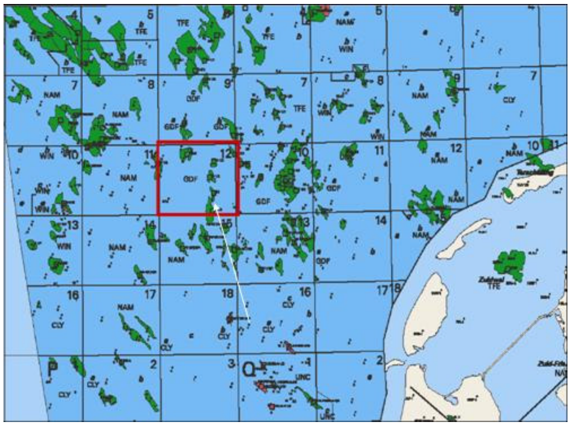

Figure 1: Field location map

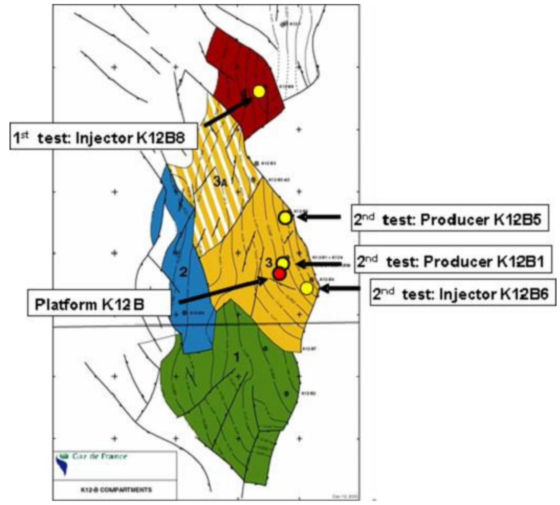

Figure 2: Schematic layout of the test locations.

CO_2 Re-injection

The gas produced at the K12-B platform has a relatively high CO_2 content (13%). This CO_2 is separated from the produced natural gas. It used to be vented into the atmosphere, but is now re-injected. The CO_2 is injected into the Upper Slochteren Member above the (original) gas-water contact. This type of injection makes the ORC project unique. K12-B is the first site in the world where CO_2 is injected into the same reservoir from which it originated. Test 1 (Figure 2) lasted from May to December 2004. The objectives of TEST 1[1] were to test the injection facility, to prove that injection is feasible and safe and to examine the CO_2 phase behaviour and the response of the reservoir.

Geological model

To upgrade the initial geological concept, a geological study[2] was carried out using mainly present-day technology and tools. This study showed that the K12-B Upper Slochteren reservoir is highly heterogeneous as a result of sedimentary, diagenetic, and tectonic processes.

Sedimentary heterogeneities include complex interfingering of high-perm (300-500 mD) aeolian facies, low-perm fluvial facies (5-30 mD), and mud-flat facies, which act as vertical permeability barriers (Figure 3). It is most likely that the several-metres-thick aeolian streaks, which form about 11% of the gross rock volume, will act as conduits for the CO_2. The lateral extent of individual streaks is estimated to be no more than a few hundred metres. Shale streaks comprise 16% of the volume and fall into two categories. A minority has a field-wide extent, while most of the shale streaks can not be correlated across more than two wells, corresponding to a distance of a few hundred metres.

The K12-B field comprises a number of tilted fault blocks which are not or barely in pressure communication. In adjacent blocks, wrench-fault tectonics strongly influence fluid flow, sometimes even resulting in further compartmentalisation of individual fault blocks. Small, sub-seismic reverse faults, in particular, form effective horizontal barriers. Indications for this have been observed in cores, but not on seismic. It is not yet known whether such horizontal barriers also play a role in the K12-B field

A 3D geocellular model was built that honours the seismic interpretation of the Top Rotliegend (Figure 4) and information on the well tops from the eight K12-B wells. The results of the petrophysical analysis of the wells were incorporated in the form of continuous well logs for porosity, permeability, and original water saturation. 3D reservoir properties were generated in accordance with the heterogeneities listed above.

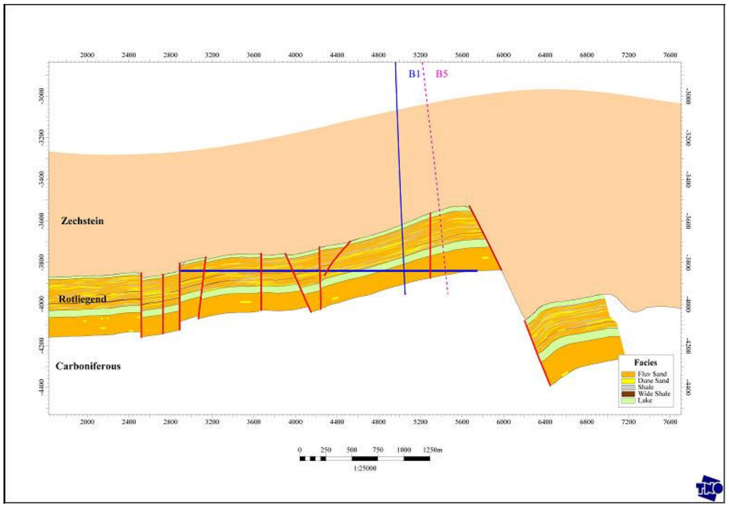

Figure 3: Cross-section of the geological model

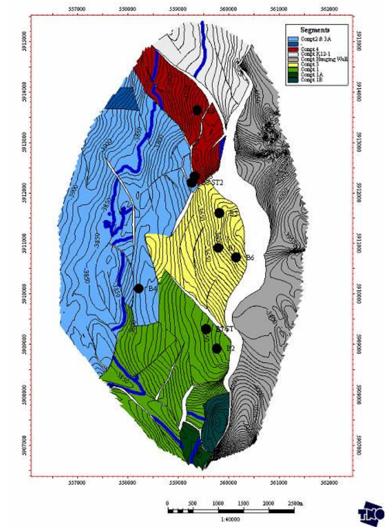

Figure 4: Structure map of the K12-B reservoir

Test results

In January 2005, CO_2 injection shifted from well K12-B8 to well K12-B6. This well is located in 'compartment 3', which also contains wells K12-B1 and -B5. These two wells are currently (January 2006) still producing some 250,000 Nm^3/d of gas. Well K12-B6 has been producing gas from November 1991 until August 1999, sometimes hampered by water-production problems. The well was intended to produce also gas from the Lower Slochteren Member, but this action was unsuccessful. The connection with deeper formations may have caused fatal problems resulting in killing the well. Unusually high tubing-head pressures were monitored in the interval in this well between the end of production and the start of CO_2 injection. These pressures may have been due to compressed gas in the well bore resulting from invaded water which formed a water column in the well. As soon as the well was used as an injector, the gas pressure dropped and the water was pushed back into the reservoir showing normal CO_2 injection pressures.

On 1 March 2005, two tracers, of 1 kg each, were injected into well K12-B6 during regular CO_2 injection. A tracer substance was needed to enable monitoring of any breakthrough of injected CO_2 into one of the two methane production wells.

During the 2005 injection period (25/2-28/12) the injection facility operated as planned. On average, some 26,000 Nm^3/d of CO_2 was injected during the entire 2005 test period. During the injection programme, several parameters were measured to monitor the reservoir response, such as: the daily gas injection and production rates; pressures and temperatures at various locations; composition of the injected gas; and the presence of tracer elements in the produced gas. These data are presented in this paper. The results are preliminary and the final results will be available after the full injection test has been completed (end 2006).

During the test period, the bottom-hole pressure was continuously monitored with the aid of down-hole memory gauges. The gauges were installed at a depth of 3610 metres TVD. The average down-hole duration of the gauges was 6 to 8 weeks. A total of 7 gauge cycles covered the reported period.

Vertical Flow Performance

The attempt to fully use the measured tubing-head pressure (THP) was successful. A vertical flow correlation has been developed to relate the pressure drop in the well bore to the gas production rate. The drop in pressure is due to the combined effect of the weight of the fluid column and the friction force in the well bore. For both wells (K12-B6 and K12-B1) we have subtracted the measured THP from the down-hole gauge data and plotted these data against the actual fluid rate (injection or production). CO_2 injection in well K12-B6 (Figure 5), in particular, shows an almost linear relationship, as a result of the relatively low injection rate with minor friction effects and the predictable weight of the gas column.

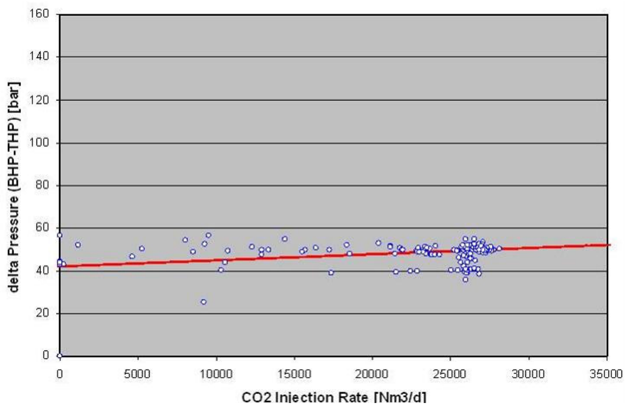

Figure 5: Well K12-B6 performance correlation for the CO_2 injection cycle.

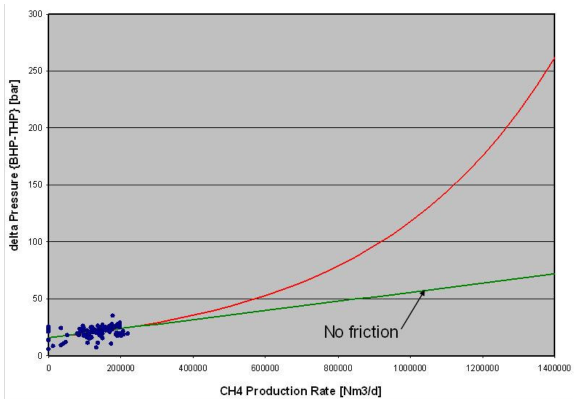

Figure 6: Well K12-B1 performance correlation for the test 2.

A cross check has been performed with the help of Schlumberger's Vertical Flow Performance prediction program VFPi™. The program predicts a similar pressure drop for the relevant operational constraints, which confirms the validity of the available CO_2 injection data. The relationship for gas production well K12-B1 (Figure 6) is more complex. The data are not very conclusive, even for the relatively low and narrow data range, which makes extrapolation towards larger production rates and higher bottom-hole pressures difficult. VFPi was also used to complement the THP conversion to "estimated" BHPs. In case of low or zero-rate conditions, an acceptable (workable) match could be achieved between estimated values and measured BHP. For the high rates and BHP conditions, acceptable matches could be generated for certain time intervals. The off periods could be matched with a different set of friction-related parameters. This observation suggests that operational parameters, such as tubing friction conditions, temperature or gas composition have changed drastically over several large time periods. Further research is needed to resolve these inconsistencies.

Reservoir Simulation Model

A reservoir simulation model[3] has been developed for the K12-B number three compartment to study the possible effects on Enhanced Gas Recovery (EGR) as a result of CO_2 injection. We were in the luxury position to have access the full operational data set of the K12-B reservoir, in particular the data related to wells K12-B1, B5 and B6. Only 27,742 grid cells of the specially built reservoir model, comprising 48 x 68 x 20 cells, were actively used. The employed grid cells cover an area of 43 by 46 metres. Care has been taken to model the sloping eastern fault to ensure an accurate Initial Gas in Place (IGIP) calculation. Part of this simulation model is depicted in Figure 7. A rectangular orthogonal grid system has been used to minimize numerical dispersion, reduce cross terms and minimise grid-orientation effects.

History Match

All available pressure data were used for the history match. The IGIP parameter (and its components, such as pore volume and gas saturation) is the most sensitive one to the overall pressure behaviour in the reservoir compared to parameters such as permeability and relative permeability data.

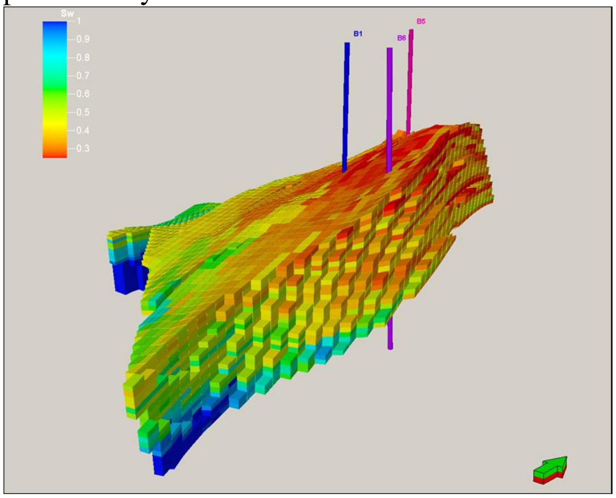

Figure 7: Reservoir simulation model.

An excellent match (Figure 8) was achieved for all three wells if the GIP was increased to 8.125 BCM for the overall pressure behaviour and adjustment to the skin factors for more local effects such as the amplitude between the static and flowing pressure. During the history matching exercise, a large number of smaller discrepancies were found in the reported production data. Such inaccuracies are, however, normal and the result of standard practice in the gas (and oil) production industry. In particular, back allocation of a total production plant gas production rates to the daily production rates of individual wells is difficult and the accuracy of these data often depends on parameters that are poorly constrained. Only the availability of a very detailed reservoir simulation model made it possible to combine "all" available data and solve their dependencies. For normal gas operations, the present data are sufficiently accurate. Further work and research is planned to find out whether consistency can be improved by making small changes to working practices.

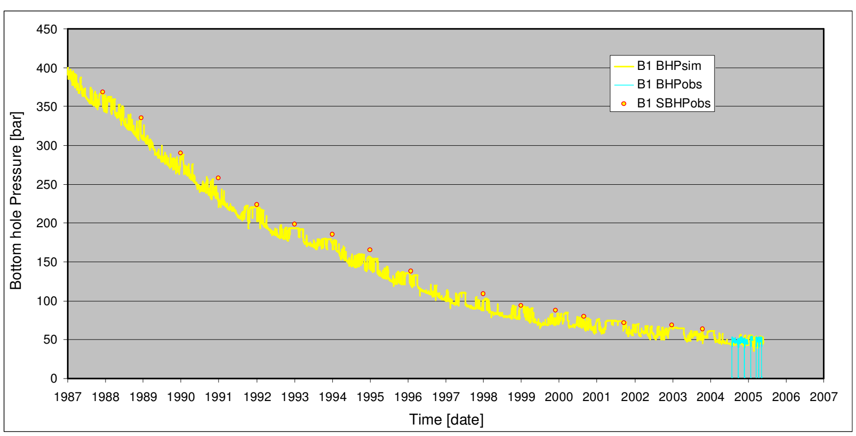

Figure 8: Pressure history match for well K12-B1

Test 2 simulation results

The results of the CO_2 injection test are shown in Figure 9. The plot on the left shows the measured and calculated results for well K12-B1. Over the full one-year test period, a good match can be observed, in particular in relation to the overall level of the pressures. The smaller differences in amplitude and shape between the pressures should be contributed to rate-allocation practice. The K12-B6 injection pressures show a much more consistent picture (Figure 9-R). All pressures are consistent, i.e. all pressures, such as the accurate down-hole measurements, BHPs estimated from THP pressures and simulated BHPs, show a clear relationship with the reported daily CO_2 injection rate. The only minor inconvenience is the inability of the simulator to calculate the correct BHP for the case that the well is shut in.

One of the main aims of the simulation was to evaluate the effect of CO_2 injection on operations. In Figure 9-L, we have plotted CO_2 production in well K12-B1 in combination with tracer observation data. The match of the breakthrough time was accurate almost to the day and this match was achieved without any modification to the model. Modifications to overall or local permeability showed insensitivity to timing and sensitivity to CO_2 production rate. A reduction in permeability by 100 doubled the CO_2 production rate.

Conclusions

The first year of CO_2 injection into a reservoir compartment that is still producing gas was successful and proceeded entirely according to plan and expectation. Test results could be evaluated and compared with a history-matched reservoir simulation model.

CO_2 breakthrough in well K12-B1 could be modelled accurately. The volumetric consequences of CO_2 breakthrough in K12-B1 were undetectable within the test period. Simulation results indicate that CO_2 increase in the gas-production well will be slow and gradual. At the end of 2005 there was no clear evidence of measurable improvement in the gas-production performance of the tested compartment. Continuing injection is needed to increase the EGR potential of CO_2 injection. Further study is needed and GPN has committed itself to continue the injection test in 2006.

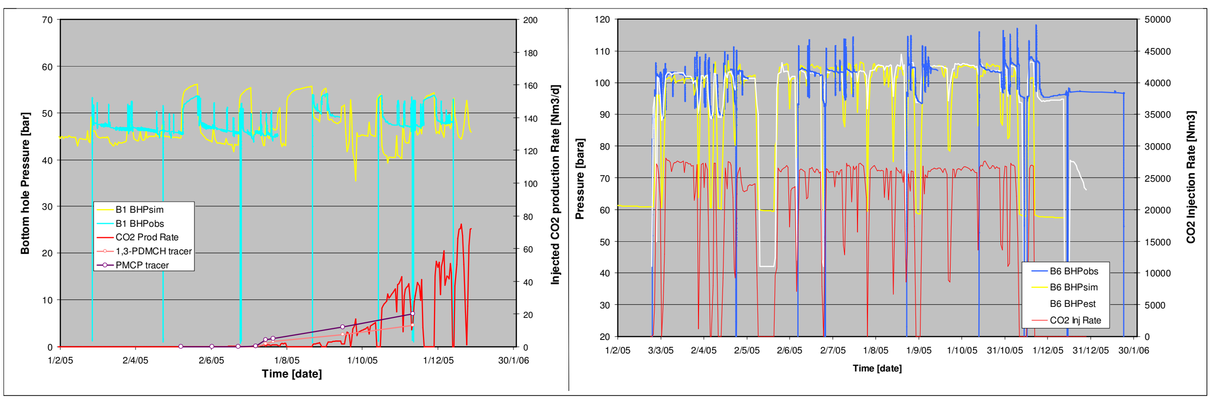

Figure 9: Test 2 performance plots for well K12-B1 (L) and K12-B6. Tracer data have been adjusted to enable plotting with the CO_2 production rate in well B1

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