4 Sequestration — The Underground Storage of Carbon Dioxide

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Abstract: Underground storage of industrial quantities of carbon dioxide in porous and permeable reservoir rocks has been taking place for the last 11 years at the Sleipner West gas field in the North Sea. A further commercial-scale CO_2 storage project has recently begun at In Salah, Algeria, and the Snohvit field, Barents Sea, is to begin injecting CO_2 underground in late 2007 or early 2008. A monitored CO_2-EOR project is underway at Weyburn, Canada and research scale injection projects have been undertaken at Nagaoka (Japan), Frio (USA) and K12-B (offshore Netherlands). This demonstrates that CO_2 can be successfully injected into underground storage reservoirs on a large scale. Natural analogues (natural fields of CO_2 and other buoyant fluids) demonstrate that under favourable conditions gases can be retained in the subsurface for millions of years. Although there is still very significant uncertainty in the actual figures, it appears that globally there is enough underground storage capacity for CO_2 storage technology to make a significant impact on global emissions to the atmosphere. Some other major issues that must be addressed if this technology is to spread to power stations, and thus make a significant impact on global CO_2 emissions, are the cost of CO_2 capture, further demonstrations of safe and secure storage and public acceptance that long-term storage will be successful.

4.1 Introduction

The major contributor to carbon dioxide (CO_2) emissions to the Earth's atmosphere is the burning of fossil fuels, which results in the emission of about 23×10^9 tonnes CO_2/year. One way to reduce our CO_2 emissions to the atmosphere whilst continuing to use fossil fuels is to retain a proportion of them in another domain of the planet rather than the atmosphere, for example the geosphere, via a process known as carbon dioxide capture and storage (CCS). If CCS with underground storage is to significantly reduce CO_2 emissions to the atmosphere, it will have to be carried out on a very large scale, safely and economically, with minimal trans-generational impacts on man or the global environment. There is considerable interest in the potential for CCS as a greenhouse gas mitigation option, e.g. the IPCC produced a Special Report on Carbon Dioxide Capture and Storage [103].

4.2 Required Storage Period

If it is to make a contribution to reducing CO_2 levels in the atmosphere, it would be desirable to retain any CO_2 stored underground permanently. After the end of the fossil fuel era, atmospheric CO_2 levels might begin a slow decline as ocean/atmosphere CO_2 levels re-equilibrate [98]. Clearly it would not be desirable for stored CO_2 to be released until there has been a significant decline in atmospheric CO_2 levels. Thus the next most desirable time frame for storage might be at least thousands of years [46]. Nevertheless, short-term storage of a few hundred years could be valuable in shaving the expected peak levels of CO_2 in the atmosphere that might occur towards the end of the fossil fuel era.

4.3 Practicality of the Underground Storage of CO_2

At the Sleipner West gas field in the Norwegian sector of the North Sea, approximately 1×10^6 tonnes CO_2 per year are being stored underground [56]. Some 10 million tonnes has been stored to date. CO_2 is also being injected underground in enhanced oil recovery (EOR) operations worldwide. The greatest concentration of such projects is in the Permian basin of west Texas, USA, e.g. [50, 88, 91], but the best monitored is at Weyburn, in Saskatchewan, Canada [96]. More recently, commercial-scale CO_2 storage projects have been started at In Salah, Algeria [78, 79] and reached the construction phase at the Snohvit field in the Barents Sea, off the shore of Norway [66]. Moreover, smaller demonstration projects have been undertaken at Nagaoka, Japan [53], Frio, Texas [49] and the K12-B gas field off the shore of the Netherlands [93]. Thus it is clear that it is technically possible to store CO_2 underground. However, this does not mean that underground storage can be carried out everywhere — a geologically suitable location is essential.

Short-term underground CO_2 storage is already being demonstrated at Sleipner. Long-term storage by man cannot be directly demonstrated but there are analogies in nature. There are many natural underground CO_2 fields around the world [e.g. 89]. These are identical to natural gas fields in every respect apart from their gas composition. Furthermore many natural gas fields contain varying quantities of CO_2 mixed in with the hydrocarbon gases [11]. Many of these fields of both pure CO_2 and CO_2/hydrocarbon mixtures have existed for thousands to millions of years. This proves that under favourable circumstances CO_2 can be retained underground for geological timescales.

The process of storing CO_2 underground can be divided into three major steps: capture, compression and transport, and injection into the subsurface.

4.4 Capture of CO_2 from Flue Gases

The most obvious places to capture CO_2 are at large industrial point sources such as power plants, cement plants and oil and gas refineries. Fossil fuel-fired power plants are the dominant industrial point sources in most countries. The CO_2 may be captured by pre-combustion techniques, such as the steam reforming of methane into CO_2 and H_2, with the H_2 being combusted and the CO_2 sent for storage [1]. Alternatively the fossil fuel may be combusted in an oxygen/CO_2 atmosphere, which results in a very CO_2-rich flue gas [52], or it may be captured post-combustion, from the flue gases of the industrial plant [4], for example by amine stripping. Even in coal-fired power plants the flue gases contain only a maximum of about 15% CO_2 and in natural gas-fired plant they commonly contain 3% CO_2 or less. It is necessary to separate CO_2 from the other components of flue gas before storing it because the available storage space beneath the ground would not be big enough to cope with the vast quantities of untreated flue gas that need to be stored to make a significant impact on global CO_2 emissions. Also, the work needed to compress flue gas would be too great a proportion of the total power output that could be obtained from the power plant. By contrast, pure CO_2 is relatively easy to compress.

4.5 Cost of CO_2 Capture

Costs for CO_2 capture from power plants (including compression for pipeline transport) are of the order of US$18 – US$72 per tonne CO_2 avoided,

= \$66 – \$264/t C avoided [25, 41, 42, 80]. However, there is great potential for technological improvements that can significantly lower costs and also the possibility of developing new types of power plants and power cycles [42]. Major joint industry projects are examining ways to reduce capture costs [e.g. 43].

Costs of CO_2 capture in other industries vary widely depending on the source and the percentage of emission reduction obtained [32, 34]. For example, in the cement industry, emission reduction costs are estimated to range between US\$50 and US\$250 t/CO_2 avoided (US\$183 – US\$917/t C avoided).

4.6 Energy Requirements for CO_2 Capture, Separation and Compression

The energy penalty associated with CO_2 capture and compression at power plants varies between 9% and 34% [42], depending mainly on the type of power plant considered. Given that a small percentage of the CO_2 emitted by the modified power plant is not captured, this results in the "net CO_2 avoided" being around 75% to 89% of the emissions of a base case plant that has not been modified for CO_2 capture.

4.7 Transport of CO_2

Because of the large volumes involved, the most likely means of transport for CO_2 between a large point source and a storage site would be by pipeline, as a liquid. However, it would be possible to use a ship to transport CO_2 to a sequestration site offshore [14] and this might be desirable for enhanced oil recovery operations because it would allow the CO_2 supply to the offshore installation to be intermittent.

CO_2 transmission pipelines already exist in the USA. These connect sources of CO_2 with EOR projects in the Permian basin, Texas. The longest is the McElmo Dome pipeline, which is some 800 km long [27]. For a 500 km delivery pipeline, assuming an infrastructure, costs are estimated at US\$7.82/t CO_2 [27]. For all pipeline systems, drying is necessary to prevent corrosion and the formation of CO_2 hydrates, and sulphur reduction may also be required.

4.8 Underground CO_2 Storage Concepts

The main concepts that have been put forward for underground storage sites for CO_2 fall into four categories: natural and man-made caverns, unused porous and permeable reservoir rocks, depleted oil and gas fields, and coal beds.

Realistically, storage in caverns and mines cannot make a significant impact on the greenhouse effect. The majority of mines are not leakproof, especially at pressures much greater than atmospheric. Most abandoned mines gradually fill with water, and any gas within them will eventually be forced out. The leakproof mines have alternative uses — for example, storage of documents, natural gas and chemical waste. Solution-mined salt caverns are also unsuitable as they are not stable in the long term because rock salt is a ductile substance that can creep and rupture under the in situ stresses within the Earth's subsurface.

4.8.1 Storage in Porous and Permeable Reservoir Rocks

CO_2 can be stored in geological formations by filling the intergranular pore space within rocks with CO_2. This is how oil, natural gas and indeed carbon dioxide, occur in the subsurface in nature. Porous and permeable sedimentary rocks (known as reservoir rocks) commonly occur in major accumulations known as sedimentary basins that may be up to a few kilometres thick and may cover thousands of square kilometres. However, although very common, sedimentary basins do not occur in every country in the world. Nor are all sedimentary basins suitable for CO_2 storage.

Pressure — Temperature conditions underground

The average temperature in many sedimentary basins increases by about 25–30 °C km^{-1} below the ground surface or seabed as a result of heat flow from the inside to the outside of the Earth. However there is considerable variation in such geothermal conditions, both locally within basins and between basins worldwide [6].

Pressure also increases downwards within the subsurface. Pressure in the pore spaces of sedimentary rocks is commonly close to hydrostatic pressure, that is, the pressure generated by a column of (commonly saline) water of equal height to the depth of the pore space. This is because the pore space is mostly filled with water and is connected, albeit tortuously, to the ground surface or seawater. However, under conditions where the pore space is either not connected to the surface, or not equilibrated to the surface, pressure may be greater than hydrostatic. Underpressure may also exist, either naturally, or as the result of abstraction of fluids such as oil and gas from a reservoir rock.

Physical properties of CO_2 underground

The physical properties of CO_2 define the density at which it can be stored underground [5, 6]. They are also relevant because large volume changes are associated with CO_2 phase changes.

When CO_2 is injected underground, there is a sharp increase in its density and corresponding decrease in volume at depths between approximately 500 m and 1000 m depending on the precise geothermal conditions and pressure [30] (Figure 1). This is associated with the phase change from gas to supercritical fluid. Consequently, CO_2 occupies much less space in the subsurface than at the surface. One tonne of CO_2 at a density of 700 kg/m^3 occupies 1.43 m^3, or less than 6 m^3 of rock with 30% porosity if 80% of the water in the pore space could be displaced. At 0°C and 1 atmosphere one tonne of CO_2 occupies 509 m^3.

Storage of large masses of CO_2 in shallow reservoir rocks is not so practical, because the physical conditions at shallow depths underground mean that relatively small masses of CO_2 would occupy relatively large volumes of pore space. Also, shallow reservoir rocks commonly have a more important use — groundwater supply.

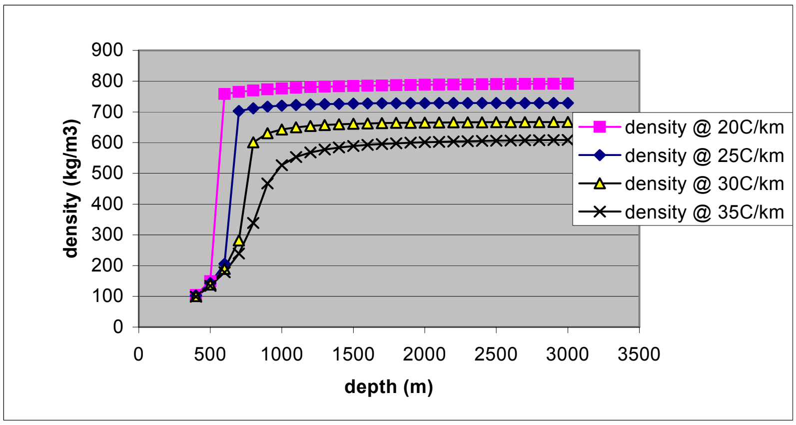

Fig. 1. Density of CO_2 at a range of geothermal gradients and CO_2 storage depths, assuming a hydrostatic gradient and a surface temperature of 10°C

4.8.2 Principles of Storage in Underground Reservoir Rocks

CO_2 can be injected into the porosity of a reservoir rock via a well or wells. CO_2 permeates the rock, displacing some of the fluid (commonly saline water) that was originally in the pore spaces. In order for injection and displacement of the native pore fluid to occur, the injection pressure must be greater than the pore fluid pressure. If the permeability of the rock is low or there are barriers to fluid flow within the rock (for example faults that compartmentalize the reservoir) injection may cause a significant increase in pressure in the pore spaces, especially around the injection well [92]. This may limit both the amount of CO_2 that can be injected into a rock and the rate at which it can be injected. For example, in Alberta, the maximum allowable injection pressure is 90% of the fracture pressure at the top of the reservoir [58]. This factor could make heavily compartmentalised reservoirs unsuitable for CO_2 injection.

Once injected into the reservoir rock, the processes of migration and trapping begin. The injected CO_2 is buoyant and migrates towards the top of the reservoir until it reaches the cap rock. A fraction of it may be retained in traps formed by internal permeability barriers within the reservoir, and these also make the migration path of the CO_2 through the reservoir more tortuous. The cap rock at the top of the reservoir retains the CO_2. Cap rocks can be divided into two categories: essentially impermeable strata such as thick rock salt layers (known as aquicludes) and those with low permeability such as shales and mudstones, known as aquitards, through which fluids can migrate, albeit extremely slowly [8]. The effectiveness of homogeneous cap rocks (or seals) is dependent mainly on their capillary entry pressure, which is essentially a function of the size of the pore throats connecting the pores within the rock and the fluid attempting to enter the rock. However, in real situations they also may contain faults or fractures that could cause them to leak. Methods for assessing the risk of imperfectly sealing cap rocks in petroleum systems are given in [90].

Providing the reservoir is big enough, it may not be necessary to inject CO_2 into a single large closed structure such as a dome, analogous to an oil or gas field, to ensure its safe and stable containment in the long term. When CO_2 is injected into a relatively flat-lying subsurface reservoir and rises to its top, it will be trapped in any small domes or other closed structures that occur on the underside of the cap rock. Once one of these structures becomes full, the CO_2 will spill from it and migrate to the next such structure along the migration path and fill that. Thus, as the CO_2 migrates within the reservoir, it may become divided into many small pools in many small closures.

Over time, depletion of these accumulations is likely to take place as a result of CO_2 dissolution into the contacted water in the pore spaces of the reservoir rock. Moreover, CO_2 will be trapped by capillary forces in pores and by adsorption onto grain surfaces along the migration path of the CO_2 within the reservoir. This “residual” CO_2 saturation along the migration path could be in the order of 5–30% [30]. The solubility of CO_2 in water depends on temperature, pressure and salinity [24]. For typical subsurface conditions, solubility of CO_2 in 1 M brine plateaus at about 41–48 kg/m^3 below 600 m depth. Increasing the salinity to 4 M decreases the maximum solubility to around 24–29 kg m^3 [30]. The solubility under typical reservoir conditions at a salinity of 3% will vary between 47 and 51 kg/m^3, corresponding to a volume of free CO_2 of 6.7 to 7.3% of the pore volume [61]. Thus, potentially, this is a very important storage mechanism if a large proportion of the formation water becomes saturated with CO_2 — the challenge is to achieve this.

The rate of dissolution will depend on how well the CO_2 mixes with the formation water once it is injected into the reservoir. Once a CO_2 accumulation has reached a stable position within the reservoir, diffusion of CO_2 into the water will be faster if it is a thin but widespread accumulation, with a high surface area to volume ratio [24, 30]. However, for many accumulations, dissolution could be slow, on the order of a few thousand years for typical injection scenarios [5], unless there is some form of active mixing induced by fluid flow within the reservoir [61]. Even so, if a relatively small amount of CO_2 is injected into a very large reservoir, the combination of a series of small traps and dissolution of the CO_2 into the formation water means it is unlikely ever to reach the edge of the reservoir, even if there are no major structures to trap it [e.g. 62]. This is the situation with the CO_2 from the Sleipner West gas field that is being stored in the Utsira Sand [101].

In other circumstances, the CO_2 may be hydrodynamically trapped [7, 8, 68]. Once outside the radius of influence of the injection well, the CO_2 will migrate in the same direction as the natural fluid flow within a reservoir rock. If it is a free gas within the reservoir, it will migrate faster than the brine (the native pore fluid) because it is less viscous. However, if it is dissolved it will migrate at the (commonly very low) rates at which natural fluid flow occurs within reservoir rocks. If the migration of the CO_2 is very slow and the proposed injection point is a very large distance from the edge of the reservoir, the CO_2 may not reach the edge of the reservoir for millions of years. Some of the CO_2 may also become trapped by chemical reaction with either the formation water or the reservoir rock (the latter will take place only over long timescales), the amount depending on the pore water chemistry, rock mineralogy and the length of the migration path [24, 35, 36, 82].

Thus, in the long term, the interaction of five principle mechanisms will determine the fate of the CO_2 in the reservoir. These are: immobilization in traps, immobilization of a residual saturation of CO_2 along the CO_2 migration path, dissolution into the surrounding formation water, geochemical reaction with the formation water or minerals making up the rock framework and, if the seal is not perfect, migration out of the geological storage reservoir. Escape of CO_2 from the storage reservoir may not necessarily be important, providing there is no adverse impact on man, the natural environment or other resources such as groundwater, and the required storage period is exceeded.

The amount of CO_2 that can be injected during a particular project or into a particular reservoir is limited by the undesirable effects that could occur. Some of these might be important in the short term, others may occur in much longer timescales, as the result of migration of the injected CO_2. They include: an unacceptable rise in reservoir pressure, conflicts of use of the subsurface (e.g., unintentional interaction with coal mining, or the exploitation of oil and gas), pollution of potable water by displacement of the saline/fresh groundwater interface, pollution of potable water by CO_2 or substances entrained by CO_2 (e.g., hydrocarbons), escape of CO_2 to the outcrop of a reservoir rock and escape of CO_2 via an unidentified migration pathway through the cap rock.

4.8.3 CO_2 Storage at the Sleipner West Gas Field

The Sleipner West gas field [19, 56] is in the centre of the North Sea approximately 200 km from land. The Sleipner West natural gas reservoir is faulted, with different pressure regimes and different fluid properties in the various fault blocks. The natural gas in the reservoir (mainly methane) includes between 4% and 9.5% CO_2. To get the natural gas to sales quality, the amount of CO_2 has to be reduced to 2.5% or less. In order for the gas to be exported under the Troll gas sales agreement, mainly via the Zeepipe export pipeline to Zeebrugge, which passes through Sleipner, this operation is carried out offshore. The gas is produced via 18 production wells drilled from a wellhead platform (Sleipner B) and transported to a process and treatment platform (Sleipner T) located next to and with a bridge connected to the main Sleipner A platform (Figures 2 and 3).

Around 1×10^6 tonnes of CO_2 are separated from the natural gas annually. This amounts to some 3% of total Norwegian CO_2 emissions. Rather than vent this CO_2 to the atmosphere, Statoil and partners made the decision

Fig. 2. The Sleipner T CO^2-processing platform (left) and Sleipner A platform (right) in the North Sea (Courtesy of Statoil)

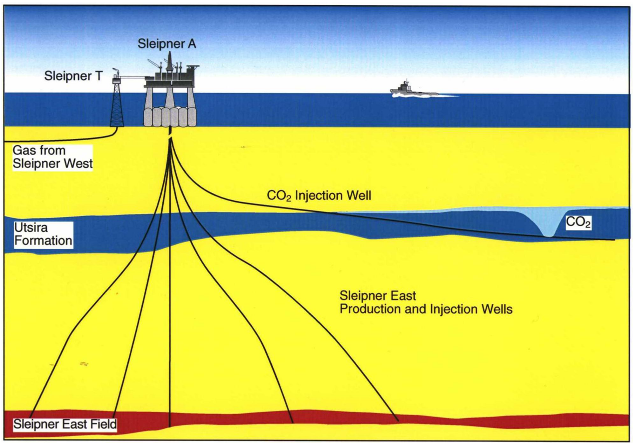

Fig. 3. Schematic cross section through the Sleipner CO^2 injection facility (Courtesy of Statoil)

to store it underground in the Utsira Sand. This is a sandstone reservoir approximately 150–200 m thick, at a depth of between 800 and 1000 m.

At the injection site, the cap rock consists of two parts: firstly a lower sedimentary unit consisting of more than 100 m of shale, the so-called “Shale Drape” that immediately overlies the reservoir, and secondly the remainder of the strata above the Shale Drape, which also appears to con-

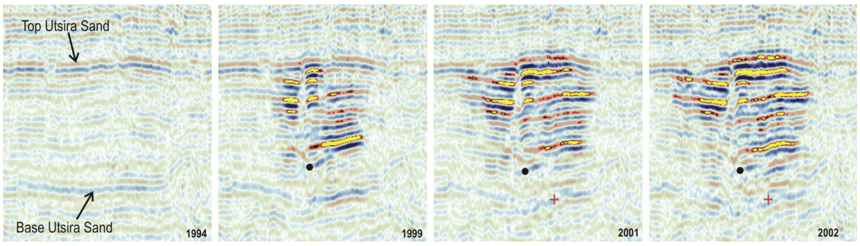

Fig. 4. Detailed time-lapse seismic images of carbon dioxide stored in the Utsira Sand at the Sleipner West field. The 1996 image was pre-CO^2 injection. The 1999–2002 images show successive increases in the amount of CO^2 stored in the Utsira Sand. The CO^2 is imaged as bright reflections corresponding to layers of sand with high CO^2 saturations accumulated beneath thin shale layers within the sand reservoir (Courtesy of the CO2STORE partners and Andy Chadwick)

sist predominantly of mudstones or silty mudstones. These strata effectively prevent the CO_2 from leaking back to the seabed and thus to the atmosphere.

CO_2 injection started in August 1996 and will continue for the life of the field (estimated to be approximately 20 years). Additional costs of the operation are about US$15/tonne of CO_2 avoided [42].

A demonstration project, acronym SACS, jointly funded by the EU, industry and national governments, and its successor, acronym CO2STORE, is currently evaluating the geological aspects of the subsurface disposal operation [2, 3, 12, 20, 64, 74]. This involves assessing the capacity, storage properties and performance of the Utsira reservoir, modelling CO_2 migration within the reservoir and monitoring the subsurface dispersal of the CO_2 using time-lapse seismic techniques. It is clear from Figure 4 that the underground situation is well-imaged; the CO_2 is currently trapped within the reservoir above and around the injection point. It has reached the base of the cap rock and is migrating horizontally beneath it. Seismic and reservoir modelling is now being carried out to further quantify and constrain the CO_2 subsurface distribution and predict its future behaviour.

The Utsira Formation appears to be an excellent repository for CO_2. It acts as essentially an infinite aquifer; fluid is being displaced from the pore spaces above the injection point without a significant measurable pressure increase at the wellhead.

4.8.4 Storage in Depleted or Abandoned Oil and Gas Fields

Oil and gas fields are natural underground traps for buoyant fluids. In many cases there is geological evidence that the oil or gas has been trapped in them for hundreds of thousands or millions of years. In such cases, they will not leak in the geologic short term (a few hundred to a few thousand years) providing their exploitation by man has not damaged the trap and the cap rock is not adversely affected by the injection of CO_2.

CO_2 is widely used for enhancing oil recovery in depleted oil fields [91] so it should be possible to sequester CO_2 in such fields and increase oil production at the same time [e.g. 9, 17, 48]. The production of additional oil would offset the cost of CO_2 sequestration. Approximately 2.5 to 3.3 barrels of oil can be produced per tonne of CO_2 injected into a suitable oilfield.

Some of the CO_2 used in EOR projects is anthropogenic; e.g., at Encana's Weyburn field in Saskatchewan anthropogenic CO_2 from a coal gasification plant in North Dakota [96, 97] is used. The progress of this CO_2 flood will be monitored from a CO_2 sequestration perspective. It is expected to permanently sequester about 18 million tonnes of CO_2 over the lifetime of the project. The Rangely EOR project in Colorado has also been monitored to determine whether CO_2 is leaking from the reservoir to the ground surface [54]. Further opportunities for EOR abound, especially if recent increases in the price of oil are maintained. There is undoubtedly significant potential in many of the world's major onshore oil provinces, for example the Middle East, and there may be potential in offshore areas such as the North Sea [16, 31].

The small amounts of CO_2 sequestered in such projects indicate that EOR would have to take place on a massive scale to have a significant impact on global CO_2 emissions to the atmosphere [88].

When natural gas is produced from a gas field, the production wells are opened and the pressure is simply allowed to deplete, usually without any fluid being injected to maintain the pressure. Thus, depending on the rate of water inflow into the porosity that comprises the gas reservoir, a large volume of pressure-depleted pore space may be available for CO_2 storage. In many cases there is little or no water flow into a gas reservoir. Therefore it may be possible to store underground a volume of CO_2 equal to the underground volume of the gas produced. Furthermore, there is a possibility that CO_2 injection could enhance natural gas production towards the end of field life.

4.9 What Is the Global Geological CO_2 Storage Capacity in Oil and Gas Fields and Saline Water-Bearing Reservoir Rocks?

The availability of sufficient storage capacity is one of the critical parameters that could decide whether the underground sequestration of CO_2 can be a major contributor to solving this century's greenhouse problem.

The storage capacity of oil and gas fields is relatively well-defined, being based on the principle that a proportion of the pore space occupied by the recoverable reserves of a field is, or will be, available for the storage of CO_2. As the pore volume of the field is well-known, the mass of CO_2 that could be stored in the total pore volume provides an upper bound, which can be discounted to take account of factors that might reduce the storage capacity of oil or gas fields. The global CO_2 storage capacity of oil and gas fields has been estimated to be 923 Gt [18, 86], equivalent to about 40 years of current global anthropogenic CO_2 emissions.

The storage capacity of saline water-bearing reservoir rocks for CO_2 can best be estimated on a site-by-site basis using reservoir simulation. This can take account of the main short- to medium-term storage mechanisms (physical trapping, either in a dome or similar closed structure or as residual CO_2 saturation along the migration path of a CO_2 plume, and dissolution) and of the potential for migration out of the storage reservoir. Unfortunately a sufficient density of appropriate data is commonly only available in oil and gas provinces, and large resources are needed to process it. Therefore high-quality estimates tend to be confined to relatively small areas such as a single closed structure in an individual formation. There are great difficulties in upscaling such estimates to obtain meaningful regional or global CO_2 storage capacity estimates because the CO_2 storage capacity of saline water-bearing reservoir rocks in individual sedimentary basins does not appear to be related to their area [85] or pore volume. Consequently, global capacity estimates have been calculated using simplifying assumptions that could easily be inappropriate. Region-, country- and basin-specific estimates are more detailed and precise, but affected by the same limitations.

Estimates of global or regional underground CO_2 storage capacity e.g., [13, 15, 38–40, 44, 47, 55, 92, 94] have produced a wide range of figures, indicating the existence of great uncertainty. This was recognised by Hendriks and Blok [47] who estimated world underground storage capacity to range between 400 and 10,000 Gt CO_2. Van der Meer [92] estimated a global capacity of 425 Gt CO_2 and Koide et al. [55] estimated 320 Gt CO_2.

Although there are many uncertainties with regard to global underground storage capacity for CO_2, it is likely to be large. Given that oil and gas fields occupy only a very small part of the saline water-bearing reservoir rocks in the world's sedimentary basins, it would be highly unlikely that the storage capacity of the latter would be less than the former. Thus total global storage capacity is likely to be sufficient for at least 80 years and probably much longer. In real situations, only a small amount of the theoretically available storage capacity will be used. For example, given a single or limited number of injection points, the migration path of CO_2 within a reservoir formation will determine how many of the traps within the reservoir rock can be filled with CO_2 [19] as those traps not on the migration path(s) will not be filled. Also, safety and stability of storage will have to be demonstrated, and economics, socio-political issues and issues relating to alternative uses of the subsurface will be involved.

4.10 Storage in Coal Beds

Coal beds (otherwise known as coal seams) can be reservoirs for gases. Coal contains a natural system of orthogonal fractures known as the cleat, which imparts some permeability, and although it does not contain significant conventional porosity it contains micropores in which a natural gas known as coalbed methane (CBM) can occur. This usually consists of >90% methane plus small amounts of higher hydrocarbons, CO_2 and N_2. The gas molecules are adsorbed onto the surfaces of the micropores. They are very closely packed and so bituminous coals can adsorb up to about 20 m^3 methane/tonne of coal [23].

The gas molecules in the coal micropores are held in place by electrostatic forces. These are much weaker than chemical bonds and sensitive to changes in temperature and pressure. If the temperature is raised, or the pressure lowered, gas will desorb from the coal [26]. Thus, if there is sufficient permeability within a coal bed, CBM production can be achieved by drilling a well into the coal bed, sealing it off from the surrounding strata and pumping water out of the cleat to lower the pressure within the coal bed.

Commercial CBM fields exist in the United States, e.g. in the San Juan basin (Colorado/New Mexico) and Warrior basin (Alabama) and also in Australia, e.g., in the Bowen basin. However, only a minority of coalfields are suitable for commercial CBM recovery using present technology, because economic production is only possible from coal beds with exceptional permeability. This could be a barrier to the coal seam sequestration option.

CO_2 has a greater affinity to be adsorbed onto coal than methane. Thus, if CO_2 is pumped into a coal seam, not only will it be stored by becoming adsorbed onto the coal, it may displace any methane at the adsorption sites [37]. Any methane recovered could have an economic value and offset some of the costs of CO_2 sequestration. Once adsorbed, the CO_2 is held in place and will not leak to the surface unless the pressure on the coal is reduced or the temperature increased.

Experiments have been conducted in the San Juan basin by Burlington Resources [77, 87, 99]. Over 100,000 tonnes of CO_2 have been injected into the Fruitland coal seams since 1996. The results of these experiments were encouraging (CO_2 injection does appear to have enhanced CBM production) [77] but inconclusive.

Nitrogen can also be used to enhance coalbed methane production. Nitrogen injections reduce the partial pressure of methane and thus encourage methane to desorb from the coal matrix. N_2 injection experiments by Amoco in the San Juan basin were highly successful, producing a large increase in methane production in a relatively short time. So it may be possible to enhance coalbed methane production by injecting flue gas (principally a mixture of N_2 and CO_2 with small amounts of nitrogen oxides and sulphur gases) into the coal beds.

Controlled experiments to test enhanced coalbed methane (ECBM) production using CO_2 [71] as a stimulant are under way in Europe [100], Alberta [37] and Japan [84].

However, the methane in coal represents only a small proportion of the energy value of the coal, and the remaining energy would be sterilised if the coal was used as a CO_2 storage reservoir; i.e., the coal could not be mined or gasified underground without releasing the CO_2 to the atmosphere.

4.11 Safety and Security of Storage

The question of whether safe and stable storage of CO_2 in the subsurface can be assured is probably the most important issue facing the underground storage of CO_2 at present, because this is likely to have a high impact on public acceptability and regulation.

To ensure safe and stable containment of the injected CO_2, a rigorous risk assessment process is required. One approach is to identify all the Features, Events and Processes (FEPs) that could affect the storage site [83] and then assess the risks associated with these. Prior to injection, detailed geological characterization of the selected site and surrounding area is needed. This should be used to help with the risk assessment process, for example by building geological models of the site, to provide information about the volume of the storage reservoir and any potential migration paths out of it. The geological data and models should also be used to construct numerical reservoir models that can be used to simulate the injection of CO_2 at the site and determine the likelihood, potential magnitude, timing and location of any CO_2 migration out of the storage reservoir or to the ground surface or seabed. This in turn should provide the basis for a monitoring plan and, if considered necessary, a remediation plan. Baseline monitoring surveys should also be acquired prior to injection.

Once injection starts, long-term monitoring would be needed to validate storage. Some types of data, such as the mass of CO_2 injected, need to be monitored continuously whereas other data, such as the distribution of CO_2 within the reservoir as imaged by seismic surveys, may only need to be acquired intermittently. Seismic reflection surveys, seismic attribute studies, gravity surveys, infra-red CO_2 detection equipment and data and samples acquired from wells are amongst the techniques being used for monitoring at present [e.g. 28, 68, 96]. Monitoring data should be history matched to predictions from the models to check whether the site is performing as predicted. If significant discrepancies are found, more geological data should be acquired and/or the models adjusted as necessary.

Once injection ends, it is considered likely that monitoring would continue for a significant period, until the operator and regulator are satisfied that the site is performing, and will continue to perform, as predicted. Site closure would then follow.

4.12 Impacts of CO_2 Leakage from Underground or Sub-Seabed CO_2 Storage

There are many places in the world where CO_2 naturally emanates from the subsurface [10, 45, 51, 72, 73, 76, 85] and many of these do not appear to pose a danger to man as long as the CO_2 does not build up in confined spaces such as housing. In general, natural CO_2 emissions in sedimentary basins are distinct from, and smaller than, those from volcanic and hydrothermal areas, where large amounts of CO_2 are sometimes present, and are commonly associated with high temperatures and steam at shallow depths. Natural emissions from sedimentary basins are therefore more likely to be useful as analogues for leaks from man-made CO_2 storage facilities than those from volcanic or hydrothermal areas. Studies of dispersion of CO_2 in the vadose zone and atmosphere [69, 70] also help to frame issues of potential impacts of leakage from underground storage sites. Cox et al. [22] noted that a major well failure in the injection period, when reservoir pressure was relatively high, could theoretically pose the danger of the development of a major cloud of CO_2 at the ground surface. However, a well blowout in a natural CO_2 field has occurred, was successfully controlled and did not cause significant damage to man or the natural environment [65].

Insights into safety and security of storage should also be gained from the study of engineering analogues for CO_2 storage and leakage such as natural gas storage facilities in aquifers [75]. Methodologies exist for determining storage security in natural gas storage projects, but these are generally significantly smaller than conjectured CO_2 storage schemes, and always confine the gas within a structural trap.

The Lake Nyos disaster [57, 59, 95] is probably the most infamous example of a major natural CO_2 emission. A description of it is included here not because it has great relevance to putative leakage from man-made underground CO_2 storage sites, rather to illustrate the low likelihood of such an event occurring as a result of purposeful storage, and the successful remediation that has taken place at Lake Nyos. Sometime during the late evening of August 21, 1986, a huge mass of concentrated CO_2 was emitted from Lake Nyos, a volcanic crater lake in Cameroon. A lethal concentration of the gas reached a height of 120 m above the lake surface, and the total volume of the lethal gas cloud may have been up to 0.63 km^3, equivalent to a mass of 1.24 Mt CO_2. It flowed out of the spillway at the northwest end of the lake and down the topographic slope, along two valleys. It killed more than 1700 people in a thinly populated area, and all animal life along its course as far as 14 km from the crater. This disaster was caused by a "limnic eruption" — a sudden release of CO_2 caused by the overturn of the 220 m deep lake, the lower part of which became saturated with CO_2 of volcanic origin, caused by a slow leak of CO_2 into the lake waters from below. The CO_2 dissolved in the water in the lower part of the lake, increasing its density. This resulted in the lake becoming stratified. The lake overturn may have been triggered by a long period of cool days that allowed cold surface water to build up and then sink, disturbing the density stratification.

Clearly the likelihood that an accident comparable to the Lake Nyos disaster could occur as a result of leakage from a man-made underground CO_2 storage facility must be considered. However, it should be noted that the topography around Lake Nyos appears to provide ideal conditions for the emitted CO_2-rich gas cloud to remain concentrated rather than disperse.

The CO_2 held in the lake waters was probably released in a few hours and would have hugged the ground rather than dispersing. High crater walls surround the lake on the east and west sides, and the natural water spillway in the northwest corner of the lake provides a natural outlet for the CO_2 into a valley system, where it would remain confined.

The sudden emissions of concentrated CO_2 from crater lakes in Cameroon are the result of slow emissions of carbon dioxide into relatively small, deep lakes. It would be relatively simple to determine whether any such lakes occur in the vicinity of a proposed CO_2 storage site and, if necessary, monitor them. Most lakes outside the tropics overturn seasonally, as a result of temperature changes in the surface waters, and so there may be less potential for stratification outside the tropics. Thus the possibility of an analogous event resulting from the leakage of CO_2 from a storage reservoir could easily be excluded. Furthermore, Lake Nyos is being degassed at the moment, precisely to prevent a recurrence of the tragedy [102]. A similar strategy could be adopted for any lake into which carbon dioxide leaked from a man-made CO_2 storage facility.

Finally, little is known about the long-term storage issues. The required storage period is greater than the likely lifetime of any corporation. This raises issues of ownership, monitoring and liability for leaks or man-made breaches of the storage integrity into the distant future. Because of the longevity of storage, it seems inevitable that ownership and liability would, at some stage, be transferred to the state.

4.13 Public Perception

A further major issue is whether people will find CO_2 sequestration underground an acceptable alternative to emitting CO_2 to the atmosphere. Research on perceptions of CCS is challenging because of: a) the relatively technical and “remote” nature of the issue, meaning that there are few immediate points of connection in the lay public’s frame of reference to many of the key concepts; b) the early stage of the technology, with very few examples and experiences in the public domain to draw upon as illustrations [84]. In a UK survey of public perceptions [84], it was found that on first hearing about carbon storage in the absence of information as to its purpose, the majority of people either do not have an opinion at all or are somewhat sceptical. Once (even limited) information is provided on the role of carbon storage in reducing CO_2 emissions to the atmosphere, opinion shifts considerably towards slight support for the concept. Support depends, however, upon concern about human-caused climate change, plus recognition of the need for major CO_2 emission reductions. It also depends upon CCS being seen as one part of a wider strategy for achieving significant cuts in CO_2 emissions. A portfolio including renewable energy technologies, energy efficiency and lifestyle change to reduce demand, was generally favoured. CCS can be part of such a portfolio but wind, wave, tidal, solar and energy efficiency were generally preferred as options. As a stand alone option, it was felt that CCS might delay more far-reaching and necessary long-term changes in society's use of energy. The notion of CCS as a "bridging strategy" to a hydrogen-based energy system was welcomed.

It was felt that uncertainties concerning the risks of CCS had to be better addressed and reduced, in particular the risks of leakage, of accidents, or environmental and ecosystem impacts, and any human health impacts.

Lenstra and van Engelenburg [60] pointed out that the current paradigm for environmental policy causes a negative reaction towards end-of-pipe solutions such as CO_2 removal when they are presented as a dedicated single technology. The authors suggest that CO_2 storage could be raised most appropriately as part of a wider debate along the lines of: "What do we the public think should be done about CO_2 emissions to the atmosphere?"

Clewes [quoted in 60] indicates the following perceived barriers to CO_2 capture and storage technology: The technology is in its infancy and unproven, it is too costly, not enough is known about the long-term storage of CO_2, the capture and storage of CO_2 are seen as being energy intensive, the option presents an enormous engineering and infrastructure challenge, and it is not a long term solution. Both Lenstra and van Engelenburg [60] and Clewes [quoted in 60] conclude that these barriers can only be overcome by R & D and effective demonstration of the technology. It will not be possible to overcome them by communication alone.

4.14 Conclusions

The underground storage of industrial quantities of carbon dioxide is technically possible, and CO_2 storage both in saline water-filled reservoir rocks and in oil and gas fields has reached the demonstration stage. However, it is important to bear in mind that the Earth's subsurface geology is an extremely variable natural system. So the question of whether important issues such as the long-term safety and stability of storage can be satisfactorily resolved is a site-specific one. Nonetheless, the indications are that underground CO_2 storage could have a significant impact on our greenhouse gas emissions, perhaps acting as a bridging technology to ease the transition from our fossil-fuel fired energy system to a low- or no-carbon energy system in the future. Consequently, this technology is being taken extremely seriously, for example by the UNFCCC through its subsidiary body the IPCC. Finally, for the UK, an international agreement to limit the rise in atmospheric CO_2 concentration to 550 ppmv would imply cuts in CO_2 emissions of around 60% by 2050 and perhaps 80% by 2100 [81]. The enormity of this proposition is illustrated by the fact that even the complete abandonment of power generation from fossil fuels would only result in about a 30% cut in emissions. However, it does suggest that the underground storage of carbon dioxide should be advanced urgently by both research and further effective demonstration projects.

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