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Determination of the CO_2 storage capacity of the Utsira formation

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Abstract

As the storage capacity especially in the shallower region is critically dependent on the phase behaviour of CO_2 a modelling of the geothermal gradient with emphasis on the Miocene and Pliocene strata where CO_2 may accumulate was performed. The geothermal model included the transient temperature changes due the long glacial cycles because they have a penetration depth that affects the Utsira formation. The results showed that CO_2 can be stored in dense phase up to a depth of approximately 500 m below mean sea level (MSL) which is significantly shallower than previously suggested. If a significant fraction of any closed aquifer shall be utilised for storage the pressure has to be controlled by production of water out of the aquifer to avoid pressure build up that could jeopardize the integrity of the sealing rock. The storage capacity of the Utsira formation was studied both by static volume estimates and by reservoir simulation of injection with up to 210 injection wells distributed over the whole formation. In simulation of several 300 years injection scenarios it was demonstrated that 7% of the pore volume corresponding 40 Gtonne (Gt) CO_2, could be utilised for storage while pressure control and CO_2 break-through control in the production wells was observed. The optimal filling will depend of the number of wells and is accordingly a result of an economic optimisation. The simulation results indicate that a cost effective utilisation of the reservoir could be in the range of 20 to 60 Gt.

Ketwords: Storage capacity; geothermal gradient; paleoclimate; phase behavoir

1. Introduction

The 25 000 km^2 Utsira formation is the largest shallow aquifers in the North-Sea and it has been identified as one of the major aquifers for long-term storage of CO_2. The formation is already being used for CO_2 storage at Sleipner where 1 million tonne CO_2 per year is being injected. This injection project has created a lot of public interest for CO_2 storage and internationally it is often used as an important reference for successful storage of CO_2. In previous projects related to the monitoring of the CO_2 injection at Sleipner (SACS, CO2Store, CO2Remove etc.) at lot of the internal geology of the Utsira formation has been revealed by combining the monitoring result with history matching

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of the observed saturation distribution. This gives an excellent opportunity to use these result to build reservoir models with improved predictive potential. The objective of this study is to determine the total safe CO_2 storage capacity in the Utsira formation. Two previous storage estimates have been performed giving respectively 42 Gt [1] and 50 Gt [2]. These estimates were based in simple key figures and geological geometrical data, without taking dynamic effects or the specific topography into account. An analysis of the topography of the top formation shows large variation in depth (Figure 1), and in the central western part it is actually so shallow that stored CO_2 may not be present in its dense phase only. It is usually assumed that CO_2 can not effectively be stored at depths above 700 m [3], but the storage performance at depths up to 500 m will be studied here.

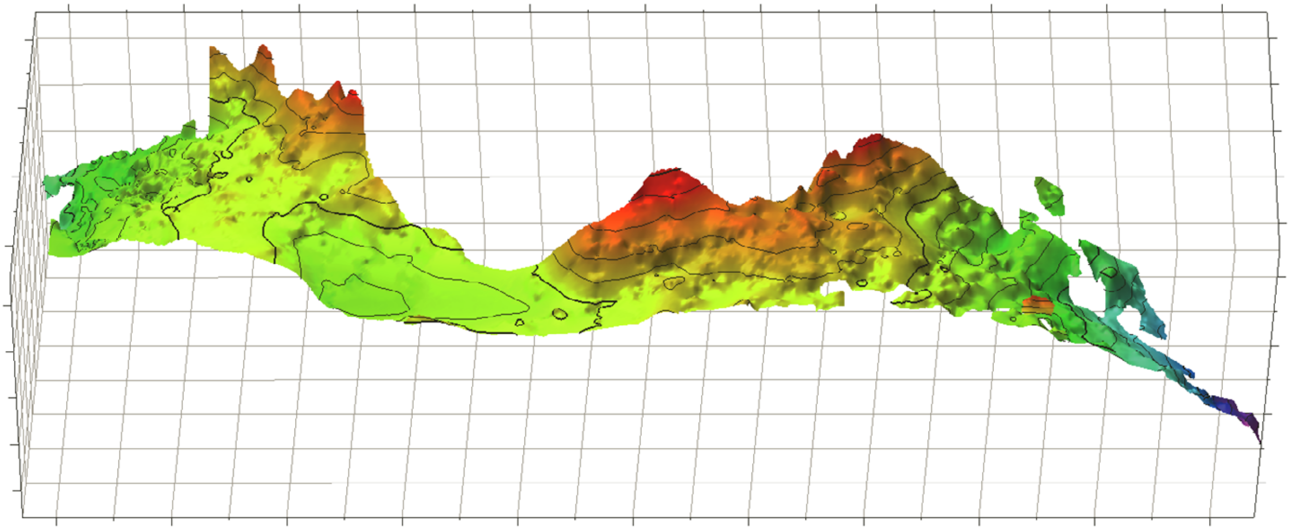

Figure 1 The 25 000 km^2 Utsira formation seen from East interpreted by [9]. The topography is exaggerated 100 times. The top depth varies from the peaks in central western parts of 500 m to the deep northern slope ending at 1500 m depth (125 km apart)

2. The geothermal gradient determines the density profile

The density of CO_2 changes strongly with temperature at the condition prevailing in the Utsira formation. There exist good temperature measurements in the oil and gas reservoirs in the North Sea, but at depths below 1500 m the measurements are scarce. A recent measurement at 769 m depth from water production well 15/9-F-7 at the Volve field (27.55 °C) and the temperature at 2600 m in the top of the Ty formation in the Sleipner field (101.7 °C) were used to model the temperature gradient. At shallow depths the paleoclimatic temperature oscillation due to the glacial cycles has to be taken into account because the penetration depth exceeds the Utsira formation depth. The temperature, T, at the surface (left Figure 2, black curve) follows a sinusoidal oscillation at with amplitude T_0, and angular velocity ω:

$$T(0,t) = T_0 \cos \omega t \tag{1}$$

The transport of heat is governed by the thermal diffusivity equation where D is the thermal diffusivity:

$$\partial T / \partial t = D \nabla^2 T \tag{2}$$

D is function of the rock properties; heat capacity, thermal conductivity and density and these will vary with the depth, z. The Earth's crust can be assumed to be a semi-infinite medium at depth $z > 0$. The boundary problem will then have the solution

$$T(z,t) = T_0 e^{-z/\delta} \cos(\omega t - z/\delta) \tag{3}$$

The quantity $\delta = \sqrt{2D/\omega}$ has the dimension of length and represents the characteristic penetration depth of the temperature variation. At this depth the variation the amplitude of the oscillation is reduced by e^{-1}. The first term in (3) describes the attenuation of the oscillation with depth, the second term describes the cosine oscillation, phase shifted *z/δ.* It may be argued the temperature cycles are not sinusoidal, but rather have a shape more like a square wave as there exists evidence for that some of the climatic changes have been relatively rapid. A square wave can be expressed as a Fourier series as a sum of cosines:

$$T(0,t) = T_0 (\cos \omega t - \frac{1}{3}\cos 3\omega t + \frac{1}{5}\cos 5\omega t - ...) \tag{4}$$

As the higher terms have both smaller amplitude and higher angular velocity (and accordingly smaller penetration depth), it would be a good approximation to consider the first term only as in (1). The period of the glacial cycle is 100 000 years (100 ka) and the surface temperature oscillates between minus 6 and plus 6 °C. It may be surprising that the surface temperature is lower than 0°C in the last glacial maximum if the North Sea was covered by glaciers, but there exists evidence that the Scandinavian and British ice sheets were separated 18 ka bp and due to the low water level, dry land was exposed to the cold atmosphere [4]. An example of the model is given at the Sleipner site with the physical data for the sand and shales from the sea floor at 82 m depth to the top of Ty formation at 2600 m depth given in Table1.

Table 1 Physical properties of the rocks above the Ty formation

	Thickness, m	**D, 10^{-7} m^2/s**
Sea depth	82	
1. shale bed	728	6.236
1. sand bed	13	2.936
2. shale bed	6	6.236
2. sand bed	245	2.936
3 shale bed	1526	3.020

The results are illustrated in Figure 2 where it is seen that the temperature oscillates more that 2 K at Utsira depths. The temperature gradient coincides with the measurement at of 37 °C at 1058 m which earlier has been questioned [5]. The temperature gradient is compared to suggestions from other authors and the differences are up to 7 K at some places in the reservoir. The corresponding density profiles are illustrated in Figure 3 and shows differences of a factor of almost 5 in the shallow regions and 75% difference near the top of Utsira at Sleipner.

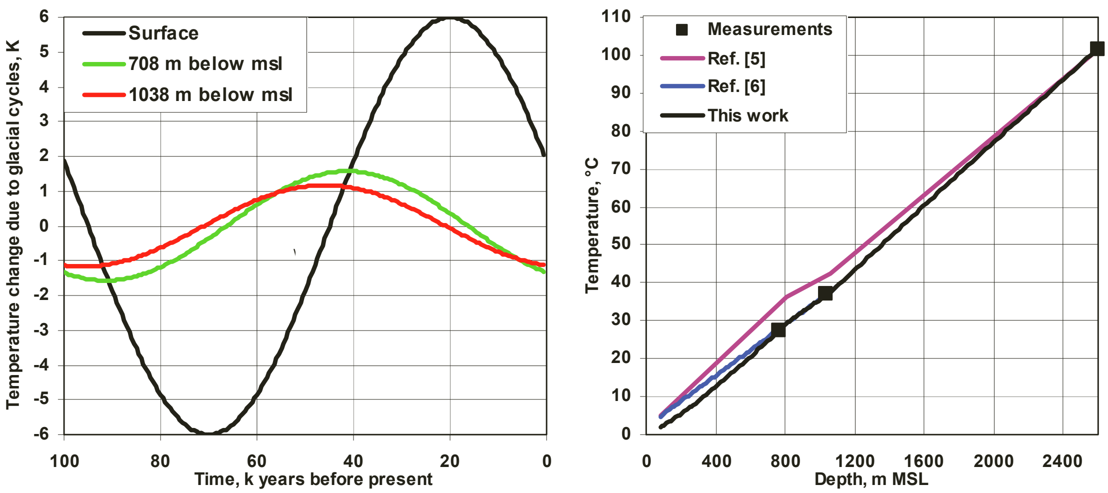

Figure 2 Temperature oscillations due the long glacial cycles (left). The resulting geothermal gradient compared with other works (right)

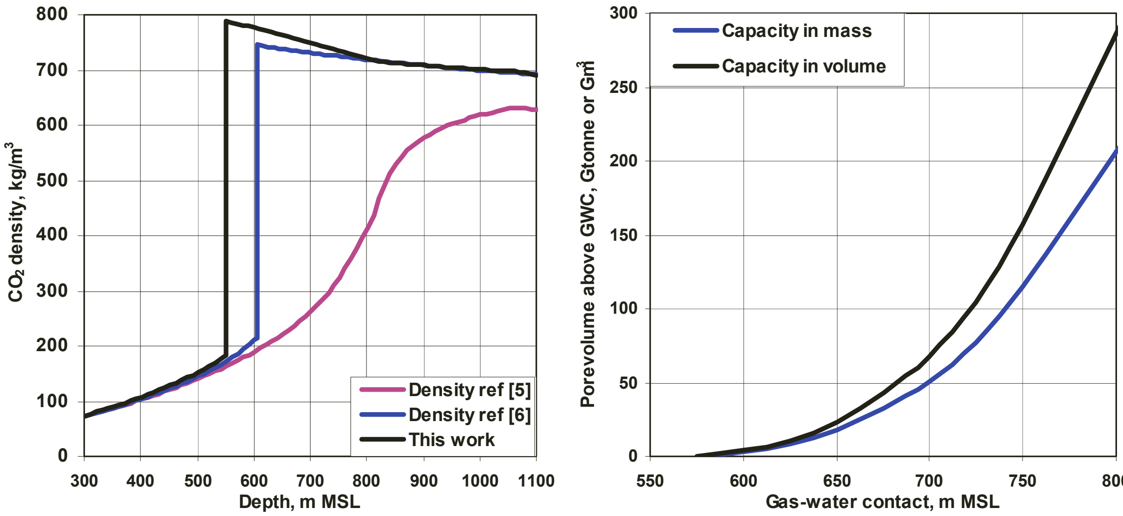

Figure 3 The density of CO_2 as function of depth (right). Pore volume as function of GWC in shallow regions of Utsira (right)

2. Storage capacity in the shallow regions of Utsira formation

By simply looking at the topography in the shallow region of Utsira and "filling" these regions by gradually moving horizontal CO_2-water contact and calculate the corresponding gas volumes a simple maximum estimate of the storage capacity in these regions can be estimated as illustrated in Figure 3 (right). The extensions of the CO_2 plume at four different CO_2-water contacts are illustrated in Figure 4.

There are, however, three important conditions that have to be met to realize this storage space and the three first will be studied in detail while the third will be generally discussed:

- The CO_2 plume must not exert an overpressure to the cap rock that exceeds the rupture pressure of the shale.
- It must be possible to fill the space by a near gravity stable displacement
- Sufficient water has to be produced to limit pressure build up
- The out-shaling of the western boundary has to be tight

To study possibility that large overpressures may risk the seal integrity in the shallow part of the formation a detailed modelling of the phase behaviour for three different temperature gradients in a growing CO_2 column reaching form the must shallow point (492 m) to the CO_2-water contact has been performed by assuming hydrostatic equilibrium. The overpressure was modelled by an accurate equation of state for CO_2 [7] and the results are illustrated in Figure 5. As the column height increases the pressure increases rapidly due to the low density. When certain overpressure is reached the vapour will start to condense as the column increases and no pressure increase will occur until all gas has condensed. The pressure will then continue to increase, but following a more gently slope corresponding to the hydrostatic head from CO_2 in dense phase. The overpressure for a 180 m CO_2 column in a temperature gradient modelled in this work is 4 bars which constitutes no risk for rupturing of the sealing shale. The phase behaviour shows a peculiarity at the lowest temperature gradient. At the start of the condensation the CO_2 will condense only at the top creating an unstable gas column. Liquid CO_2 will flow down the column and vaporize while more CO_2 is condensed at the top. This will continue until the gas column has reached a height of 38 m indicated as the inversion depth in Figure 5. Similar effects were not observed for two other temperature gradients were the CO_2 condensed at the bottom of the column.

The feasibility of filling the dipping structure effectively depends on the injection rate and the critical rate for obtaining stable displacement. Because both dip angle, typically 0.4°, and the density difference (typically 250 kg/m^3) are small, the critical rate for obtaining gravity stable displacement is also low [8]. This is tested by a simulation of CO_2 injection into one of the shallow regions from only one injection well with a rate of 10 Mt/year. The 3D reservoir model was constructed similar as [10], but with a density model corresponding to the results above and covering the whole Utsira formation. With a vertical mesh of 500 m x 500 m this gave approximately 1 million

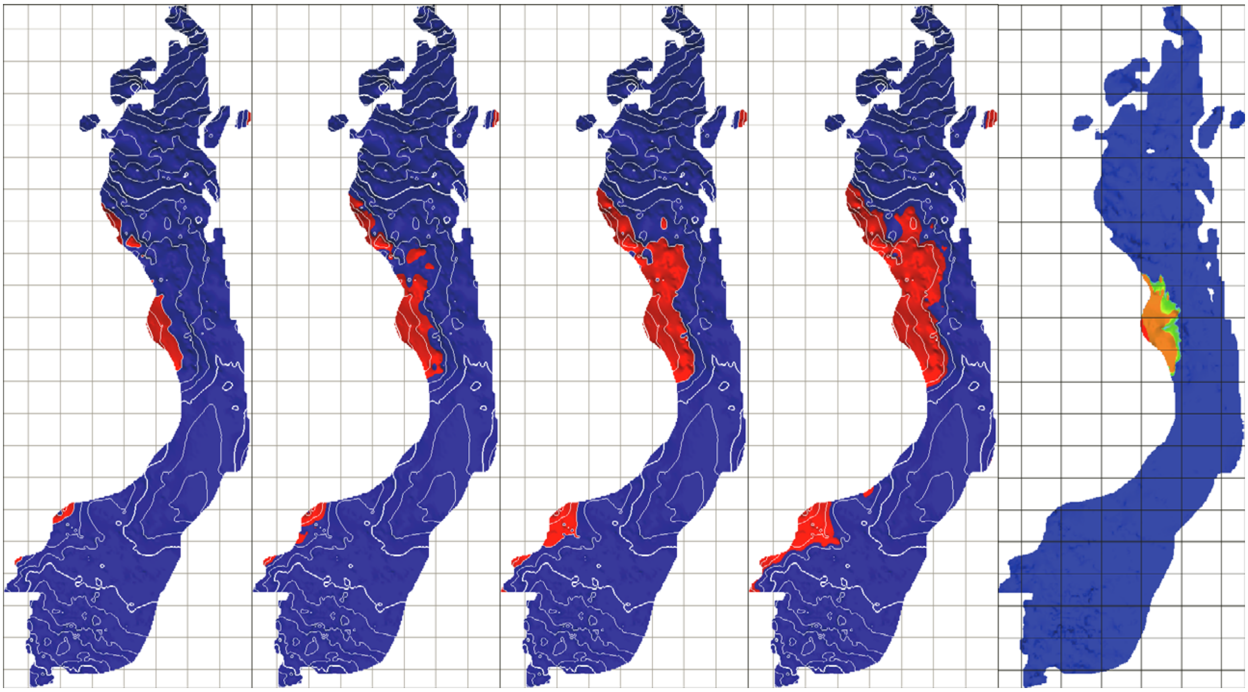

Figure 4 Extension of CO_2 plume with a CO_2 water contact of respectively 600, 625, 650 and 675 m depth. The 5th figure illustrates the distribution of CO_2 from a reservoir simulations injecting totally 1.5Gt with a single well over a 150 year period.

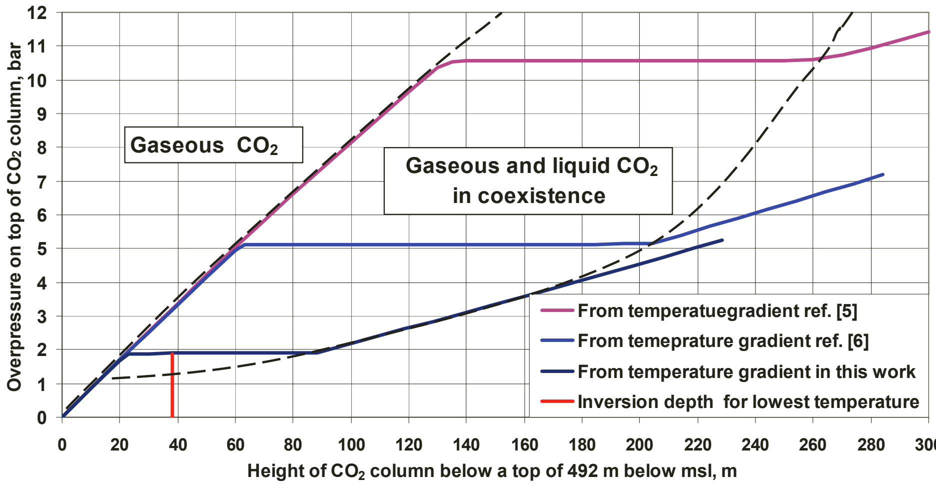

Figure 5 Overpressure under the cap rock and phase behaviour in the CO_2 column as function of column height. Coexistence between liquid and gaseous CO_2 can only occur between the stippled lines

grid blocks. The results are illustrated in the map in Figure 4 (rightmost) and the profile in Figure 6 and shows that the displacement is not gravity stable at this injection rate from one well as a tongue of CO_2 is propagating faster than the flatter part of the CO_2-water contact marked with the dashed line. By distributing the injection to all the shallow fingers in the western region, it will take approximately 300 years to utilize only 4-10 Gt of storage capacity. This storage concept is therefore not feasible for an optimal utilisation of the pore volume. Even with this limited CO_2 injection, it will be necessary to control the reservoir pressure water production to avoid pressure build up that may compromise the integrity of the seal. This will be discussed more in detail in next paragraph

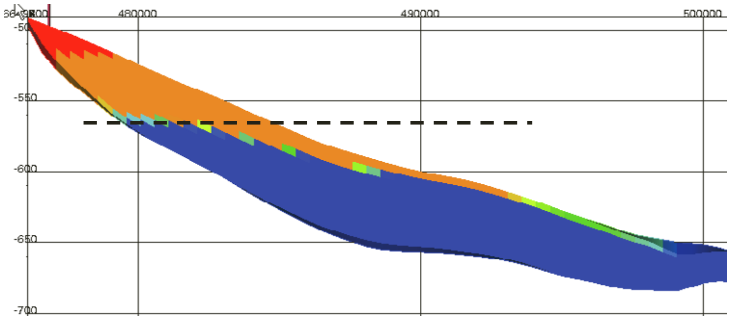

Figure 6 Filling of one of the shallow Utsira finger with an injection rate of 10 Mt/ year (1.5 Gt totally injected). The height is exaggerated 50 times to bring the details of the propagating CO_2 tongue

3. Distributed storage in the whole Utsira formation

A totally different approach of storing CO_2 in the Utsira formation is to inject CO_2 in several wells evenly distributed in the whole formation. This was tested with a set of scenarios with 210 injection well and another set with 70 injection wells distributed in a rectangular pattern with a second grid of water producers placed in between, corresponding to the 5-spot pattern known from onshore oil production. The distance between injection wells and producers was 7 km in the first and 13 km in the second scenario. The location of the wells was strictly geometrical and no measures were taken to optimize their location with respect to the topography of the cap rock. The reservoir model was the same as descried in previous paragraph. In the simulation tests CO_2 was injected in the bottom of the formation (similar to Sleipner) and also the water producers were perforated the bottom to reduce the risk of CO_2 break through. In all cases the injection period was selected to 300 years corresponding to a time horizon well within an expected era for fossil fuels. The total injection rate was 0.15 Gt/year and typical distribution of CO_2 are illustrated in Figure 7 for the two cases injection of 13 Gt CO_2. A few poorly located water producers had to be shut in to avoid CO_2 production. These were typically located in the thinner parts of the formation. The water was assumed to be produced directly into the sea requiring a minimum of infrastructure support. An emission permit for 160 Mt per year Utsira formation water (3% brine) would be required. Millions tonnes of water containing up to 40 ppm oil is today being disposed into the North Sea from oil production. A permit for emission for the relatively pure brine could therefore be expected.

The key challenge is to control the pressure and at the same time minimising co-production of CO_2. A few different configuration of the water production wells were tested with different length of the perforation and also including also horizontal wells with long perforations. With long horizontal perforations it was possible to limit the pressure increase to 2 and 9 bars for respectively 210 and 70 wells configuration. This is illustrated in Figure 8 were the average reservoir pressure is plotted versus time for the first hundred years of injection. Some of the data and results are summarised in Table 2. For reference the CO_2 injection rate at Sleipner has been maximum 1 Mtonne per year.

Table 2 Summary of some data and result from selected scenarios

Number of wells	**70 injectors 70 producers**	**210 injectors 210 producers**
Average injection rate per well, Mtonne pr year	2.258	0.752
Aver. incr. in reservoir pressure, bars (best case, horizontal wells)	2	9
Aver. incr. in reservoir pressure, bars (worst case, short perforations)	16	75

The pressure build up under the cap rock is evenly distributed and no local pressure build up was observed near the injection wells. The pressure drop controlling the total pressure in the reservoir is the near-well pressure gradient at the water producers. The injection rate will be different for each well due to the varying reservoir properties throughout the Utsira formation. In the case with fewest wells the maximum injection rate for any wells was less than 6 Mt CO_2 per year. To optimise the scheme economically the wells located in the thinnest part of the formation could have been omitted since they contribute with a very small fraction of the injection capacity In the case with the larger well spacing, the water producers had to be perforated not only in the bottom, but in 80% of the lower part of the well to achieve safe pressure operation. This made the wells more prone to gas coning and more wells had to be closed during the 300 years injection period than in the scenarios with the horizontal production wells. The cases with only 70 production wells required a tighter programme to control CO_2 break-through than in the for the case with 210 wells were interventions was necessary at periods longer than a typical life-time of a well.

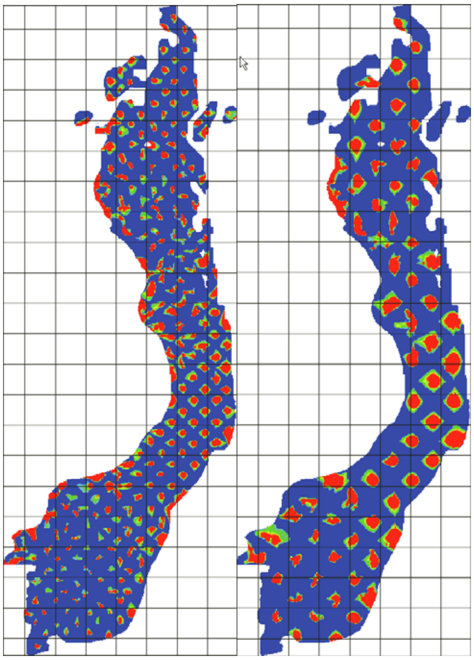

Figure 7 Distribution of CO_2 after injection of 13 Gt of CO_2 have been injected for the 210 well (left) and 70 well (right) scenario

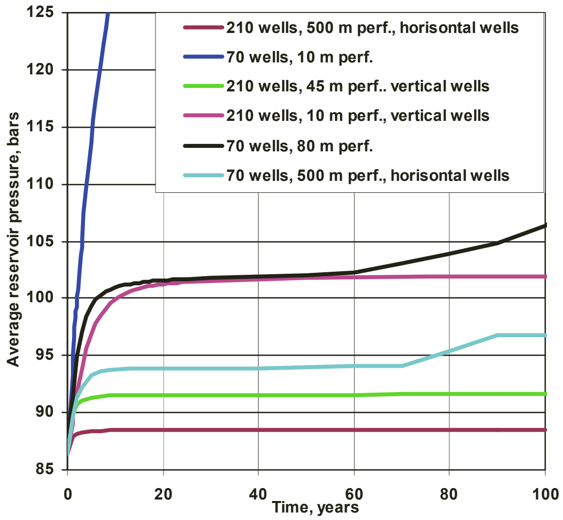

Figure 8 Average reservoir pressure for the first 100 years of injection for different configuration on the water production wells. The pressure stabilizes after typically 10 years. The humps on the curves thereafter are associated with shut downs of wells to avoid break through of CO_2 into the production wells. Except for one case with poor configuration of the wells, the pressure increase varies from 2 to 16 bar which are all within safety pressure limits to avoid fracture of cap rock

4. Discussion

A strict control of the pressure in Utsira by production of water during in injection period will be necessary to avoid risk that the sealing integrity cap rock if any significant fracture of the pore volume should be utilised for storage. The maximum design pressure should be selected from geomechanical criteria at the point of Utsira that is most shallow (approximately 500 m) because the pressure diffuses vary rapidly throughout the formation. This will also comply with an optimal management of the aquifer storage resources since it must be assumed that these resources will be limited in case CO_2 injection will be applied in large scale to combat climate change.

In this study it was assumed that the seal of the whole Utsira formation is tight and that it can withstand an overpressure of 15 bars. The formation was assumed to be totally closed and in no communication to neighbouring or deeper aquifers. To verify the sealing integrity further exploration and tests have to be performed. In the reservoir model the intra Utsira shales was not included as separate layers, but the vertical permeability was modified to give the same effective vertical permeability as on Sleipner CO_2 injection project. To further optimize the injection strategy CO_2 could preferably injected in the top to avoid that any low permeably shale in the bottom of the formation could short tracked the CO_2 to any water production well. Due to that no optimization of the well location has been performed some well was suboptimal located. By relocating some wells from regions where the reservoir is thin to regions where the reservoir is thicker a more aggressive utilization of the pore volume will be achieved. The CO_2 plumes will expose approximately one to two hundred exploration wells and the exact location and status of these wells should be mapped for planning a monitoring programme associated to the project.

This study is not a suggestion for a specific utilisation of the Utsira formation, but a conceptual study to illustrate the basic ideas of pressure control in a large aquifer and various operational challenges that have to be met. Any conflicts with other industrial activities in the area have not been considered.

5. Conclusion

As the storage capacity especially in the shallower region is critically dependent on the phase behaviour of CO_2 a modelling of the geothermal gradient with emphasis on the Miocene and Pliocene strata where CO_2 may accumulate was performed. The geothermal model included the transient temperature changes due the long glacial cycles because they have a penetration depth that affects the Utsira formation. The results showed that CO_2 can be stored in dense phase up to a depth of approximately 500 m below mean sea level which is significantly shallower than previously suggested. If a significant fraction of any closed aquifer shall be utilised for storage the pressure has to be controlled by production of water out of the aquifer to avoid pressure build up that could jeopardize the integrity of the sealing rock. The storage capacity of the Utsira formation was studied both by static volume estimates and by reservoir simulation of injection with up to 210 injection wells distributed over the whole formation. The results showed that it was possible perform both pressure control and CO_2 break-through control in the production wells by simple means. There is no exact limit of the storage capacity in the Utsira formation because it is an economic optimization of the well and infrastructure that will determine the optimal filling over a very long time perspective. Similar to oil production a higher "yield" can be achieved by closer well spacing. The results indicate that a cost effective utilization of the reservoir could be in the range of 20 to 60 Gt.

The concept with pressure control by simultaneous CO_2 injection and water production should be applied generally when CO_2 storage is applied in large scale. This is motivated both from a safety aspect and the aspect of optimal management of a limited resource.

Acknowledgement

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