DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2005/9

Storage of CO_2 in the Havnsø aquifer – a simulation study

A CO2STORE contribution

Niels Bech & Michael Larsen

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Abstract

The objective of this work is to evaluate the potential for CO_2 storage in the Havnsø structure situated near Kalundborg in the western Sealand. The injection of CO_2 in the aquifer, the dissolution of the CO_2 in the brine and the migration of the CO_2 to the top of the structure are described by the ECLIPSE reservoir simulator. Various injection scenarios have been examined in order to determine how the target injection rate of 200 kg CO_2/sec ($6x10^6$ ton/year) can be maintained without exceeding the maximum permissible injection pressure. Due to two very low-permeable layers the reservoir is divided into five compartments, so it is necessary to inject the CO_2 at five different locations to fully exploit the available storage volume which is estimated to 846 million tons of CO_2. In the present simulations the CO_2 is injected at just one location from which 77% of the storage volume is accessible corresponding to 651 million tons of CO_2. The injected CO_2 migrates to the top of the reservoir compartment while partly dissolving in the water. The CO_2 will eventually escape by molecular diffusion, but it will take more than one million years before the CO_2 reaches the surface.

Introduction

Based on experience from underground storage of natural gas and from the CO_2 storage currently taking place at the Sleipner Field offshore Norway, one of the most promising options for underground CO_2 disposal are in deep saline aquifers. At a depth of more than approximately 800 m the injected CO_2 will behave as a supercritical fluid resulting in the formation of a two-phase CO_2/water mixture. With time some of the CO_2 will dissolve in the formation water and some will react with the reservoir rock.

In order to predict reservoir behaviour and long term fate of the injected CO_2, reservoir simulation models form a valuable tool. In this study we describe calculations performed in order to obtain an estimate of the injectivity and storage capacity of the onshore Havnsø structure in Denmark. The Havnsø structure was chosen as case study 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), and the formation is well known as an excellent reservoir.

In a previous study some preliminary calculations were performed in order to obtain an initial estimate of the storage capacity of the Havnsø structure. The applied simulation grid was very coarse and dissolution of CO_2 in the water was neglected (Bech and Larsen 2003). In the present work, a much more detailed simulation grid is applied and the solubility of CO_2 in the water phase is taken into account. The CO_2 is injected at a rate of 200 kg/sec ($6x10^6$ ton/year) for 100 years and the simulator describes the dissolution of CO_2 in the brine, the migration of CO_2 to the top of the structure and the eventual escape of CO_2 by molecular diffusion. 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).

The work is a contribution to CO2STORE, an EU funded project aimed at the study of underground storage of CO_2 in saline aquifers.

Havnsø Structure and Reservoir Model

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 Gassum Formation is well-known as an excellent reservoir. The reservoir is sealed by a several hundred metres thick succession of marine mudstones of the Fjerritslev Formation.

Reservoir model. Southeast of Havnsø, the Gassum Formation forms the main reservoir in a natural gas storage facility. Injection/production wells drilled at the natural gas storage and old exploration wells drilled at similar structures provide reservoir parameters used for evaluation of the CO_2 storage potential in the yet undrilled Havnsø structure. Based on the geological data a 15-layer reservoir model was build with lateral and vertical permeabilities ranging from 30 to 1300 mD and 0 to 130 mD, respectively (Table 1). Two sealing layers (zero vertical permeability) separate the volume available for storage in five compartments. The definition, pore volume and estimated storage capacity of the five reservoir compartments in the Havnsø structure are given in Table 2.

Estimated Storage Capacity. The storage capacity of the Havnsø aquifer is estimated from the expression:

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

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 total 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 630 million tons injected after 100 years amounts to about 74% of the storage capacity. If injection takes place in reservoir compartment No. 5 only, 97% of the storage capacity is utilized after 100 years of injection, see Table 2.

Havnsø Simulation Model

ECLIPSE 300 vs. ECLIPSE 100. The compositional ECLIPSE 300 simulator accounts for CO_2/water phase behaviour but it can not describe diffusion of CO_2 in the water phase. Therefore, we use ECLIPSE 100 for these simulations by letting the simulator oil model the water and simulator gas model the CO_2. The phase behaviour is described by black-oil PVT tables. In this way the CO_2-in-water diffusion may also be taken into account.

Grid and Reservoir Parameters. A 114x105 areal grid with grid cell side lengths of 221 m in the central part inside the spill contour is superimposed the top structure map (Fig. 1). Vertically, the 15 geological layers (Table 1) are model by 26 simulation layers, the total number of grid cells thus beeing 114x105x26 = 311220. The thickness, porosity, permeability and net-to-gros ratio of each simulation layer are summarized in Table 3. The pore volume compressibility is 6.96×10^{-5} 1/bar at a pressure of 158.6 bar.

External Boundary Conditions. All external boundaries are no-flow boundaries. The outer grid cells are, however, so big that the aquifer surrounding the CO_2 storage volume inside the closure can be considered an infinte acting, constant pressure aquifer. Areally, the simulation grid covers 1.7 million km^2.

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 (Table 4 and Fig. 4) are evaluated at the Havnsø reservoir temperature of 50 ^oC by PVTsim (Calsep 2001). The water data which accounts for dissolved CO_2 are obtained from Chang, Coats and Nolen 1998 (Table 5 and Fig. 5). The viscosity of water is assumed constant as the effect of dissolved CO_2 is very small according to this reference.

A value of 2×10^{-9} m^2/sec is used for the CO_2-in-water diffusion coefficient. This value has been determined at 25 ^oC (Reid, Prausnitz and Sherwood 1977). The tortuosity of the porous medium has been set to unity, so the 2×10^{-9} m^2/sec is also equal to the effective diffusion coefficient used. A tortuosity value around 2 is probably more correct which means that the simulated diffusion rates are somewhat overestimated.

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 and Period. 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. The selected injection period is 100 years.

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 et al. (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 that 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 injection location is approximately 2000 m below the surface. The resulting maximum injection pressure is therefore set to 300 bar corresponding to 1.5 times the hydrostatic pressure.

Injection Location. Reservoir model **l**ayer no. 15, the bottom layer, is by far the thickest and most permeable layer, so it is obvious to inject the CO_2 here. Moreover, it is located in the largest reservoir compartment (No. 5, Table 2) containing 77 % of the total pore volume. As observed previously, the 630 million tons of CO_2 injected after 100 years amounts to about 97% of the estimated storage capacity of compartment No. 5. Simulations confirm that it is possible to store this amount in the deepest and largest reservoir compartment of the Havnsø structure. Reservoir compartment No. 3 is the second largest and contains 15% of the total pore volume. If the injection well is completed here as well then, ideally, 15/(15 + 77) = 0.16 or 16% of the CO_2 should be injected here. However, the injectivity in reservoir compartment 3 is considerably smaller than in compartment 5. Trial runs show, that the completion length must be at least three times larger than the one used in compartment 5 order to achieve this. This corresponds to more than 600 m (conf. Completion Length section below). For this reason the CO_2 is injected in reservoir compartment 5, only.

The injection is performed in one horizontal well completed in simulation model layer 23 (Table 3) approximately 8 km from the emission sources (Figs. 1 and 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. Preliminary simulations have shown that the target injection rate of 200 kg/sec can be maintained throughout the injection period except maybe for the first couple of days if the well is completed over 200 m in reservoir compartment No. 5.

ECLIPSE assumes instant equilibrium between CO_2 and water which means that the water in a grid cell must be saturated with CO_2 before any free CO_2 appears. The result is that the initial injection pressure is underestimated. Simulations where the two phases are considered immiscible show however, that the maximum permissible injection pressure of 300 bar is reached during the first few days, only.

Results and Discussion

The simulated distributions of free and dissolved CO_2 after 5, 100, 300 and 5000 years are illustrated in Figs. 7 – 20. Figs. 7 - 10 show the vertical distributions in the injection plane after 5 and 100 years. In Figs. 11 - 16 are shown the vertical distributions in the central xz - plane after 100, 300 and 5000 years. The corresponding areal distributions in the injection layer and in the top layer of reservoir compartment 5 where the injection takes place are show in Figs. 17 – 20. The injected CO_2 migrates to the top of the reservoir compartment while partly dissolving in the water (Figs. 7, 9, 11, 13 and 15). The dissolved CO_2 behaves differently because CO_2 saturated water is heavier than pure water. It will therefor have a tendency to migrate downwards. (Figs. 8, 10, 12, 14 and 16). But even after 5000 years all the CO_2 is contained inside the closure, except for the small amount that have escaped by molecular diffusion. Note, that the dissolved CO_2 diffuses through the tight layers, reaches the top of the structure and finally escapes through the top seal.

Fate of CO2 Bubble. The CO2 bubble will gradually dissolve, but it will take a very long time before it finally disappears as can be seen in Fig. 21 which shows the fraction of free and dissolved CO_2 vs. time. Extrapolation of the curve for the free CO_2 indicates that it will take more than 350 0000 years before the CO_2 bubble has dissappeared corresponding to a rate of 2.5×10^{-6} 1/year or 1.6×10^{6} kg/year. This is a much slower dissolution rate than what is estimated in case of the Utsira formation (Lindeberg and Bergmo 2002). With 85% of the injected CO_2 existing as free CO_2 the Utsira dissolution rate is estimated to 800×10^{-6} 1/year or 20×10^{6} kg/year which is about 12 times faster than in the Havnsø case. In Utsira the convective transport of dissolved CO_2 is predominantly vertical which means that the driving force is parallel to the force of gravity. In Havnsø the direction is down flank which results in an effective driving force about 14 times smaller, conf. Figs. 15-16. But other factors such as permeability and free CO_2/water surface area will also affect the dissolution rate.

CO_2 Escape by Diffusion. The CO_2 will eventually escape through the top seal by molecular diffusion. In order to get an idea of the time frame of this proces a vertical, one dimensional model was set up with height 1500 m and a cross section of 44 km^2 corresponding to a diameter of 7500 m. The permeability is 200 mD and the porosity 0.4. The diffusion coefficient is to 2×10^{-9} m^2/sec and the tortuosity is conservatively set to one. Initially the model contains pure brine (R_{sb} = 0 sm^3 CO_2/sm^3 brine) and the boundary conditions are R_{sb} = 0 at the top and S_{CO2} = 1 at the bottom. The CO_2 source is thus a bubble with a constant diameter of 7500 m.

Results are shown in Table 6 and Fig. 22. It takes more than 1 million years for the CO_2 to reach the surface and this is a conservative estimate. If the overburden is modelled more correctly taking into account the layering and using at least a 2-D description the simulated time for the CO_2 to reach the surface would be much longer. According to the present simulation 41% of the CO_2 has escaped from the reservoir after 1 million years and 92% after 5.

Integrity of Top Seal. It has been assumed that the top seal forms a completely tight barrier against convective flow**.** Southeast of Havnsø, the Gassum Formation forms the main reservoir in a natural gas storage facility. Here, extensive measurements of top seal capil-

lary pressures have shown that the natural gas/water capillary entry pressure is well above 100 bar. Assuming

$P_{ce,CH4w}$ = 100 bar [2]

and

$$p_{ce,CO_2w} = p_{ce,gw}\frac{\sigma_{CO_2w}}{\sigma_{gw}} \quad [3]$$

σ_{gw} = 0.072 N/m [4]

σ_{CO2w} = 0.027 N/m [5]

leads to

$p_{ce,CO2w}$ = 37.5 bar [6]

To penetrate the seal the height, h_{CO2}, of free CO_2 must not exceed the height

$$h_{\max} = \frac{p_{ce,CO_2w}}{g\Delta\rho} \quad [7]$$

where

$$\Delta\rho = (\rho_w - \rho_{CO_2}) \quad [8]$$

ρ_w = 1020 kg/m^3 [9]

ρ_{CO2} = 640 kg/m^3 [10]

or

h_{max} = 1006 m [11]

This height can never be reached as the vertical distance between the top and the bottom of the reservoir is around 800 m.

Influence of Grid Size. As discussed previously, Eclipse assumes instantaneous phase equilibrium and this implies that the amount of free CO_2 is quite sensitive to the grid size. In Fig. 23 is shown the fraction of free CO_2 with time as function of the x-direction grid length in a 2D, x-z central cross section. It is seen that the axial grid size must be about 75 m or less before the amount of free gas after 25 years of injection is little affected. In the 3D case the computation time will be so large if the areal grid size is reduced from the present 220 m to 75 m that the simulation is practically impossible to carry out. It is also believed that the conclusions that can be drawn concerning storage capacity and long term fate of

the CO2 are, by and large, unaffected by this grid sensitivity.

The large areal grid size (220 m) used in the simulations leads to an underestimation of the amount of free gas in the reservoir (conf. Fig. 23) which means that also the attained maximum injection pressure is underestimated. It has however, been ensured that the maximum permissible injection pressure of 300 bar is reached during the first few days, only. This has been done by means of a simulation where the two phases are considered immiscible. (See also the subsection **Completion Length).**

Summary and Conclusions

The Havnsø reservoir is divided into five compartments, which means that it is necessary to inject the CO_2 at five different locations to fully exploit the available total storage volume which is estimated to 846 million tons of CO_2. However, the largest of the five compartments contains 77% of the total storage volume corresponding to 651 million tons of CO_2 and the present simulation study demonstrates that this is large enough to hold the emission from the Asnæs power plant and nearby refinery at Kalundborg for 100 years. That emission is 6 million tons of CO_2 per year (1994–1999) corresponding to 200 kg/sec or 630 million tons over 100 years. The CO_2 is injected into the reservoir through a horizontal well 8 km long and completed over a length of 200 m. The maximum permissible injection pressure of 300 bar is reached, but only during the first few days.

The injected CO_2 migrates to the top of the reservoir compartment while partly dissolving in the water.

The CO_2 will eventually escape by molecular diffusion, but it will take more than one million years before the CO_2 reaches the surface.

The present simulation model is subject to a number of limitations and uncertainties:

- Possible reactions between CO_2 and the reservoir rock have been neglected.
- 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.

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List of Tables

Layer no.	Height (m)	Porosity (-)	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

Table 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.

Compartment no.	Reservoir model layer(s)	% of total pore volume	Pore volume (m^3)	Storage capacity (tons)
1	1	5.7	$0.21x10^9$ m^3	$48x10^6$ tons
2	2	1.3	$0.05x10^9$ m^3	$11x10^6$ tons
3	3 – 7	14.9	$0.55x10^9$ m^3	$126x10^6$ tons
4	8	1.2	$0.04x10^9$ m^3	$10x10^6$ tons
5	9 - 15	76.9	$2.85x10^9$ m^3	$651x10^6$ tons
Total reservoir	1 - 15	100.0	$3.70x10^9$ m^3	$846x10^6$ tons

Table 2. Definition, pore volume and estimated storage capacity of the five reservoir compartments in the Havnsø structure.

Layer no.	Height (m)	Porosity (-)	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	5.2	0.261	200	20	0.97
10	5.2	0.261	200	20	0.97
11	5.2	0.261	200	20	0.97
12	0.1	0.261	500	50	0.97
13	0.8	0.261	100	10	0.97
14	4.8	0.261	350	35	0.97
15	4.8	0.261	350	35	0.97
16	0.1	0.261	500	50	0.97
17	5.5333	0.209	200	1	0.59
18	5.5333	0.209	200	1	0.59
19	5.5333	0.209	200	1	0.59
20	5.2286	0.26	1300	130	0.98
21	5.2286	0.26	1300	130	0.98
22	5.2286	0.26	1300	130	0.98
23	5.2286	0.26	1300	130	0.98
24	5.2286	0.26	1300	130	0.98
25	5.2286	0.26	1300	130	0.98
26	5.2286	0.26	1300	130	0.98

Table 3. Simulation layer parameters.

P_{CO2}	B_{CO2}	μ_{CO2}
(bar)	(rm^3/sm^3)	(cp)
1.	1.	0.0149
25.	0.04100	0.0174
50.	0.01780	0.0188
75.	0.009674	0.0215
100.	0.005150	0.0392
125.	0.003464	0.0594
150.	0.002973	0.0681
175.	0.002722	0.0743
200.	0.002559	0.0795
225.	0.002440	0.0839
250.	0.002348	0.0879
275.	0.002273	0.0916
300.	0.002212	0.0951

Table 4. CO_2 formation volume factor and viscosity as function of pressure evaluated by PVTsim (Calsep 2000) at 50 ^oC. The CO_2 standard condition density is ρ_{CO2} = 1.87 kg/m^3.

R_{sb}	P_w	B_w	μ_w
(sm^3 CO_2/sm^3 brine)	(bar)	(rm^3/sm^3)	(cp)
0.568500E+00	0.101320E+01	0.101765E+01	0.775000E+00
	0.500000E+02	0.101588E+01	0.775000E+00
	0.100000E+03	0.101409E+01	0.775000E+00
	0.150000E+03	0.101230E+01	0.775000E+00
	0.200000E+03	0.101051E+01	0.775000E+00
	0.250000E+03	0.100873E+01	0.775000E+00
	0.300000E+03	0.100696E+01	0.775000E+00
	0.350000E+03	0.100520E+01	0.775000E+00
	0.400000E+03	0.100344E+01	0.775000E+00
0.192812E+02	0.542889E+02	0.104267E+01	0.775000E+00
	0.100000E+03	0.104098E+01	0.775000E+00
	0.150000E+03	0.103914E+01	0.775000E+00
	0.200000E+03	0.103730E+01	0.775000E+00
	0.250000E+03	0.103548E+01	0.775000E+00
	0.300000E+03	0.103365E+01	0.775000E+00
	0.350000E+03	0.103184E+01	0.775000E+00
	0.400000E+03	0.103003E+01	0.775000E+00
0.265999E+02	0.107564E+03	0.105232E+01	0.775000E+00
	0.150000E+03	0.105074E+01	0.775000E+00
	0.200000E+03	0.104888E+01	0.775000E+00
	0.250000E+03	0.104703E+01	0.775000E+00
	0.300000E+03	0.104518E+01	0.775000E+00
	0.350000E+03	0.104334E+01	0.775000E+00
	0.400000E+03	0.104151E+01	0.775000E+00
0.298362E+02	0.160840E+03	0.105657E+01	0.775000E+00
	0.200000E+03	0.105510E+01	0.775000E+00
	0.250000E+03	0.105324E+01	0.775000E+00
	0.300000E+03	0.105138E+01	0.775000E+00
	0.350000E+03	0.104952E+01	0.775000E+00
	0.400000E+03	0.104768E+01	0.775000E+00
0.315227E+02	0.214116E+03	0.105878E+01	0.775000E+00
	0.250000E+03	0.105743E+01	0.775000E+00
	0.300000E+03	0.105556E+01	0.775000E+00
	0.350000E+03	0.105370E+01	0.775000E+00
	0.400000E+03	0.105184E+01	0.775000E+00
0.326200E+02	0.267391E+03	0.106021E+01	0.775000E+00
	0.300000E+03	0.105898E+01	0.775000E+00
	0.350000E+03	0.105711E+01	0.775000E+00
	0.400000E+03	0.105524E+01	0.775000E+00
0.335212E+02	0.320667E+03	0.106139E+01	0.775000E+00
	0.350000E+03	0.106029E+01	0.775000E+00
	0.400000E+03	0.105841E+01	0.775000E+00
0.343937E+02	0.373943E+03	0.106252E+01	0.775000E+00
	0.400000E+03	0.106154E+01	0.775000E+00

Table 5. Water PVT data accounting for dissolved CO_2. Data from Chang, Coats and Nolen 1998. The water standard condition density is ρ_w = 1020 kg/m^3.

1-D simulation		
Height: 1500 m		
Cross section: 44 km		
Permeability: 200 mD		
Porosity: 0.4		
Diffusion coefficient: $2x10^{-9}$ m^2/sec		
Totuosity: 1.		
Initial condition: R_{sb} = 0. sm^3 CO_2/sm^3 brine		
Boundary condition at bottom: S_{CO2} = 1.		
Boundary condition at top: R_{sb} = 0. sm^3 CO_2/sm^3 brine		
	Million tons	Fraction
Initial amount of CO_2 in reservoir	630	100 %
CO_2 escaped after 1 million years	260	41 %
CO_2 escaped after 2 million years	368	58 %
CO_2 escaped after 5 million years	585	92 %

Table 6. Escape of CO_2 by molecular diffusion from the Havnsø aquifer assuming that the CO_2 source is a bubble with constant diameter of 7500 m.

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Fig. 20. Areal distribution of free and dissolved CO_2 in injection layer and top layer of reservoir compartment 5 in the Havnsø structure after 5000 years. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.

Fig. 21. Fraction of free and dissolved CO_2 vs. time in the Havnsø structure. The injection rate was 200 kg/sec or 6 million tons/year for 100 years.

Fig. 22. Distribution and amount of CO_2 escaped by molecular diffusion from the Havnsø structure after 1, 2 and 5 million years. The injection rate was 200 kg/sec or 6 million tons/year for 100 years.

Fig. 23. Fraction of free CO_2 with time as function of axial grid length, Δx. Havnsø 2D, x-z central cross section.

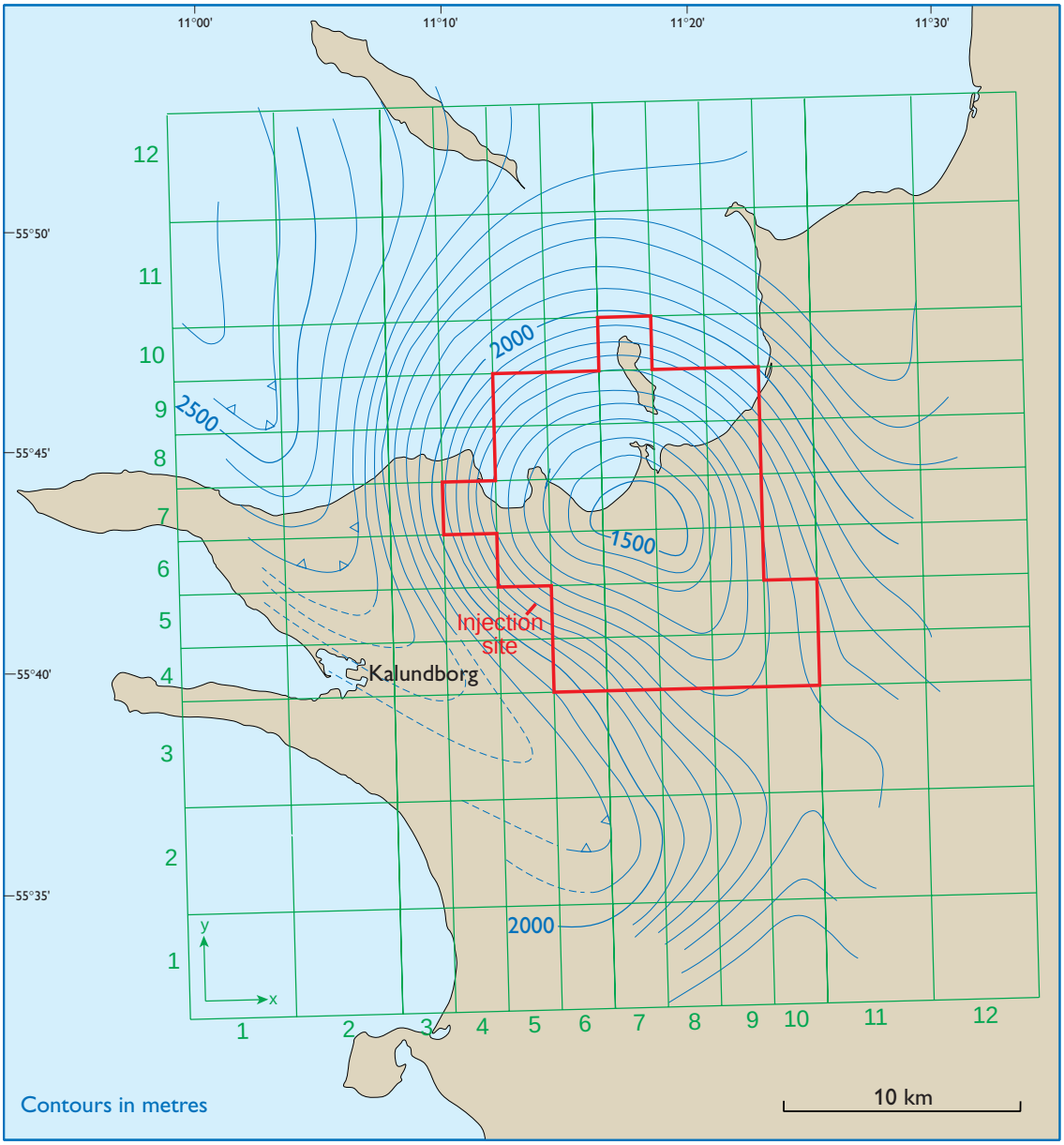


Fig. 1. Havnsø structure – Top structure map and coarse difference grid. In the grid actually used, the cells 2-11 in the x- and 3-11 in the y-direction are refined by a factor of ten. The red line indicates the area inside the closure.

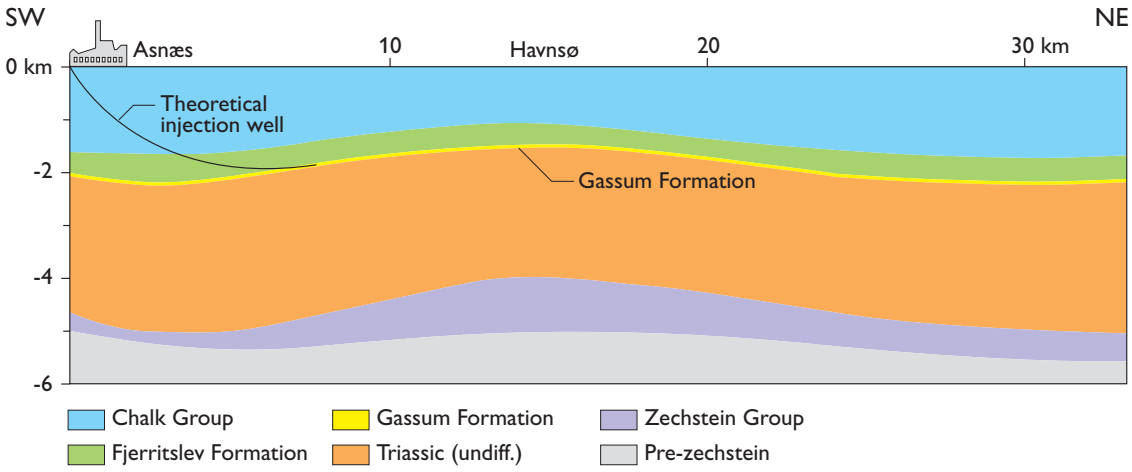


Fig. 2. Geological cross-section of the Havnsø structure. Note the theoretical injection well drilled from the industrial site into the flank of the structure.

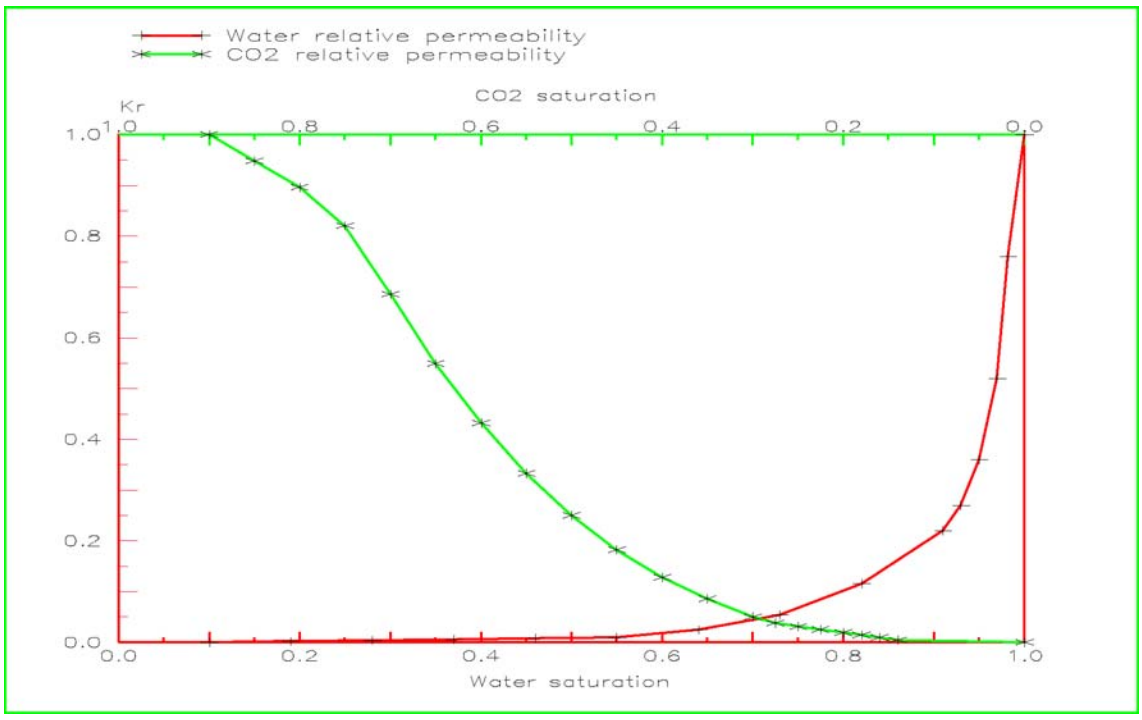


Fig. 3. Water and CO_2 relative permeabilities as function of water and CO_2 saturations. Note that the irreducible water saturation is equal to 0.1.

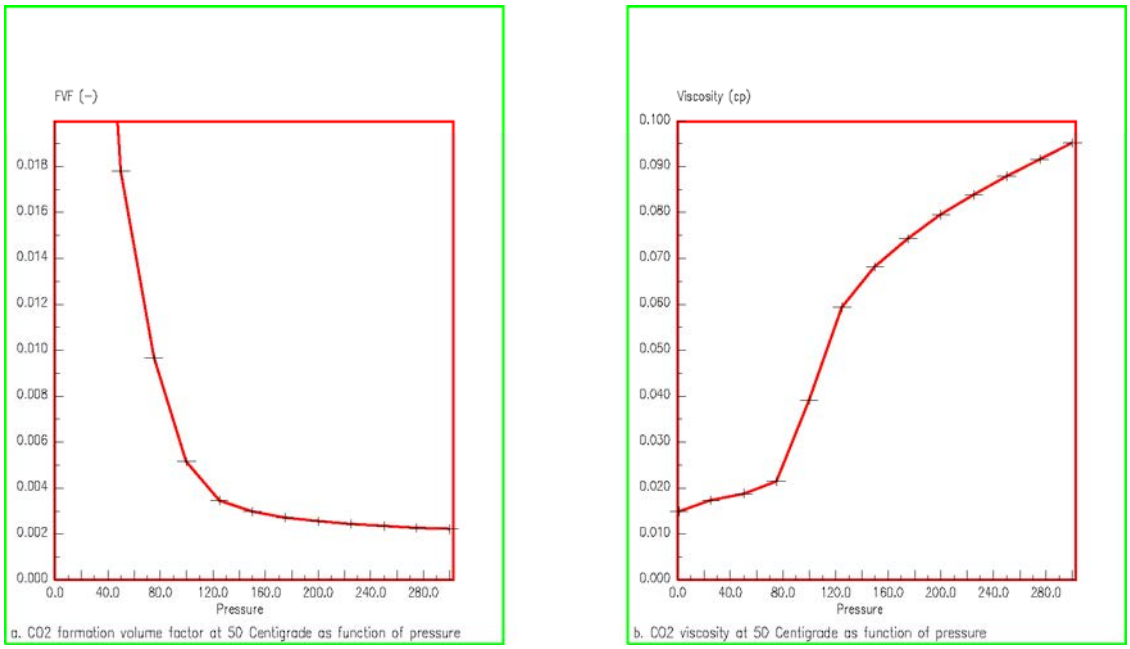


Fig. 4. CO_2 formation volume factor and viscosity as function of pressure evaluated by PVTsim (Calsep 2000) at 50 ^{o}C.

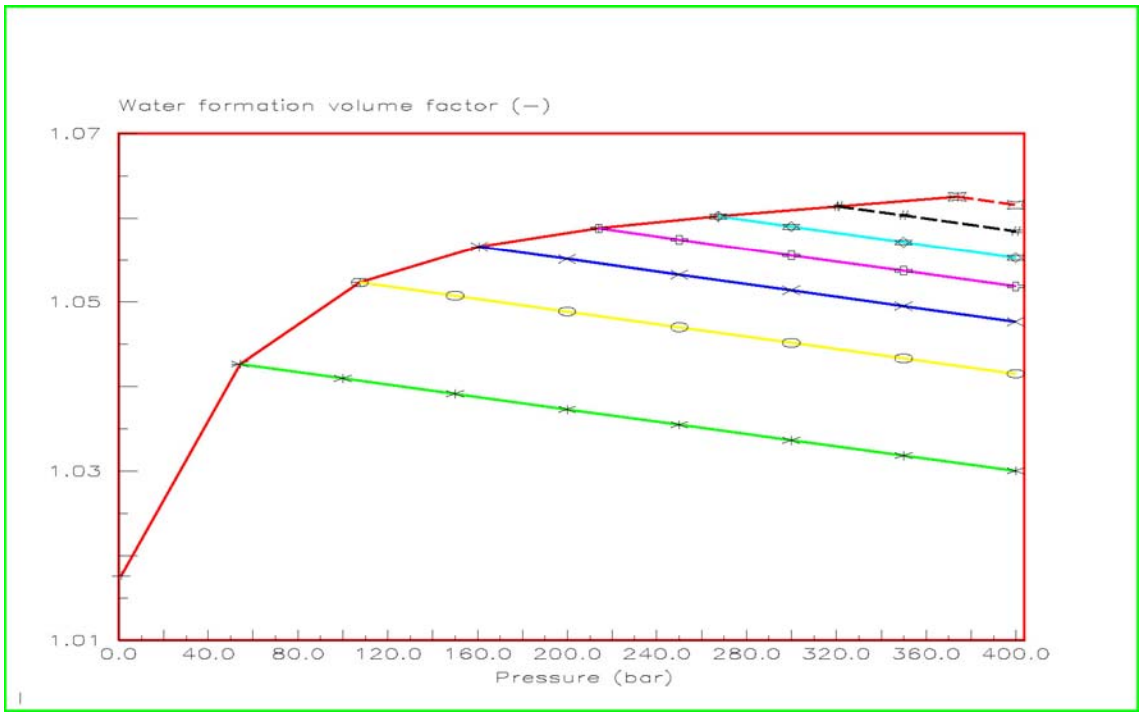


Fig. 5. Water formation volume factor as function of pressure at 50 ^{o}C. Data from Chang, Coats and Nolen 1998.

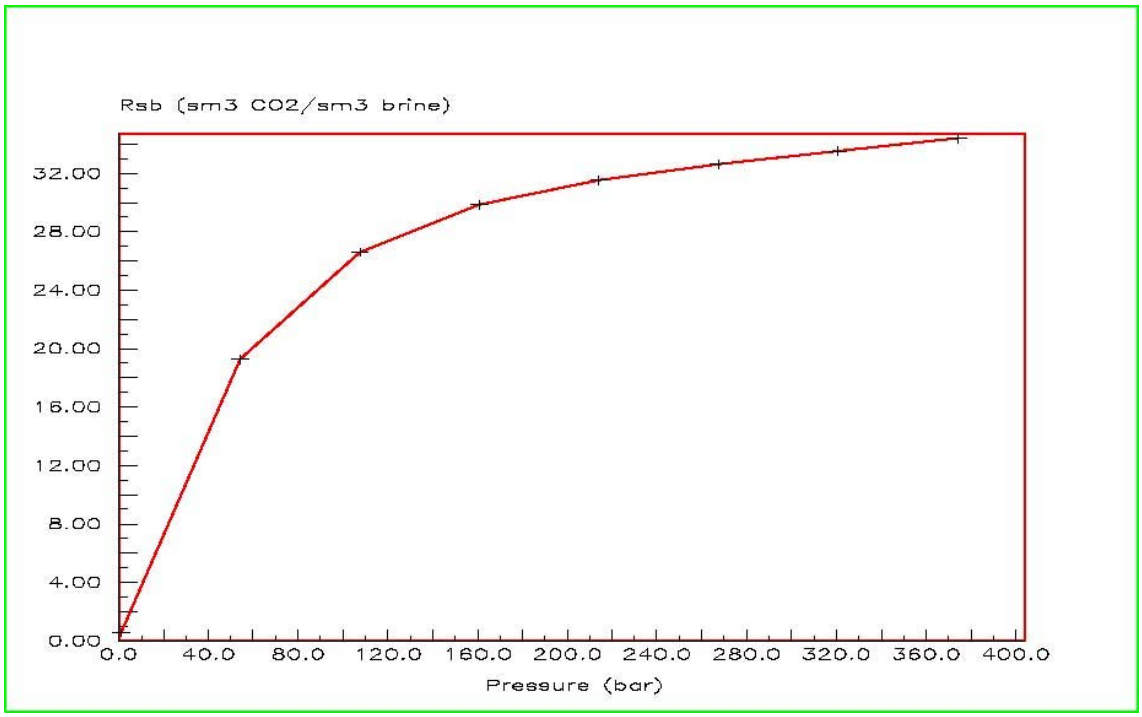


Fig. 6. Solubility of CO_2 in water as function of pressure at 50 ^{o}C. Data from Chang, Coats and Nolen 1998.

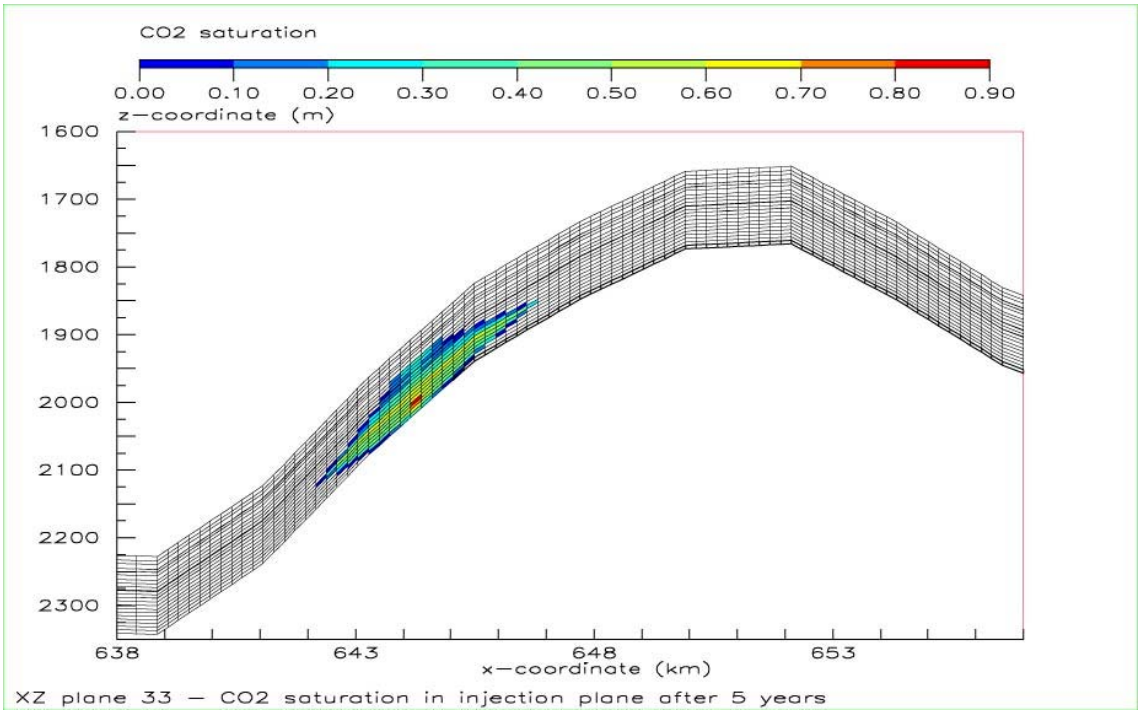


Fig. 7. Vertical distribution in injection plane of CO_2 saturation in the Havnsø structure after 5 years of injection. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.

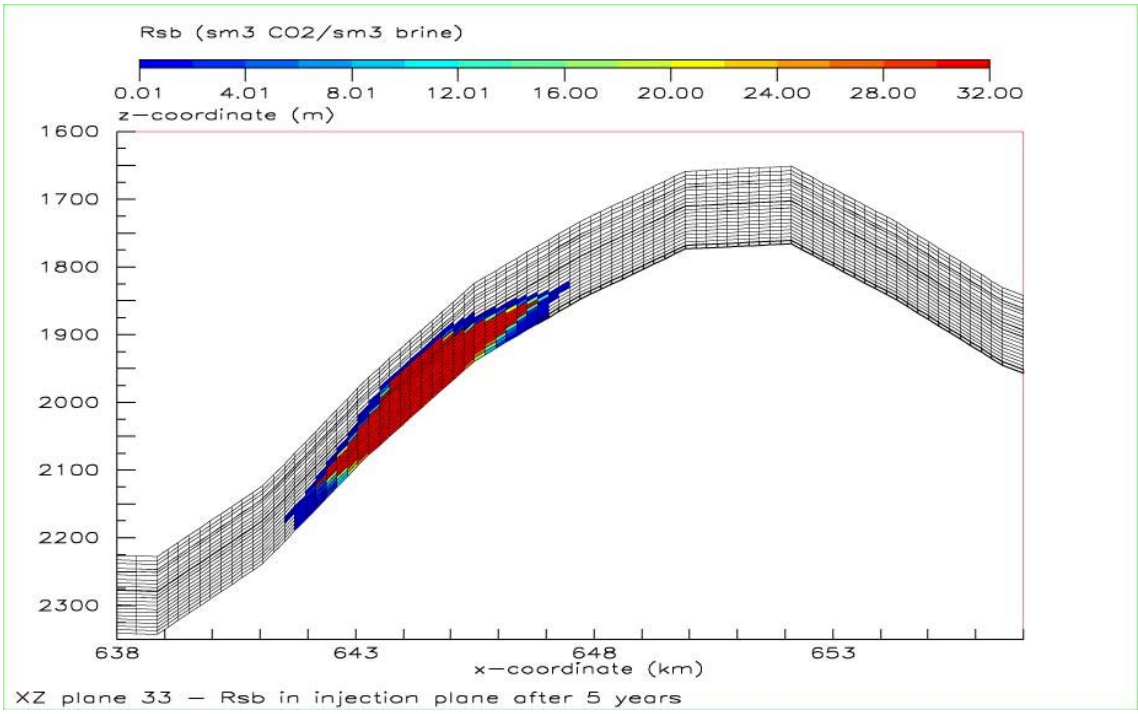


Fig. 8. Vertical distribution in injection plane of dissolved CO_2 in the Havnsø structure after 5 years of injection. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.

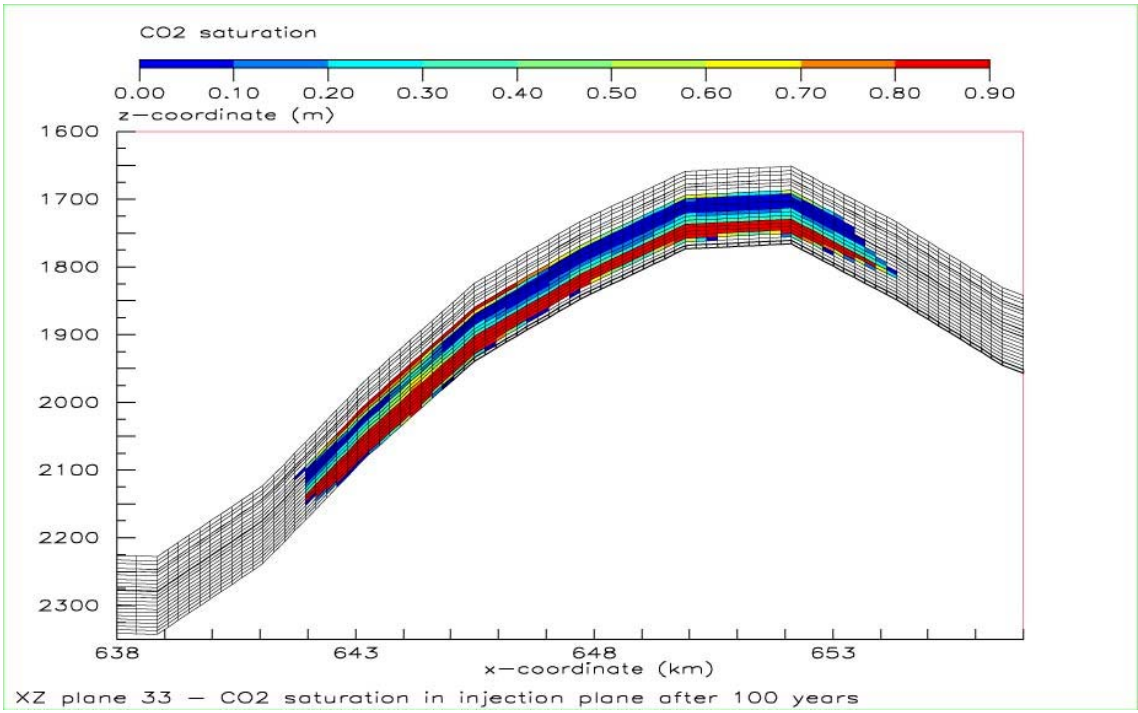


Fig. 9. Vertical distribution in injection plane of CO_2 saturation in the Havnsø structure after 100 years of injection. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.

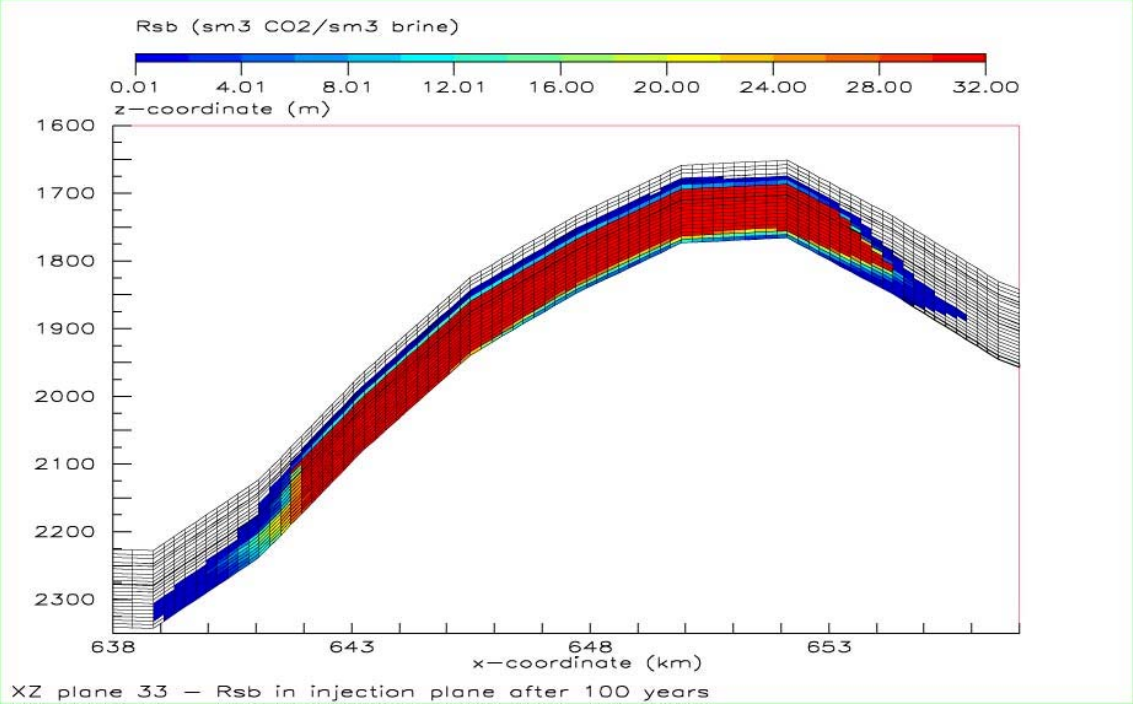


Fig. 10. Vertical distribution in injection plane of dissolved CO_2 in the Havnsø structure after 100 years of injection. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.

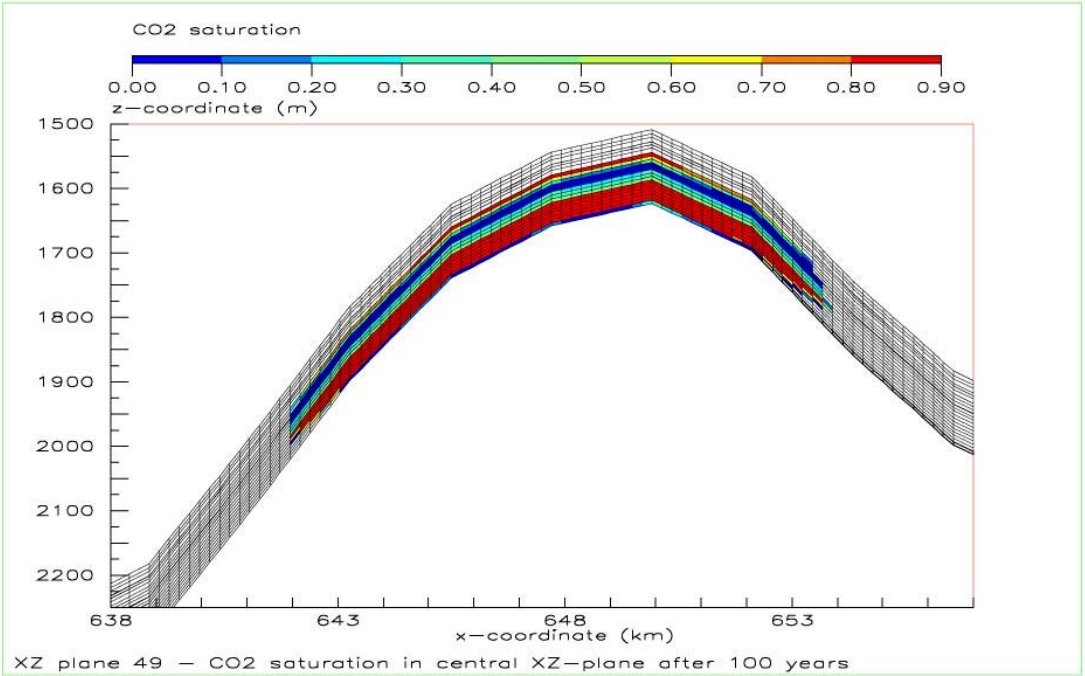


Fig. 11. Vertical distribution in central xz-plane of CO_2 saturation in the Havnsø structure after 100 years of injection. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.

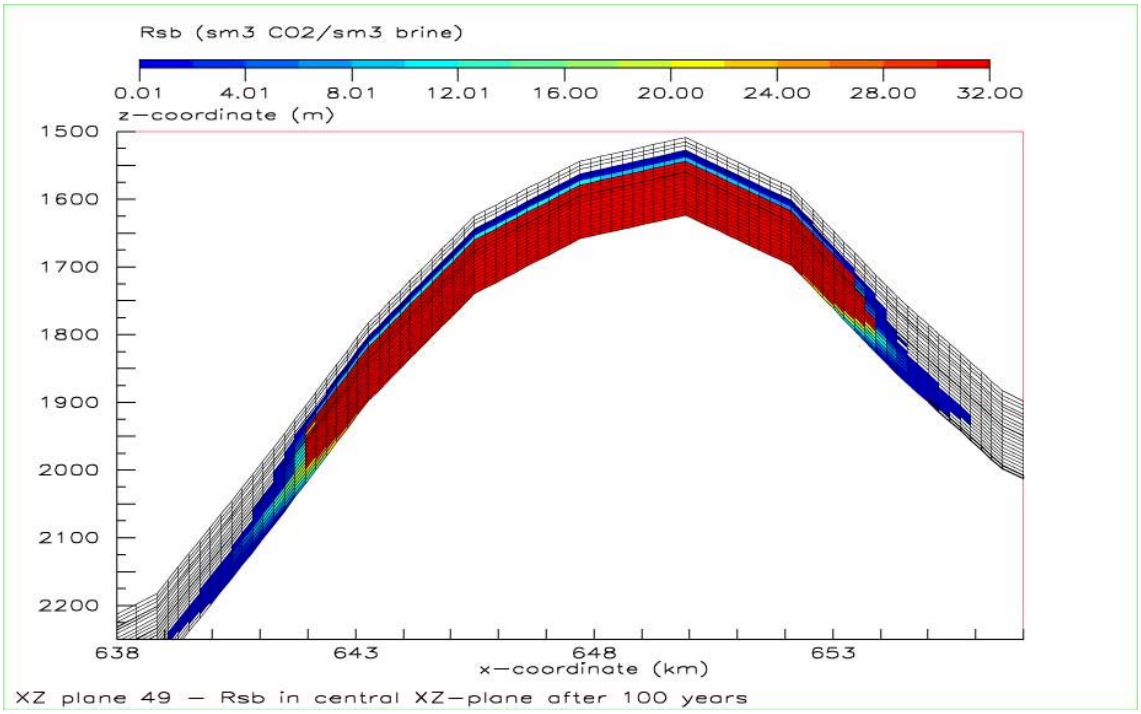


Fig. 12. Vertical distribution in central xz-plane of dissolved CO_2 in the Havnsø structure after 100 years of injection. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.

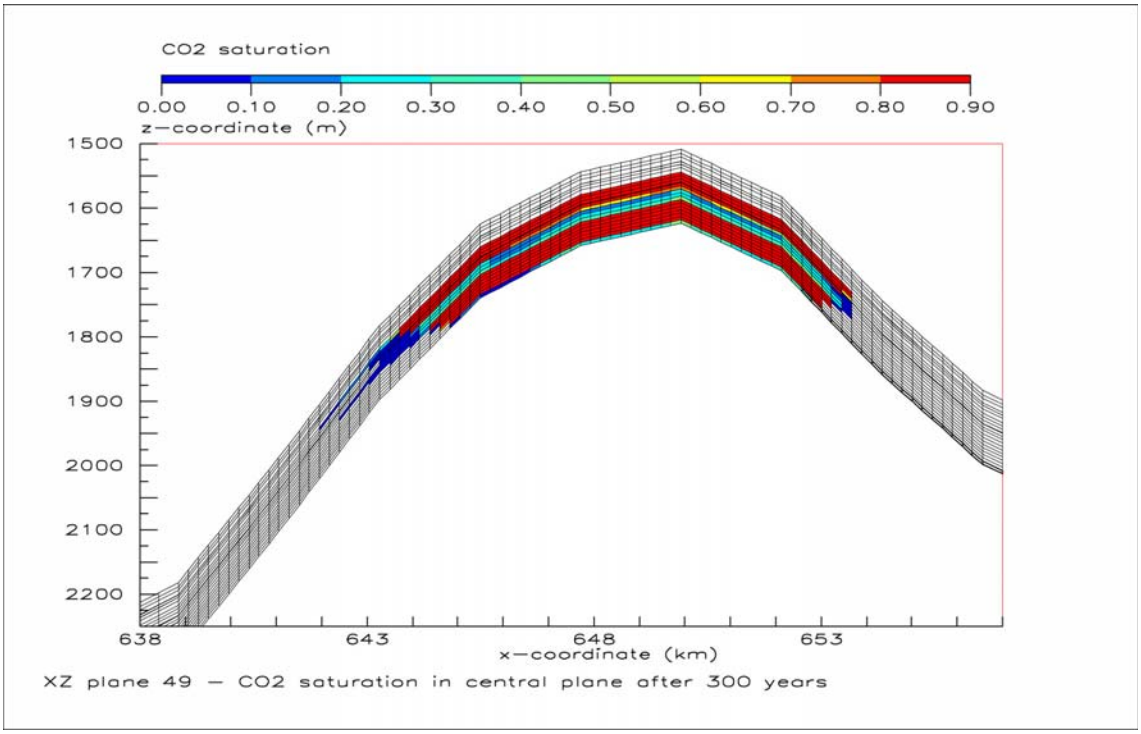


Fig. 13. Vertical distribution in central xz-plane of CO_2 saturation in the Havnsø structure after 300 years. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.

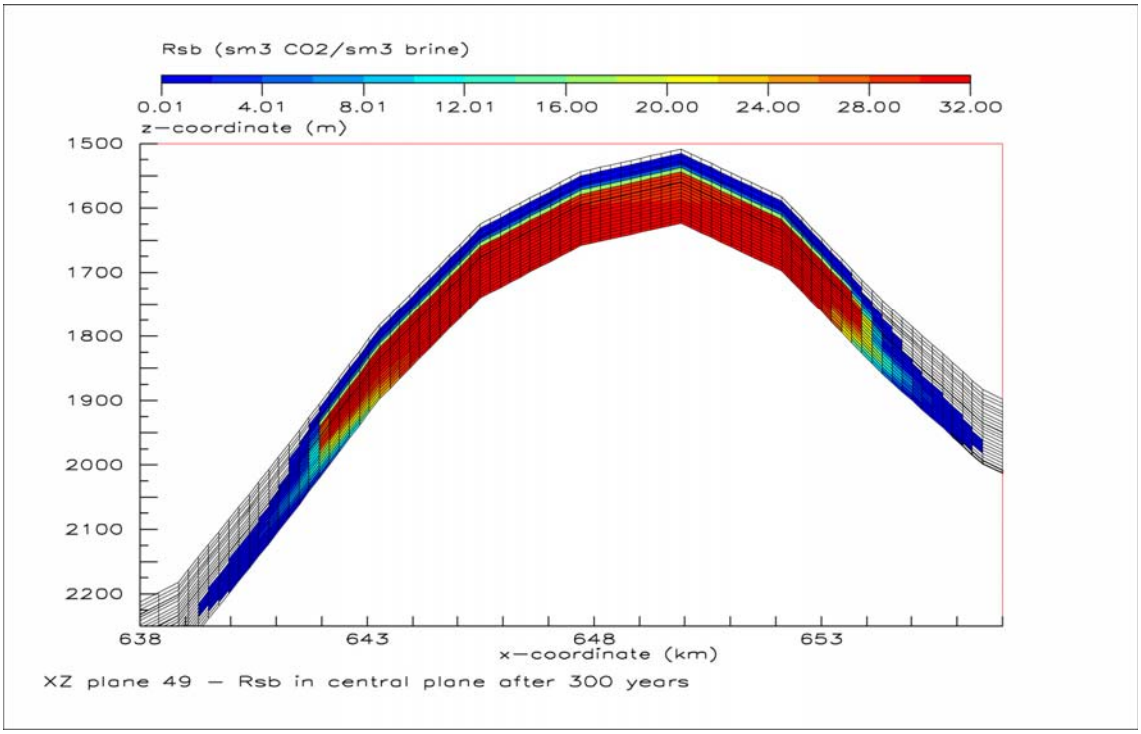


Fig. 14. Vertical distribution in central xz-plane of dissolved CO_2 in the Havnsø structure after 300 years. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.

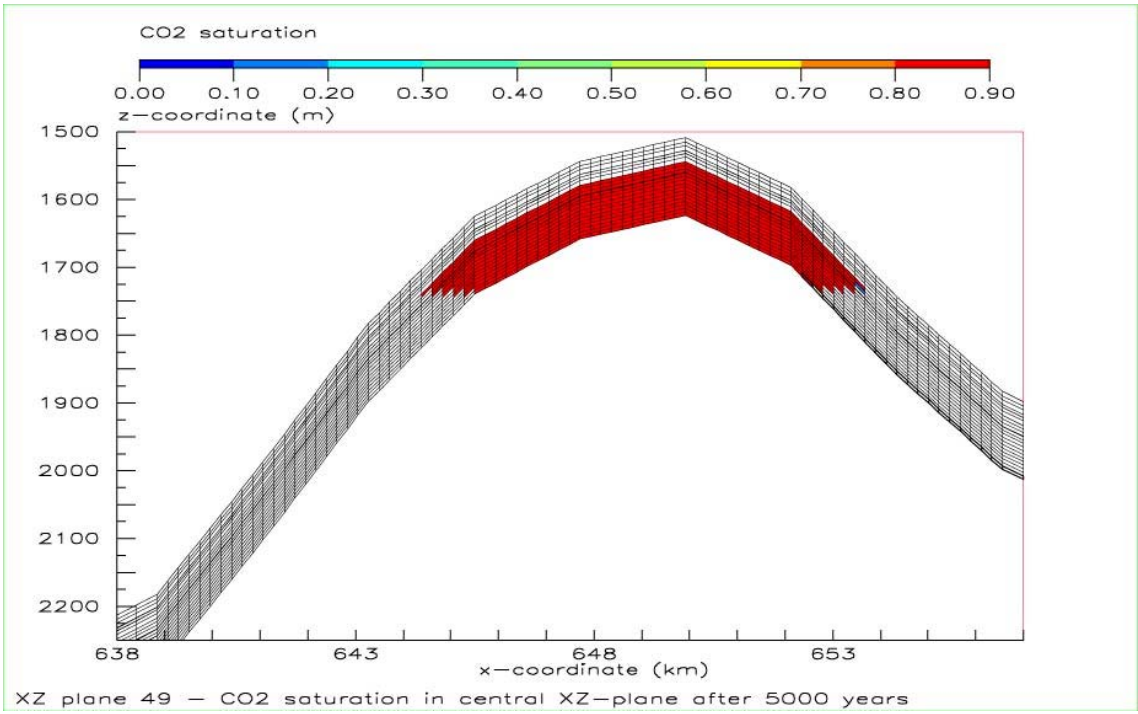


Fig. 15. Vertical distribution in central xz-plane of CO_2 saturation in the Havnsø structure after 5000 years. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.

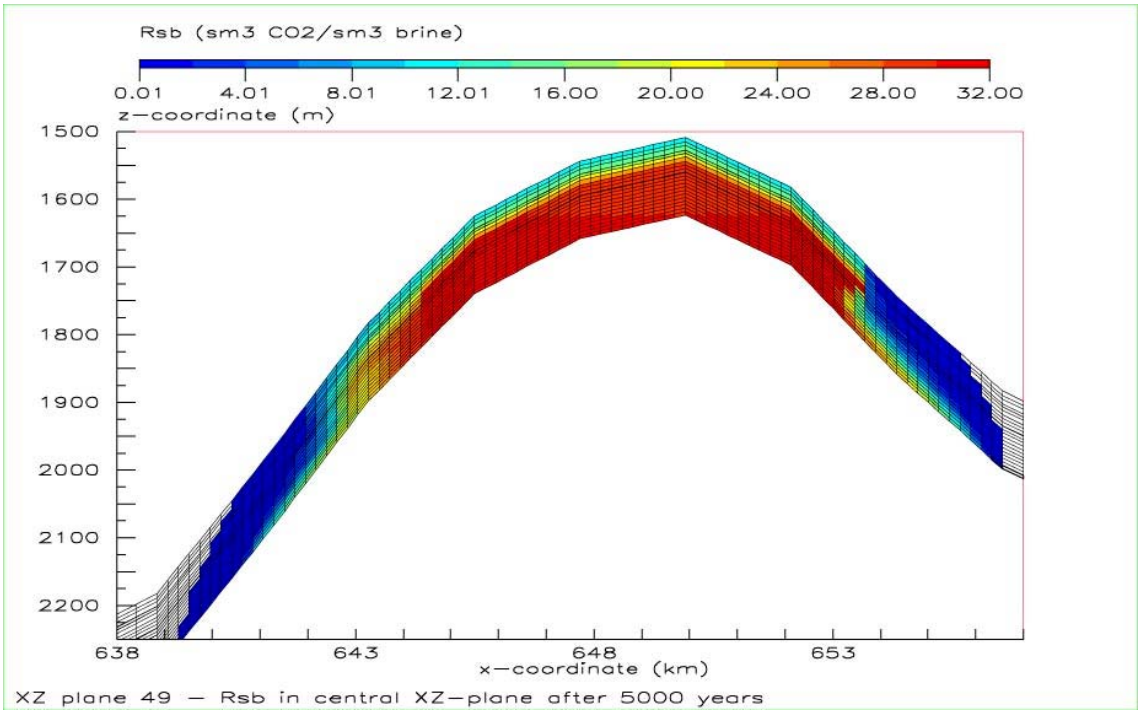
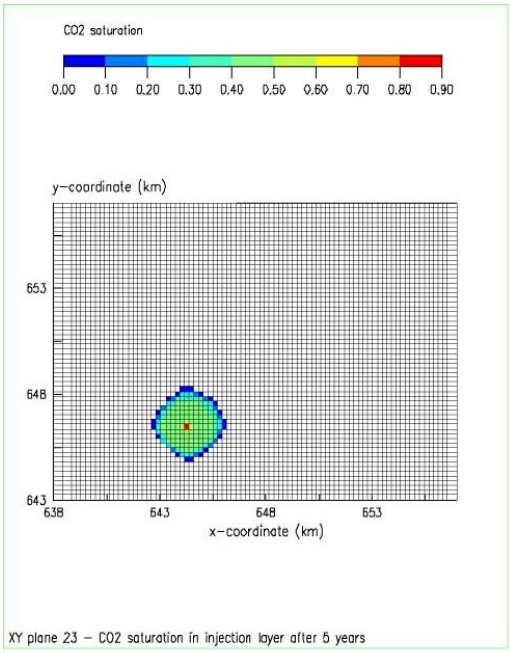
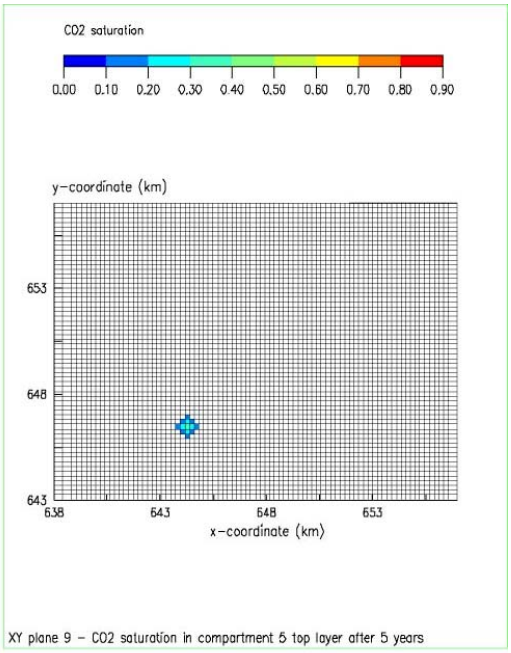
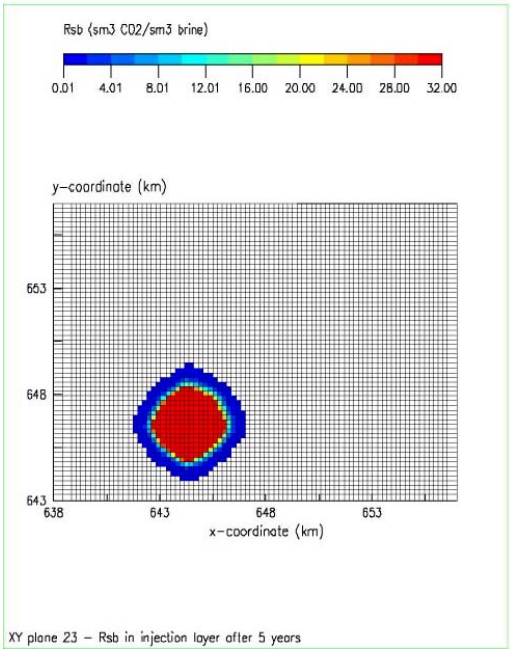


Fig. 16. Vertical distribution in central xz-plane of dissolved CO_2 in the Havnsø structure after 5000 years. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.







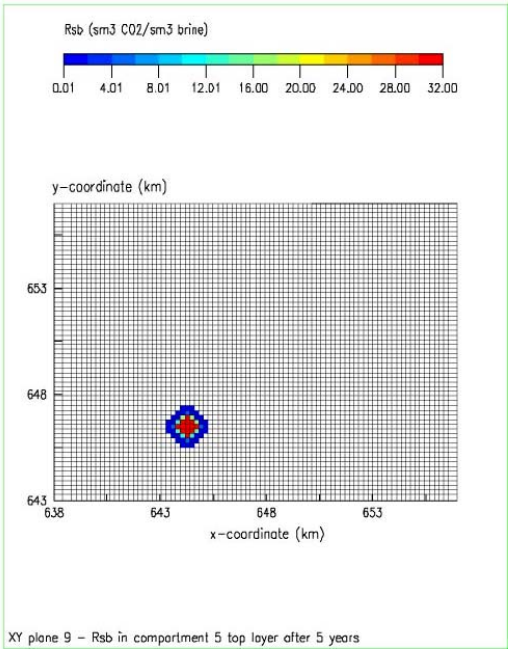
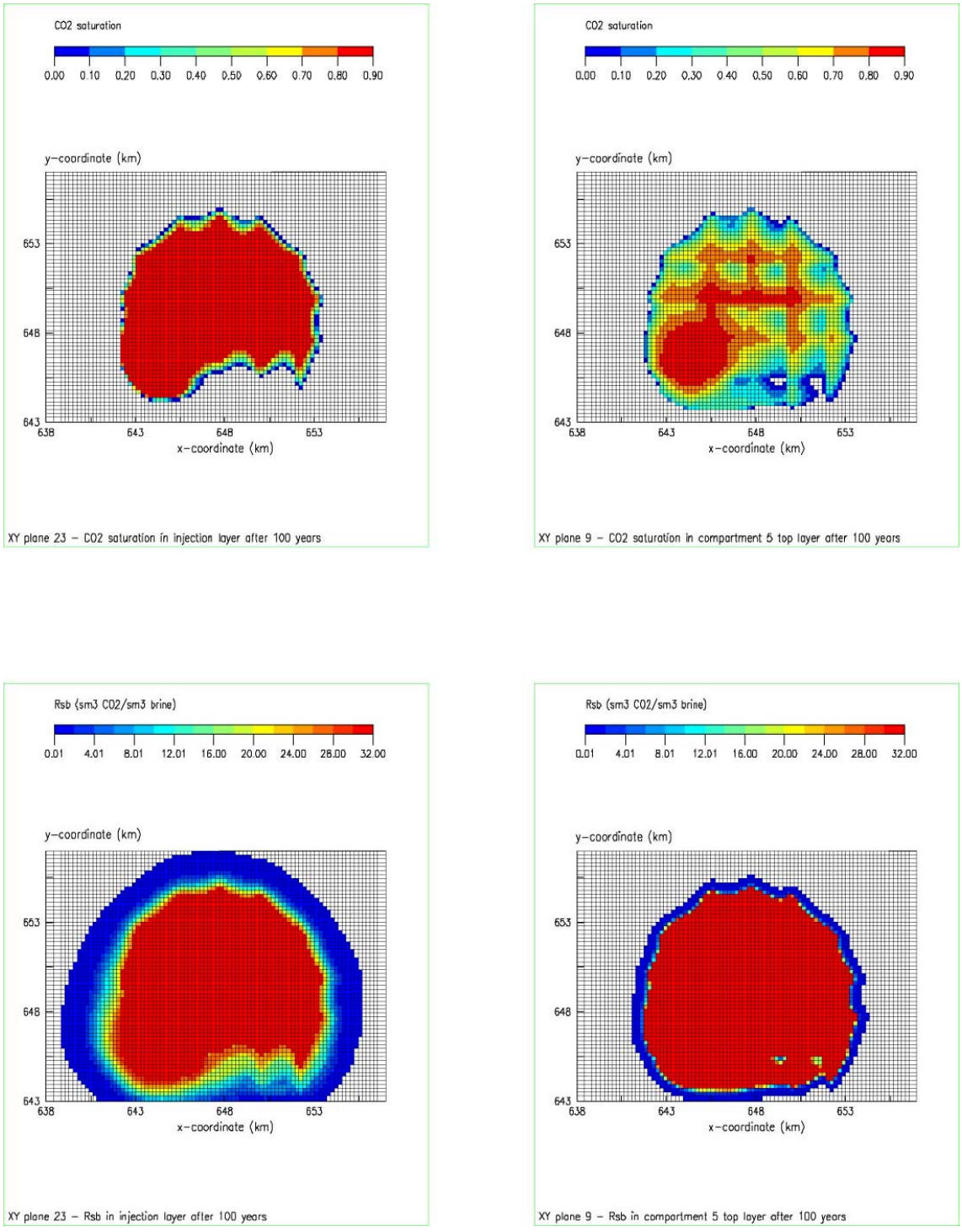


Fig. 17. Areal distribution of free and dissolved CO_2 in injection layer and top layer of reservoir compartment 5 in the Havnsø structure after 5 years of injection. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.



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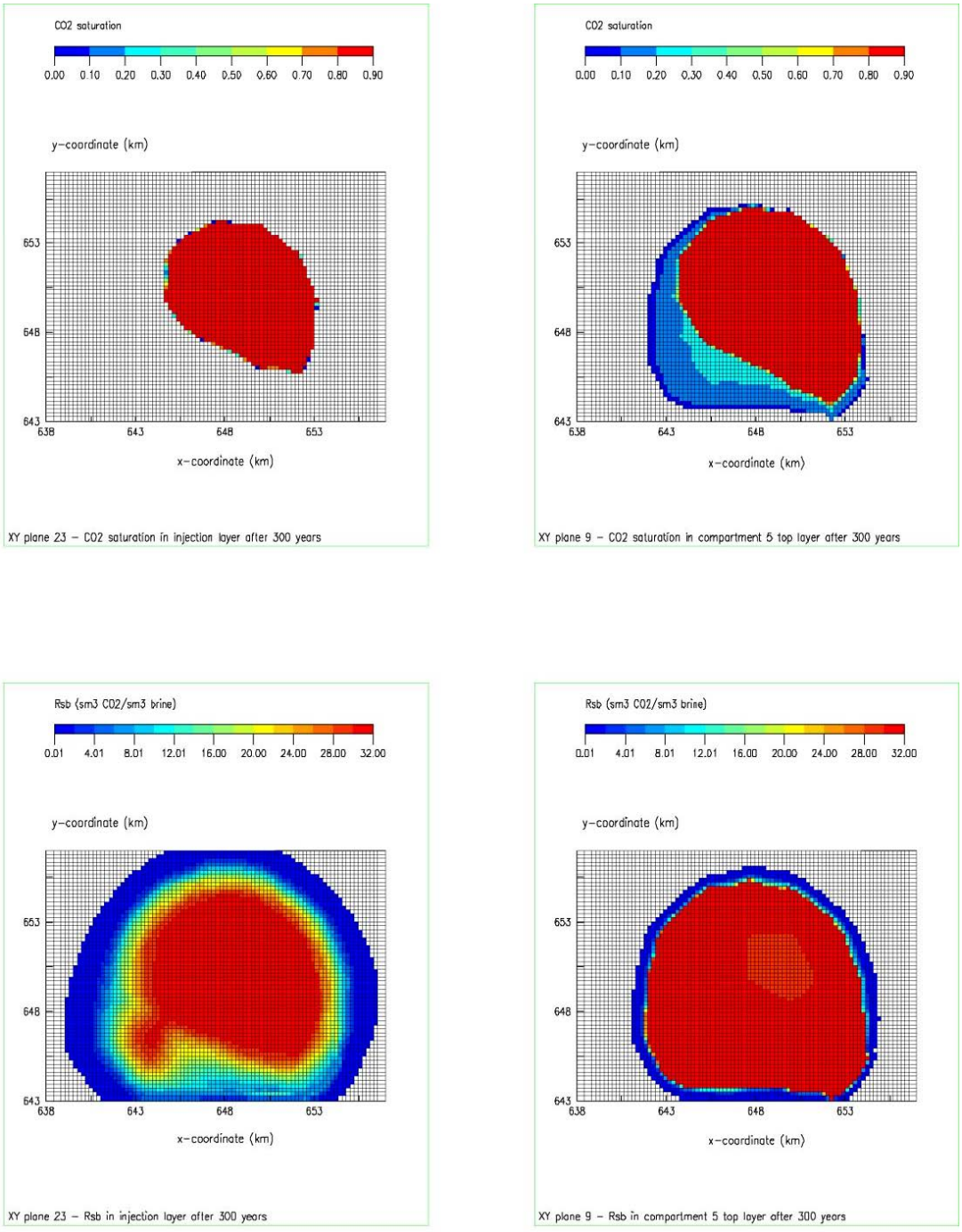


Fig. 19. Areal distribution of free and dissolved CO_2 in injection layer and top layer of reservoir compartment 5 in the Havnsø structure after 300 years. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.

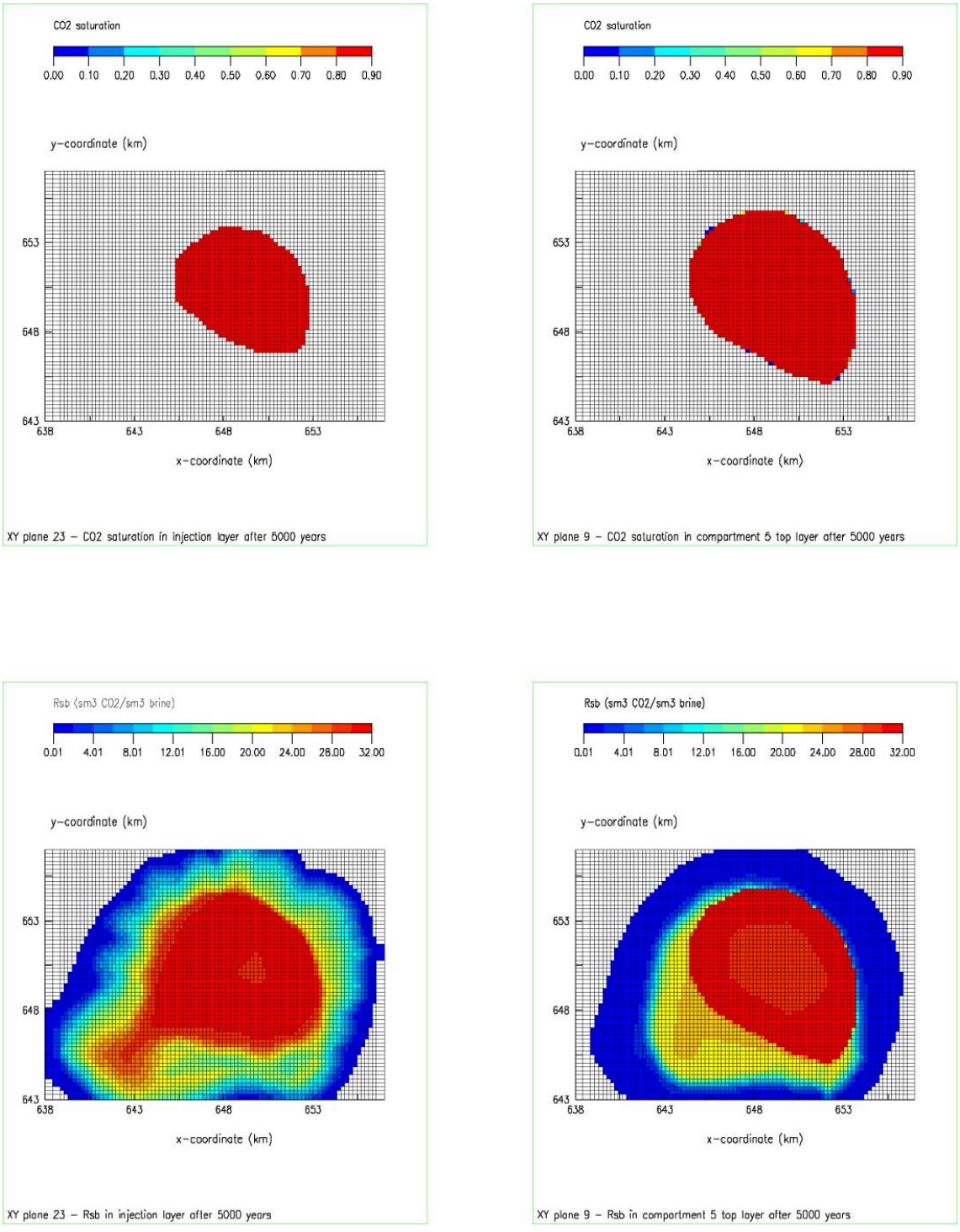


Fig. 20. Areal distribution of free and dissolved CO_2 in injection layer and top layer of reservoir compartment 5 in the Havnsø structure after 5000 years. The injection rate was 200 kg/sec or 6 million tons/year in 100 years.

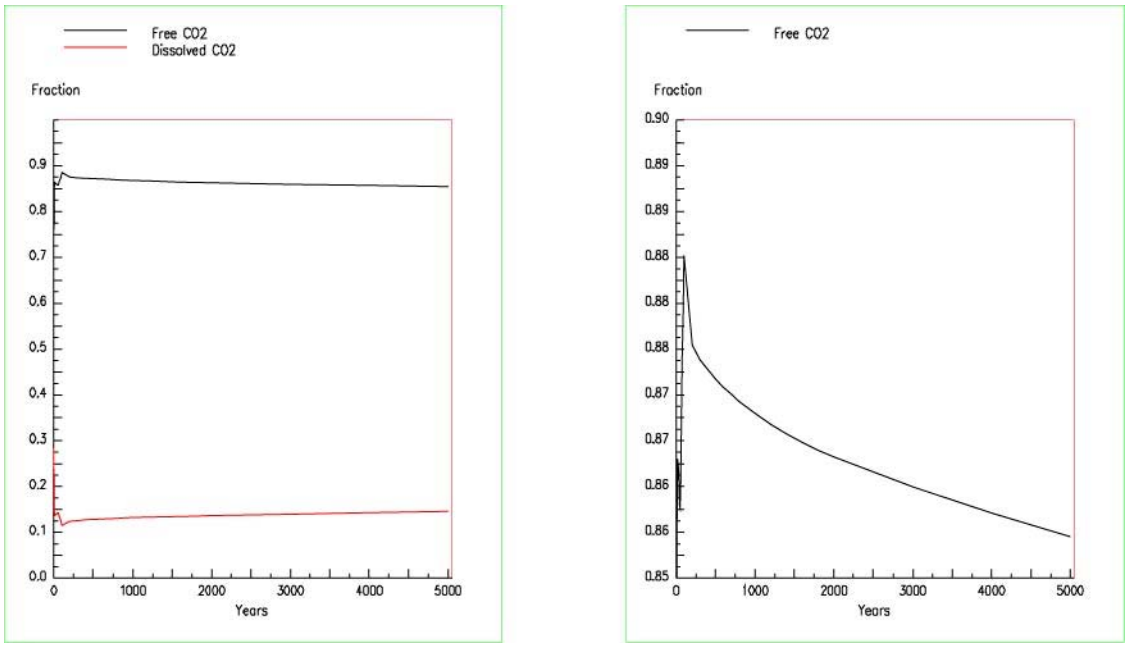
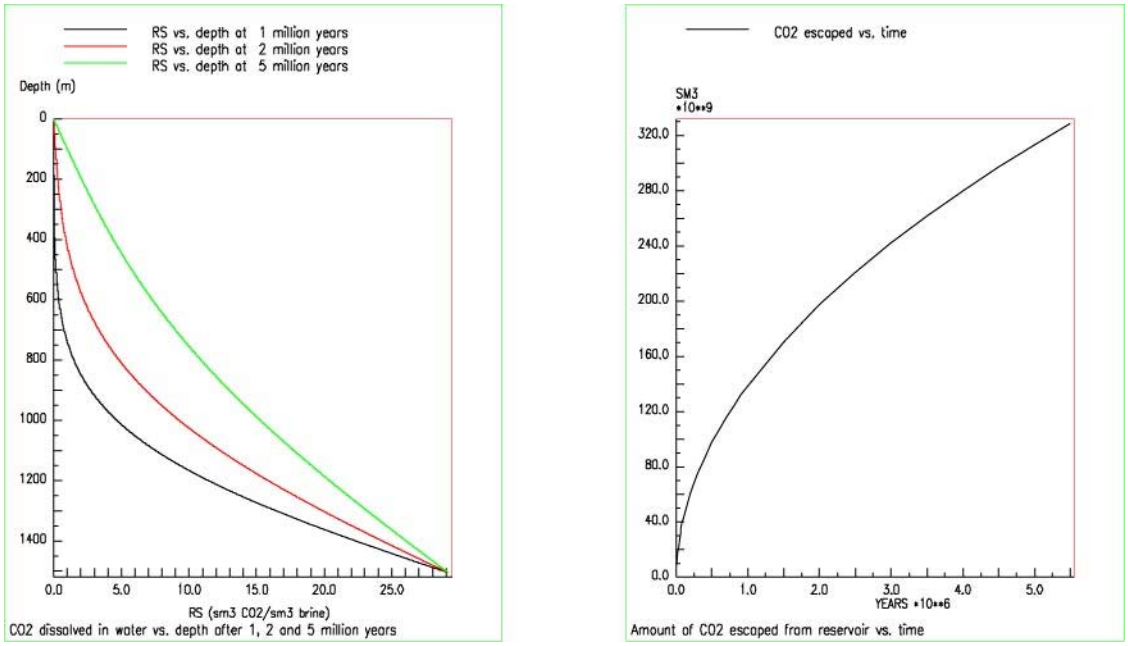


Fig. 21. Fraction of free and dissolved CO_2 vs. time in the Havnsø structure. The injection rate was 200 kg/sec or 6 million tons/year for 100 years.



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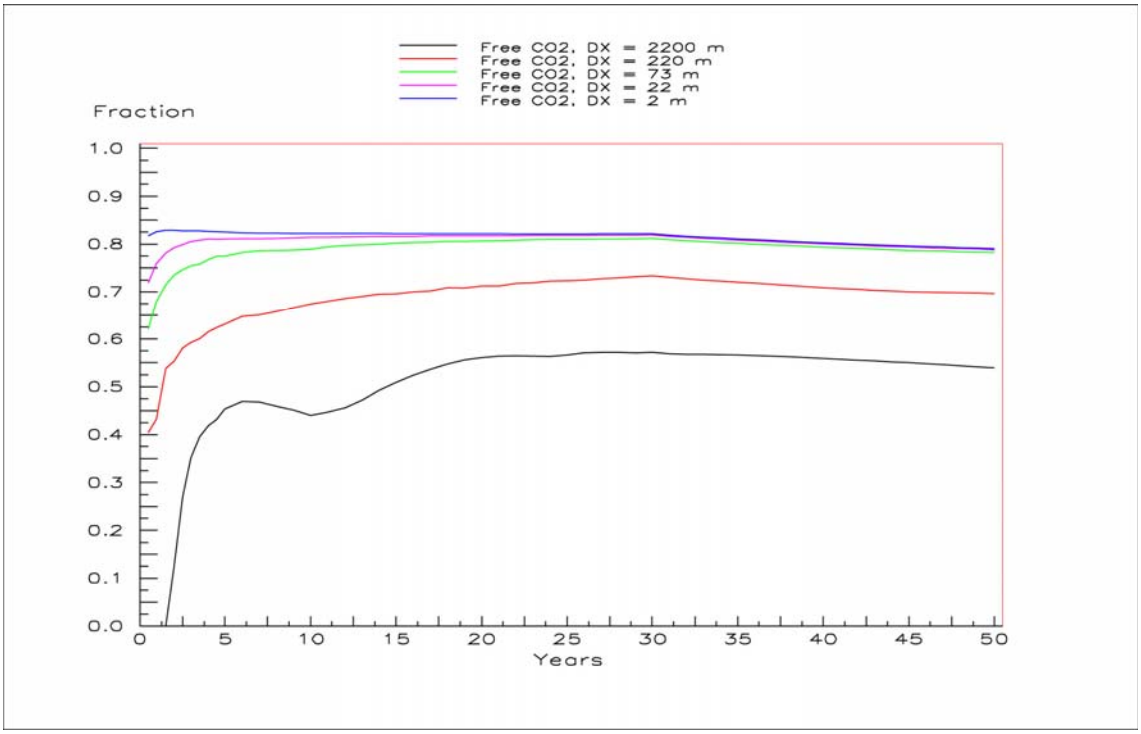

Fig. 23. Fraction of free CO_2 with time as function of axial grid length, Δx. Havnsø 2D, x-z central cross section.