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**CO₂ STORAGE AND TESTING ENHANCED GAS RECOVERY IN THE
K12-B RESERVOIR**

Main author

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ABSTRACT

As part of the Dutch Climate Policy on the implementation of the Kyoto protocol, the Dutch Minister of Economic Affairs introduced a new policy on 7 February 2002 to promote feasibility studies concerning CO₂ storage in the subsurface. TNO Built Environment and Geosciences - *National Geological Survey of the Netherlands* is currently investigating to what extent CO₂ sequestration in the deep subsurface could help reduce CO₂ emissions.

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 CO₂ emissions into the atmosphere.

The gas produced at one of GPN's platforms, the K12-B platform, contains a relatively high proportion of CO₂. This CO₂ 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 CO₂ back into the reservoir. Hence GPN's K12-B platform offered a good opportunity to test CO₂ injection at large depths. Deployment of a CO₂-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 CO₂. It covers the findings of the CO₂ 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 CO₂ injection. Further study is needed and GPN has committed itself to continue the injection test in 2006.

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1. INTRODUCTION

The Netherlands has very actively contributed to research into the possibility of subsurface CO₂ storage. In fact, the first Greenhouse Gas Mitigation conference was held in Amsterdam, in 1992^[1]. In the 14 years since then, the Dutch have been looking for a suitable field-scale test site in the Netherlands. In the meantime, storage plans and objectives were modified and the project suffered greatly from financial constraints. However, the key question remained: “can underground storage of CO₂ be achieved, and can CO₂ that has been stored underground be recovered and re-used”.

GPN's Offshore Re-injection of CO₂ (ORC) project is partly funded by a CRUST subsidy. The ORC project aims at investigating the feasibility of CO₂ injection and storage in depleted natural gas fields with the objective to develop a permanent CO₂ 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 three phases:

Phase 1: A feasibility study: a desk-top study to investigate the feasibility of underground CO₂ injection into the K12-B reservoir by making optimum use of existing installations, equipment and techniques;

Phase 2: A demonstration phase: actual offshore underground CO₂ re-injection at a small-scale operational test facility. During this implementation test, about 30,000 Nm³ CO₂ will be re-injected per day, this equals about 20,000 tonnes per year.

Phase 3: The full-scale phase: scale-up to a full-scale CO₂ injection unit including the investigation of possibilities for future re-use of the injected CO₂. Eventually, about 20,000 to 30,000 Nm³ CO₂ will be injected per hour, this equals about 310,000 – 475,000 tonnes per year.

Phase 2 of the ORC project is currently in progress. TNO Built Environment and Geosciences - *National Geological Survey* was requested to assist GPN during this phase. Phase 2 consists of two tests at different locations in the K12-B reservoir:

- Test 1: CO₂ injection into a single-well (K12-B8), depleted reservoir compartment.
- Test 2: CO₂ injection into a nearly depleted reservoir compartment with two gas-production wells (K12-B1 and K12-B5) and one CO₂-injection well (K12-B6).

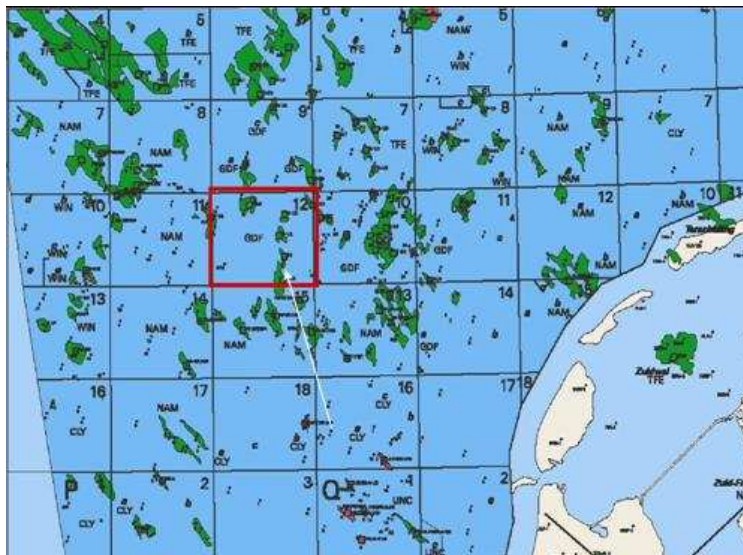


Figure 1: Field location map

2. 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^[2]. By that time the reservoir is expected to be fully depleted.

3. CO₂ RE-INJECTION

The gas produced at the K12-B platform has a relatively high CO₂ content (13%). This CO₂ is separated from the produced natural gas. It used to be vented into the atmosphere, but is now re-injected. The CO₂ 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 CO₂ 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 were to test the injection facility, to prove that injection is feasible and safe and to examine the CO₂ phase behaviour and the response of the reservoir.

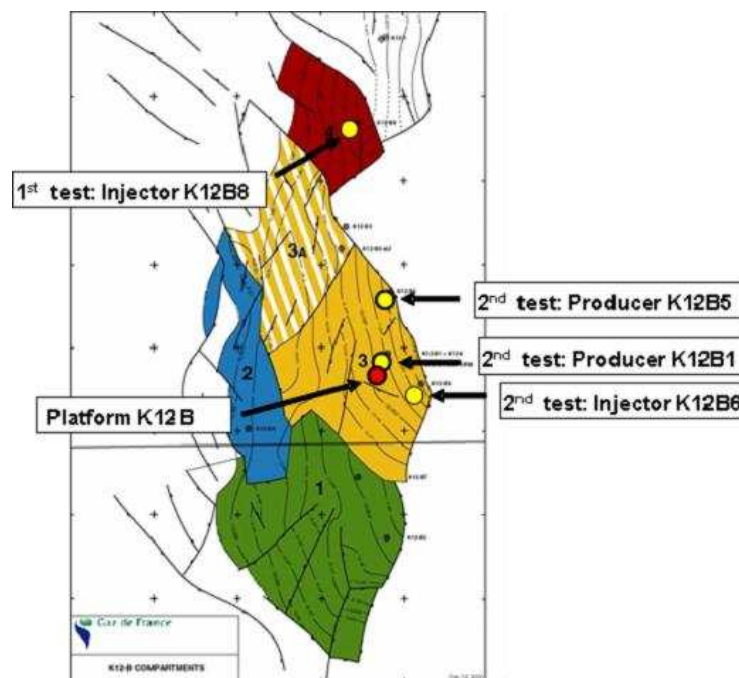


Figure 2: Schematic layout of the test locations.

The results of test 1 were used to optimise the measurement programme of test 2, which started in February 2005. The objectives of test 2 are to examine the reservoir response in an area that is

currently under production, to assess the potential for enhanced gas recovery and to examine the degree of corrosion along the tubing of the CO₂ injection well. The first results of test 2 became available late 2005.

4. 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 CO₂. 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.

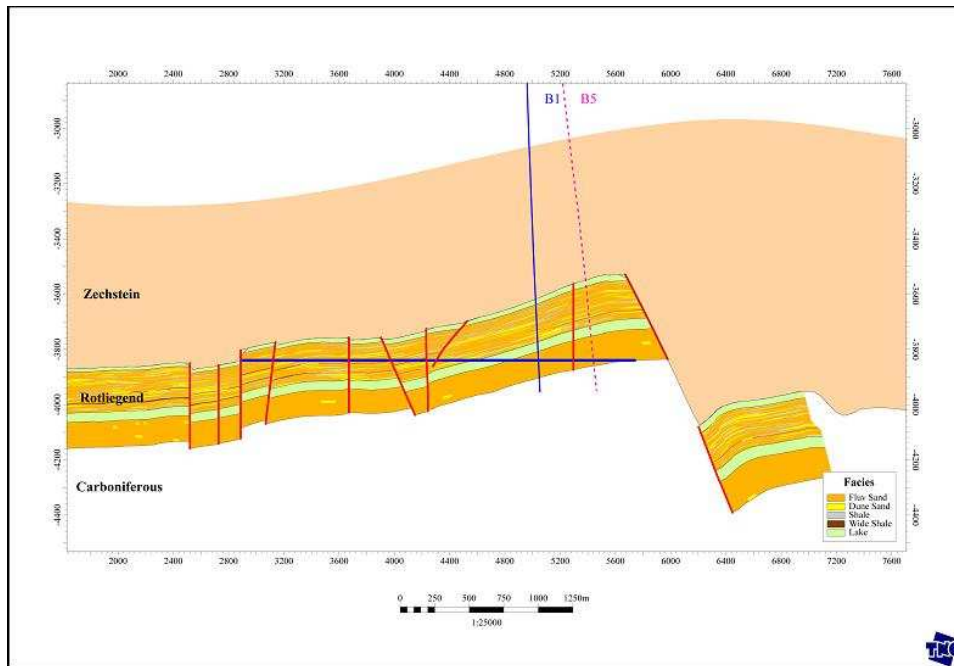


Figure 3: Cross-section of the geological model

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 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.

5. Test results

GPN's project phase 2 involves a small-scale operational implementation test (Test 1). This test phase was set up in such a way that CO₂ well-bore behaviour could be studied and the CO₂ injectivity of the K12-B gas field could also be tested.

5.1 Test 1

On the 6th of May 2004, CO₂ injection started in well K12-B8 into the number 4 compartment. The injection history of test 1 was relatively stable over the period May until December 2004. The average injection rate was 2350 kg per hour. This corresponds to an average injection rate of 29,200 Nm³ per day. Cumulative injection was 9,000 tonnes CO₂. The reported values include traces of methane.

In the period May – December 2005 the bottom-hole pressure was continuously monitored with the aid of down-hole memory gauges. The gauges were installed at a depth of 3657 metres TVD, which is 12 metres above the top of the reservoir. The average down-hole duration of the gauges was three weeks. A total of ten gauge cycles covered the monitoring period.

Over the entire period of CO₂ injection, the bottom-hole pressure increased by nine bars. This is in line with the prediction of the reservoir simulation. The simulated prediction shows an excellent fit with the measured pressure data. It is concluded that the injectivity of the well falls within the expected range. The difference between the down-hole injection pressure and the reservoir pressure is in the order of 1.3 bars at an injection rate of nearly 30,000 Nm³ per day. This injectivity is very good, given the low average permeability of the reservoir rock.

5.2 Test 2

In January 2005, CO₂ 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 Nm³/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 CO₂ 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 CO₂ injection pressures.

On 1 March 2005, two tracers, of 1 kg each, were injected into well K12-B6 during regular CO₂ injection. A tracer substance was needed to enable monitoring of any breakthrough of injected CO₂ into one of the two methane production wells.

During the 2005 injection period (25 February - 28 December) the injection facility operated as planned. On average, some 26,000 Nm³/d of CO₂ was injected during the entire 2005 test period. During the injection programme, several parameters were measured to monitor the reservoir response:

- The daily gas injection and production rates;
- The pressures and temperatures at various locations such as:

- In the compressor;
- At the well head;
- At reservoir depth;
- The composition of the injected gas;
- The presence of tracer elements in the produced gas.

In addition, for each of the three wells, data of daily methane production rates and well-head pressures are available for the entire production periods. 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.

5.2.1 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). CO₂ injection in well K12-B6 (Figure 4), 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.

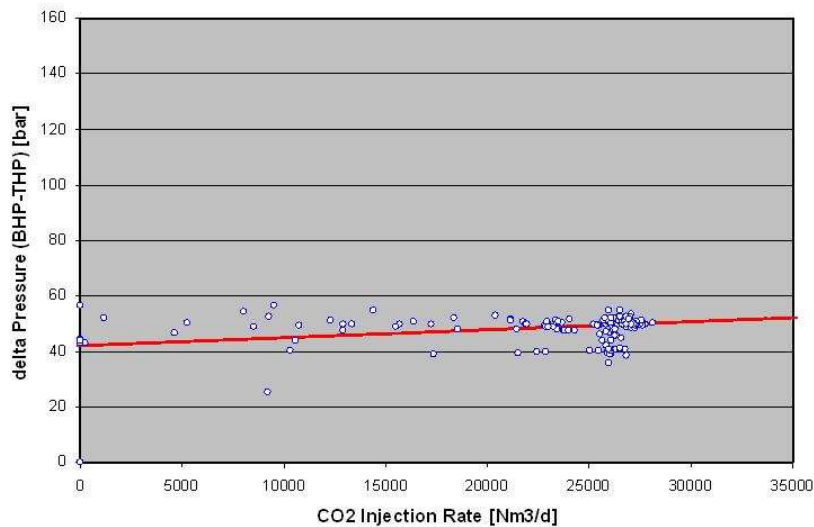


Figure 4: Well K12-B6 performance correlation for the CO₂ injection cycle.

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 CO₂ injection data. The relationship for gas production well K12-B1 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.

5.2.2. Reservoir Simulation Model

A reservoir simulation model has been developed for the K12-B number three compartment to study the possible effects on Enhanced Gas Recovery (EGR) as a result of CO₂ 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 5. A rectangular orthogonal grid system has been used to minimize numerical dispersion, reduce cross terms and minimise grid-orientation effects.

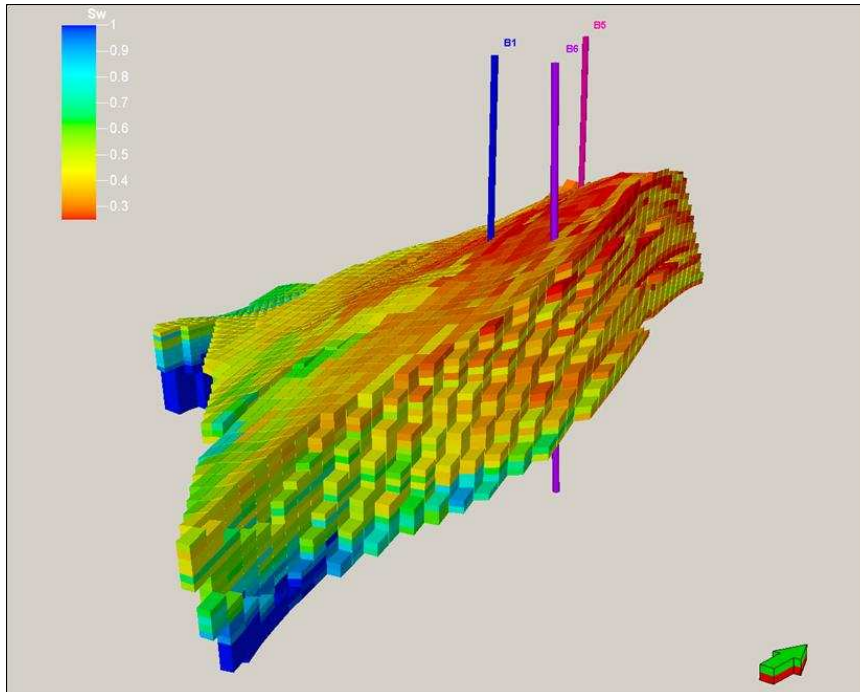


Figure 5: Reservoir simulation model.

The reservoir simulation model^[3] was initialised with a Gas Water Contact (GWC) at 3840.5 mSS with an initial pressure at this level of 401 bars. The resulting IGIP was nearly 7 BCM which corresponds to GPN material balance calculations^[4]. We already knew from gas-production data that this figure was conservative. The well response in compartment 3 must be the result of an IGIP of nearly 8.125 BCM. This may be due to gas migration from other compartments, or for some other unknown reason.

5.2.3. 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. An excellent match (Figure 6) 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.

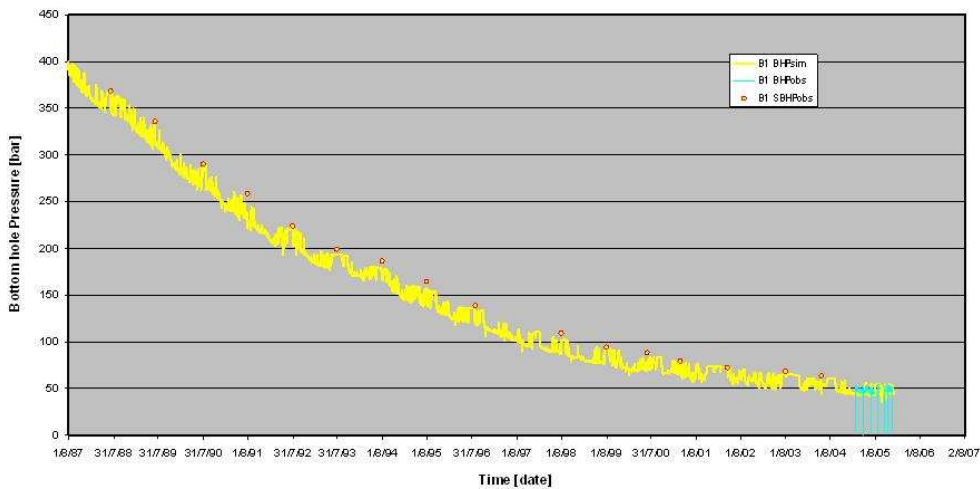


Figure 6: Pressure history match for well K12-B1

5.2.4. Test 2 simulation results

The results of the CO₂ injection test are shown in Figure 7. 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 7-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 CO₂ 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 CO₂ injection on operations. In Figure 7-L, we have plotted CO₂ 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 CO₂ production rate. A reduction in permeability by 100 doubled the CO₂ production rate.

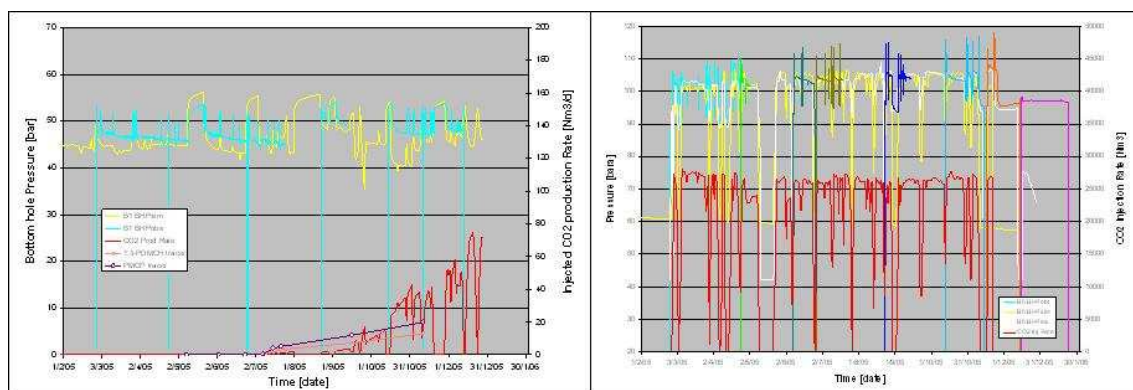


Figure 7: Test 2 performance plots for well K12-B1 (L) and K12-B6. Tracer data have been adjusted to enable plotting with the CO₂ production rate in well B1

6. CONCLUSIONS

Test 2: the first year of CO₂ 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.

CO₂ breakthrough in well K12-B1 could be modelled accurately. The volumetric consequences of CO₂ breakthrough in K12-B1 were undetectable within the test period. Simulation results indicate that CO₂ 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 CO₂ injection. Further study is needed and GPN has committed itself to continue the injection test in 2006.

8. ACKNOWLEDGMENTS

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