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STORAGE OF CARBON DIOXIDE IN AQUIFERS IN THE NETHERLANDS

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Abstract

This paper presents the results of a study about the technical feasibility of the underground storage of carbon dioxide (CO_2) in aquifers. Special attention was paid to physical processes, limiting geological conditions and geochemical and environmental aspects. The CO_2 storage capacity of aquifers below the Dutch onshore is estimated based on these results. In addition, the long-term CO_2 storage potential of a hypothetical CO_2 storage reservoir is estimated.

1. INTRODUCTION

The investigations were commissioned by the Dutch Ministry of Housing, Physical Planning and Environment and the Dutch National Research Programme on global air pollution and climatic change. This study of the technical feasibility, limiting geological conditions and consequences of carbon dioxide storage in aquifers was carried out as part of a programme entitled: A preliminary research programme for CO_2 removal and storage.

2. DISPLACEMENT BEHAVIOUR

In order to elucidate the dispersive character and the fluid flow mechanism of CO_2 in an aquifer system we have unravelled the individual mechanisms affecting the displacement process. In general, the dispersion or spreading out of CO_2 in an aquifer can be described at three different scales: pore-scale, stratum-scale, and reservoir scale. Each scale is characterized by a particular process. Although smaller scale processes are active in the dispersion process at reservoir-scale, they will play only a minor role. All the processes and/or effects are understood and well described in the literature. For further information, the reader is referred to publication of van der Meer[1].

If CO_2 is injected into an aquifer, it will be able to displace the pore water in the aquifer to a large extent. The displacement process is determined by many individual mechanisms related to fluid properties and the specific conditions of the rock matrix. One of the most important parameters in this displacement process is the relative ability of the two fluids to flow in the porous medium. This property is referred to as the relative mobility of the fluid. When one fluid displaces another, the mobility ratio (M) of the displacement is defined as the mobility of the displacing fluid divided by the mobility of the displaced fluid. For average reservoir parameters, we calculated M=40 for an aquifer at 800 metres depth and M=13.2 for an aquifer at 1800 m depth. This means that CO_2 is 13 to 40 times as mobile as the formation water and because the CO_2 is pushing the water, it tends to by-pass the water.

The effect of one fluid being displaced by another can be considered as a complex process. The large differences in the physical properties of the three main items (two fluids and the reservoir rock) for the adopted range of depths make it difficult to predict the results of their interaction in a displacement process. A CO_2/water displacement process will be dominated by a gravity segregation effect. A layered permeability distribution i.e. a large kv/kh ratio will have a negative influence on the upwards migration of CO_2.

The calculated mobility ratios for a process in which CO_2 displaces water enable us to predict substantial viscous fingering effects. The resulting areal sweep efficiency will be in the order of 25 to 60 %, whereas the vertical sweep efficiency will be very small (in the order of 2-25 %), due to the combined effects of gravity segregation and viscous fingering. With the exception of the permeability distribution, all other small and medium scale effects will have an insignificant influence on the displacement process.

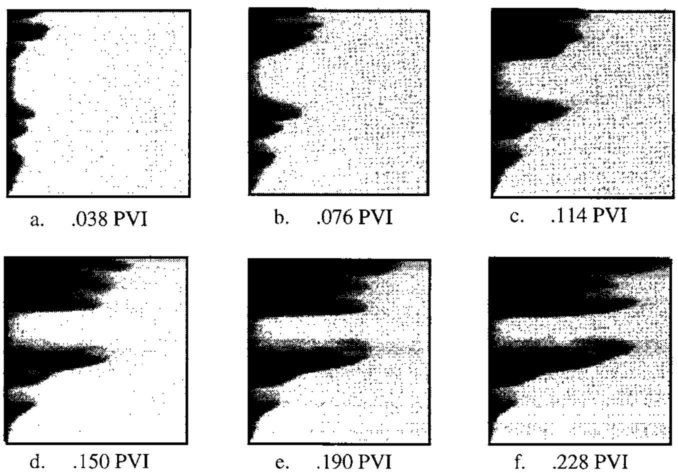

Fig. 1. *Results of numerical displacement simulations. Concentration distribution maps for increasing time slices. (PVI = Pore Volume Injected)*

3. GEOCHEMICAL ASPECTS

Two types of geochemical processes are associated with the injection of CO_2 in deep-seated aquifers. The first is enhanced dissolution of carbonate minerals due to an increase in the dissolved CO_2 in formation water. The amount of dissolution is almost independent of depth (and temperature) for depth below 750 m. The total groundwater composition is not greatly affected by this process. Effects on aquifer properties (permeability and porosity) are also small. The second process relates to the characteristics of electric double layers of clay minerals. The double layer thickness of (swelling) clay minerals depends on the di-electric constant of the fluid present. The change from water to CO_2 as pore fluid may lead to a decrease in double layer thickness for swelling clay minerals such as smectite. This may effect the aggregate structure of clay minerals. Unfortunately, no applicable information was available on this topic. Clay minerals with a swelling interlayer may shrink. The associated consequences for the permeability of the aquifer and the sealing characteristics of cap rock need to be investigated.

4. LIMITING ASPECTS OF CO_2 INJECTION IN AN AQUIFER

Much information about aspects limiting fluid injection in the subsurface was obtained from the practice of flooding with water when extracting oil. Flooding with water is the main fluid injection method. This information yielded two possible limiting aspects in respect to CO_2 storage in aquifers: well/formation damage and injection pressure.

Laboratory and field studies indicate that almost every operation that has to do with drilling, completion, workover, production, particle induction and stimulation are a potential sources of damage to well injectivity. After evaluating all possible causes of well damage, we have concluded that well damage can have no direct limiting effect on CO_2 injection. All problems associated with well clogging or well damage are understood and technically solvable.

The injection of fluids into an aquifer will result in an increase of the fluid pressure of the aquifer: this causes the grain pressure to decline. This shift in pressure regime can cause fracturing of the rock matrix, opening up existing faults and/or induction of microseismicity. These effects depend largely on the mechanical properties of the reservoir rock. If the average aquifer pressure exceeds the overburden pressure, there is a risk of absidence.

5. ENVIRONMENTAL ASPECTS

The major risks of the underground storage of CO_2 are suffocation, groundwater acidification and pollution, and damage by CO_2 blow outs or absidence of the earth's surface. If large amounts of CO_2 leak to the surface they will create blanket-like cloud of CO_2 that fills topographic depressions. Since this CO_2 will drive away all oxygen, any people or animals that enter theses areas may suffocate. Malfunctioning of the CO_2 injection system can be reduced by the use of appropriate materials and by intensive maintenance. A simple additional device, integrated in the pressure monitoring system, could shut off the failing subsystem from the rest of the system and limit the emission of CO_2 to minimal quantities.

If large amounts of CO_2 escape the reservoir rock and invade the subsurface, the groundwater may be affected. Groundwater naturally contains CO_2. Escaped CO_2 could increase the natural CO_2 concentration of the groundwater. A tenfold increase of CO_2 concentration in the groundwater will decrease the pH number by 1. The risk of CO_2 escaping from a storage location can be reduced by introducing peripheral observation wells.

As a result of manmade pressure changes in the subsurface the earth's surface may gradually sink or rise. A symptom of these changes is the occurrence of microseismicity. Several cases of sinking or subsidence are well known and have been extensively documented. The data on the occurrence of absidence is limited but it is understood that the same theories as for subsidence can be applied. Regular monitoring of the possible rise of the earth surface is recommended.

6. SUBSURFACE ASPECTS

The similarities between natural gas storage in aquifers and CO_2 storage in aquifers are obvious. The technical reservoir engineering knowledge gained in underground gas storage can be directly applied. In the following sections the subsurface aspects of CO_2 storage are discussed, using a hypothetical aquifer. We deal with subsurface aspects from the surface downwards.

From the results of calculations it can be concluded that all the pipeline diameters we investigated (4.0-7.0 inch) are capable of delivering the CO_2 at the aquifer injection location. A smaller pipeline diameter or an increased injection flow rate will reduce the CO_2 delivery pressure at this location.

lopment during these two time periods. A simulation model was constructed, representing a 30x30 km part of the subsurface. An injection period of 50 years followed by a shut-in period of 100 years was simulated.
Figure 3. shows the results of this simulation run. The delta CO_2 distribution map shows only the upper part of the subsurface model. The observed CO_2 bubble diameter at the top of the storage location can be estimated as 16 km at the end of injection period and grows to 18 km during the shut-in period. CO_2 movements are only active if there are large differences in pressure between the injected CO_2 bubble and the constant pressure boundary of the model. From the simulation results it can be concluded that CO_2 storage in a quasi-infinite aquifer is possible. It is however impossible to define a storage efficiency factor due the infinite nature of the storage location.

From all simulation work performed it can be concluded that the suitability of aquifers depends entirely on their size, within the boundary conditions stipulated. Displacement process will be dominated by channelling, viscous fingering and gravity segregation.

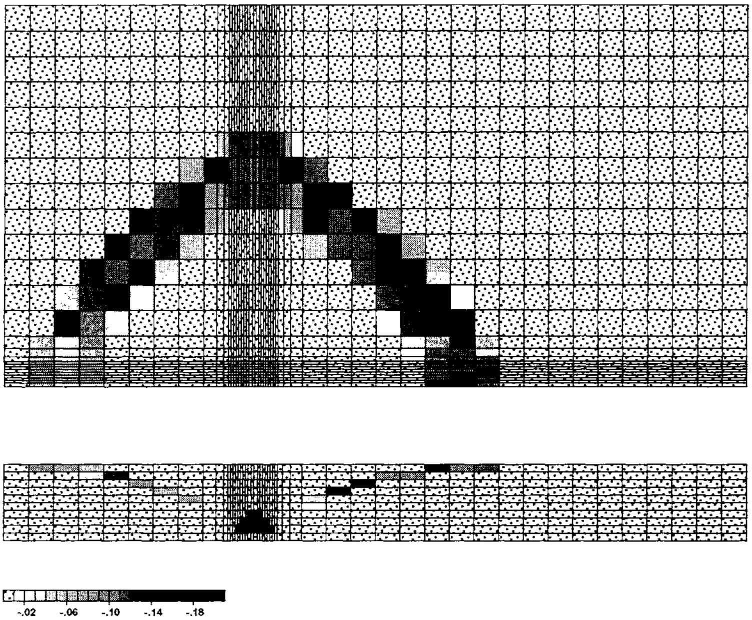

Fig. 3. *Map of the difference in CO_2 concentration between 150-year map and the 50-year map*

7. CO_2 STORAGE CAPACITY IN THE NETHERLANDS

The underground CO_2 storage capacity of the Permian to Quaternary aquifers of the Dutch onshore has been estimated from published data about the subsurface. First, an inventory was made of potentially suitable aquifers for CO_2 disposal (permeability > 50 mD, a depth below 800 m and covered by cap rock) and information was gathered on net reservoir thicknesses

We investigated the sensitivity of aquifer parameters and the scale of the CO_2 injectivity in an aquifer. A computer program was written to compute the pressure at increasing drainage radius as function of the permeability and the skin factor. Analysis of the results clearly shows that the aquifer permeability and the well skin factor are the controlling parameters of a CO_2 aquifer storage operation. It was observed that in nearly all cases when the permeability is 0.025 μm^2 there are large pressure gradients near the well bore. Clearly, the overall aquifer permeability will play a decisive role when selecting potential aquifers for CO_2 storage .

An aquifer in the Netherlands was selected to investigate and estimate the technical reservoir aspects of CO_2 storage in aquifers. (Aquifer data: porosity Brussel sand 30 - 36 %, permeability .05 - .6 μm^2, thickness 50 m). From the outset it was assumed that 6 wells would inject 15 000 ton a day of CO_2. This, in combination with the domed shape of the aquifer under study, makes it possible to reduce the simulation model to one-sixth of its original aquifer size. A pie-slice segment, with an angle of 60 degrees, was selected. The results of the CO_2 storage simulation runs reveal that CO_2 will breakthrough at the spillpoint after a cumulative CO_2 injection of 5.921×10^9 Nm^3. The results clearly indicate that the CO_2 distribution is dominated by gravity segregation. If we compare the results of the theoretical storage volume calculation with the results of simulation, than only 4.3 % of the volume is used. Figure 2 is a graphical representation of the model selection procedure and shows in cross section the CO_2 distribution at breakthrough. A further parameter sensitivity study[2] has shown that the CO_2 storage efficiency of a predefined part of an aquifer is small. For practical purposes a CO_2 storage efficiency of 1 to 6 % can be used, depending on the vertical transmissibility of the potential reservoir.

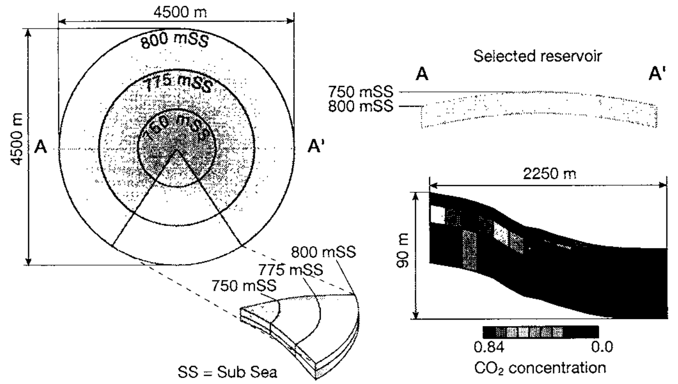

Fig. 2. *Selection of simulation model, and the simulation results.*

All the above work and reported efficiency factors refer to predefined storage locations with a known maximum storage volume, i.e. a storage location within a geological trap and an outer storage boundary. However, large aquifers without a geological trap structure are known to exist.

If we relax the trap constraint it will be essential to uphold the constraint that the aquifer will need a impermeable top layer to prevent any CO_2 from leaking out through the top of the aquifer. The omission of a trap and the presence of a top seal will require the size of the CO_2 bubble to be controlled during the active injection period as well as in the subsequent period of storage. We performed a limited simulation study to investigate the CO_2 bubble size deveand porosities. Next, the percentage of the volume confined by traps was assessed by determining the area occupied by closed structures on available depth maps and extrapolating these data to the entire Dutch onshore. Finally, the storage capacity was calculated from the trapped pore volume, assuming a CO_2 occupation of 2% and a CO_2 reservoir density of 700 kg/m^3.

The uncertainty introduced by extrapolation may be considerable. The Triassic structures in the study area, for example, are all related to salt tectonics. Similar structures do not occur elswhere in the Netherlands. In addition, we were not able to define stratigraphic traps (created by facies changes) or very large structures extending beyond the mapped area. This also forms a major uncertainty. The Permian aquifers, for example, are thought to be confined by large fault blocks below a thick package of Zechstein salt. These blocks are expected to form huge traps, but are not included in the storage estimate because they could not be defined.

We indentified more than 100 traps in those parts of the Netherlands where suitable depth maps were available. Of these only 50 traps are potentially suited for CO_2 disposal. The remaining structures are either too shallow or do not contain appropriate aquifers. The pore volume in these 50 traps is about 15.7 km^3, of which 2.1 km^3 contains oil or gas. Extrapolation of these results to the entire Dutch onshore leads to a total trapped pore volume of about 35.7 km^3. This corresponds to a CO_2 storage capacity of approximately 0.50 Gt .

Previous storage estimates were considerably more optimistic. Van Engelenburg & Blok[3] proposed a capacity of 40 to 82 Gt CO_2. Huurdeman[4] made an estimate of 2.5 to 10 Gt CO2. The discrepancy between these figures and ours can be readily explained by the use of different information and constraints. Van Engelenburg & Blok did not take into account the presence of trapping structures whereas Huurdeman assumed that the entire pore volume in a trap can be saturated with CO_2, an assumption that has to be revised in the light of the results of our simulation experiments.

8. CONCLUSIONS

1) CO_2 storage in aquifers is technically possible. The knowledge about the technology of CO_2 injection in aquifers is adequate, but there is a lack of reliable subsurface data.

2) The CO_2 water displacement will be dominated by gravity segregation, by channelling, and viscous fingering over the whole subsurface depth range investigated .

3) The CO_2 storage efficiency of a predefined part of an aquifer is small. For practical purposes a CO_2 storage efficiency of 1 to 6 % can be used, depending on the vertical transmissibility of the potential reservoir.

4) The storage capacity of traps on onshore aquifers in The Netherlands is estimated at 0.5 Gt CO_2.

5) The estimated CO_2 storage capacity of quasi-infinite aquifers in general is problematic. It can, however, be stated that they have a large potential.

References

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