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CO_2 temporary storage in big underground caverns

Začasno skladiščenje CO_2 v velikih podzemnih kavernah

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Abstract

After the CO_2 has been captured at the source of emission, the CO_2 would have to be transported to the storage site using different technologies. In some countries (i.e. USA) real possibilities exist so that available and new oil and water pipe lines could be used for such operations. In practice it means that transportation could be carried out with motor carriers, railway and water carriers. If the present experiences are taken into account and the real situation checked, such transportation systems are mainly used in praxis. For maximum throughput and to facilitate efficient loading and unloading, the physical condition with respect to pressure and temperature for the CO_2 should be the liquid or supercritical/dense phases. Temporary storage of CO_2 is of importance for finding a comprehensive solution for long-term storage under various environmental circumstances. Underground caverns are one of the possibilities of temporary storage. Geotechnical analysis of stress and strain changes that are present in the rocks around underground caverns filled with CO_2 under high pressure provides a realistic assessment of conditions for temporary storage. This paper presents the analysis described above, for different parameters relating to underground storage of CO_2.

Key words: temporary storage, big underground caverns, numerical modelling, boundary element method – BEM, CO_2 high-pressure

Izvleček

Po zajemu CO_2, ki ni namenjen izpustu v atmosfero, je več možnosti transportiranja večjih količin tega plina v skladišče. V nakaterih državah (npr. ZDA) je realna možnost za transport CO_2 uporaba obstoječih ali novih cevovodov za oskrbo območij z ogljikovimi derivati. Prav tako je v delu več projektov, ki upoštevajo navedeno možnost transporta CO_2 v Severnem morju. Predlogi za transport CO_2 s cestnimi, železniškimi in vodnimi transportnimi sistemi, ki jih je mogoče prilagoditi posebnim zahtevam, upoštevajo specifične lastnosti CO_2, saj bi bila najbolj ekonomična cena transporta na enoto dosežena, če bi bil plin v tekoči oz. superkritični gosti fazi.

Začasno skladiščenje CO_2 ima velik pomen pri iskanju celovite rešitve dolgoročnega skladiščenja v različnih okoljih. Podzemne kaverne so ena izmed možnosti začasnega skladiščenja. Geotehnična analiza napetostnih in deformacijskih sprememb, ki so v hribinah okrog podzemnih kavern, napolnjenih s CO_2 pod visokimi tlaki, omogoča realno oceno razmer začasnega skladiščenja. V prispevku je prikazana navedena analiza za različne parametre začasnega podzemnega skladiščenja CO_2.

Ključne besede: začasno skladišče, velike podzemne kaverne, numerično modeliranje, metoda mejnih elementov – BEM, visok tlak CO_2

Introduction

Carbon dioxide (CO_2) is a greenhouse gas that occurs naturally in the atmosphere. Human activities, such as the burning of fossil fuels and other processes, are significantly increasing its concentrations in the atmosphere, thus contributing to the Earth's global warming. One technique that could limit CO_2 emissions from human activities into the atmosphere is CO_2 capture and storage (CCS). It involves collecting, at its source, the CO_2 that is produced by power plants or industrial facilities and storing it away for a long time in underground geological layers, in the oceans, or in other materials. It should not be confused with carbon sequestration, which is the process of removing carbon from the atmosphere through natural processes such as the growth of forests. It is expected that fossil fuels will remain a major energy source until at least the middle of this century [1–5]. Therefore, techniques to capture and store the CO_2 produced, combined with other efforts, could help stabilise greenhouse gas concentrations in the atmosphere and fight climate change. CO_2 could be captured from power plants or industrial facilities that produce large amounts of it [6–9]. Technology for CO_2 capture from small or mobile emission sources, such as home heating systems or cars, is not sufficiently developed yet. The question is whether it could be realised in the near future? A significant proportion of the CO_2 produced by fossil fuel power plants could potentially be captured. By 2050 the amount captured could represent 21 % to 45 % of all the CO_2 emitted by human activities. After the CO_2 has been captured at the source of emission, the CO_2 would have to be transported to the storage site. Such transportation would require large scale infrastructures due to the large volumes to be handled. Nowadays existing CO_2 transportation systems has its basic location in the USA, where several million tons of CO_2 are transported annually, over long distances on shore in high pressure pipelines for use in the EOR industry (Gale et al. 2002) [10]. Using CO_2 in EOR (Enhanced Oil Recovery) projects has the advantage of adding a value to the CO_2, e.g. oil producers in the USA are willing to pay between 9 US$/t and 18 US$/t of »end of pipe« delivered CO_2. Pipelines for off-shore transportation of CO_2 have not been applied yet but are technologically feasible today, and a CO_2 pipeline infrastructure-off shore was investigated in the CO_2 for EOR in the North Sea (CENS) project [11]. In practice it means that transportation could be carried out with motor carriers, railway and water carriers. If the present experiences take into account and check the real situations, such transportation systems are mainly used in the food and brewery industry, and the amounts transported are within the range of some 100 000 t of CO_2 annually, so that is much smaller than the amounts associated with Carbon Capture and Storage (CCS) (Figure 1). In contrast the transportation conditions for CO_2 have some similarities with LPG (Liquefied Petroleum Gas) technologies, which are transported by water carriers, railway and motor carriers on a relatively large scale. Hence, from these points of view, experiences from the LPG industry could also be used for establishing a large scale CO_2 transportation infrastructure. For maximum throughput and to facilitate efficient loading and unloading, the physical conditions with respect to pressure and temperature for the CO_2 should be the liquid or supercritical/ dense phases. It should be noted that pipelines suffer from pressure drops along the transportation route, which can result in two phase flows and operational and material problems (e.g. cavitation) in components such as booster stations and pumps. Utilising pipelines still needs stable conditions of operation where the transported media is in the supercritical/dense phase [12–15]. This condition occurs at temperatures higher than 60 °C and pressures above the critical pressure of 7.38 MPa, giving a good margin for avoiding two phase flows. For the other means of transportation, i.e. motor carriers, railway and water carriers, which have constant pressure, liquid conditions are suitable. The density for CO_2 approaches 1 000 kg/m^3 as liquid, as well as during the supercritical/dense phase.

If available conditions are weighted in the goal to find optimal technical solutions the intermediate storage can be usable in different ways. A pipeline has the advantage of providing steady state flow, i.e. a continuous flow from the emission source to the final storage site. That means the complex transportation system should include appropriate intermediate storage facilities for handling the reloading of CO_2 at the middle points or at the final point close to harbour's facilities. There are two main technologies for intermediate storage of LPG, either underground in great rock and salt caverns or in large steel tanks above ground which have many disadvantages. But at present, only the steel tank technology is used for CO_2, in the contra version that both technologies can be applied in practice. Existing rock caverns for LPG have storage capacities up to around 500 000 m^3, which should approximately correspond to 500 000 t of CO_2. In the other hand salt caverns have similar storage capacities of LPG but are excluded in this work due to uncertainties with respect to the dissolution behaviour of CO_2. Steel tanks have storage capacities up to 3 000 t of CO_2 [12, 13]. Rock caverns within the LPG industry are constructed in two different ways, either as pressurised or as cooled caverns. If the caverns are intended for storage of CO_2, these techniques must be combined to create favourable conditions with respect to pressure and temperature for the CO_2. So, the construction cost of rock shelter depends mainly on the rock quality, which is available at the decided location. Low bearing capacity of »poor rock quality« increases the need for strong support measures which include lining and reinforcement of the rock strata. In those cases nonlinear increases in costs should be expected. In many technical and scientific studies the safety and public acceptance are not included enough. CO_2 is not toxic but can be fatal, due to asphyxiation, at concentrations exceeding around 10 % by volume [16], levels that can be achieved at a discharge as CO_2 is heavier than air and, hence, will tend to collect in depressions. Statistics from the EOR industry clearly show that the risks for pipeline leakage are lower than for natural gas or hazardous pipelines. Anyway in the goal to minimise risks, transportation of CO_2 should be routed away from large centres of population. Another issue, which can indirectly affect the transportation, is the public opinion concerning storage of CO_2. The concept of off shore disposal on average is considered to be safer, if the leakage is under question, than on shore systems. For this reason the support of the public is more easily implemented for the off shore system [14, 15, 17–19]. The above facts and assessing the need for the construction and use of temporary CO_2 storage are the basis for further work in this specialised field of underground construction. Already in several sentences it has also been suggested that the appropriate price for the construction of underground structures, essential important geological, hydrogeological and geotechnical conditions should be present at the selected location. Within the scope of the presented work the addition of the basic features of the behaviour of CO_2, given orientation are necessary and analysis of some possible construction of temporary underground storage facilities. In the analyses should take into account the economic viability of the storage of CO_2 at pressures between 80 bar and 100 bar at the ambient temperature of rock mass. It is possible to take into account the technological requirements of CO_2 transport in terms of maintaining the highest possible density of CO_2 in the liquid state, which is an economically important item for establishing the final price of permanent storage of CO_2 [20–23].

Some information about CO_2 producers

Coal power plants are a good example of a large point source of CO_2 emissions. Three systems are available for power plants: post-combustion, pre-combustion, and oxfuel combustion systems. The captured CO_2 must then be purified and compressed for transport and storage. It is possible to reduce the CO_2 emissions from new power plants by about 80 % to 90 % but this increases the cost of electricity produced by 35 % to 85 %. For industrial processes where a relatively pure CO_2 stream is produced, the cost per ton of CO_2 captured is lower. Except when the emission source is located directly over the storage site, the CO_2 needs to be transported. Pipelines have been used for this purpose in the USA since the 1970s. CO_2 could also be transported in liquid form in ships similar to those transporting liquefied petroleum gas (LPG). For both pipeline and marine transportation of CO_2, costs depend on the distance and the quantity transported. For pipelines, costs are higher when crossing water bodies, heavily congested areas, or mountains. Compressed CO_2 can be injected into porous rock formations below the Earth's surface using many of the same methods already used by the oil and gas industries (Figure 1). The three main types of geological storage are oil and gas reservoirs, deep saline formations, and un-minable coal beds [24–28]. CO_2 can for instance be physically trapped under a well-sealed rock layer or in the pore spaces within the rock. It can also be chemically trapped by dissolving in water and reacting with the surrounding rocks. The risk of leakage from these reservoirs is rather small. Storage in geological formations is the cheapest and most environmentally acceptable storage option for CO_2. Oceans can store CO_2 because it is soluble in water. Captured CO_2 could potentially be injected directly into deep oceans and most of it would remain there for centuries. CO_2 injection, however, can harm marine organisms near the injection point. It is furthermore expected that injecting large amounts would gradually affect the whole ocean. CO_2 storage in oceans is generally no longer considered as an acceptable option. Through chemical reactions with some naturally occurring minerals, CO_2 is converted into a solid form through a process called mineral carbonation and stored virtually permanently. This is a process which occurs naturally, although very slowly. These chemical reactions can be accelerated and used industrially to artificially store CO_2 in minerals. However, the large amounts of energy and mined minerals needed make this option less cost-effective. It is technically feasible to use captured CO_2 in industries manufacturing products such as fertilisers. The overall effect on CO_2 emissions, however, would be very small because most of these products rapidly release their CO_2 contents back into the atmosphere. It is expected that carbon capture and storage would raise the cost of producing electricity by about 20 % to 50 % but there are still considerable uncertainties. In a fully integrated system including carbon capture, transport storage and monitoring, the capture and compression processes would be the most expensive steps. Geological storage is estimated to be cheaper than ocean storage, the most expensive technology being mineral carbonation. Overall costs would depend both on the technological choices and on other factors such as location or fuel and electricity costs. Capture and storage of the CO_2 produced by some industrial processes such as hydrogen production can be cheaper than for power plants.

Basic physical and chemical parameters of CO_2

CO_2 is a naturally-occurring substance made up of carbon and oxygen, two of the more common chemical elements on earth. Under normal atmospheric conditions, CO_2 is a gas. It can be compressed into a liquid, frozen into a solid (dry ice) or dissolved in water (carbonated beverages, beer and sparkling wines) (Figure 2).
In the atmosphere, CO_2 comprises about 0.04 % of the air we breathe. It also occurs naturally in both fresh and sea water, and in the ground Meanwhile, green plants absorb CO_2 for photosynthesis and emit oxygen back into the atmosphere CO_2 is also exchanged between the atmosphere and the oceans and is emitted or absorbed in other natural processes. Working together in a natural system called the carbon

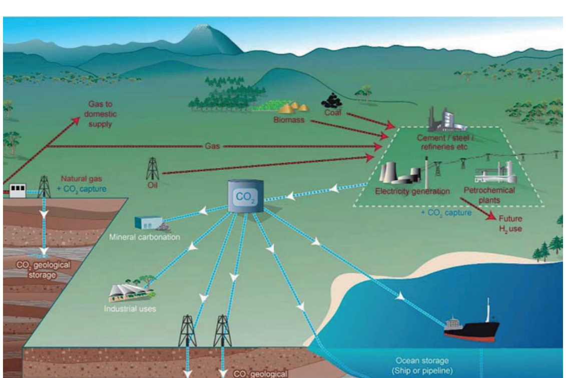


Figure 1: *Possible CO_2 capture and storage – CCS system* [12].

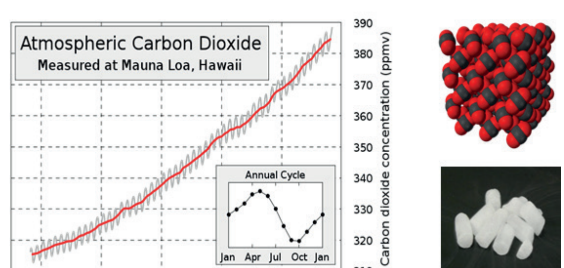


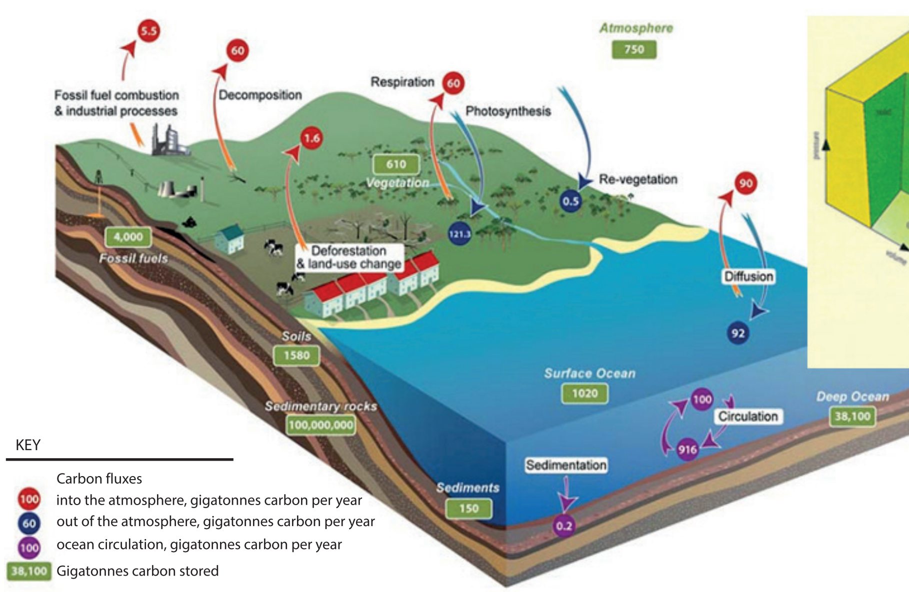
Figure 2: *Crystal structure of dry ice and sample of solid carbon dioxide or »dry ice« pellets and arising atmospheric carbon dioxide versus time* [29].

cycle; these processes have in the past kept the levels of CO_2 in the atmosphere stable over time. Nature's carbon cycle normally keeps CO_2 levels in balance but human activity, mostly the burning of fossil fuels, produces more CO_2 than nature can absorb. The arrows in this diagram show the annual flows of carbon in billion tones (metric tons). The human contribution is relatively small but enough to throw the cycle off balance. The extra CO_2 stays in the atmosphere, where it causes global warming. CO_2 is a greenhouse gas. That is, its presence in the atmosphere traps heat energy from the sun. This keeps the climate warm enough for life to continue.

As atmospheric CO_2 levels increase from natural levels the climate becomes warmer, changing the natural balance in most parts of the world. This has a wide range of major disruptive impacts on the environment, natural resources and human communities throughout the world. Living things consist largely of water and molecules containing carbon. When fuels derived from living things such as wood or fossil fuels (oil, coal or natural gas) are burned, the carbon combines with oxygen to form CO_2 that is released into the atmosphere. People haven't thrown the natural carbon cycle out of balance by burning fossil fuels (Figure 3). More CO_2 is now entering the atmosphere than can be naturally absorbed, contributing to global warming.

Chemical and physical characteristics of CO_2

CO_2 is one of the gases in our atmosphere, being uniformly distributed over the earth's surface at a concentration of about 0.033 % or 330×10^{-6} . Commercially, CO_2 finds uses as a refrigerant (Figure 2, dry ice is solid CO_2), in beverage carbonation, and in fire extinguishers. Because the concentration of carbon dioxide in the atmosphere is low, it is impractical to obtain the gas by extracting it from air. Most commercial carbon dioxide is recovered as a by-product of other processes, such as the production of ethanol by fermentation and the manufacture of ammonia. Some CO_2 is obtained from the combustion of coke or other carbon-containing fuels. Carbon dioxide is released into our atmosphere when carbon-containing fossil fuels such as oil, natural gas, and coal are burned in air. As a result of the tremendous world-wide consumption of such fossil fuels, the amount of CO_2 in the atmosphere has increased over the past century, now rising at a rate of about 1×10^{-6} per year. Major changes



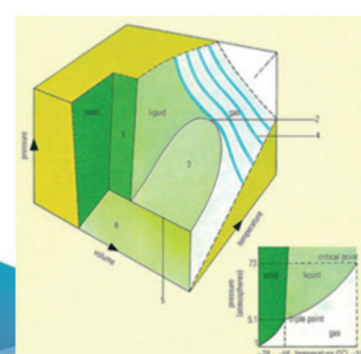


Figure 3: *Image courtesy of CO_2 CRC, with values of carbon fluxes and sinks sourced from NASA Earth Science Enterprise and the International Energy Agency* [12].

in global climate could result from a continued increase in CO_2 concentration. In addition to being a component of the atmosphere, carbon dioxide also dissolves in the waters of the oceans. As carbon dioxide dissolves in sea water, the equilibrium is established involving the carbonate ion, CO_3^{2-}. The carbonate anion interacts with cations in seawater. According to the solubility rules, »all carbonates are insoluble except those of ammonium and Group IA elements.« Therefore, the carbonate ions cause the precipitation of certain ions. For example, Ca^{2+} and Mg^{2+} ions precipitate from large bodies of water as carbonates [2]. Carbon dioxide does not exist in liquid form at atmospheric pressure at any temperature. The pressure-temperature phase diagram of CO_2 shows that liquid carbon dioxide at 20 °C requires a pressure of 30 bar (Figure 4). The lowest pressure at which liquid CO_2 exists is at the triple point, namely 5.11 bar at –56.6 °C. At the critical point (31.1 °C, 73 bar – located upper right in the phase diagram for CO_2), the temperature and pressure at which the liquid and gaseous phases of a pure stable substance become identical.

The high pressures needed for liquid CO_2 require specialised washing machines. Clothing is immersed in liquid CO_2 in a highly pressurised cylinder and agitated by high-velocity fluid jets to remove soils, then dried in a high-velocity spin cycle. Liquid CO_2 has drawn high marks in Consumer Reports' tests for its cleaning results, and it is environmentally-friendly as it produces no chlorinated pollutants.

Practical CO_2 storage capacities

The theoretical CO_2 storage capacity represents the mass of CO_2 that can be stored in hydrocarbon reservoirs assuming that the volume occupied previously by the produced oil or gas will be occupied in its entirety by the injected CO_2. The effective CO_2 storage capacity represents the mass of CO_2 that can be stored in hydrocarbon reservoirs after taking into account intrinsic reservoir characteristics and flow processes, such as heterogeneity, aquifer support, sweep efficiency, gravity override, and CO_2 mobility. However, there are also extrinsic criteria, which need consideration when implementing CO_2 storage in oil and gas reservoirs on a large scale and that further reduce the CO_2 storage capacity in oil and gas reservoirs to practical levels. The storage capacity of oil reservoirs undergoing water flooding is significantly reduced, making it very difficult to assess their CO_2 storage capacity in the absence of detailed, specific numerical simulations of reservoir performance. It is very unlikely that these oil pools, and generally commingled pools, will be used for CO_2 storage, at least not in the near future. The low capacities of shallow reservoirs, where CO_2 would be in the gas phase, make them uneconomic because of storage inefficiency [3]. On the other hand, CO_2 storage in very deep reservoirs could also become highly uneconomic because of the high cost of well drilling and of CO_2 compression, and the low 'net' CO_2 storage (CO_2 sequestered minus CO_2 produced during

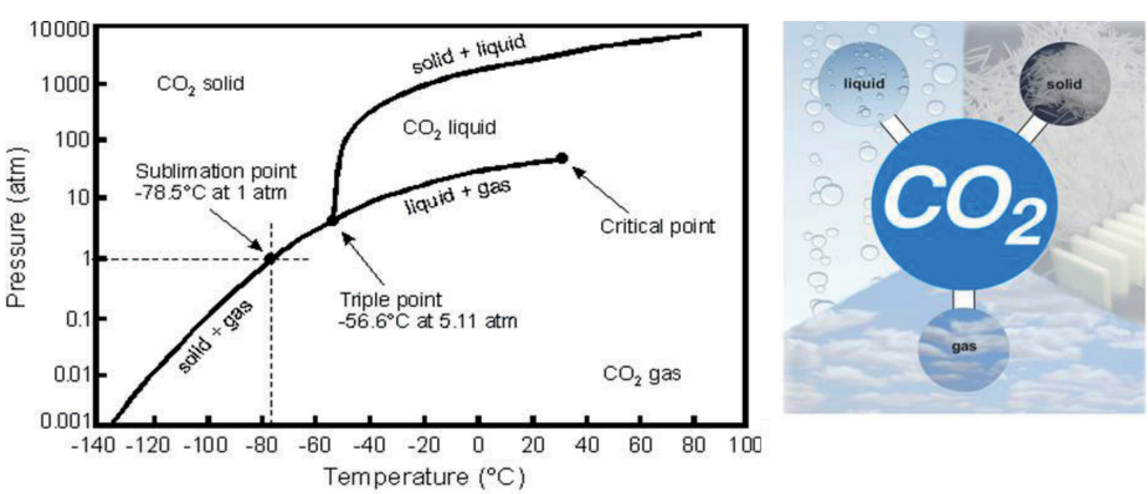


Figure 4: *Pressure-Temperature phase diagram for CO_2 and three phases of CO_2 [30].*

compression). Thus, the pressure window of 9 MPa to 34.5 MPa is considered as being economic for CO_2 storage in depleted hydrocarbon reservoirs [3], which roughly translates to a depth interval of 900 m to 3 500 m. In terms of CO_2 storage capacity, most reservoirs are relatively small in volume, and have a low capacity for CO_2 storage, rendering them uneconomic. On the other hand, associated oil and gas reservoirs (oil reservoirs with a gas cap) have a CO_2 storage capacity that is equal to the sum of the individual capacities of each reservoir. Considering the size of the major stationary CO_2 sources, it is most likely that only reservoirs with large CO_2 storage capacity would be considered in the short and medium terms. Building the infrastructure for CO_2 capture, transportation and injection is less costly if the size of the sink is large enough and if its lifespan is long enough to justify the needed investment and reduce the cost per ton of sequestered CO_2. Thus, only reservoirs with individual CO_2 storage capacity greater than 1 Mt CO_2 per year were selected at the end of the capacity assessment process.

Storage mechanisms of super-critical CO_2

It weighs like a liquid and flows like a gas. The CO_2 would generally be injected underground as a so-called supercritical fluid. The somewhat alarming term 'super-critical' simply means that the CO_2 has a liquid-like density and flows like a gas, and with a decrease in pressure will expand to form a gas without a phase transition. The CO_2 density would still be less than water. The viscosity an inverse measure of how well the CO_2 flows would be typically less than a tenth of the brine resident in the rock. CO_2 cannot burn or explode; the only reaction that it can undergo in the subsurface is the precipitation of a solid. The injected CO_2 would migrate to the top of the rock layer because of buoyancy forces. Real interest is the long term of trapping the CO_2 for hundreds to thousands of years, it is imperative that the CO_2 could not escape. There are four principal ways in which the CO_2 is prevented from reaching the surface such as cap rock. Structural or stratigraphic trapping refers to low-permeability layers of rock (cap rock) that prevent the upwards movement of CO_2. Similar traps have held oil and gas underground for millions of years. The traps are comprised of salt, shale or clays: they need not be completely impermeable but have pore spaces that are so small that the CO_2 has insufficient pressure to enter. In well characterised formations, this is a good way to ensure storage. For instance, in Sleipner, the use of periodic seismic surveys (using sound waves to image the subsurface) have shown that the injected CO_2 rises to the top of the aquifer and then spreads out underneath low permeability cap rock layers at the top. However, if CCS is to be applied on a global scale, some storage sites may not be as well characterised as major oil and gas producing basins such as the North Sea. In this case another approach is required in case the cap rock contains gaps or fractures or is absent.

Dissolution

Over hundreds to thousands of years, the CO_2 would dissolve in the formation brine forming a denser phase that would sink. CO_2 at high pressure has a reasonably high solubility in water, although this solubility decreases as the brine becomes more saline, as an example, a 6 % sodium chloride solution almost twice as salty as sea water would dissolve approximately 30–40 kg/m^3 of CO_2 at temperatures of 80 °C and pressures of 10 MPa, representative of a reservoir at a depth of around 1 000 m where heat from the earth's core makes it hotter than near the surface. While this is promising, the dissolution of CO_2 is a slow process, mediated by molecular diffusion and the flow of the denser CO_2 laden brine. Simulation studies indicate that it takes hundreds to thousands of years for a significant fraction of the CO_2 to dissolve in typical reservoir settings [31, 32].

Reaction

The CO_2 dissolved in brine forms a weakly acidic solution that may react over thousands to millions of years with the host rock, forming solid carbonate. This is a complex geochemical process but in essence, oxides in the rock dissolve and then re-precipitate as carbonate. The opposite can also occur, in that the acidic brine dissolves part of the rock, increasing the volume of the pore space and the permeability. The speeds, extents and natures of these reactions depend principally on the mineralogy of the rock. Dissolution and precipitation both render the CO_2 less mobile over time. The storage security increases over hundreds to thousands of years. The problem is that these are slow processes: in the worst case, by the time a significant fraction of the CO_2 has dissolved, much of the CO_2 may already have escaped to the surface.

Capillary trapping

The final process, which is more rapid, is capillary trapping. This occurs when water displaces CO_2 in the pore space. Figure 5 shows this process coupled with dissolution at the field scale and illustrates CO_2 trapped at the pore scale.
Figure 5 shows the increasing storage effectiveness for CO_2 with depth and in the critical depth CO_2 is in gaseous state (balloons), below critical depth it is in liquid-like state (droplets). Volumetric relationship shown by blue numbers (e.g. 100 m^3 of CO_2 at surface would occupy 0.32 m^3 at a depth of 1 km). Simulation studies of CO_2 storage have emphasised the importance of this mechanism. This process is well established in the oil industry. Water is used to displace oil from reservoirs but typically only around half the oil is recovered as much remains trapped in the pore space. Further water injection simply leads to excessive recycling of water from injection to the production wells with little or no further oil recovery this is why three barrels of water are recovered for every barrel of oil on average. The CO_2 would be trapped when it is displaced by water due to a regional movement of groundwater or when a buoyant CO_2 plume migrates upwards. Recent work has suggested that pumping out saline water (brine) from the aquifer and then re-injecting would enhance this natural process, leading to the proposal of an injection scheme where CO_2 and brine are injected together followed by chase brine. The idea is to design injection so that all the CO_2 is trapped during the injection phase, making significant leakage very unlikely [31, 32].

Pressure responses

In the oil industry there is a net removal of fluid from the subsurface. The pressure in the reservoir drops and the rock, water and hydrocarbon expand to fill the space vacated by hydrocarbon. In most reservoirs, the natural expansion of rock and water surrounding the reservoir is insufficiently fast to prevent a very rapid drop in pressure. To compensate for this, to maintain pressure and push the oil out, water is usually injected hence the comments on water production in the preceding paragraph. In gas fields this is unnecessary, simply allowing the pressure to decrease allows the gas to expand and be produced. The obvious storage solution is to inject CO_2 to replace the oil and gas produced in old hydrocarbon fields. This has some advantages i.e. the field must have a good cap rock in order to contained the hydro-carbon for millions of years and so safe storage would be possible, the injection of CO_2 can enhance

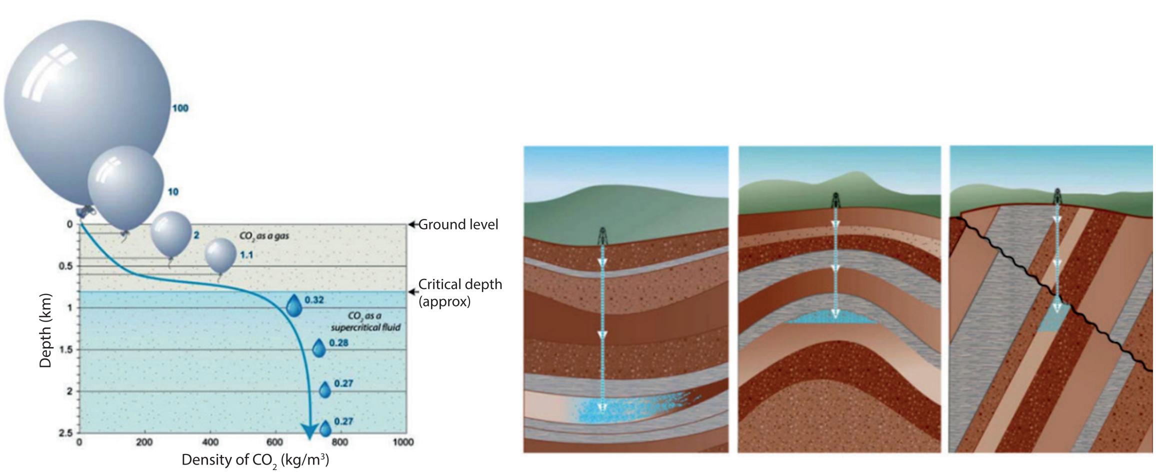


Figure 5: *Density of CO_2 versus ground depth and Different types of CO_2 trapping* [12].

oil and gas production, giving some economic pay-back, next there is a pipeline infrastructure in place for injection. The injected CO_2 would cause the reservoir pressure to rise again, replacing the volume of produced hydrocarbons. The main disadvantage is that the extra production causes more CO_2 to be burnt when extra oil and gas is produced typically at least as much CO_2 as is stored. The CO_2 displaces brine and the increased fluid pressure tends to expand the pore space, pushing the rock apart. If the fluid pressure is too high, this can fracture the rock, creating cracks through which the CO_2 could escape. This squeezing of the subsurface also leads to regional pressure increases, which again could cause extensive fracturing, or the seepage of salty water to displace fresh water, contaminating drinking water supplies. The experience of Sleipner and other sites where large volumes of CO_2 have been injected without significant increases in pressure provides evidence that large aquifers do have substantial storage capacities. Some indications have shown there are huge volumes in which the pressure can be dissipated. In reality the amount of CO_2 that can be stored is a function of how the injection is engineered, how many wells are drilled, what sort of wells and whether or not brine is produced. The storage design depends on economics and the field properties, and so it is usually unrealistic to talk of a single capacity estimate.

Dynamic capacity

The first consideration is injectivity, or dynamic storage capacity. This means, can the CO_2 be injected at the rate required in the single well. The use of additional wells or horizontal wells through layers of high permeability come with an additional cost but would allow CO_2 to be injected more rapidly [33]. Current field experience indicates that a single well can readily inject up to 1 Mt of CO_2 per year but more than one injection well would therefore be required for large storage projects, especially if CO_2 is collected from several sources before injection.

Static capacity

Large, regionally-extensive aquifers almost certainly have sufficient storage capacity even under rather modest constraints on pressure increase. The second concern is the extent of the CO_2 itself, since this indicates the potential footprint for any escape. Simulation studies suggest than in highly heterogeneous systems, the lowest storage capacity is around 2 % of the pore space. As the pore space itself is around 25 % of the rock volume, this represents around 0.5 % of the total rock volume, which is similar to the capacity estimated using pressure constraints. The storage capacity and storage security could be improved, through improved injection design. If it is known that there is a good cap rock (such as in hydrocarbon reservoirs), CO_2 could be allowed to accumulate under the cap rock, where it could occupy the majority of the pore space. In the oil industry, it is standard practice to inject gas and water together or in alternating slugs, as the mobility of the combination of the two phases has a lower mobility than CO_2 alone, leading to a more stable displacement and a more efficient sweep of the reservoir. In contrast, CO_2 alone has a very high mobility (low viscosity) and tends to rise to the top of the reservoir and channel along high permeability channels. The results of a simulation study on a North Sea aquifer indicated that, with only a short period of brine injection, the vast majority of the CO_2 could be capillary trapped, ensuring permanent storage [11, 34]. It is never possible to guarantee that a cap rock will be impermeable to CO_2, or that the permeability would be sufficiently high to allow rapid injection. Compressibility is defined as the fractional change in volume for a unit increase in pressure. When CO_2 is injected at high pressure, it compresses the resident brine and pushes the rock apart, increasing the pore volume. The combination of rock and brine has a compressibility of around 10^{-9} Pa^{-1}. An aquifer at a depth of 1 000 m would typically have a pressure of around 10 MPa to avoid fracturing it would be wise to limit the pressure increase to between 10 % and 50 %. Hence the pressure should increase by no more than 1 MPa to 5 MPa. This leads to a fractional change in volume of the order $1–5 \times 10^{-3}$ or 0.1–0.5 % a regionally extensive aquifer some 100 km long and 100 km wide with permeable layers of a total thickness of 1 km has a total rock volume of the order of 10^4 km^3 or 10^{13} m^3. Using typical density of 600 kg/m^3, this would allow the storage of 6 Gt to 30 Gt of CO_2 but application of CCS at a global scale for several decades; it would still need to store CO_2 in many large aquifer units around the world.

Temporary CO_2 storage in existing or new underground caverns

Temporary storage of CO_2 in underground facilities requires detailed analysis of all influencing factors, which include in addition to the geological structure of the area and engineering geological, hydrogeological and geotechnical evaluation includes depth below the ground surface and not least information about the inhabited environment. Temporary storage of CO_2 has a practical goal in the case finding out a location of proper sound rock mass between the place of CO_2 capture and the compressed and final storage phases. In Figure 6 the proposed location of temporary storage is possible between the previous mentioned primary and final technological procedure of long term storage of CO_2.

For such storage the specific conditions laid down by the goal of optimal CO_2 pressure and temperature should be taken into account to achieve the appropriate density during its storage. Based on the phase diagram of CO_2 (Figure 4) the gas pressure has to be calculated from 80 bar to 90 bar at temperatures between 10 °C and 15 °C [35]. In practice there may be other combinations of temperature and pressure which depend of the natural conditions of a potential storage area. In these decisions, it is necessary to have sufficient reliable data of the rock environment including projected depth of storage, natural rocks temperature, and finally information about possible seismic activity.

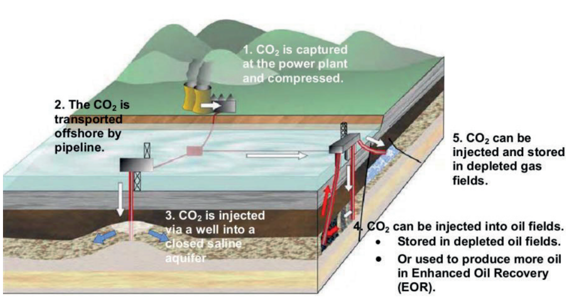


Figure 6: *A Schematic Illustrating Carbon Dioxide Capture and Storage (© British Geological Survey)* [12].

Existing types of underground caverns

Man-made cavities

Great Britain has a very long history of mining and there are very few minerals that have not been worked underground at some stage in the past. Coal mining was by far the most extensive but metal mining formerly also covered large areas. However, many other minerals, including oil shale, fireclay, ball clay, fuller's earth, limestone, building stone, silica sand, fluorspar, barytes, slate and, notably the evaporate minerals salt, gypsum/anhydrite and potash have all been mined to a greater or lesser extent. All these activities have created underground caverns of varying sizes and shapes over a wide range of geological settings. For most minerals this has produced voids, which are unstable, particularly where early mining methods were employed [36]. The type of void created and its suitability for storage use depends on the rock worked and the type of mining method used. Modern room and pillar mining is used for generally flat-lying, sedimentary strata. Typically 25–50 % of the rock is left in the form of square pillars to provide a permanent support for the roof. Rock salt mining is a good example. Modern salt solution mining techniques also have the capacity to produce stable cavities ideally suited for certain types of storage.

Salt caverns and abandoned coal mines

Salt occurs in nature either in solid form as rock salt (halite) in beds ranging from a few centimetres to hundreds of meters thick, or in solution as brine. Salt caverns are constructed in naturally occurring thick salt domes, deep underground. Salt can be found in almost every part of the world with some exceptions around the Pacific Rim. Salt caverns are a proven medium for hydro-carbon storage as salt acts as a natural sealant, trapping the natural gas inside the cavern. Salt caverns for gas storage use are formed with a leaching process by pumping hot water to dissolve the salt and removing the resulting brine via a single well, which then serves for gas injection and withdrawal. The storage capacity for a given cavity volume (several hundreds of thousands to several million cubic metres) is proportional to the maximum operating pressure, which depends on the depth. Salt caverns are typically much smaller than depleted gas reservoirs and aquifers, usually covering only one-hundredth of the acreage taken up by a depleted gas reservoir. As such, they are particularly suited for short-term storage of natural gas because of their high deliverability as well as the ability to quickly switch from injection to withdrawal. As with depleted gas reservoirs and salt caverns, CO_2 stored in coal mines is inspired by storage projects for natural gas in abandoned coal mines, the oldest of which dates back to 1961. One of the typical cases is the Leyden coal mines, located near Denver Colorado, which were in operation from 1903 until 1950, producing 5.4 Mt sub-bituminous coals from two horizontal seams at 210 m and 225 m depth in the upper Cretaceous Laramin formation. The second case is two abandoned mines converted into natural gas storage reservoirs, both located in the gassy Hainaut coalfield in southern Belgium [23, 37]. Experts carried out a detailed feasibility study on using abandoned coal mines for long-term CO_2 storage, with special reference to a Belgian colliery. CO_2 stored in an abandoned coal mine may exist in the gas phase, in solution in water and adsorbed on remaining coal. The storage capacity has been estimated at between 7.5 Mt to 12.5 Mt CO_2, which maybe small but accounts for approximately 3 % to 6 % of the emission reduction for Belgium required under the Kyoto agreement. The technical set-up of an abandoned coal mine storage project is relatively simple. Unlike unminable coal seams, CO_2 induced swelling is not an issue here. In fact, the seams surrounding former mine workings are naturally stimulated and thus high injection rates can be achieved. On the other hand, fractured rock which exists around an abandoned coal mine may provide leakage paths for CO_2 which would be unacceptable for a storage site [23, 37]**.** The same authors have suggested some special requirements which need to be met in order to obtain a safe and stable reservoir with sufficient capacity. Firstly, the highest level of the mine should be at least 500 m deep, with well-sealed shafts and a tight, mostly dry cap rock. Secondly, in order to prevent mine flooding, the storage pressure should be higher than the hydrostatic pressure of the surrounding strata. This overpressure, typically around 130 % of the hydrostatic pressure, in turn places a stringent leak-proof requirement on the top seal of the reservoir and the existing shafts.

Existing underground caverns used for different storages

In some places around the world you can find many underground caverns over the last six decades. Some of them were done connected to military activities, defence regulations and many other requests in the goal to improve conditions for storage energetic, water and air masses. Big advantages were done in Norway, where all the mentioned time has clearer strategy in which way can underground available space been used. In the scientific and technical literature can found many usable technical solutions including geological and geotechnical assessments of hoisted rock masses in the goal to find proper economic and environmental acceptation. It is not unknown, that natural physical, chemical and geotechnical characteristics of rocks mass in these cases have played enormous important game because the hoisted media has more than one influence on the potential used of available underground space. In the next chapter high attention will be paid to Norwegian and other Scandinavian experiences [9, 36–38].

Self-standing capacity

Most rock mass have a certain self-supporting capacity, although this capacity may vary within a wide range. An appropriate engineering approach is to take this capacity into account when designing permanent support. As for any type of underground structures the selection of the site location, orientation and shape of the caverns are important steps preceding the dimensioning and the laying out of the underground site. Rock strengthening may, however be needed to secure certain properties/specified capacities, the same way as is the case for any other construction material. The fact that, the rock mass is not a homogenous material should not disqualify the utilisation of its self-standing and load bearing capacity. Typically, rock support application in Norwegian oil and gas storage facilities consists mainly of rock bolting and sprayed concrete. The application of cast-in-place concrete lining in such facilities has been limited to concrete plugs and similar structures and is normally not applied for rock support purposes. The rock support measures are typically not considered as contributing to the containment, other than indirectly by securing the rock contour and thus preventing it from loosening. Furthermore, the Norwegian tunnelling concept applies widely as a drained concept, meaning that the rock support structure is drained and the water is collected and lead to the drainage system. Thus the rock support is not designed to withstand the full hydrostatic pressure in the rock mass because the self-load-bearing capacity was applied in the design process. The experience with large underground caverns was obtained in Norway during the development of hydroelectric power schemes for which purpose a total of 200 underground plants were constructed. Commonly the caverns for power-houses and hydrocarbon storage were all typically sized to some 15–20 m width, 20–30 m height and tens-hundreds meter length. That geometrical data, based on past experiences can be usable for CO_2 storage systems. Various types of monitoring to follow-up the behaviour of the rock mass and the support structures are available and used to document the stability and behaviour of the rock mass [38–40].

Identification of design parameters

The locations of the rock caverns are normally fixed within the design concept and being based on information gathered during a comprehensive pre-investigation phase, however, depending on the actual rock mass conditions as encountered during tunnelling in the approach to the designed and planned location, relocation of the underground structure may of course take place. Several underground projects in Norway have experienced changed locations and local optimisation to better adapt to the actual rock mass conditions. It is common to take into account the next information relating to:

— rock types and mechanical properties
— characteristics and frequency, spacing of rock mass discontinuities
— in-situ rock stresses
— groundwater conditions.

During the approach to the planned location of the cavern(s) the rock mass is thoroughly mapped, joint systems are observed and characterised, weakness zones are interpreted, in-situ rock stresses are measured, ground water is monitored (Figure 7). If these conditions are not in accordance with the expected and required quality of the rock mass, it may be conclusively decided to shift the location of the storage caverns to other adjacent caverns and tunnels, or make some layout adjustments. Typically, the final layouts of the caverns, their locations, geometries, alignments, lay-outs of the tunnel system and rock support design may not be finally decided upon until the above information is obtained from the excavation of the approaches of access tunnels. Numerical analyses as well as analytical calculations are useful tools for the designing and planning of the caverns. These must of course be verified during the construction phase by adequate monitoring and follow-up of the stability of the underground caverns.

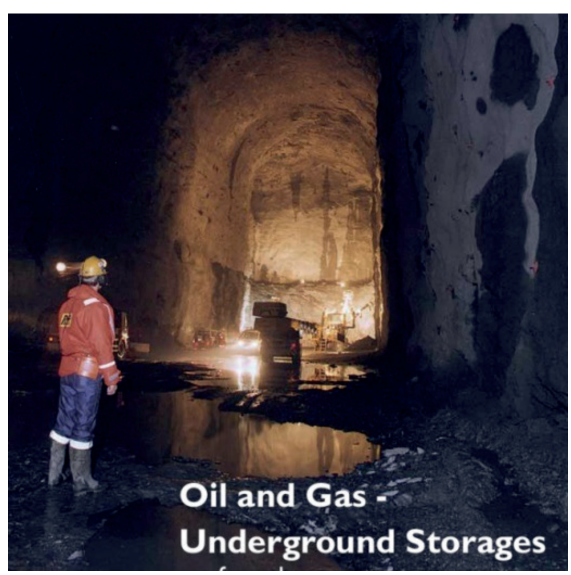


Figure 7: *Underground cavern under construction [36].*

Assessment of the CO_2 pressure impact of on the walls of caverns

The statically base of the CO_2 pressure acting on the caverns' walls we can apply for calculating stress and strain relationships in the lining and surrounding rock structure. According to the strain nonlinear softening constitutive model of practical rock, the pressure tunnel with liner is analysed. The model is considers the influence of intermediate principal stress σ_2. Stress distribution laws of surrounding rock plastic zone of tunnel, the mechanism of load bearing and acting relationship between surrounding rock and support are studied. Some important concepts of the working status of practical tunnel surrounding rock are obtained: such a superior certain limit [S_{max}] of self-support geostress and inferior certain limit [S_{min}] of support less tunnel surrounding rock. The relations between [S_{max}] and geo-stress, between [S_{min}] and geo-stress are given. Calculation shows that the assumed model agrees well with practical conditions of the rocks. Analysis shows that the ideal plastic model and the brittle model are special cases of the proposed solution.

It is well known that the stability of tunnel surrounding rock is decided by the interaction results of stresses in the surrounding rock and its strength, i.e. surrounding rock states. If its surrounding rock is in elastic or plastic state after a tunnel is driven, the surrounding rock is stable. However, if its surrounding rock is in a broken state after the tunnel is driven, the surrounding rock is unstable. In addition, lots of in-situ observation data have shown that a broken zone exists widely in surrounding rocks of tunnels. Therefore, it can be seen that the thickness of the broken zone, a geometrical parameter indicating the broken range in the surrounding rocks of tunnels, can be taken as a comprehensive index of stresses in the surrounding rock and its strength to evaluate the stability of surrounding rock of a deep tunnel. Kastner's solution is often used in elastic-plastic analysis for surrounding rock of a circular tunnel. It is well known that Kastner's formula is based on an ideal elastic-plastic model. This leads to the Kastner's solution and is far away from corresponding actual values in surrounding rock. Following along the path pioneered by Kastner, researchers have published different solutions for surrounding rocks of circular tunnels [41]. However, these solutions are restricted to very simple material models, such as the simple linear relationship between stress-strain.

Numerical analysis used BEM– EXAMINE 2D

For preliminary analysis the stability assessment of unlined rock caverns in more stages without and with CO_2 pressure, the 2D modelling was used [42]. The main advantages of the presented modelling were in the parametrical analysis which shows what influences of each of them on stability are present. Using BEM to determine the strength factor of the host rock mass the calculations were done in the cases when the caverns with dimensions W/H 21 m/31 m were empty and in the case where CO_2 was filled with 8 MPa pressure (Figure 8). Technology of CO_2 pumping in to the caverns in the analysis are not included in detail because in the presented type of preliminary analysis is unnecessary. The important question is the factor of safety of the cavern's stability explains the real situation enough as to which can be present in the underground environment. Results of calculations, which are shown below, clearly explain that the influence of CO_2 pressure 8 MPa on the unlined rock cavern wall is very high. At the same case it is clear that the depth of the cavern location below ground surface has an important influence on stability, too. The results of calculation shows that in the proposed geometry of an underground unlined cavern with no loaded and loaded with CO_2 inner pressure P_a = 8 MPa, the host rock would not have enough strength in practically all calculated cases. The geotechnical characteristics of the host rock which were used in the present calculations are the same as used in the paper Thermal Behaviour of Rock in Relation to Underground Gas Storage, prepared by Ming Lu (2007) [43].

— Horizontal stress ratio = 1.5
— Out of plane stress ratio = 1.7
— E-modulus = 30 GPa
— Poisson's ratio= 0.28
— Friction angle = 38°

— Cohesion = 0.5 MPa
— Tensile strength = 0.7 MPa
— Unit weight = 27 kN/m^3.

For detailed analysis of the geotechnical stability of the virtual temporary CO_2 storage another geotechnical parameters can be used. It's no doubt, that in previous experience in underground big caverns construction in better rock mass conditions, the stability analysis should not be a part of the problem. Short looking through geological environments which are possible locations of the future CO_2 storages gave optimistic plans for underground space used for such types of projects.

The caverns stability analysis was given in the comparison of calculated strength factors (FS) for different load and geometric cases. In the next figures the results of calculations are shown in the name of the Strength factor, as results of the mentioned analysis. In the first case only one cavern was analysed. First analysis of the single unlined cavern stability was done for empty available volume space (Figure 8) and the cavern filled with CO_2 (Figure 9). In the figures the geometry of the proposed cavern is shown, too. The dimensions which are included in the analysis are close to that used in construction practice in Norway.

Based on previous research of primary stress states at different locations, the coefficient of primary stress ratio 1.5 is accepted. In Figures 8, 9, 10, 11 and 12 where the results of 2D numerical modelling are shown, it can found that the cavern in the proposed rock mass environment is unstable without installation of the support system. The greater differences exist between the depths 100 m, 200 m and 300 m but deeper location i.e. 400 m has no important influence on the calculated strength factors. They are similar to the factors, which were found for the case where the virtual cavern was at the 300 m depth. In a similar way the 2D analysis was done for a single cavern filled with CO_2 under 8 MPa pressure. Geometrical and loading position and the results of analyses for four different location depths it can be found in Figure 11. The results, which are shown in Figure 11, were not looked at as surprising regarding those given in the input data. They are understandable, as the pressure of CO_2 in this case even improved the stability of the cavern.

The case where two caverns are located 58 m between axis shows that that the unlined caverns are unstable without some support measures. The stress influence between caverns is higher in the greater depths. That is easily understandable because the coefficient of primary stress state is 1.5 which means that in such primary conditions the axes distance should be longer. Calculated SF for the unlined caverns where only left loaded with CO_2 pressure at different depths. Interesting results are shown in Figure 11 where the effect of CO_2 pressure on the temporary stability of the left cavern is evident. The main positive influence on stability is present at the depths below the 100 m for both cases presented in Figure 11 and Figure 12.

The presented results of 2D calculations are informative. The purpose of this numerical analysis was to show some limitations which are necessary when planning or updating existing underground caverns, which were probably used for temporary storage of CO_2. Indeed, the geotechnical input parameters that were considered in this analysis took the pessimistic values, so that it is possible with a greater degree of optimism to look at more favourable rock mass circumstances. For further activities in this field of underground space used, detailed plan for the necessary in-depth research and analysis of real sites, which are potential sites in the future, would be needed.

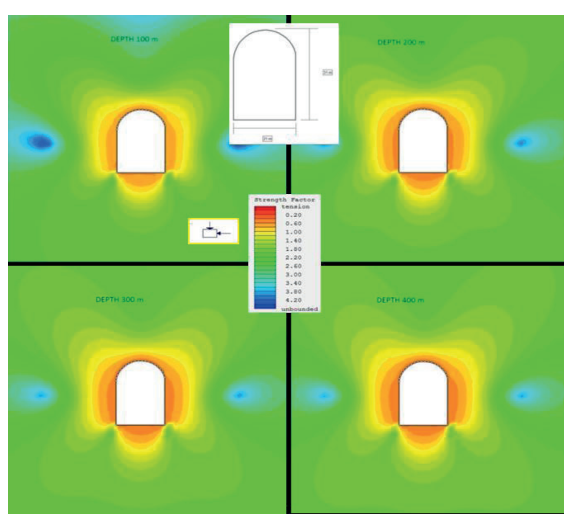


Figure 8: *Geometry of single cavern with no loading with CO_2 pressure and calculated FS for different depths of cavern positions.*

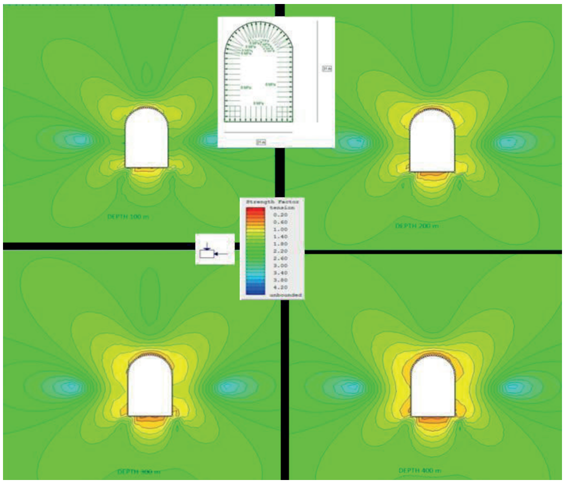


Figure 9: *Geometry of the single cavern for CO_2 storage with pressure* 8 MPa *and calculated FS for a single unlined cavern located at different depths.*

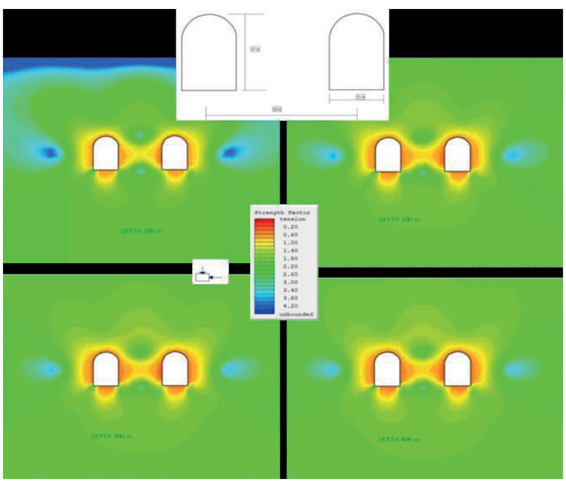


Figure 10: *Two unlined caverns not loading with CO_2 pressure and calculated SF for different depths below the surface.*

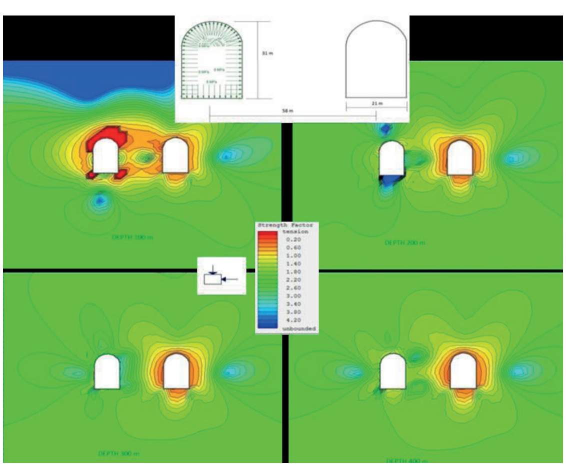


Figure 11: *Layout of two unlined caverns, left filled with CO_2 with* 8 MPa *working pressure, right with no inside pressure and calculated SFs for different depths.*

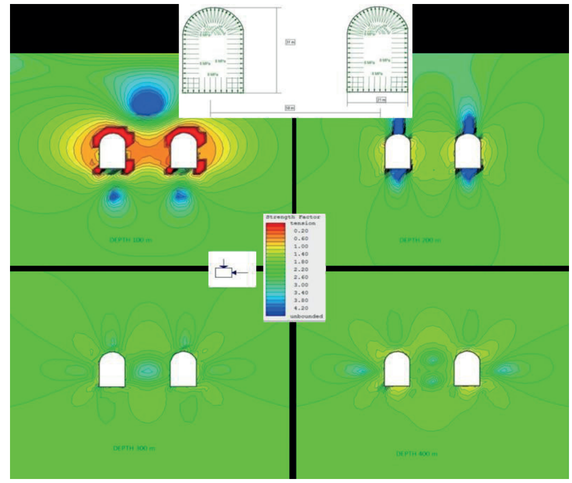


Figure 12: *Layouts of two caverns filled with CO_2 under working pressure* 8 MPa. *Calculated Strength factors for the unlined two caverns, loaded with* 8 MPa *CO_2 pressure at different depths.*

Specific requirements for lining caverns for providing storage of CO_2

If the CO_2 pressure has over 100 bar, when the cavern is closed and the surrounding rocks have temperature around 10 °C, the big advantage would not achieved. The main reason is when the pressure of CO_2 is lower than 45 bar it will act as a gas (gas law for real gases). When the temperature of the CO_2 is the same as the temperature of surroundings rocks i.e. approx. 10 °C, the equilibrium pressure between liquid and gas is 45 bar. If CO_2 continues to be pumped into the cavern, the gas will follow the characteristics which are adequate to fluid and will still continue volume of fluid increases. The volume of gas above the liquid CO_2 is less until the cavern full of liquid CO_2, but the pressure is still 45 bar. If CO_2 pressure is slowly increased with additional pumping, say from 45 bar to 150 bar, liquid CO2 is indeed a bit compressed, but the compressibility of fluid is very small, so the pressure increase from 45 bar to 150 bar gain just fluid volume [26, 35]. In the case that the higher pressure CO_2 by the offline, faster pumping gas into the cavern, the balance is not changed. At the beginning CO_2 pressure is of course somewhat higher but when the gas is cooled to 10 °C, the equilibrium pressure would be 45 bar. Of course, it may take several days / weeks / months for the surrounding rock environment and CO_2 in the caverns to reach equilibrium. At the beginning, when the pumping gas is warm (25 °C), the pressure above 45 bar may even have 100 bar or high value. When the surroundings cool; more and more the pressure would decrease and in the end, if time allows, would stabilise at 45 bar (if there is already some liquid).The density of liquid at 10 °C should be somewhere around 0.45 kg/l, at the critical temperature it was 0.47 kg/l. The problem could arise if CO_2 were to be warmed at the critical temperature i.e. 31 °C. In that case the CO_2 would be changed to gas which causes increasing pressure because it would behave as a gas and no longer a liquid.

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. Nonetheless, the indications are that underground CO_2 storage could have a significant impact on our greenhouse gas emissions.

Underground storage may involve substantial construction work, including major surface infrastructure provision (access roads, rail links, pipelines, head works buildings) and not just restricted to the immediate locality. All of these may create more or new impacts in terms of amenities and traffic. Offshore storage may require new or expanded onshore installations and infrastructure. Concerns in relation to stability, pollution and safety would also need to be addressed.

In some situations underground storage can be considered as a three stage activity; a short-term development stage (the 'temporary' work involved in construction of the void and the associated surface works including infrastructure); a long-term operational stage (the permanent use of the resulting void); and finally a decommissioning and post abandonment stage (when the planning impacts arising from the presence of the facility and the infrastructure may need relevant considerations for a considerable period of time.

Storage of CO_2 underground could reduce construction costs and offer protection from storms, accidents, arson, acts of terrorism and also prevent 'shrinkage' (loss by theft). It may also provide an ideal ambient environment in terms of stable humidity and temperature and be dry, reducing energy costs for heating or air conditioning. However, some storage facilities may be wet, hot or very dry with issues of air quality inhibiting access and might raise concerns about managing fire or pollution events. Ventilation, access and fire escape structures may be required at the surface. Surface stability would also be a major planning consideration.

Experience with the use of water curtains at the three Norwegian air storages discussed herein, at pressures from 4 MPa to 8 MPa, is encouraging. It has been found that a properly designed water curtain totally eliminates any gas leakage from the storage, even for a storage pressure head that is only twice the thickness of the rock overburden. A water curtain may provide not only a cost-effective method for restricting gas leakage from unlined hard rock caverns; currently it also appears to be the only practical way of totally preventing gas leakage from high pressure storage.

The main advantages of CO_2 underground storage in rock mass formation are very wide including utilising rock mass properties, environmentally-friendly, protection during wartime, operation and maintenance, and not least protection from natural catastrophes.

The rock mass has a number of important parameters that are utilised in the underground storage of hydrocarbon products. These capacities allow a variety of storage conditions and enable a number of diverse types of products to be stored in unlined rock caverns.

With the current knowledge of the mechanical and thermodynamic behaviour of the rock mass and the current use of such storage facilities the proven technologies could take place during the construction process.

As far as the environmental aspects are concerned the experience from Norwegian underground storage projects are unreservedly positive. So far product leakages have not been reported at any of these projects indicating clearly that the applied concept and techniques for obtaining the required confinement are appropriately proven.

For a subsurface solution, dedicated systems for collection and handling of various types of spill could be planned thus limiting the spread of any spill. Bringing these storage tanks below the surface allows valuable surface areas to be utilised for other purposes; recreational, cultural and residential. In addition unsightly structures can be hidden away underground.

Protection from natural disasters and catastrophes such as earthquakes is a beneficial advantage of underground storage. It has been acknowledged that subsurface structures have several intrinsic advantages in resisting earthquake motions. Experience and calculations show this clearly.

The total construction cost would be within the range of 150–310 USD per m^3 storage which would be many times competitive in the open construction market.

For any decision about working pressure and temperature of CO_2 a phase diagram should be used regarding the names and technological possibilities. Two potential solutions exist; first include pressure 80 bar to 100 bar at the normal rock temperature 8 °C to 12 °C. In this case additional isolation and a freezing system aren't needed. The second case is close to CO_2 transport parameters at pressure of about 7 bar and temperature –50 °C. The final decision depends of the financial and technological closed cycle of the CO_2 long-term storage.

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