DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2003/46

Simulation of CO_2 storage in the Havnsø aquifer

A GESTCO contribution

Niels Bech and Michael Larsen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

GEUS

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2003/46

Simulation of CO_2 storage in the Havnsø aquifer

A GESTCO contribution

Niels Bech and Michael Larsen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

GEUS

Abstract

The objective of this work is to evaluate the potential for CO_2 storage in a geological structure situated near to Havnsø in the western Sealand. The present report describes the preliminary calculations performed by the use of the reservoir simulation programme ECLIPSE 100 in order to obtain an initial, rough estimate of the storage capacity. The storage capacity is estimated to amount to 846 million tons of CO_2. This is 141 times the total annual emission of CO_2 from Asnæs Værket and the Statoil refinery of 6 million tons (average emissions 1994 –1999). The simulation model demonstrates that the annual emission of 6 million tons of CO_2 corresponding to 200 kg/sec can be injected into the reservoir through a horizontal well 8 km long and completed over a length of 500 m if the maximum injection pressure is permitted to reach 233 bar or 1.55 times the hydrostatic head.

Introduction

The study of the Havnsø structure is a contribution to GESTCO, an EU funded project examining the viability of wide-scale application of geological CO_2 storage in Europe. The principal objective of the GESTCO project is to make a major contribution to reducing the European emissions of CO_2 to the atmosphere. The project will aim at determining the potential for geological storage of CO_2 in Europe through mapping of subsurface reservoirs and detailed studies of selected case studies from different regions (Christensen 2000).

Based on experience from storage of natural gas and from the CO_2 storage taking place at the Sleipner Field the most promising option for underground CO_2 disposal are in deep saline aquifers. Located at a depth of more than approximately 900 m the injection of CO_2 in saline aquifers will take place at supercritical conditions resulting in the evolution of a two-phase CO_2/water mixture with some of the CO_2 dissolving in the water and some reacting with the reservoir rock.

The reservoir unit of the Havnsø structure consists of sandstones of the Upper Triassic – Lower Jurassic Gassum Formation located at a depth of approximately 1500 m. The Havnsø structure is particularly attractive because it is situated very close to one of the main Danish CO_2 point sources, the Asnæs power plant and nearby refinery at Kalundborg, with a total emission of approximately $6x10^6$ tons of CO_2 per year (1994–1999).

The present study describes some preliminary calculations performed in order to obtain an initial estimate of the storage capacity of the Havnsø structure. Dissolution of CO_2 in the water and possible reactions between CO_2 and the reservoir rock have been neglected. All simulations have been carried out by use of the simulation programme ECLIPSE 100 (Schlumberger GeoQuest 2000).

Havnsø Structure

The Havnsø structure is a 4-way domal closure covering an area of approximately 166 km^2 with top reservoir situated 1500 m below sea level (Larsen et al. 2002) (Figs. 1 and 2). The structure is unfaulted and governed by salt movements in the underlying Zechstein Group. The main reservoir consists of siliciclastic sandstones of the Upper Triassic – Lower Jurassic Gassum Formation with an anticipated net-sand thickness of approximately 100 m. The sandstones are laterally extensive and have been followed throughout the Danish Basin although the net sand thickness decreases towards the northwest. The reservoir is sealed by a several hundred metres thick succession of marine mudstones of the Fjerritslev Formation.

The Gassum Formation is well-known as an excellent reservoir. Southeast of Havnsø the Gassum Formation forms the main reservoir in the natural gas storage facility at Stenlille. Injection/production wells drilled at the Stenlille natural gas storage facility and old exploration wells drilled at structures in Sealand and Jutland provide access to reservoir parameters which are used for evaluation of the CO_2 storage potential in the yet undrilled Havnsø structure .

Havnsø Simulation Model

Grid and Reservoir Parameters. A coarse 12x12 areal grid with grid cell side lengths of 2.2 and 4.4 km is superimposed the top structure map as shown in Fig. 1. Vertically the reservoir is divided into 15 layers the total number of grid cells thus beeing 12x12x15 = 2160. The thickness, porosity, permeability and net-to-gros ratio of each layer are summarized in Table 1. The pore volume compressibility is 6.96×10^{-5} 1/bar at a pressure of 158.6 bar. The reservoir parameters and the division into 15 layers are based on well information and sedimentological models for the reservoir formation.

External Boundary Conditions. Laterally, i.e. in the x^-, x^+, y^- and y^+ directions, each reservoir layer is connected to an infinite acting analytical Carter-Tacey aquifer (Schlumberger GeoQuest 2000). The pressure of the analytical aquifers is set equal to the initial reservoir pressure (150 bar). In the vertical directions (z^- and z^+) the reservoir boundaries are assumed closed.

Saturation Functions. The applied gas/water relative permeabilities represent a natural gas/water system (Fig. 3). The applicability to the present CO_2/water system is open to question. CO_2 is quite different from natural gas at 150 bar and 50 ^oC as exemplified by the densities and viscosities: ρ_{CO2} = 629 kg/m^3, ρ_{CH4} = 100 kg/m^3, μ_{CO2} = 0.0681 cp and μ_{CH4} = 0.0162 cp.

The CO2/water capillary pressure is put equal to zero. This is probably a reasonable assumption, particularly in sandstone. Nevertheless, capillary effects may be important for the way in which the injected CO_2 is distributed in the reservoir even in this case.

PVT Data. The CO_2 formation volume factor and viscosity used for these preliminary calculations are the same used for the Roar calculations (Bech and Frykman 2002), Fig. 4. They are evaluated at the Roar reservoir temperature of 72 ^oC by PVTsim (Calsep 2001). In subsequent calculation they should be replaced by a CO_2 PVT data set corresponding to the temperature in the Havnsø aquifer which is 50 ^oC.
The water data used are:

- Reference pressure, p_{ref} : 155.1 bar
- Formation volume factor at p_{ref} : 1.0072
- Compressibility : 3.55×10^{-5} 1/bar
- Viscosity at p_{ref} : 0.775 cp
- Viscosibility : 6.38×10^{-5} 1/bar

The formation value factor is defined as $B = \frac{\rho_{sc}}{\rho}$, where ρ_{sc} and ρ are the densities at standard conditions and reservoir conditions, respectively.

The viscosibility is defined as $\frac{1}{\mu}\frac{\partial \mu}{\partial p}$, where μ is the viscosity.

Initial Conditions. It is assumed that the initial pressure in the reservoir is 150 bar at a depth of 1500 m. This corresponds to the hydrostatic head.

CO_2 Injection

Injection Rate. The total annual emission of six million tons of CO_2 from the power plant and the refinery corresponds roughly to 200 kg/sec. The density of CO_2 at standard conditions is 1.87 kg/m^3 so the volume injection rate to input to the simulator is 9.23×10^6 sm^3/day.

Injection Pressure. The permissible injection pressure is a key parameter. The injection rate is directly proportional to the injection pressure. Based on an extensive set of well leak off pressure and pressures measured in wellbores (RFT data) Obdam and Van der Meer (2002) suggests that: "The maximum injection pressure is 1.35 times hydrostatic pressure for a depth down to 1000 m; this factor is enlarged to 2.4 for depths ranging from 1000 down to 5000 m". They note hat this formula is in reasonable agreement with the rule the French are using which is: 1.3 to 1.5 times the hydrostatic pressure for depths from 300 down to 1200 m. In the present case the top point of the reservoir is situated approximately 1500 m below the surface. The resulting maximum injection pressure is therefore initially set to 225 bar corresponding to 1.5 times the hydrostatic pressure.

Injection Location. Layer no. 15 representing the bottom layer in the reservoir model, is by far the thickest and most permeable layer. It was therefore decided to simulate the injection of CO_2 in that layer. Moreover, to make sure that the injection location is inside the structural closure and well away from spill points the injection well was perforated in cell (5,

5, 15). (Cell (1, 1, 1) is in the south west corner of the grid, Fig. 1). The injection location is situated approximately eight km from the emission sources (Fig. 2).

Completion Length. Given the injection rate and the maximum injection pressure the length of the well completion (and a possible skin) is the only free parameter left. It follows from the results presented below that the conditions imposed can be satisfied with a horizontal well with a completion lengths in the order of 500 – 800 m.

Results and Discussion

The simulation was run for a period of 30 years and shows that the target injection rate of 200 kg/sec can be optained for 30 years with a completion length of 500 m except for the first 1.5 years where the injection rate drops to around 175 kg/sec. The reason for the lower initial injectivity is that the compressibility of the water is much smaller than that of CO_2. After the formation of a CO_2 bubble in the reservoir the injectivity increases due to the enhanced system compressibility. From the PVT data (Fig. 4) the CO_2 compressibility can be calculated from the equation

$$C_{CO_2} = -\frac{1}{B_{CO_2}} \frac{dB_{CO_2}}{dp}$$

The value at 150 bar is C_{CO2} = 7.19x10^{-3} 1/bar as opposed to C_w = 3.55x10^{-5} 1/bar for water.

It was found that if a maximum injection pressure of 233 bar is permitted then this initial reduction in the injection rate will not occur. The 233 bar is 1.55 times the hydrostatic head of 150 bar and this value appears not in any way to violate the rule cited above. Alternatively the initial drop in the injection rate can be removed by increasing the completion length to 800 m.

The distribution of the CO_2 in the reservoir unit after 30 years of injection is illustrated in Figs. 5 – 6. Fig. 5 shows the lateral distribution in layers no. 15, 14, 12 and 9. The CO_2 which is injected in cell (5, 5, 15) spreads out in layer 15 and rises into the layers above due to gravity until it reaches layer 8 which forms a barrier to vertical flow, conf. Table 1. In other words, the uppermost eight layers which correspond to about one third of the formation height and 23% of the pore volume are not available for CO_2 storage in the simulated injection case. In order to remedy this situation the injection well must be completed in at least one of the layers above layer 8.

Fig. 6 shows the distribution of CO_2 in yz-plane no. 5. It is seen here that some of the CO_2 is expelled beyond the spill point. The saturation outside the closure is small, however, and below the specified critical gas saturation of 0.12 (conf. Fig. 3). In order to avoid leakage beyond the structural closure, however, it is suggested to place the the completion closer to the centre of the dome structure.

Following the injection period of 30 years the CO_2 will continue to migrate in the reservoir unit due to gravity forces. In Fig. 7 the distribution of CO_2 after 5000 years is shown. As might be expected most of the injected CO_2 rises towards the top of the reservoir compartment sealed by layer 8 to form a gas cap, although a small portion is left behind corresponding to the irreducible CO_2 saturation of 0.12. The CO_2 saturation in the gas cap is 0.9 corresponding to the irreducible water saturation of 0.1, conf. Fig. 3.

The total amount of CO_2 injected during the 30 years is 189×10^9 kg or 189 million tons. The estimated storage capacity is however much larger. We have

$$SC = PV(1 - S_{wir}) f_{se} \rho_{CO_2}$$

where

SC Storage capacity (kg)
PV Pore volume (m^3)
S_{wir} Irreducible water saturation (-)
f_{se} Sweep efficiency (-)
ρ Density (kg/m^3)

The pore volume inside the closure is estimated to $PV = 3.7 \times 10^9$ m^3. The irreducible water saturation is $S_{wir} = 0.1$ and the average CO_2 density at reservoir conditions is $\rho_{CO2} = 635$ kg/m^3. The sweep efficiency is put equal to 0.4 a value which is based on results from natural gas storage facilities in Europe. The resulting storage capacity is 846×10^9 kg or 846 million tons of CO_2. In other words, the 189 million tons injected after 30 years amounts to about 22% of the storage capacity.

The results from the simulation model are only preliminary and are subject to a number of limitations:

- Interactions between CO_2 and the formation water is not modelled (Solubility of CO_2 in water, diffusion of CO_2 in the aqueous phase, hydrodynamic instability between water and the CO_2 phase (fingering).
- It is assumed that no reaction of CO_2 with formation rock takes place during the injection period.
- The simulation grid is not detailed enough.
- Uncertainties in the specified input data (Geology, permeability map, relative permeability end points, capillary effects, PVT data, maximum injection pressure).

The solubility of CO_2 in water can be taken into account by using the more advanced simulation programme ECLIPSE 300. But apparently it is not possible to describe CO_2-in-water diffusion with ECLIPSE. The viscosity of the CO_2 is an order of magnitude smaller than that of water. This means that the injection is subject to a very unfavourable mobility ratio and hydrodynamic instabilities, so-called fingering, may be expected. However, considerations in Pruess et al. (2001) suggest that fingering arising from hydrodynamic instabilities will not be a significant issue for field-scale problems.

The reactions between CO_2 and the rock matrix will depend on the lithology of the reservoir formation. The Gassum Formation consists of quartzitic sandstones with carbonate and silica cement and only minor solution is likely to take place. Future studies however should address the problmes related to solution and fines migration.

The calculations were made on a preliminary and very coarse simulation grid. It is important that this is considerably refined in particular in the neighbourhood of spill points. The detailled simulation model will be part of a future research project, CO_2Store, which will be initiated in 2003.

All information concerning geologi including porosity and permeability used in the present study comes from wells drilled through the reservoir at other localities the top structure depth map beeing the only exception. The same is the case with the specified gas relative permeability relationship which is valid for natural gas but not necessarily for CO_2. This holds in particular for the critical and residual saturations. Also capillary effects may be important for the way in which the injected CO_2 is distributed in the reservoir. The capillary pressure has been put equal to zero in the present calculations.

It was mentioned previously that the CO_2 PVT data applied was evaluated at a temperature of 72 ^oC and not 50 ^oC which is the temperature in the Havnsø aquifer. This of course should be corrected. Also the correct composition of the CO_2 gas injected should be taken into account. The CO_2 data applied so far are valid only for pure CO_2.

Summary and Conclusions

The simulation study has demonstrated that the annual amount of 6 million tons of CO_2 corresponding to 200 kg/sec can be injected into the reservoir through a horizontal well 8 km long and completed over a length of 500 m if the maximum injection pressure is permitted to reach 233 bar or 1.55 times the hydrostatic head. The following is recommended:

- The completed interval should be moved closer to the centre of the dome structure in order to reduce the risk of leakage below spill point.
- The well should be drilled into and completed in the upper part of the closure as well in order to make this volume accessible to storage.
- The solubility of CO_2 in water should be taken into account.
- The simulation grid should be refined, especially in the neighbourhood of spill points.
- The geological model should be improved.
- The gas relative permeability data should be improved.
- The importance of capillary effects should be quantified.

Based on the assumption that the sweep efficiency is 0.4 the CO_2 storage capacity of the Havnsø aquifer can be estimated to be approximately 846 million tons of CO_2. This is 141 times the annual emission of CO_2 in the Kalundborg area.

References

Bech, N. & Frykman P. 2002: Storage of CO_2 in Depleted Hydrocarbon Reservoirs in Low-Permeability Chalk, Sixth International Conference on Greenhouse Gas Control Technologies, GHGT-6, Kyoto, October 1-4, 6 p.

Calsep A/S 2001: PVTsim 11

Christensen, N.P. 2000: The GESTCO Project: Assessing European potential for geological storage of CO_2 from fossil fuel combustion. In Williams, D., Duric, B., McMullan, P., Paulson, C. & Smith, A. (Eds) Proceedings of the Fifth International Conference on Greenhouse Control Technologies (GHGT-5). CSIRO, Australia. 261–265.

Larsen, M., Christensen, N.P.C. & Bidstrup, T. 2002: Saline Aquifer Storage of CO_2 from Major Point Sources – A Danish Case Study, Sixth International Conference on Greenhouse Gas Control Technologies, GHGT-6, Kyoto, October 1-4, 6 p.

Obdam, A & van der Meer, L. 2002: GESTCO Simulation cases of CO_2 sequestration, TNO, May

Pruess, K.P. et al. 2001: Numerical Modeling of Aquifer Disposal of CO_2, SPE/EPA/DOE Exploration and Production Environmental Conference, San Antonio, TX, 26-28 February, 16 p.

Schlumberger GeoQuest 2000: Eclipse Reservoir Simulators 2000A.

List of Tables

List of Figures

Layer no.	Height (m)	Poprosity (-)	Perm. h (mD)	Perm. v (mD)	Net-to-gross (-)
1	6.5	0.234	200	20	0.88
2	5.3	0.189	30	0	0.3
3	7.2	0.234	200	20	0.92
4	0.2	0.25	500	50	0.97
5	4.1	0.25	200	20	0.97
6	0.1	0.25	350	35	0.97
7	5.1	0.235	150	15	0.721
8	6.8	0.193	200	0	0.22
9	15.6	0.261	200	20	0.97
10	0.1	0.261	500	50	0.97
11	0.8	0.261	100	10	0.97
12	9.6	0.261	350	35	0.97
13	0.1	0.261	500	50	0.97
14	16.6	0.209	200	1	0.59
15	36.6	0.26	1300	130	0.98

Tabel 1. Reservoir parameters for the Gassum Formation forming the reservoir unit in the Havnsø structure. The parameters are based on information from the Stenlille natural gas storage.

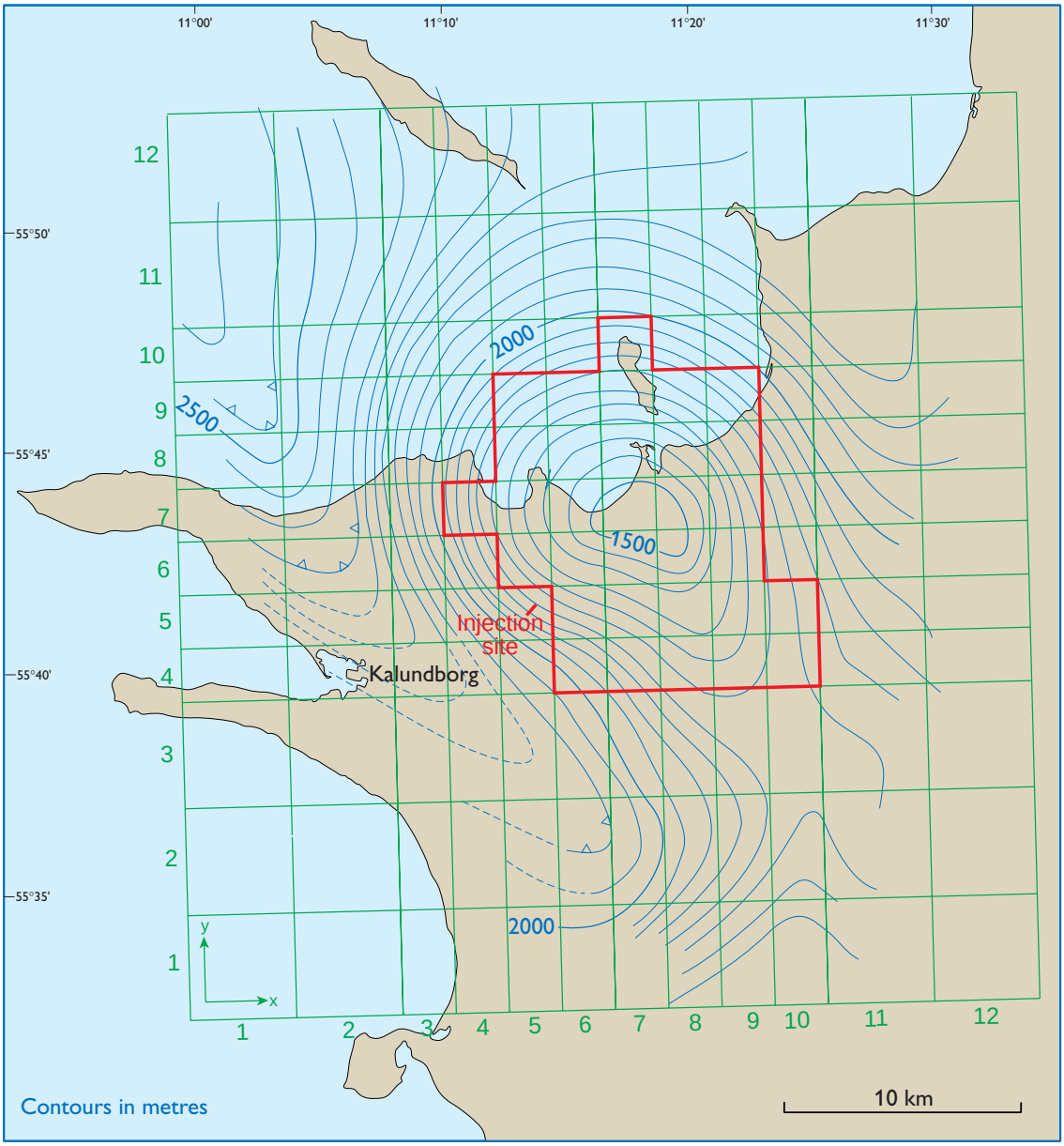

Fig. 1. Havnsø structure– Top structure map and difference grid

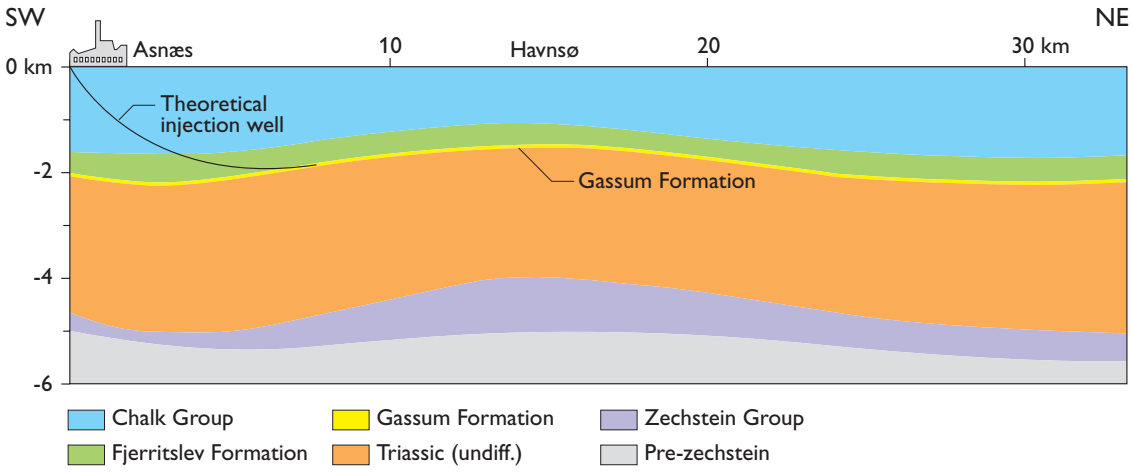

Fig. 2. Geological cross-section of the Havnsø structure. Note the theoretical injection well drilled from the industrial site into the flank of the structure.

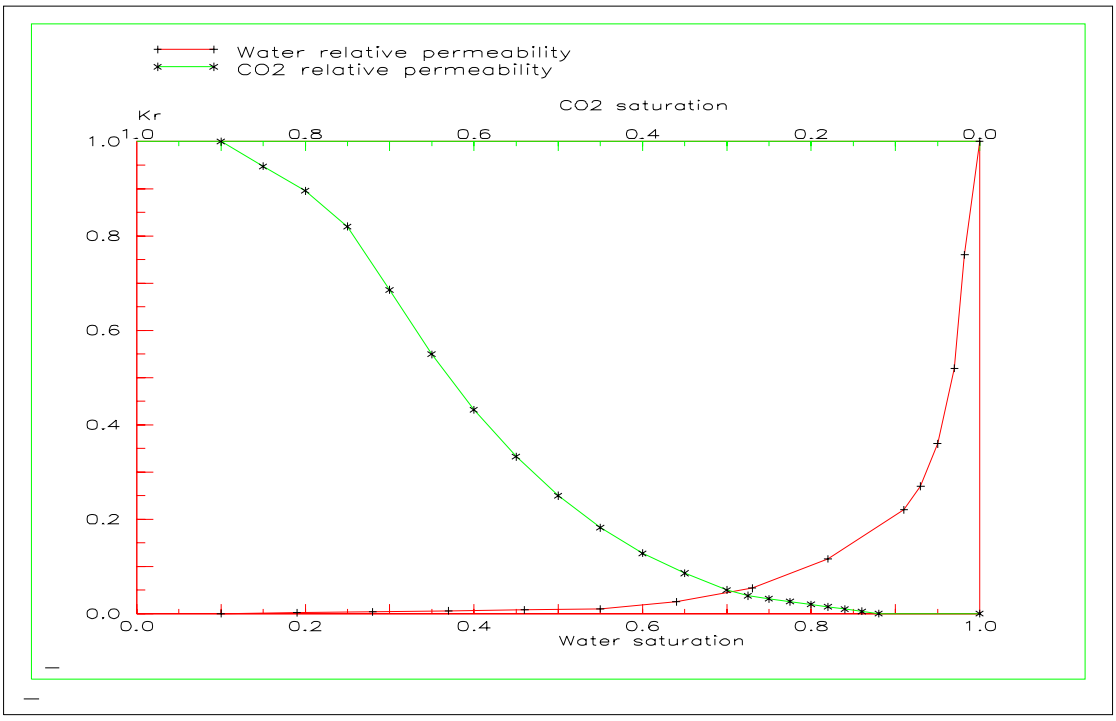

Fig. 3. Water and CO_2 relative permeabilities as function of water and CO_2 saturations. Note that the irreducible water saturation is equal to 0.1.

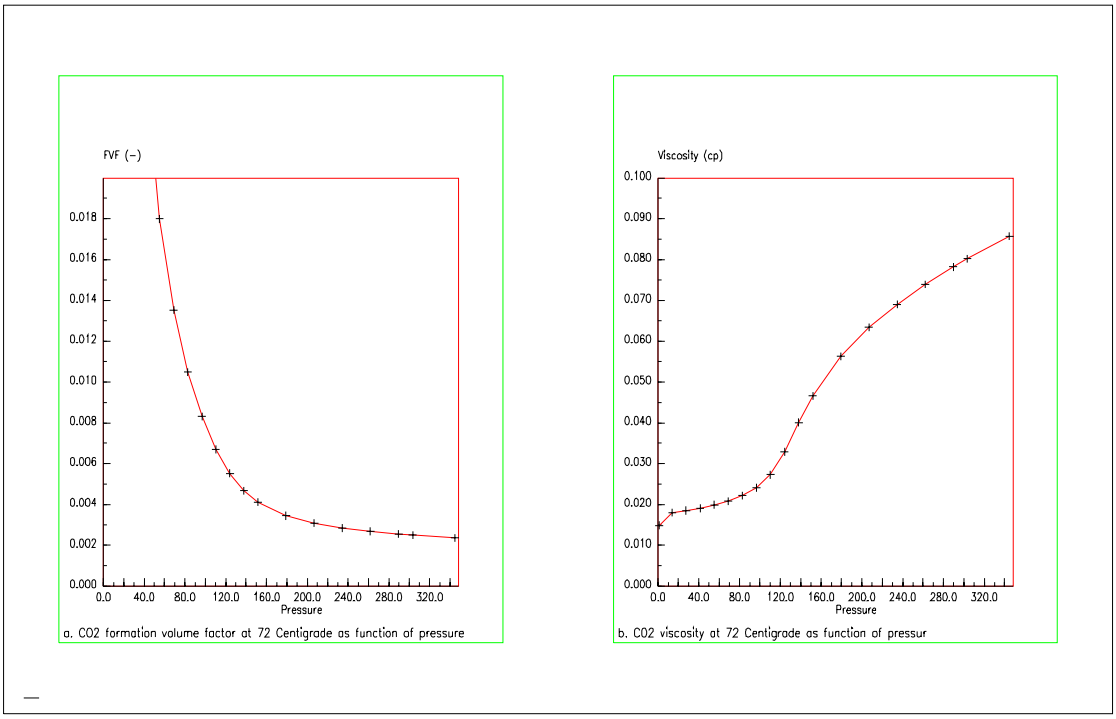

Fig. 4. CO_2 formation volume factor and viscosity as function of pressure evaluated by PVTsim (Calsep 2000) at 72 ^{o}C.

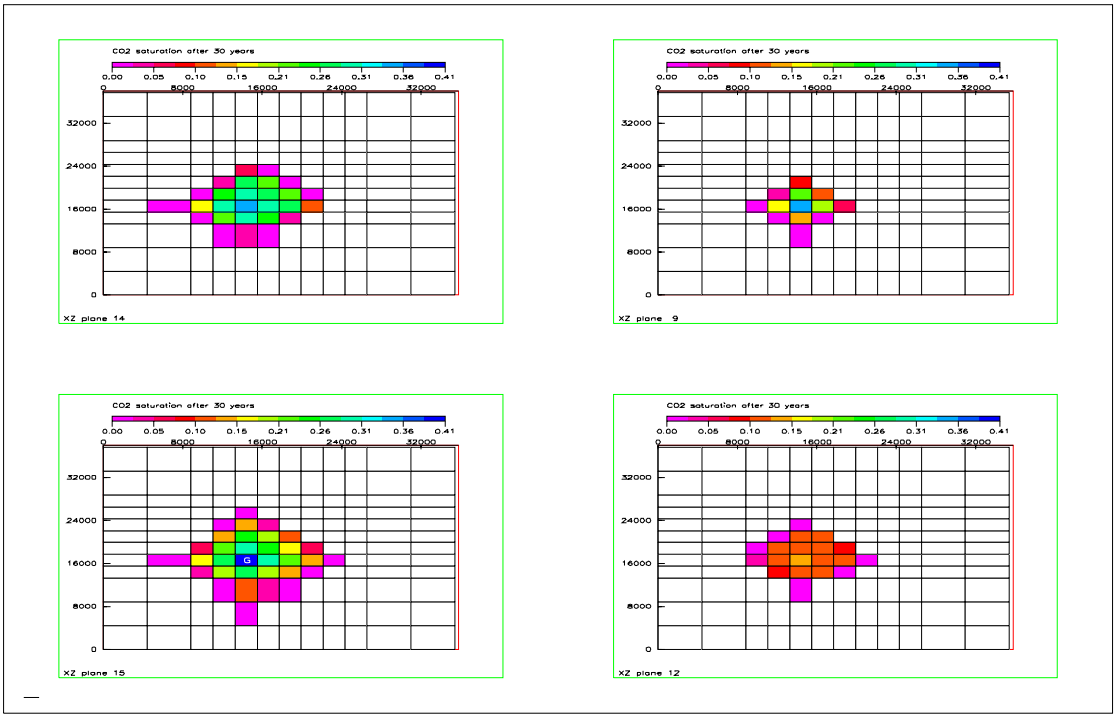

Fig. 5. Lateral distribution of CO_2 in the reservoir simulation model of the Havnsø structure after 30 years of injection – xy-planes 15, 14, 12 and 9. The injection rate was 6 million tons of CO_2 per year.

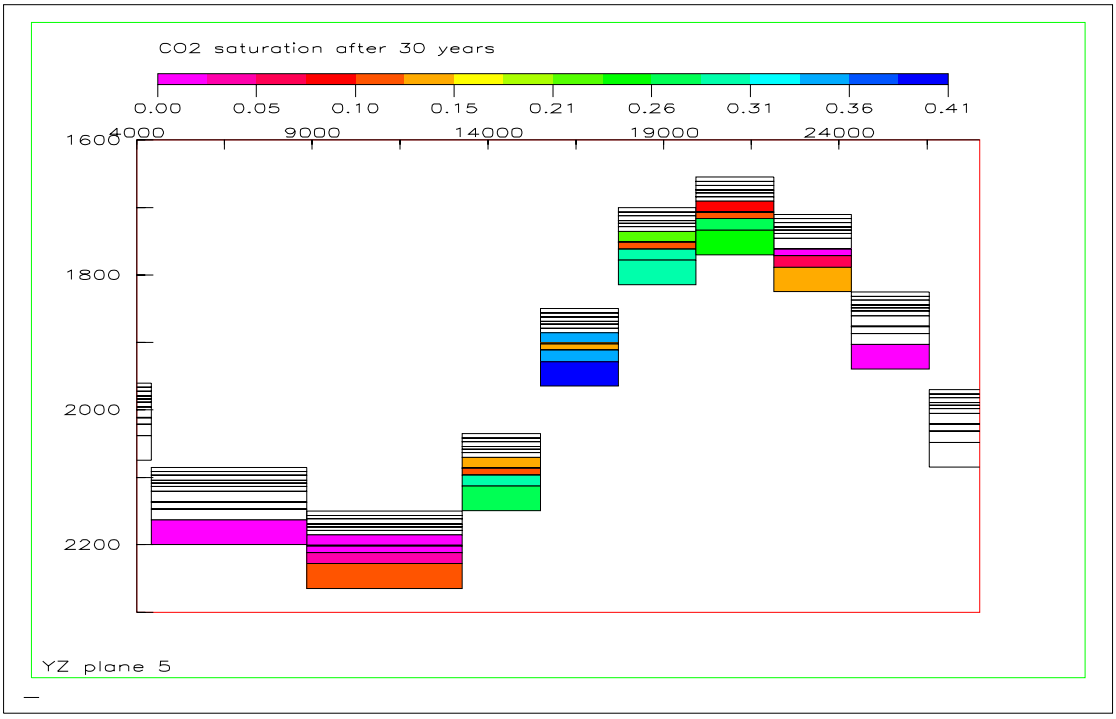

Fig. 6. Vertical distribution of CO_2 in the reservoir simulation model of the Havnsø structure after 30 years of injection – yz-plane 5. The injection rate was 6 million tons of CO_2 per year.

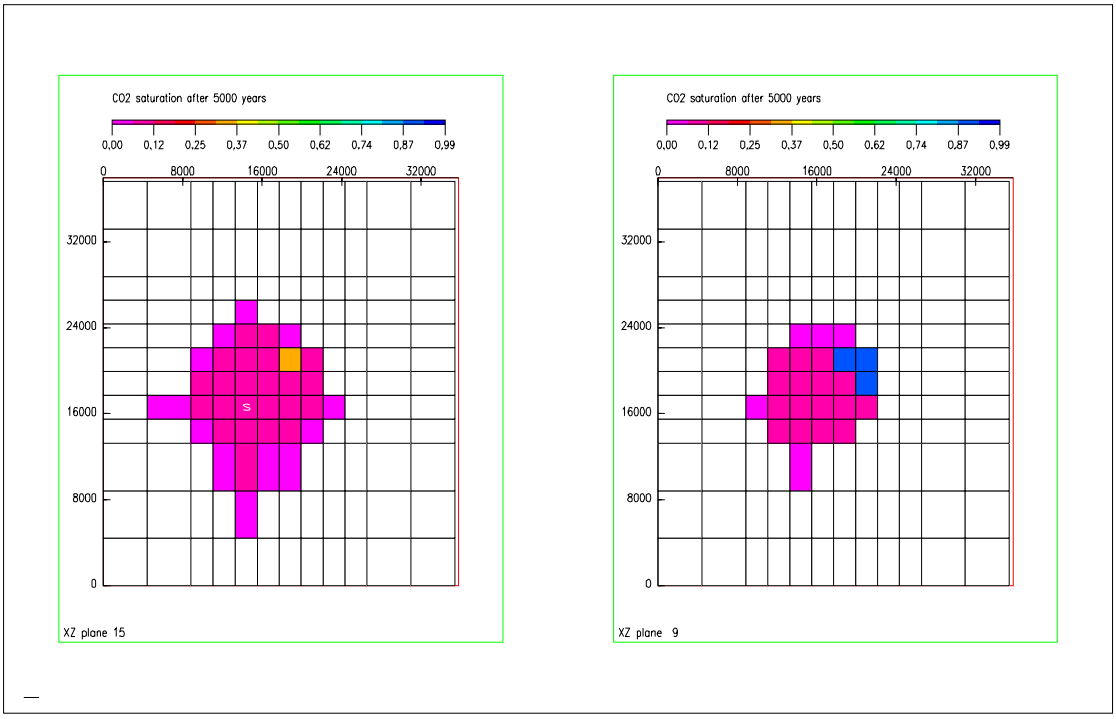

Fig. 7. Lateral distribution of CO_2 in the reservoir simulation model of the Havnsø structure after 5000 years of injection – xy-planes 15 and 9. The injection rate was 6 million tons of CO_2 per year.

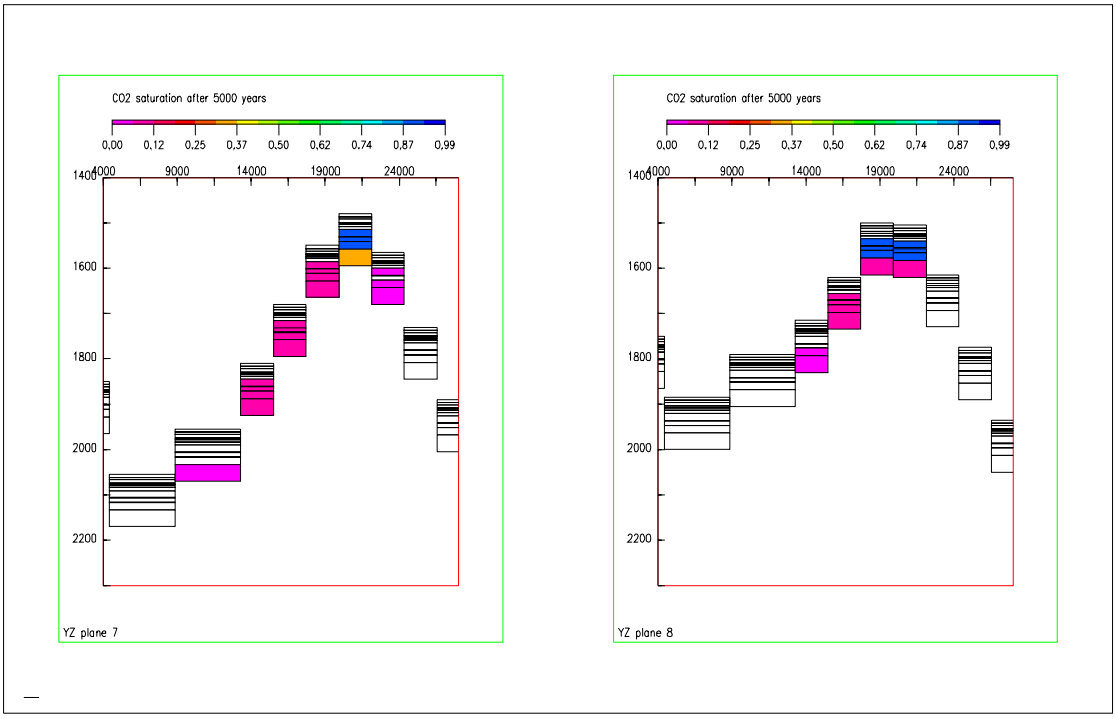

Fig. 8. Vertical distribution of CO_2 in the reservoir simulation model of the Havnsø structure after 5000 years of injection – yz-planes 7 and 8. The injection rate was 6 million tons of CO_2 per year.