WHAT HAPPENS

WHEN CO_2 IS STORED UNDERGROUND

Q&A from the IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project

This report was developed by: ptrc

What Happens When CO_2 is Stored Underground?
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This document is also available in electronic format from the Global CCS Institute at www.globalccsinsitute.com and from the Petroleum Technology Research Centre (PTRC) at http://ptrc.ca

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1. Carbon capture and storage
2. Carbon dioxide sequestration
3. Carbon dioxide measurement and monitoring

Front Cover: A CO_2 injection well, covered in a fibreglass hut, rests in field near Weyburn, Saskatchewan.

Back Cover: A worker inspects the Cenovus Energy Weyburn plant. (Photograph courtesy of Cenovus Energy)

INTRODUCTION

The IEA Greenhouse Gas Programme Weyburn-Midale Carbon Dioxide (CO_2) Monitoring and Storage Project was a world-leading research program designed to examine the effects of injecting and storing carbon dioxide (CO_2) into oil reservoirs in southeastern Saskatchewan, Canada.

The project was completed in two stages between 2000 and 2012, and studied the large-scale injection, monitoring and modeling of CO_2 stored in deep geological formations. The results from the first phase of this research project were published in 2005[1] and second phase results were included in a 2012 book called ***Best Practices for Validating CO_2 Geological Storage: Observations and Guidance from the IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project.***[2] This latter publication marked the completion of the investigation into storage of CO_2 at the oilfields.

The much smaller booklet you are now reading presents common questions often raised by the general public about carbon capture and storage (CCS) and gives answers based on the extensive data and results from the 12 years of research at the oilfields. The intent of this booklet is to offer fact-based answers to some common questions about CO_2 storage.

The first question, "What is the Weyburn-Midale Project?" provides context around the scope of the Weyburn-Midale study. The remaining questions move from general ("What is carbon dioxide (CO_2)?") to more detailed ("If I own the mineral rights beneath my land, will I be paid for CO_2 storage?"). The questions have been split into three categories:

1. The Basics
   a. Carbon dioxide (CO_2)
   b. Carbon capture and storage (CCS)
2. What happens to CO_2 underground?
3. What ifs? The most common questions about CCS

More extensive technical details are presented in the Best Practices book noted above. Information about the availability of this larger book is provided at the end of this booklet.

For the sake of brevity, reference to the IEA Greenhouse Gas Programme Weyburn-Midale Carbon Dioxide (CO_2) Monitoring and Storage Project throughout this document will be condensed to the term "WMP."

CONTENTS

WEYBURN-MIDALE PROJECT (WMP)

Between 2000 and 2012 – the years that research was conducted as part of the WMP – some 22 million tonnes of CO_2 were injected 1.5 km deep into the Weyburn and Midale oilfields in southeastern Saskatchewan, Canada.

WHAT IS THE WEYBURN-MIDALE PROJECT (WMP)?

The IEA Greenhouse Gas Programme Weyburn-Midale CO_2 Monitoring and Storage Project (WMP for short) was among the world's first studies to examine injection of carbon dioxide (CO_2) into geologic reservoirs. CO_2 is a greenhouse gas considered to be a major contributor in causing changes to climate patterns. Its storage underground is drawing interest because it provides an option to prevent this gas from reaching the atmosphere. To be successful in this effort, a storage site would have to safely contain the CO_2 for a very long time – thousands or even tens of thousands of years.

Between 2000 and 2012 – the years that research was conducted as part of the WMP – some 22 million tonnes of CO_2 were injected 1.5 km deep into the Weyburn and Midale oilfields in southeastern Saskatchewan, Canada. The reason that CO_2 is being injected into these older, or mature, fields is to increase the amount of oil that can be removed (this process is called enhanced oil recovery or EOR). Without EOR, oil production from these fields would be declining below the cost of production, but as a direct result of CO_2 injection, production of oil from each of the reservoirs has increased by three times the levels experienced before injection began. Today, CO_2 is still being injected at over 2.5 million tonnes per year and will likely continue for several more decades. See Figure 1 for a summary of the amount of CO_2 stored deep underground in the two oilfields by the end of the research project in 2012, as well as daily injection totals.

Although EOR is the main reason for injecting CO_2 into the oilfields, the WMP was not focused on the additional oil produced, nor the day-to-day operations of the CO_2 capture facility and the CO_2 pipeline, nor the CO_2 injection. The WMP focused on understanding what happened to the CO_2 once it was injected.

The WMP addressed three main questions: 1) where does CO_2 go once injected; 2) how does CO_2 interact deep underground with the subsurface environment; and 3) will it be securely stored? To answer these questions various measuring and monitoring methods were used.

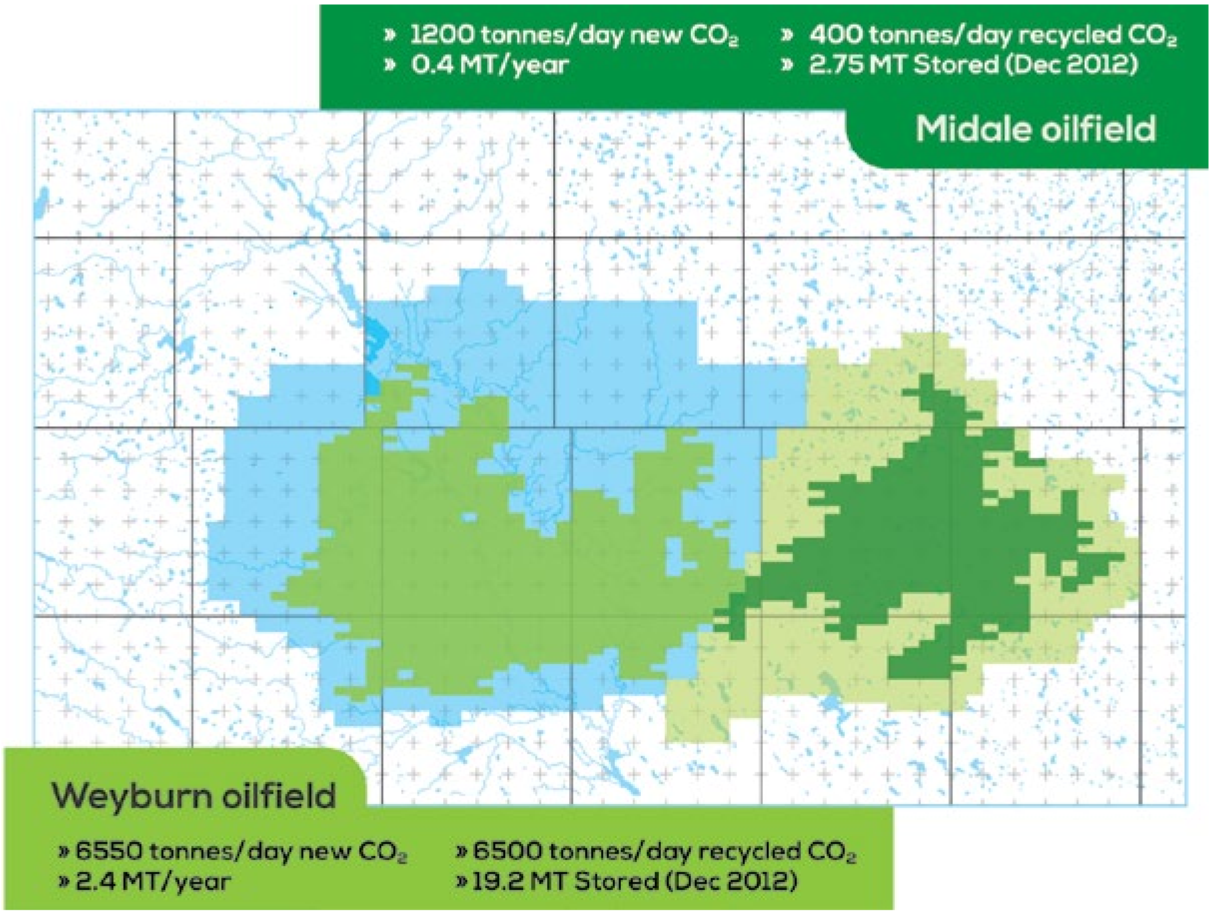
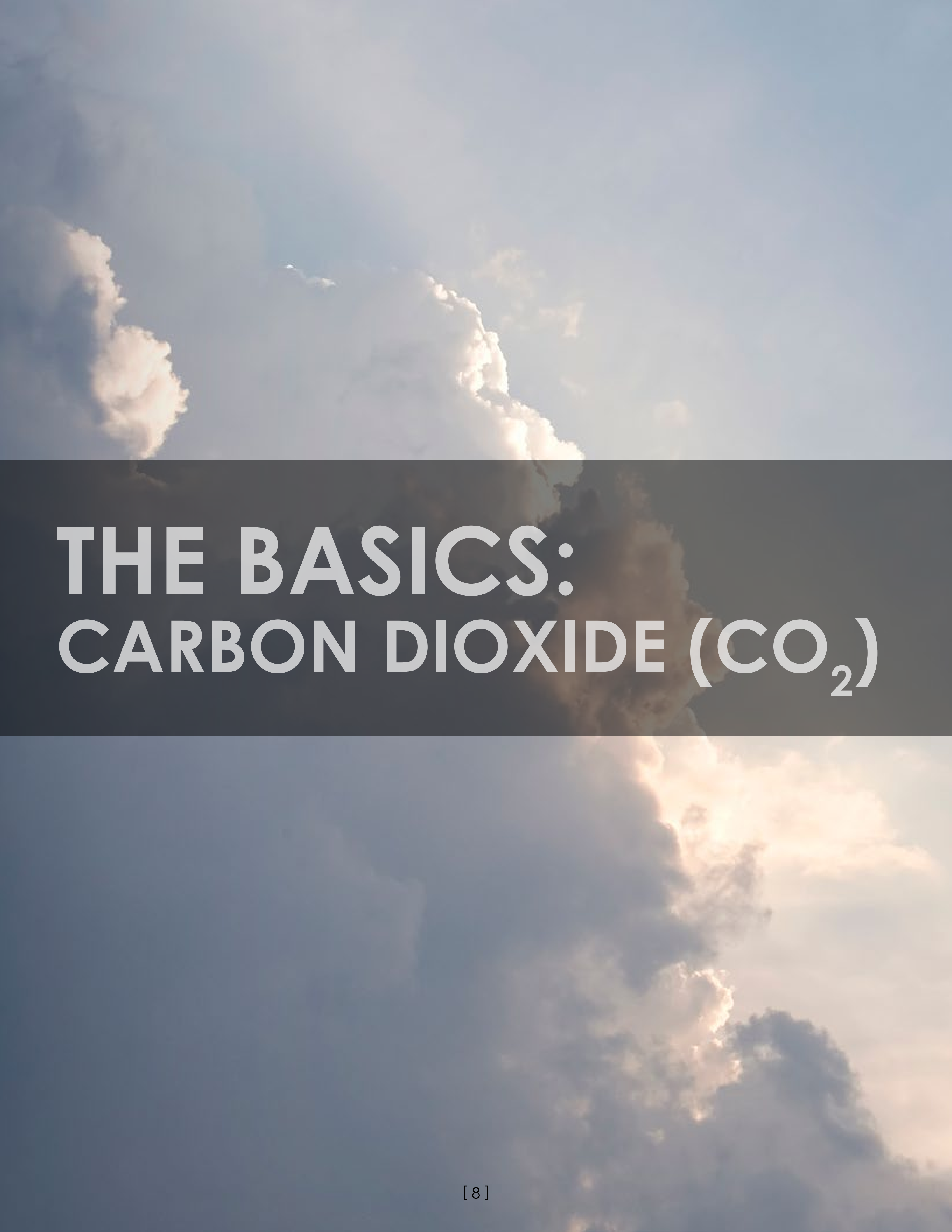


Figure 1. Total storage of CO_2 in both the Weyburn and Midale oilfields as of 2012 are included here (metric tonnes), along with the amounts of CO_2 that are injected each day into each field (both that newly arrived from Dakota Gasification Company, and that produced with oil and then reinjected). The total amount stored in both oilfields (22 million tonnes or MT) is the same amount that about 4 million cars emit each year. (Original picture courtesy of the PTRC)

The WMP research focused on seven key areas related to CO_2 storage:

- **Understanding the storage site characteristics:** Involves looking at the overall geological setting of the storage site to determine its suitability to safely and permanently store CO_2. This includes focusing on the reservoir, but also examining the rocks surrounding the storage layer. In the case of Weyburn, over 50,000 cubic kilometers of layers beneath the ground were mapped.
- **Predicting the storage performance:** A number of factors impact how much CO_2 can be injected and held within a given reservoir. This work investigated the storage potential at the Weyburn oilfield assuming several scenarios that include physical aspects of the rock, but also economic and policy considerations.
- **Measuring and tracking stored CO_2:** Ways of detecting and measuring changes in rocks and fluids resulting from injection of CO_2 (or any fluid) are part of monitoring surveys. The resulting data generally shows us how and where the carbon dioxide is moving in the subsurface. Monitoring can be done in the deep layer of rock in which the carbon dioxide is being injected and also in higher or shallower geological levels, including at surface, or even using satellites.
- **Modeling to confirm the research:** Advanced computer modeling can simulate the effects of injecting carbon dioxide to predict future distribution or reservoir performance. One way of checking the models' accuracy is to use them to predict past behaviour in what is known as history matching.
- **Wellbore integrity:** Old wells may provide potential leakage routes out of the reservoir. The WMP had a unique testing program conducted within an old well to examine its condition so a realistic assessment could be made of the likelihood of leakage.
- **Risk assessment:** Some research helped identify, evaluate, and rank potential risks posed by long-term geologic storage of CO_2. Risks considered included those to human health and safety, the environment, changing economic conditions and future operations. Weyburn has a low technical, or geological, risk for leakage.
- **Communicating results and complying with regulations:** An extensive outreach program was developed to help inform the general public and governments about the scientific research being undertaken, and to involve people in this ground-breaking research.



THE BASICS:
CARBON DIOXIDE (CO_2)

"Levels of CO_2 in the Earth's atmosphere have reached their highest recorded levels in over 350,000 years because of the amount of fossil fuels currently being burnt world-wide, and because of the reduction in forests and vegetation that are important for absorbing the CO_2 out of the atmosphere. The high levels of CO_2 in the atmosphere are a major concern for influencing global climate change."

1. What is carbon dioxide (CO_2)?

Carbon dioxide, or CO_2, is a very common, naturally occurring molecule that contains two oxygen atoms and one carbon atom. In everyday conditions on Earth, carbon dioxide is a commonly occurring gas that is all around us. It is colourless, odourless, is naturally present in Earth's atmosphere and is an important part of Earth's carbon cycle. All humans and animals exhale carbon dioxide when they breathe, and plants absorb it during a process called photosynthesis in order to grow.

CO_2 is called a greenhouse gas (GHG) because as part of Earth's atmosphere CO_2 traps the energy from the sun and keeps the world at a livable temperature. But increases in atmospheric CO_2 associated with human activities can pose problems. For example, on the one hand, burning of fossil fuels releases extra CO_2 into the atmosphere (along with other greenhouse gases), and, on the other, destruction of forested areas causes less CO_2 to be absorbed by trees, etc. Both cases lead to too much energy or heat being trapped in our atmosphere. This extra energy causes increasing climatic instability, which results in major changes in weather patterns.

The CO_2 injected into the Weyburn and Midale oilfields is produced by the conversion of coal into methane from a coal gasification plant in the United States and transported to southeastern Saskatchewan (Canada) by pipeline. The methane produced in the plant is used to heat homes and businesses. As part of this process for turning coal into methane, CO_2 is produced as a by-product. The carbon dioxide provider – Dakota Gasification Company in Beulah, North Dakota – captures the CO_2 produced during this gasification process and compresses it (puts it under great pressure) using large compressors until it is liquid-like. It is then sent by pipeline to southeastern Saskatchewan for injection into Weyburn and Midale oilfields, where it helps to produce more oil from the ground. For the two oil companies operating in those fields, CO_2 is, therefore, a valuable commodity used to increase the production of oil.

2. What is the carbon cycle?

All living things contain carbon. Carbon is also a part of the air (atmosphere), ocean (hydrosphere) and the ground (geosphere). Carbon is constantly being recycled through all these spheres in different forms – this movement is described as the carbon cycle.

In the atmosphere, carbon is always combined with oxygen to form CO_2. Plants, trees, algae and some bacteria absorb (or "photosynthesise") CO_2 out of the atmosphere, breaking down the carbon and oxygen – using the carbon to grow and releasing the oxygen. Humans and animals breathe in the oxygen and eat carbon-rich plants and animals. In a process called "respiration" they use the plants and meat for energy and breathe out CO_2. Animal waste and dead plants are broken down in the soil and over many millions of years some of that plant and animal matter ends up buried deep in the ground and, under the pressure of layers of rock, is turned into highly concentrated carbon or hydrocarbons – fossil fuels (coal, oil and gas).

From the end of our last ice age about 12,000 years ago, the amount of CO_2 in the atmosphere was relatively steady at below 280 parts per million (ppm – see Figure 3). Over the last 200 years carbon dioxide has been increasingly produced by human activities like the burning of trees and vegetation as well as the burning of fossil fuels. These human activities have affected the carbon cycle by currently adding around 33 billion tonnes (gigatonnes) of CO_2 to the atmosphere every year (that is 33,000,000,000 tonnes)[3]. While levels of CO_2 in the atmosphere may have been even higher in ancient times (in the era of the dinosaurs, for example) current levels of CO_2 in the Earth's atmosphere have reached their highest recorded levels in over 350,000 years. The high levels of CO_2 in the atmosphere are a major concern in influencing global climate change.

The WMP studied the injection of one source of manmade or anthropogenic CO_2 – from a coal gasification plant in North Dakota – into the Weyburn and Midale oilfields. This manmade CO_2 was injected as part of enhanced oil recovery operations, but an additional benefit is that the manmade CO_2 has remained permanently underground rather than being released into the atmosphere.

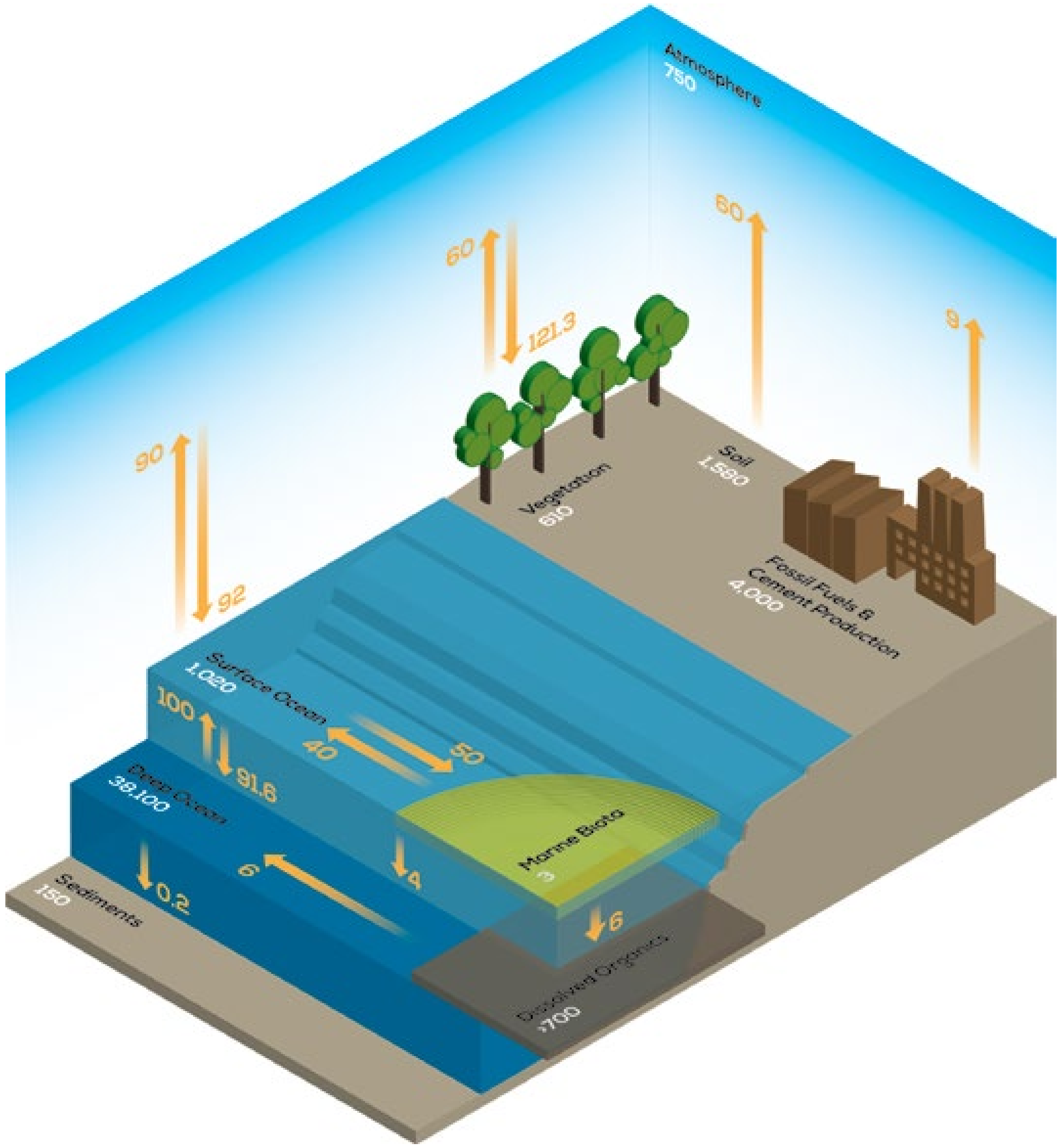


Figure 2. The carbon cycle is a process in which tens of billions of tonnes of carbon move between the atmosphere (air), hydrosphere (water) and geosphere (soil). The numbers in this illustration are billions of tonnes (gigatonnes). Current human activity adds about 9 gigatonnes of carbon to the atmosphere (33 gigatonnes of CO_2, which is made up of one-third carbon and two-thirds oxygen). This amount is increasing each year as we burn more and more of the estimated 4000 gigatonnes of oil, gas and other hydrocarbons that contain carbon.

Q

3. What are the properties of CO_2?

A

Pure carbon dioxide is an invisible, odourless gas. When put under pressure or in very cold conditions, it can transform into a liquid or solid. At temperatures below minus 78.5°C, carbon dioxide becomes a solid (also known as "dry ice").

The CO_2 that is pipelined to Saskatchewan from North Dakota for injection into the Weyburn and Midale oilfields is 95% pure; it contains a few other components that are produced in the coal gasification process. The CO_2 is pipelined under high pressure, which transforms the gas into a liquid-like state (also called a "dense phase") that can be better injected into the two oil reservoirs.

Q

4. Is CO_2 explosive or flammable?

A

CO_2 is not flammable and cannot be ignited – in fact CO_2 is very commonly used in fire extinguishers to put out electrical fires. However, the pipeline bringing CO_2 from North Dakota to the Weyburn oilfield is under high pressure in order to transport the CO_2 in a liquid-like state. Should the pipeline rupture, the CO_2 would be released rapidly and would solidify on contact with the air (forming a dry ice snow) and then evaporate slowly. Depending on the rate of pressure in the pipeline, CO_2 would rapidly release but as a non-flammable gas it would not ignite.

Q

5. Is CO_2 toxic?

A

At everyday levels of concentration, CO_2 is not toxic; rather, it is very useful. CO_2 is in the air we breathe, the water we drink and the food we eat. Humans and animals breathe it out, plants need it to grow, and it is a common ingredient in many drinks and candies.

However, when CO_2 is more concentrated (10% or greater of the composition of the air that we breathe) it can cause intoxication or poisoning over prolonged periods. The concentrations of CO_2 in the pipeline from North Dakota to Saskatchewan are near 95%. At these levels, exposure to CO_2 would cause asphyxiation.

But because all gas pipelines – whether carrying natural gas, oil, CO_2 or other compounds – carry potentially dangerous substances, strict monitoring and maintenance regulations are in place to ensure they are safely operated. In 13 years of injection there has not been a single injury or death caused by the CO_2 pipelined and injected into the Weyburn and Midale oilfields.

Q

6. Are there other ways to use CO_2?

A

There are a number of uses for CO_2. It is used as a supplement to food products (carbonated drinks and popping candies are two examples). CO_2 can also be used in greenhouses and other plant growing operations, to increase crop production. Solid CO_2 (better known as dry ice) is used to keep food and other items frozen – CO_2 becomes a solid at temperatures less than minus 78°C.

However, CO_2 used for these purposes must be 100% pure – particularly if it is being put into foods that we eat. The CO_2 being used for injection into the Weyburn and Midale oilfields contains small amounts of other compounds that mean it cannot be used for food production.

In the Weyburn oilfield, CO_2 is used as a thinner that mixes with the oil to increase production. The CO_2 is "miscible," meaning that it can mix and absorb into the oil. This causes the oil to expand out of cracks and pores in the oilfield. When the oil expands, more of it can flow to the production wells. Oil production in the Weyburn oilfield has almost tripled because of the injection of CO_2.

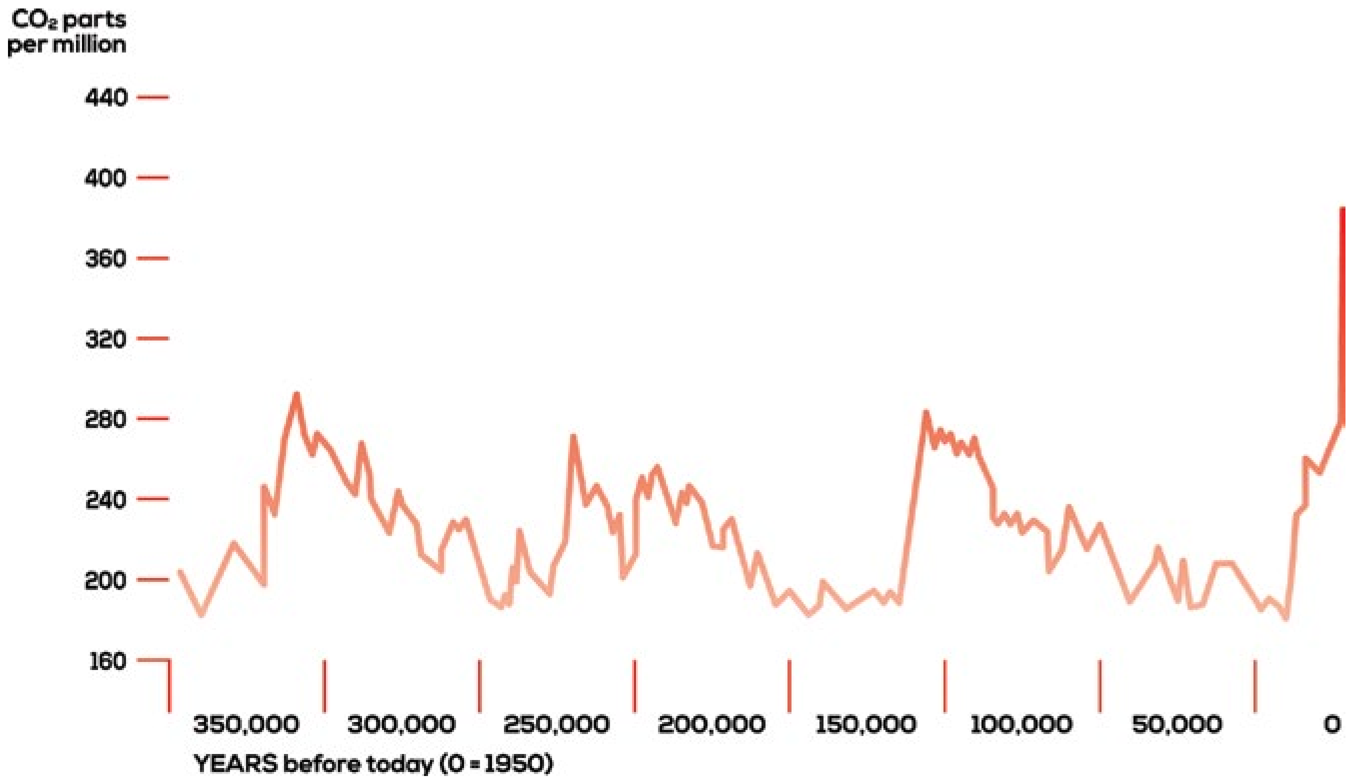
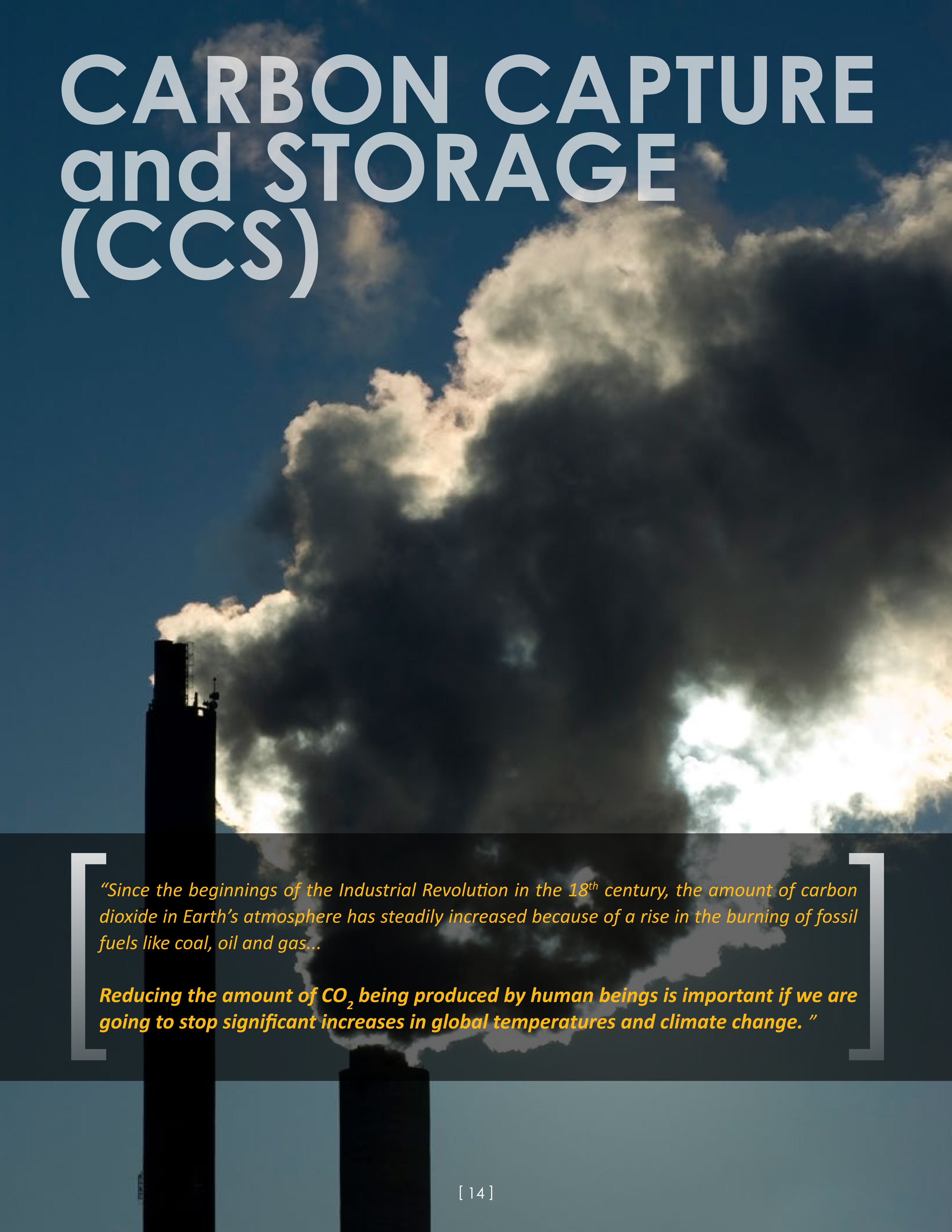


Figure 3. In the 350,000 years prior to human industrial activity, CO_2 readings in the atmosphere never went above 300 parts per million (ppm). Since the industrial revolution (18th century) and at an increasing rate into the 21st century, CO_2 in the atmopshere has surpassed 400 ppm and continues to climb at an increasing rate. Since 1950 CO_2 in the atmosphere has gone up by 30%.



CARBON CAPTURE and STORAGE (CCS)

“Since the beginnings of the Industrial Revolution in the 18th century, the amount of carbon dioxide in Earth’s atmosphere has steadily increased because of a rise in the burning of fossil fuels like coal, oil and gas...

Reducing the amount of CO_2 being produced by human beings is important if we are going to stop significant increases in global temperatures and climate change. ”

Q

7. What is carbon capture and storage?

A

Carbon capture and storage (CCS) is an emission reduction process designed to prevent large amounts of carbon dioxide (CO_2) from being released into the atmosphere. The technology involves capturing CO_2 produced by large industrial plants, compressing it for transportation and then injecting it deep into a rock formation at a carefully selected site, where it is permanently stored. Although CCS is often referred to as a single idea, it involves three major steps and different types of technologies:

Capture

The separation of CO_2 from other gases produced at facilities such as coal and natural gas power plants, oil and gas refineries, steel mills and cement plants.

Transport

Once captured and separated, the CO_2 is compressed to a "dense phase" or liquid-like state to make it easier to transport. The CO_2 is usually transported to a suitable site for geological storage using pipelines, but some countries use ships and – for small amounts of CO_2 – trucks or trains can also be used.

Injection/Storage

CO_2 is injected into deep, underground rock formations, usually at depths of one kilometre or more. The formations into which CO_2 is injected for storage are often depleted oil and gas reservoirs, or very similar deep rock formations that, rather than oil, contain brines or water several times saltier than the ocean. These porous rock formations are referred to as deep saline formations or saline reservoirs and they are almost always sedimentary rocks like sandstones or limestones. These rock formations offer secure space to permanently store CO_2 – they are rocks containing tiny pores that have stored vast quantities of liquids and gases safely for many millions of years.

At the Weyburn oilfield, the reservoir is a 1.5 km deep limestone that contains oil as well as brine in its pores.

At the Weyburn and Midale oilfields, the companies involved with the use of CO_2 have deployed this same set of technologies:

Capture

CO_2 is captured from the Dakota Gasification Company's coal gasification plant in Beulah, North Dakota; compressors turn the CO_2 into a liquid-like state.

Figure 4. These compressors, at the Dakota Gasification Facility in North Dakota, condense the CO_2 into a "dense phase" so that it will flow like a liquid in the pipeline to Canada. (Photograph courtesy of Dakota Gasification Company)

Transportation

A 320 km pipeline from Beulah, North Dakota, to the Weyburn and Midale oilfields in Saskatchewan is used to transport the CO_2. The pipeline varies from 14 to 12 inches in diameter.

Figure 5. The CO_2 pipeline from Beulah, North Dakota, to the Weyburn oilfield is 320 km long and transports approximately 8000 tonnes of CO_2 per day. (Image courtesy of Dakota Gasification Company)

Injection/Storage

WMP research was attached to two commercial enhanced oil recovery projects. The oil companies use carbon dioxide to get more oil out of an oilfield 1.5 km underground (see Question 8), and hydraulic pumps and compressors distribute and inject the CO_2 into many dozens of injection wells. The CO_2 helps improve oil production by mixing with the oil in the reservoir and making it flow easier. As the oil is pumped to surface, the pressure and temperature begin to decrease and the contained carbon dioxide begins to get released from the oil. This freed-up carbon dioxide is collected at the surface, compressed, and re-injected. About 40% of the injected carbon dioxide stays in the reservoir and never comes back with the oil. The WMP spent 12 years providing measurement and monitoring of the injected CO_2 to assure it remains safely in place.

For projects where CO_2 is not being used to increase oil production, and is being injected purely for storage into a location deep in the earth where no oil or gas is located, the number of wells would be much smaller than in an oilfield.

Figure 6. Here, the CO_2 at the Weyburn oilfield is pumped to various locations in the field for injection underground. The yellow indicates the pipelines are transporting CO_2. (Photograph courtesy of Cenovus Energy)

Q

8. What is CO_2-EOR?

A

EOR stands for "enhanced oil recovery." When an oilfield has begun to slow its oil production (this can happen for many reasons such as a drop in pressure that stops the oil from traveling to the production well, or because the oil that remains in the reservoir is very thick and unable to flow,) different methods can be used to "enhance" the production and increase the amount of oil being produced.

One well-known EOR method is called "waterflooding," whereby water is injected to increase the reservoir's pressure and help to push oil to the production well. Other methods include "steam injection" and "solvent injection" whereby heat and/or solvents are injected to help thin heavier kinds of oil so that they flow more freely.

CO_2-EOR involves the injection of compressed carbon dioxide into an oil reservoir. CO_2 acts like a solvent, and causes the oil to expand and flow more easily to production wells. In the case of the Weyburn oilfield, CO_2 is injected at several injection wells in the field (up to 70 or more at a time). After several days of injecting CO_2, the wells are then switched to water injection. This alternating water-and-gas injection (or WAG, as it is called) allows the oil to first expand and become better able to flow because of the CO_2, and then the water increases the pressure in the reservoir to flush this newly freed oil to production wells.

The Weyburn oilfield was producing only 8,000 barrels of oil per day by 1990. CO_2 began to be injected in 2000, and within 5 years oil production had grown to nearly 30,000 barrels per day [see Figure 7]. Because the CO_2 is miscible with the oil (miscible means it blends with the oil and becomes part of the oil mixture as it comes to the surface) a certain amount of CO_2 returns to the surface during oil production. The oil company at the Weyburn field separates this CO_2 from the oil mixture at the surface, and compresses and re-injects it along with the new CO_2 arriving from the United States.

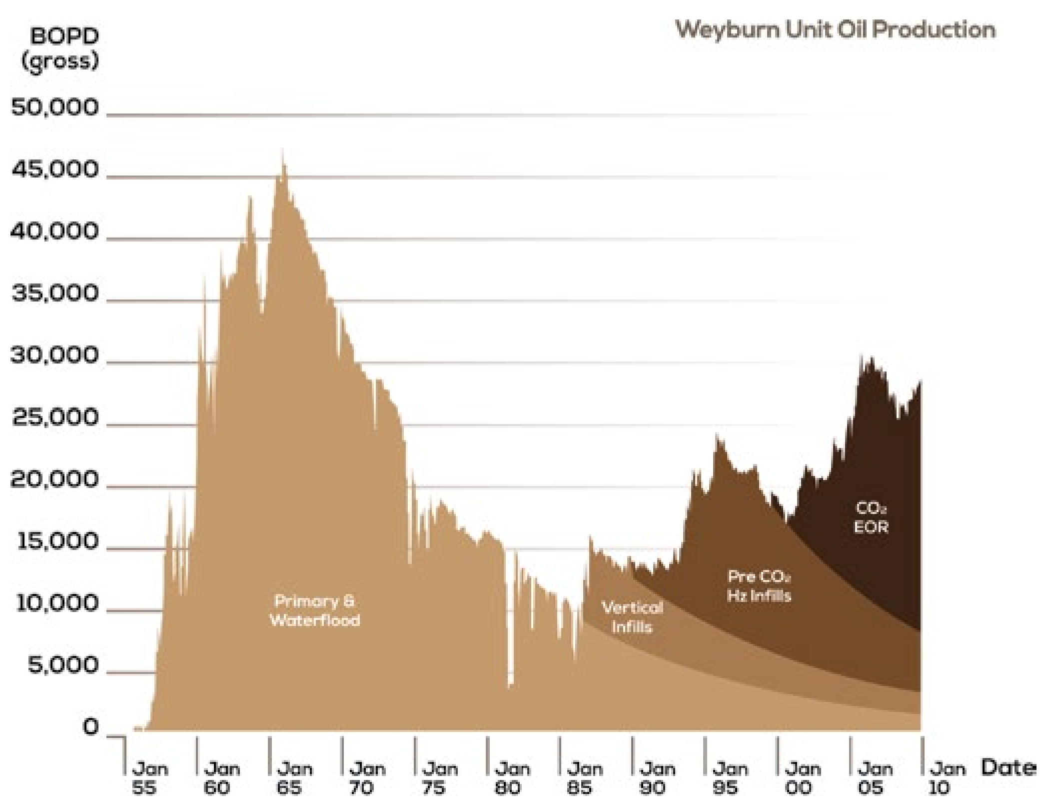


Figure 7. Production graph from the Weyburn oilfield, showing a peak production during CO_2 injection of just over 30,000 barrels of oil per day (BOPD). "Infills" mean additional wells drilled into the field, first vertical and then, when the technology was developed in the 1990s, horizontal wells. Both of these measures temporarily increased oil production. The injection of CO_2, starting in January 2000, has led to a significant jump in production. (Image courtesy of Cenovus Energy)

Q

9. Why do we need carbon capture and storage?

A

Since the beginnings of the Industrial Revolution in the 18th century, the amount of carbon dioxide in Earth's atmosphere has steadily increased because of a rise in the burning of fossil fuels like coal, oil and gas. Over the past 300 years, the amount of CO_2 in the atmosphere has gone from 280 parts per million (ppm) to over 400 ppm in 2013. The rate of increase has gone up sharply in the past 50 years. See Figure 8 below.

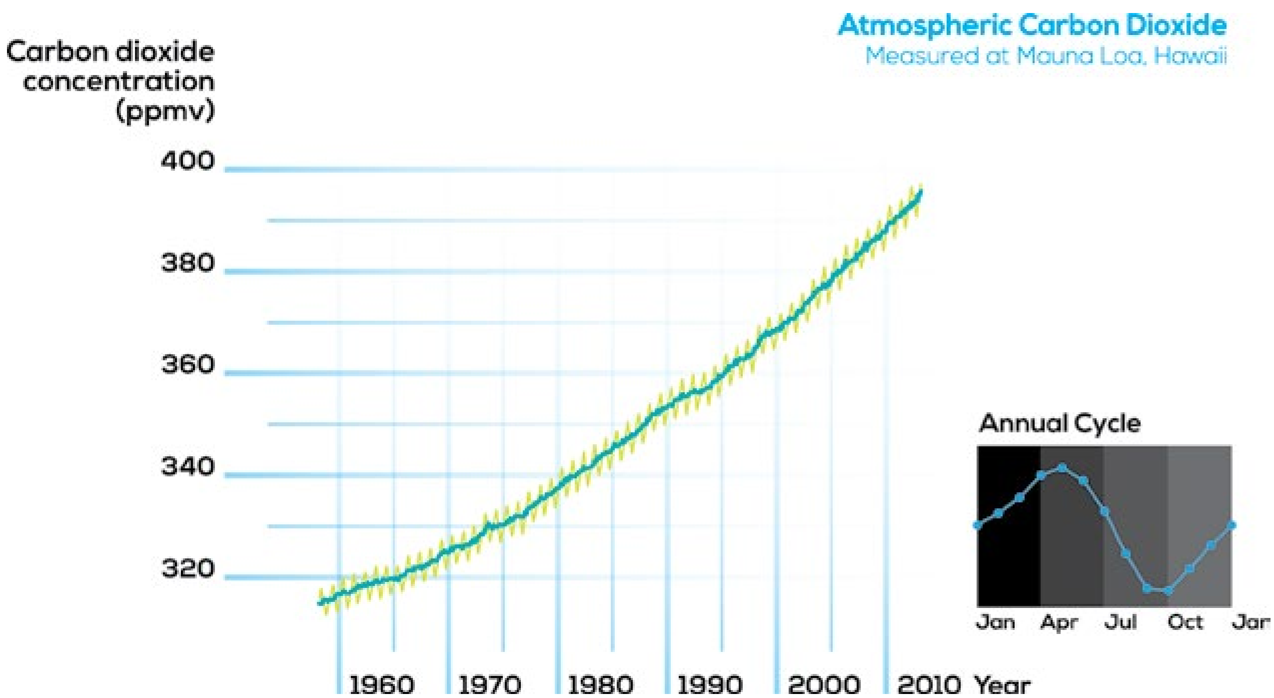


Figure 8. Increase in CO_2 in the Earth's atmosphere, as measured at the Mauna Loa Observatory in Hawaii, 1960 to 2013. The rising graph means we have increased CO_2 in the atmosphere by 30% in just 50 years of monitoring. (Source: Mauna Loa Observatory)

This increase is a problem because CO_2 in the atmosphere acts as a warming blanket for the earth, allowing the sun's heat to be trapped rather than reflected back out into space.

Reducing the amount of CO_2 being produced by human beings is important if we are going to stop significant increases in global temperatures and climate change. According to the International Energy Agency (2012), the largest contributing sector to global CO_2 emissions is the generation of electricity and heat – this made up 41% of world CO_2 emissions in 2010, and demand for heat and electricity is set to dramatically increase over the coming years (See Figure 9).

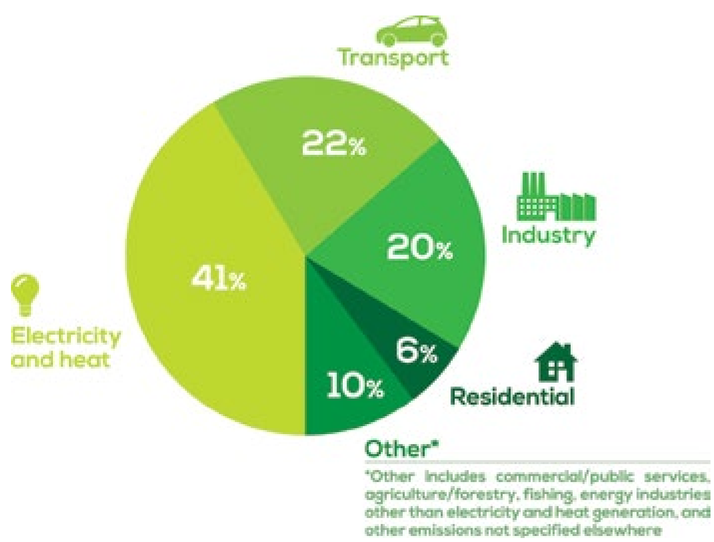


Figure 9. CO_2 emissions by sector (IPCC: www.iea.org/co2highlights/co2highlights.pdf, page 9)

Reducing CO_2 emissions in the electricity and industrial sectors can be done through many means, including improved energy efficiency (people and industry wasting less energy and changing their behaviour to make the most of the energy we have), greatly increasing the amount of renewable resources of energy used (like solar, wind, wave and geothermal), and the use of emissions reduction technologies like carbon capture and storage (CCS), which captures the CO_2 produced from burning fossil fuels and stores it so that it cannot enter the atmosphere. The world is still very dependent on fossil fuels, so CCS is a very important technology to greatly reduce the emissions arising from their use.

The oil production operations studied in the WMP take close to three million tonnes of CO_2 each year, produced from a coal gasification plant, and prevent it from being emitted into the atmosphere by injecting it deep underground into two oilfields. Between 2000 and 2012, 22 million tonnes of CO_2 that would otherwise have been vented into the air have been injected underground. This is the equivalent of taking over 4 million cars off the road for one entire year.[4]

Q

10. What if we don't bother storing our manmade CO_2?

A

The overwhelming majority of climate scientists agree[5] that if we do not reduce our CO_2 emissions, significant climate change will occur. Indeed, there is strong evidence to support the fact that our climate is already changing. This includes an anticipated global rise in temperatures of between 4 to 8 degrees Fahrenheit (2 to 4 degrees Celsius), a rise in sea levels that may swamp many of the most populated coastal regions of the world, and increasingly severe weather events such as droughts and storms. Average temperatures since 1880 have risen by 1.6 degrees (see Figure 10).

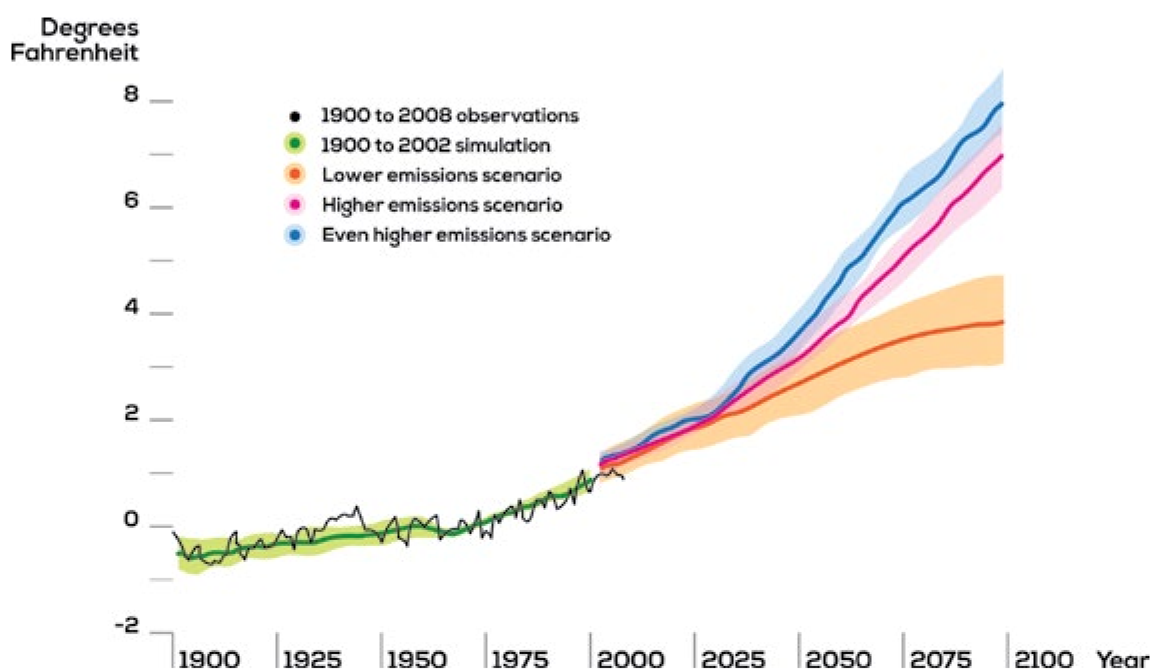


Figure 10. Estimated global increase in temperature, given low and high CO_2 production scenarios. (Source: www.epa.gov)

CO_2 storage is just one of many initiatives that need to take place to help reduce the amount of CO_2 in our atmosphere. Improved energy efficiency and conservation, increased use of renewable sources of energy, improved protection of forests and oceans which absorb significant quantities of CO_2, and a reduction in our fossil fuel use are all important.

Renewable resources are becoming more and more efficient, and could eventually meet a much higher percentage of our energy needs. But for the foreseeable future, fossil fuels will remain crucial to our energy mix, and CCS is an essential technology for reducing CO_2 emissions from those sources.

Q

11. How do you capture CO_2?

A

Three main technologies are currently used to capture CO_2 from large, fixed CO_2 sources: pre-combustion, post-combustion and oxyfuel. A full description of these processes will not be provided here, since the engineering is very complex. Full descriptions of these capture processes can be found online: www.ccs101.ca and www.globalccsinstitute.com/understanding-ccs.

For the Weyburn and Midale oilfields the CO_2 supplied by the Dakota Gasification Company comes from a pre-combustion process. Coal, through heat and pressure processes, is turned into methane gas (for burning in homes or businesses) and CO_2. The resulting CO_2 is compressed before it is sent by pipeline to Weyburn and Midale for enhanced oil recovery.

Q

12. How much does CCS cost?

A

In the carbon capture and storage (CCS) chain, it is the building of the capture and compression facilities that costs the most money. SaskPower's Integrated Carbon Capture and Storage facility in southeastern Saskatchewan was constructed between 2011 and 2014 for a reported total cost of 1.35 billion Canadian dollars (as of April, 2014). A final breakdown of these costs between the capture and compression facility and the replacement of the turbine in the power plant is not currently available, but most coal-fired plants thinking of fitting existing turbines with carbon capture technology would also need to include changes to infrastructure as part of the overall costs. The high costs of capture are associated with the fact that, so far, there have been so few capture facilities built globally. The capture technologies have not been employed on a broad level across many projects; as more get built, savings are likely to be identified. The engineering and deployment of the technologies will become more efficient and, as a result, prices will come down.

Transportation and storage of the CO_2 cost considerably less than capture, since most of the technologies are well known and have been deployed in other industries such as oil and gas production. For injection of CO_2 into the Weyburn and Midale fields, there were two significant capital costs – the 320 km pipeline that runs from North Dakota up to the oilfields, and the infrastructure required in the oilfields themselves to inject the CO_2 at different locations.

These were significant capital costs – in the hundreds of millions of dollars for the pipeline and similar for the infrastructure at the oilfields – and do not include ongoing operating costs. But the costs and benefits of CCS need to be weighed on a project-by-project basis. In the case of Weyburn and Midale, costs have been weighed against the higher income to the oil companies from the increased oil production. These total costs and benefits associated with the Weyburn and Midale CO_2-EOR operations are confidential to the oil companies involved, but if costs were exceeding profits then it is unlikely CO_2 would be injected.

Q

13. How valuable is CO_2?

A

The value of CO_2 is variable and dependent on the details of specific CCS projects. CO_2 that is injected for the purposes of recovering more oil (like in the Weyburn and Midale oilfields) is purchased at a specific price by the oil companies involved, since it is a valuable commodity used to get more oil out of the ground. CO_2 that is being injected into a deep saline formation, for disposal and storage and not for economic gain, would only have a value if there were a carbon tax, or carbon credit, offered for disposal (see Question 15 for more information on carbon taxes).

In the Weyburn oilfield, each tonne of CO_2 has led to an increase in production of approximately 2.5 to 3 barrels of oil. In 2013, oil was valued at approximately 90 dollars a barrel; thus each tonne of CO_2 was providing 220 to

270 dollars of increased production. Capital and operating costs associated with the oilfield's injection wells and infrastructure would need to be applied against these benefits.

Q

14. Who owns the CO_2?

A

In the WMP, the CO_2 is owned by the Dakota Gasification Company (DGC), which captures the CO_2 from its coal gasification plant in Beulah, North Dakota. DGC has a signed agreement with both Apache Canada and Cenovus Energy to sell the CO_2, at a set price per tonne, to each company. On receipt, the CO_2 is then owned by the two purchasing companies and remains in their ownership for injection and re-injection into the oilfields.

Q

15. Are carbon capture and storage (CCS) and CO_2-EOR economically viable?

A

The economic viability of carbon capture and storage for reducing greenhouse gas emissions is still very dependent on climate policies. Where CO_2 is injected for the purpose of enhanced oil recovery, the capture, transport and storage of CO_2 can be, and has proven to be, economically viable because of the incentives of more oil production. In the oilfields studied for the WMP, the CO_2 is valued as a commodity that produces more oil. The capital and operating expenditures for the capture facilities, the pipeline to move the oil, and the infrastructure to inject the oil are offset by the profits made from increased oil production.

The current costs associated with CCS, independent of enhanced oil recovery, can make many large-scale projects costly and difficult to justify without securing additional public funding or putting in place a sufficient level of carbon pricing to help create a more level playing field relative to other low carbon technologies.

For CCS to realise its potential as a significant contributor to the reduction of carbon dioxide emissions globally, there needs to be a greater level of ambition by all countries to reduce CO_2 emissions with locally appropriate incentive programs put in place that will help motivate large stationary emitters, such as power plants and cement factories, to capture their CO_2 and store it. To reduce greenhouse gas emissions overall, CCS purely for storage purposes (storing CO_2 not to produce more oil and gas, but to stop manmade sources of CO_2 from going into the atmosphere) will be needed to reduce our total CO_2 emissions.

Different governments around the world have put various carbon pricing arrangements in place, which basically charge emitters a financial amount per tonne of CO_2 emitted. If these arrangements are sufficient, then emitters could be further motivated to capture and store CO_2 so as to avoid paying these costs. For example, some nations have put carbon taxes into place. These include Norway (approximately US$75 a tonne) and the province of Alberta in Canada (Can$15 per tonne). These sorts of incentives are generally considered necessary for CCS to become a major technology solution for reducing emissions. As well, the costs of CCS technologies will come down when more capture and storage projects go forward due to growing economies of scale. The learnings from more projects coming on stream will help reduce the costs of building more CCS facilities in the future, but large industrial-scale CCS projects are not likely to occur without incentives.

WHAT HAPPENS TO CO_2 UNDERGROUND?

Geological storage sites for CCS will be selected, mapped out (characterised) and designed on the basis of "zero leakage." In other words, the sites are chosen and operated so that all of the injected CO_2 will be permanently stored in the reservoir(s) or storage site.

Q

16. How do you store CO_2 and how do you decide where CO_2 can be stored?

A

Four key elements are important for CO_2 storage:

- **Depth and Location:** The storage location needs to be at sufficient depth and be made up of a porous rock (a rock full of tiny holes) that is permeable (the holes are connected) so the CO_2 can move through the rock and get trapped in the pores. The CO_2 being injected should be in a "dense phase," which means that it is put under pressure (compressed) until it turns from a gas into a kind of liquid. Because liquids take up much less space than gases, when large amounts of CO_2 are injected, less space will be needed underground if the CO_2 is in liquid form. It will mix more easily with water and other compounds, helping to secure the CO_2 underground. The storage location must be deep enough in the earth that the pressures of the multiple layers of rock above the storage site keep the CO_2 in this dense phase, to help it stay in the secure storage location, and not rise up like a gas. It is possible for CO_2 to be injected as a gas, but the storage location would have to have a higher storage capacity since a gas takes up more space than a liquid.
- **Containment:** A storage site must also have a layer of dense, impenetrable rock above it (called caprock) to stop any upward movement of CO_2. There is often more than one such layer above the target storage formation that offers protection to keep the CO_2 in the storage site.
- **Capacity:** The storage site must also have enough pore space to hold the amount of CO_2 planned to be injected over the life of a project.

If these criteria have been met, CO_2 storage should be possible.

The oil reservoirs studied in the WMP are about 1500 metres deep, which is deep enough so that the CO_2 remains like a liquid. The reservoirs are made of limestone and a similar rock-type called dolostone. Both rocks contain lots of pore space where the oil has been trapped for millions of years. The top of the reservoir is capped by a rock called anhydrite that is very dense and has no pores. The anhydrite acts as a seal which has both trapped oil in the reservoir and, in turn, keeps the CO_2 contained.

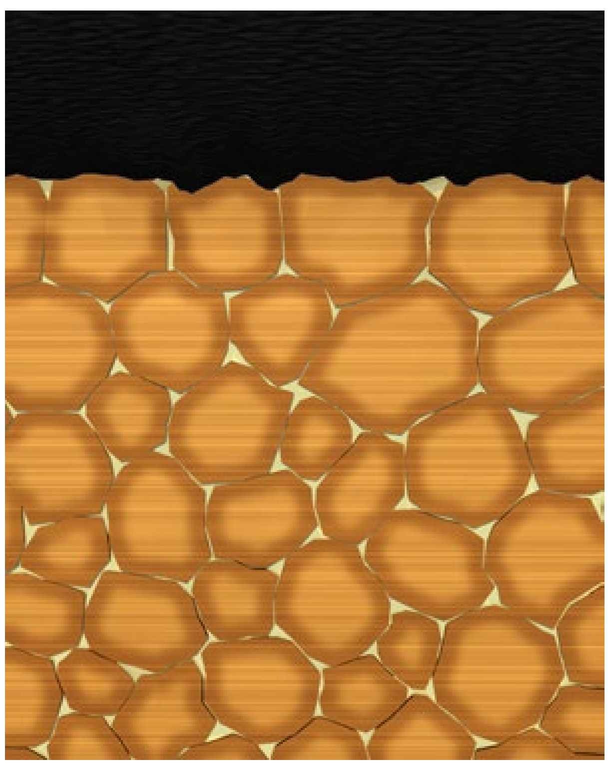


Figure 11. Saline reservoirs are made up of porous rock such as sandstone that contains small spaces such as these, which hold water or other liquids. When liquid CO_2 is injected, it is trapped within these small pores in the rock where it mixes with the liquids already there. The impermeable caprock above the reservoir also helps keep the CO_2 trapped. (Image courtesy of University of Regina)

For storage sites, these types of geological features are needed: a good porous (and permeable) reservoir and a non-porous (impermeable) cap rock. Sedimentary rocks like limestones, dolostones (both are carbonates formed from ancient organisms) and sandstones make great reservoirs, and shales and anhydrites make good seals or caprocks. Other rock types can also be used, but these are the most common. Rocks must therefore be mapped out, studied and characterised before any CO_2 is injected to make sure they have good storage site characteristics. A model of the rocks from the oil reservoir up to the surface at the Weyburn oilfield is shown in Figure 12.

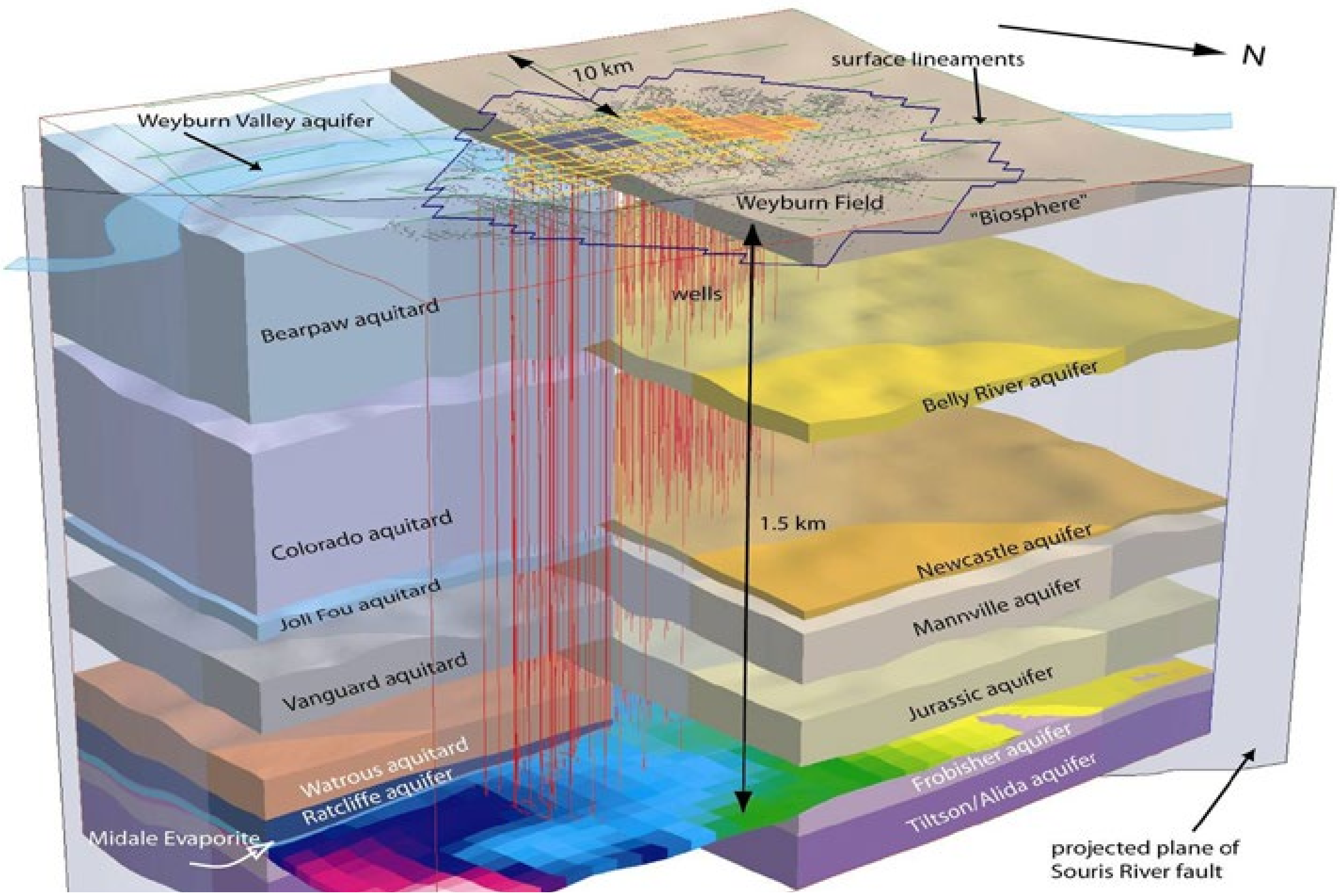


Figure 12. A three-dimensional geological model of the Weyburn oilfield created from characterisation data, showing barriers to vertical movement on the left, aquifers on the right, and wellbores stretching into the formation. "Aquitards" are layers of rock and earth that stop the vertical movement of liquids. "Aquifers" are the more porous layers of rock – often sandstone – that contain liquids such as briny water or oil.

Q

17. How much CO_2 can be stored at different locations?

A

The amount of CO_2 that can be injected and stored in a geological formation is different for every site. Storage capacity depends on the porosity and permeability characteristics of the individual rock formations. Porosity refers to the measurement of the number of void spaces in a rock or material. Permeability refers to the ability of the rock to allow for the injection and passing of fluids. How much carbon dioxide can be stored and how fast it can be injected are tied to these two concepts.

The amount of CO_2 that can be injected also depends on the number and arrangement of the injection wells. For example, at the Weyburn and Midale oilfields, the porosity and permeability are not as high as in a saline sandstone formation. In addition, many wells are used to inject the carbon dioxide into the oilfields, because the CO_2 is being used to recover oil (EOR) and not primarily for storage. In a project, however, that is solely about storing CO_2 in a deep saline formation, or some other highly permeable location, fewer wells for injection would be required. This is the main difference between CO_2 injection at Weyburn and Midale, which is used to recover oil, and CO_2 injection in other projects that are purely for storage.

Deep saline formations that are chosen for storage sites are usually very large and therefore have a capacity to store CO_2 in the tens-to-hundreds of millions of tonnes. These geological formations are made up of highly porous and permeable rocks (most often sandstone) that contain very salty water. Because these types of formations are so vast in size and are highly permeable and porous, very large volumes of CO_2 can be injected and stored using far fewer injection points, and without a significant increase of pressure in the formation. Globally these types of formations have been estimated by the International Panel on Climate Change (IPCC) to have a storage capacity of up to 10,000 gigatonnes (Figure 13).

Reservoir type	Lower estimate of storage capacity ($GtCO_2$)	Upper estimate of storage capacity ($GtCO_2$)
Oil and gas field	675	900
Unminable coal seams (ECBM)	3-15	200
Deep saline formations	1000	Uncertain, but possibly 10^4

Figure 13.Estimated total storage potential for CO_2, worldwide. The 10^4 in the chart's right hand column refers to 10,000. (From www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter5.pdf)

The IPCC estimates that there is potentially enough storage space in deep saline formations to store all the manmade CO_2 from large fixed sources for approximately 600 years.

The WMP did not examine the storage of CO_2 in a deep saline formation, but rather in an oil reservoir. Oil and gas reservoirs are also excellent places for storing CO_2 because they are like saline formations where naturally occurring gases and fluids have been trapped and stored for tens of millions of years. Their total CO_2 storage volumes are dependent on the unique characteristics of each reservoir. The Weyburn field will have stored 30 million tonnes of CO_2 by the end of the oil production life of the field, but it has been estimated that an additional 25 million tonnes could be injected safely into the reservoir (see Figure 14). Right now, the oil company operating the Weyburn field is injecting CO_2 strictly to increase oil production. By the end of the production life of the oilfield (the point where recovery of oil will no longer be economically viable), the operator could continue to inject CO_2 into the reservoir up to a total of 55 million tonnes. Figure 14 shows the point, in 2035, at which the field will no longer be producing oil. At that time, the Weyburn field could continue to receive CO_2 but only for storage purposes, not for enhanced oil recovery.

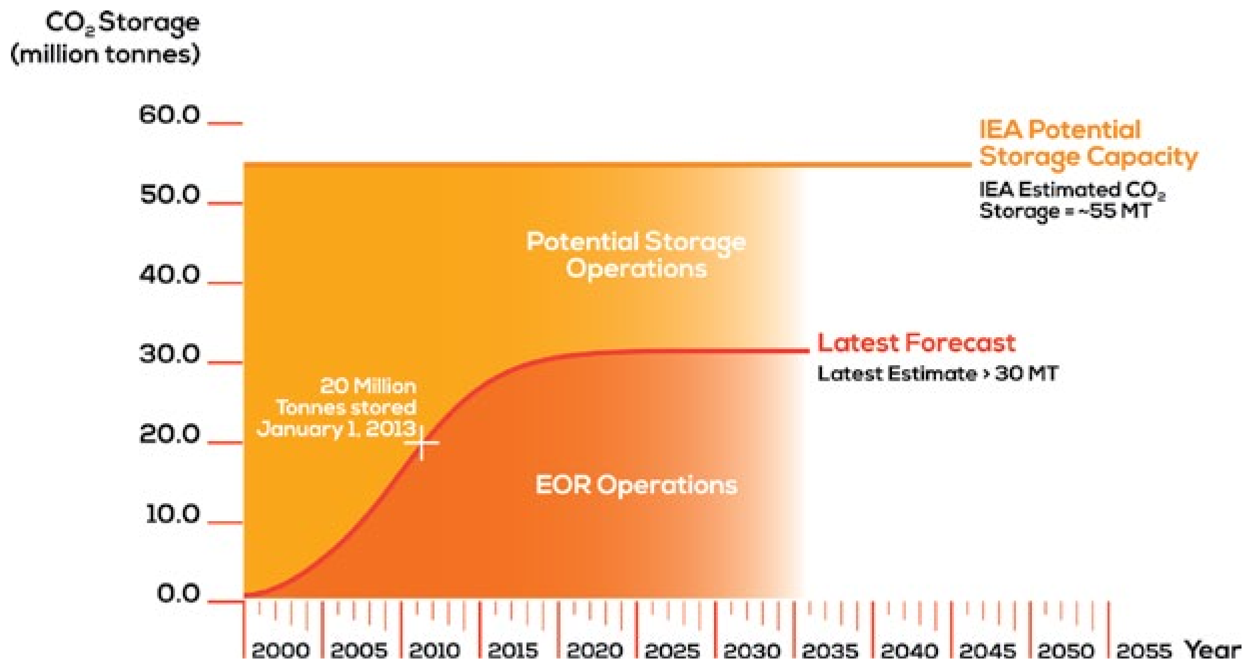


Figure 14. Estimated total CO_2 storage potential in just the Weyburn oilfield at the end of EOR operations. The field has the potential to hold an additional 25 MT of CO_2 after the 30 MT that will have been injected at the end of EOR. The Midale field, not shown here, will hold an estimated additional 10 MT by the end of EOR. (Image courtesy of IEAGHG)

Q

18. How deep do you store CO_2?

A

Generally, storage formations are targeted for depths of 800 metres or deeper because at these depths the carbon dioxide is more like a liquid than a gas so it is denser and requires less pore space. Storage could occur at shallower depths if there is a suitable porous reservoir with an effective "trapping" layer (caprock) immediately above it. However, most storage projects will target storage sites deeper than about 1 km, and some regulations are in place (Alberta, Canada) that state that storage must be deeper than 1 km.

The Weyburn and Midale oilfields are located 1.5 km below the surface. They are capped by a dense anhydrite layer which in turn has an impenetrable caprock of approximately 30 metres immediately above the oilfield. In addition, several thick packages of shales occur in the sequence of rocks above the caprock. These shales are termed aquitards; they would restrict any flow of fluids and each would be an effective seal (see Figure 12).

Q

19. What do you mean by 'permanent storage' of CO_2?

A

Geological storage sites for CCS will be selected, mapped out (characterised) and designed on the basis of "zero leakage." In other words, the sites are chosen and operated so that all of the injected CO_2 will be permanently stored in the reservoir(s) or storage site. There is no specific time period linked to the term "permanent," although various organizations have suggested time periods in the order of a thousand years.

The WMP spent four years at the beginning of the project looking at the suitability of the Weyburn and Midale oilfields for storing CO_2. Part of that process included looking at what are called "natural analogues" in southern Saskatchewan and other locations in Canada and North America. Natural analogues are large, naturally occurring deposits of CO_2 in the ground. These are locations that have securely trapped CO_2 over geological time (tens of millions of years) without any of that CO_2 escaping. This includes a small amount of CO_2 that exists in the Weyburn oilfield, trapped there over 65 million years ago. Figure 15 shows the various locations, globally, where significant amounts of CO_2 occur naturally underground.

CO_2 storage projects attempt to identify or artificially recreate these similar reservoir conditions. If the rock formations containing natural deposits of CO_2 can demonstrate to us the features that have kept the CO_2 in place, then making sure those features are also present in the proposed storage site will provide confidence that effective long term storage is also probable in a given storage location. The work in the WMP included identifying these conditions for long term storage in the Weyburn and Midale fields. Once they were identified as features of the two fields, CO_2 injection began and ongoing testing was done to make sure that the CO_2 acted in the predicted way.

All emerging CCS regulations around the world are based on a "risk management framework." In other words, sites have to be designed and operated to contain all of the injected CO_2 over long periods, and risk assessments will be used to work out if there is any likelihood of a leak and what would be the worst case scenario if there were a leak. All CCS developers will have to commit to a comprehensive monitoring and testing program over the life of a project; this includes complete plans in place to minimise and deal with any possible risks. The WMP conducted an extensive risk assessment of the storage site and surrounding area, and provided 12 years of measurement and monitoring of the injected CO_2 to verify its location and behaviour in the oilfields. The risk assessment conducted at Weyburn and Midale, and the site characterisation and monitoring all concluded that the location is highly stable and very unlikely to leak.

Q

20. Does CO_2 occur naturally underground, like water, oil and gas?

A

CO_2 occurs naturally in soil and water through the decomposition of organic material, as well as in underground rock formations. CO_2 can also be produced by geological processes within the earth such as the formation of volcanoes or through the same mechanisms that produced oil and natural gas over many millions of years. This naturally occurring, or geological, CO_2 occurs in many different locations (Figure 15). When the organisms (plants and tiny bacteria) that led to the creation of gas and oil were trapped underground many millions of years ago, so too were the organisms that decomposed and led to the creation of carbon dioxide. In fact, when oil and gas companies are drilling for oil and gas they sometimes come across CO_2 at different depths in the earth, both on its own or mixed with natural gas or oil.

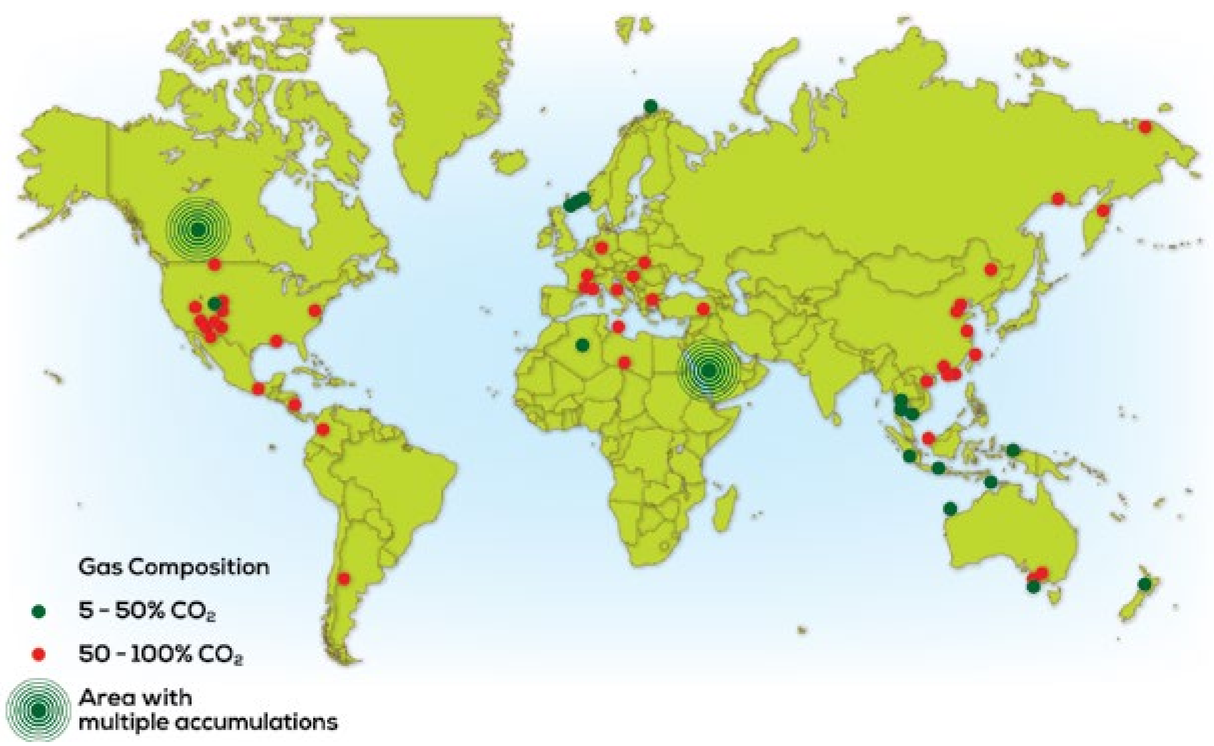


Figure 15. Examples of natural accumulations of CO_2 around the world. (Image adapted from: IPCC, Special Report on Carbon Capture and Storage, 2005, p. 210)

As an example, the Sleipner gas field in the North Sea (owned by Norway's national oil company Statoil) has for many years been producing gas that contains about 9% naturally occurring CO_2. Rather than simply vent the CO_2 into the atmosphere, the Sleipner project captures, compresses and injects it back into a sandstone formation containing large amounts of salty water over 1000 metres below the seabed.

CO_2 is also produced from power stations, automobiles or other human sources. These manmade sources are called "anthropogenic." The large emitters of CO_2 – such as fossil fuel power plants – could capture these emissions and store them underground. The Dakota Gasification Company in North Dakota captures and compresses approximately 8000 tonnes of anthropogenic CO_2 per day and transports it to the Weyburn and Midale oilfields where it is injected.

Q

21. How does CO_2 move underground?

A

CO_2 is injected into storage reservoirs at pressures high enough to overcome the pressure in the reservoir, but low enough not to fracture the rocks in the formation. This injection forces the CO_2 out of the wellbore and into the surrounding rock (for a definition of "wellbore", see Question 38). The CO_2 then spreads out from the well through connected pores and fractures within the rock, mixing with and displacing fluids already present. When injection is completed, the pressure that drives the movement gradually dissipates and any CO_2 movement will only be in response to the natural flow of liquids within the deep formations, which is usually very slow.

In the case of the WMP, CO_2 injected into the oilfield helps to displace and expand the oil contained in the pore spaces and move the oil towards the production wells. Some of the CO_2 stays in the reservoir, but some comes up with the oil where it is separated, compressed, and re-injected.

This is different from a project that is injecting CO_2 just for storage and not for enhanced oil recovery. In a storage project in which CO_2 is injected into a saline formation, for example, the CO_2 displaces and mixes with the brines in the formation, and over time – because of the sheer size and volume of such formations – pressures dissipate and CO_2 remains stored.

Detailed research at Weyburn has shown that CO_2 can move along pre-existing fractures within the reservoir rock. The oilfield operators can influence this movement through reservoir engineering so that the CO_2 will move mainly into the pores of the rock where the oil is trapped, and improve oil recovery by mixing with the oil and replacing it in those pores. The result is that a large amount of the CO_2 remains trapped permanently in those pores.

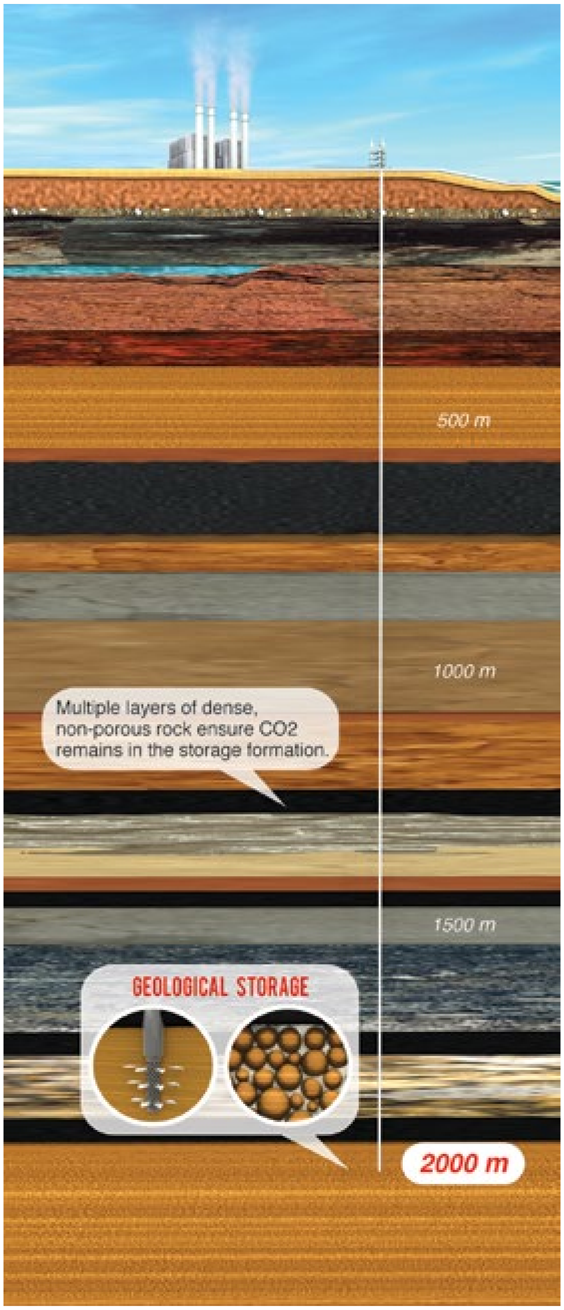


Figure 16. CO_2 is injected deep into the earth and trapped in the pore spaces of rock. (Image courtesy of University of Regina)

Q

22. How do you confirm the CO_2 stays within the formation?

A

Before injection begins, CO_2 storage sites are mapped out (characterised) and modelled to provide a basis for predicting how the CO_2 will act underground once it is injected. Part of the characterisation is to identify the different barriers to CO_2 movement and ways in which the CO_2 may become trapped. CO_2 is kept in place underground through several means:

Structural Trapping

Layers of impenetrable rock (caprock) above the formation can stop the vertical (upward) movement of liquids and gases and trap them for millions of years. There are many examples of this type of trapping. Impermeable layers have kept oil, natural gas and CO_2 in place underground for many millions of years.

Dissolution Trapping

Over time, some of the carbon dioxide will dissolve into the water naturally contained in the rocks. The amount and rate of dissolution is dependent on how salty the water is and the temperature and pressure of the formation. This type of trapping is very effective for long term storage.

Residual Trapping

When the CO_2 moves through pores in the rock, it can get stuck in very tiny passages or in a dead-end pore. This is residual trapping and it can be quite an effective and important way to store carbon dioxide in certain situations.

Mineral Trapping

Finally, over time, the CO_2 that is trapped in the rock pores can react with the reservoir rock itself and some of the salts in the water to form a new mineral. This can be a slow process but is effectively the most permanent and secure form of storage.

Within a well-characterised storage site there are many natural barriers and processes within and above the storage site to help keep the CO_2 underground. One main potential pathway out of the storage reservoir is related to the wellbores that have been drilled into the storage site. In the Weyburn oilfield there are thousands of active and enclosed wells that reach down into the reservoir where the CO_2 has been injected. Wellbores are monitored and maintained through regulations that are put in place by governments and regulators. Wells that are no longer in use are filled with cement from the depth of the reservoir all the way up to the surface to ensure CO_2 and other substances in the reservoir do not travel up the well. In gas reservoirs or saline formations there are far fewer wellbores to maintain than in an active oilfield.

The WMP used a number of measurement and monitoring technologies to look at where the CO_2 was located in the field; these measurements also indicated how the CO_2 was behaving underground (was it moving in one direction, for example, or changing in the formation). More information about these technologies can be found in Questions 24 and 25.

Q

23. How does an underground storage site change when CO_2 is injected?

A

Injection of CO_2 into the storage reservoir can result in increases in pressure, although these are carefully managed to avoid damage to the reservoir and surrounding layers of rock. In oilfields such as Weyburn and Midale, the production of oil and other mixed fluids is actively managed to balance any pressure increase caused by the injected CO_2. The injection of CO_2 can also slightly alter the minerals within the rock through chemical reactions, although these changes tend to happen over very long periods of time and have limited effects on the overall structure of the rock – in fact this is one of the best ways of permanently storing CO_2 when it reacts chemically with other minerals in the rock.

Over the decade of research at Weyburn and Midale, scientists have been able to monitor changes in the composition of reservoir fluids due to CO_2 injection, by sampling production fluids from wells. These changes have not caused any negative effects in the reservoir or surrounding rocks. The CO_2 continues to be safely stored and scientists can now use the collected data to model and verify safe storage into the future.

Q

24. How do you monitor the CO_2 once it is underground?

A

The WMP used several tools to monitor the CO_2 in the oilfields. These included seismic imaging, which provides data to create images of what the rocks look like underground (this is similar equipment to the sonograms used on pregnant women to view their unborn babies). See Figure 17, and also Question 25, "How do you know where the CO_2 will go?"

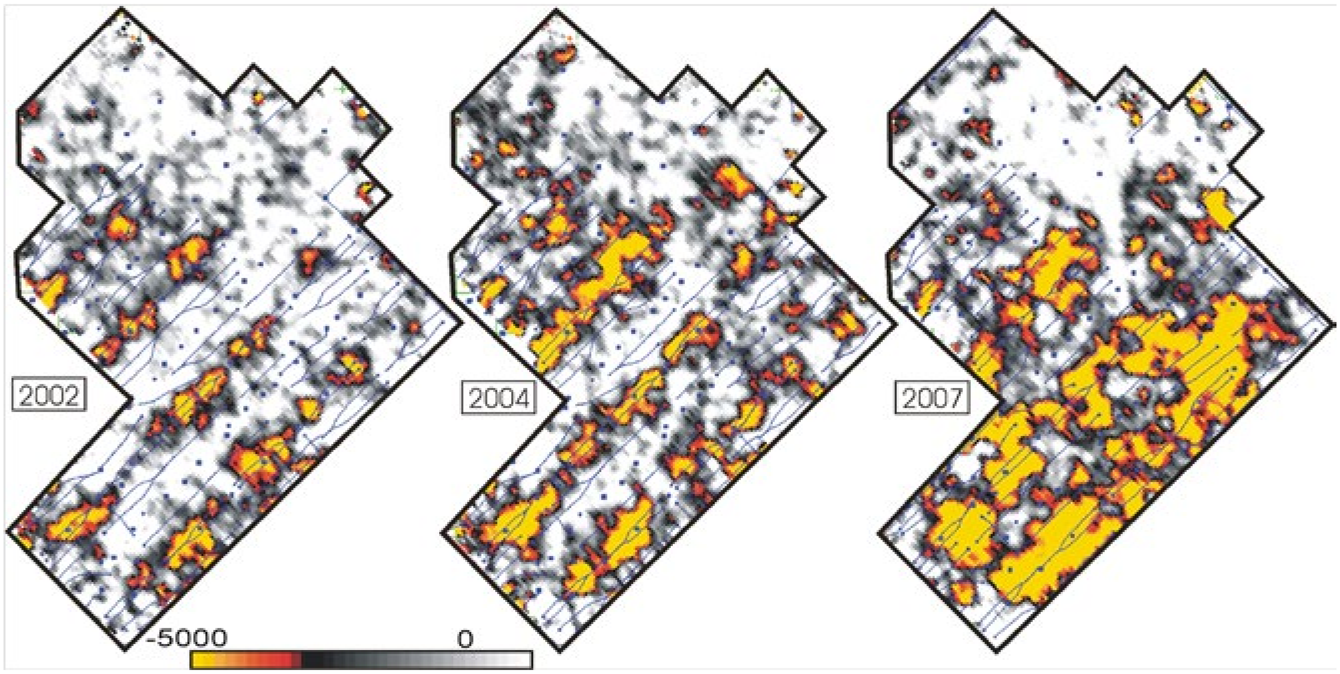


Figure 17. 4D (time lapse) seismic images of the injected CO_2 at Weyburn, taken in 2002, 2004 and 2007. Differences in wave amplitude from the baseline seismic survey performed before injection are highlighted in yellow and are interpreted to represent the distribution of CO_2 within the Weyburn reservoir.

CO_2 is monitored underground in various other ways. These include measuring the water and fluids in both injection and, in the case of CO_2-EOR projects, production wells for changes in chemical composition, and measuring the pressures within the reservoir for evidence that the CO_2 is staying in place.

Q

25. How do you know where the CO_2 will go?

A

Scientists can gain a thorough understanding of the storage reservoir and surrounding rocks through standard techniques including visual examination of drilling rock samples (see Figure 18) and geophysical measurements of the earth such as seismic imaging (see Figure 19). Computers are used to construct models and run simulations based on accumulated geological data and comparisons with other models, to anticipate where the CO_2 is likely to go, and then to verify that it goes where expected. Storage locations and surrounding areas are also mapped, geologically, to show subsurface features and likely routes for the CO_2 to move.

Figure 18. Examining core samples from a drilled well, such as the ones above from southern Saskatchewan, helps to determine how CO_2 will move underground. (Photograph courtesy of the PTRC's Aquistore Project)

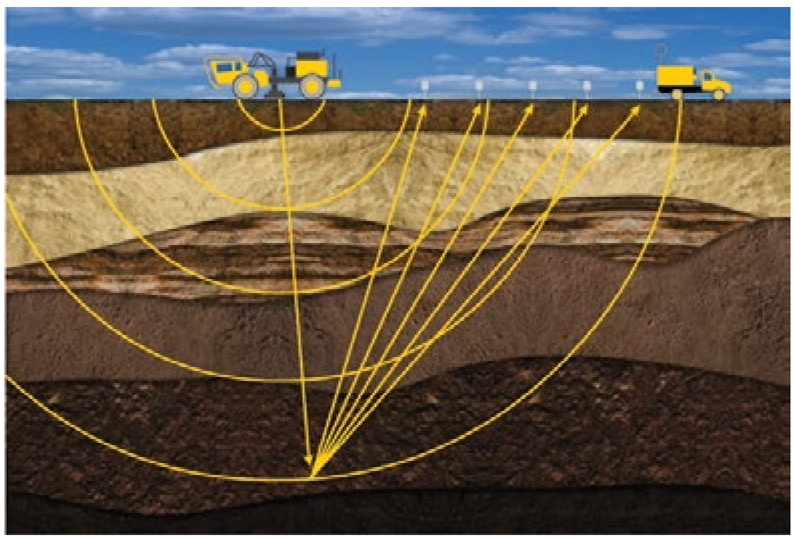


Figure 19. Seismic surveys are conducted before injection of CO_2 begins, to show what the reservoir is like and whether it can safely contain the CO_2. Here, vibrations are transmitted into the earth and then measured as they bounce back, helping to reveal the different rock layers. (Image courtesy of Schlumberger Carbon Services)

Long term, slow migration of the CO_2 may still occur within the reservoir in response to natural formation water movement, but CO_2 will remain safely trapped by mechanisms like physical confinement (for example, rock formations above or around the CO_2 that are solid and not porous) or reactions with water and minerals.

The WMP used computer models and simulations, based on the geological details from the site, to anticipate the potential directions and movements of the CO_2 both during and before injection. Monitoring during injection, through both seismic measurements and the measurement of pressures in the reservoir, allowed scientists to see where the CO_2 was in the reservoir.

Such detailed research at Weyburn and Midale has shown that CO_2 may move along fractures within the reservoir rock. Oilfield operators can direct CO_2 movement so that the CO_2 moves into pores in the rock, where the oil is trapped. The oil expands through contact with the CO_2 and moves out of the pores, where it travels to production wells. The result is that a large amount of the CO_2 remains trapped permanently in the pores where the oil had been, and movement of CO_2 remains minimal.

Q

26. How do you know if CO_2 has leaked?

A

The same tools used to measure where the CO_2 is located and what is happening to CO_2 in the reservoir are also used to ensure that the CO_2 has not leaked. Seismic imaging in the WMP allowed researchers to check that the CO_2 had remained in the reservoir, beneath the caprock, and had not migrated upwards. As well, regular (approximately every two years) chemical measurements of the well water and soils in the area above the injection area showed that there had been no CO_2 leaks from wellbores into groundwater or soil.

Any leak of CO_2 to the surface would be measurable in the soil gases and water wells. Leaks above the injection zone, but still contained underground, would also be measured through sampling fluids and gases in the wellbores and through seismic imaging.

Q

27. Does CO_2 injection increase pressure in oil reservoirs?

A

Pressure in oil reservoirs needs to be maintained in order to ensure that the oil keeps flowing up to the surface. After an oil reservoir has been producing for several years, the pressure can drop to a point at which almost no production is occurring. At this point, different methods of enhanced oil recovery (EOR) are used to get production to increase.

One of the most common methods to increase pressure in a reservoir and improve oil production is called "waterflooding," whereby large volumes of water are injected into the oilfield to bring the pressures back up to the level they were at when oil production first began. Waterflooding usually brings oil production back up for a brief period of time, but because water and oil are not miscible (they do not mix) eventually the effectiveness of the water comes to an end.

In the Weyburn oilfield, water was first injected in the 1970s and 80s to help increase pressures and oil production, but eventually the effectiveness of the waterflood trailed off. In 2000, the oil company began the CO_2 injection program to increase oil production. Oil production increased mainly because CO_2 is miscible (mixes) with oil, which causes it to flow more easily (become less heavy and thick) and also causes it to expand somewhat (volume increase), which helps to increase pressure slightly.

As with many oilfields, Weyburn showed that injection of water and CO_2 can increase pressures, and one of the benefits of pressure increase is to improve oil recovery. But CO_2 injection into larger reservoirs, such as deep saline formations, does not necessarily increase pressures because of the vast sizes of these formations. However, before any CO_2 storage project commences, safe pressure levels would be established for each reservoir involved to regulate acceptable pressure increases.

Q

28. How long will you need to monitor the CO_2 once it is underground?

A

Monitoring of the reservoir or formation begins prior to CO_2 injection, while injection is occurring, and after injection is complete. Monitoring also extends beyond the period of injection until the operator can show regulatory authorities that the CO_2 is behaving in a predictable manner within the reservoir in accordance with the computer models. Monitoring can include atmospheric (measuring the air around wells) and surface (measuring ground soils for CO_2). It can occur near the surface (measuring for CO_2 in water wells, for example, or near surface wellbores to see if it is coming up from below) and also occur in the subsurface (seismic imaging from deep in the reservoir).

Demonstration that the storage is permanent and safe is a necessity. Once regulators are satisfied, monitoring should no longer be necessary. The exact amount of time that monitoring will be required to satisfy these requirements will vary according to the specific nature and circumstances of each storage site, but is likely in all cases to extend beyond at least a decade after CO_2 injection has ceased.

Q

29. Are there regulations around CO_2 storage?

A

Different countries, provinces and states have different levels of regulations related to CO_2 storage. In the province of Saskatchewan, Canada, where the WMP took place and the Weyburn and Midale oilfields are located, the provincial government has extensive regulations governing the injection and storage of substances into the subsurface (including waste water, solvents and CO_2) as well as regulations governing the maintenance of wellbores into oilfields and other formations. These standards govern all aspects of subsurface injection and storage, and do not isolate CO_2 as a substance separate from others that might be injected underground. The regulations relate to the safety of injection practices and wellbores regardless of the substances being injected.

In the United States, the Environmental Protection Agency (EPA) introduced regulations in 2012 related to the construction of wells specifically for CO_2 injection. This type of well, called a "Class 6 Well," requires specific safeguards to assure the safe injection and storage of CO_2.

The world's first standards for the safe geological storage of CO_2 were finalised in 2012 by the Canadian Standards Association (CSA), and were developed to provide guidelines for future CCS operations in Canada and the United States. The CSA standards are also being considered as a basis for international standards. The WMP's research results, which included looking at wellbores and the measurement, monitoring and verification (MMV) of CO_2, may also help inform future regulations as projects become more common in Canada and the rest of the world.

WHAT IFS?

THE MOST COMMON QUESTIONS ABOUT CCS

Geological time is measured in the millions of years, not just in hundreds or thousands. The naturally occurring CO_2 deposits that exist in the world – many of them in underground formations similar to the Weyburn and Midale oilfields – have remained stable and in place for tens of millions of years.

CO_2 storage sites are chosen for the ways in which they are similar to these exact sorts of natural storage sites.

Q

30. How do you know CO_2 storage is safe?

A

Twelve years of research into the WMP has illustrated that CO_2 storage is safe. The CO_2 has been extensively monitored in the oilfields using different technologies, revealing to researchers where the CO_2 is in the reservoir and how it has moved. In addition, well water and soils have been sampled across various locations above the injection site, and there has been no evidence of CO_2 moving into the groundwater or the topsoil.

At the Weyburn and Midale oilfields, the CO_2 has been injected to a depth of 1.5 kilometres, the equivalent of 15 football (or soccer) fields stood end-on-end. In addition to this depth, there are several thick layers of impermeable rock above the injected CO_2 to stop it from coming back to the surface. It is also important to remember that the CO_2 is not being injected into a blank space or body of water below the surface, but rather into rock formations that hold the CO_2 in billions of pores that are typically the size of a grain of sand, or smaller. Movement of CO_2 within such a formation is usually slow and can be monitored.

Q

31. Will drinking water be affected by CO_2 storage?

A

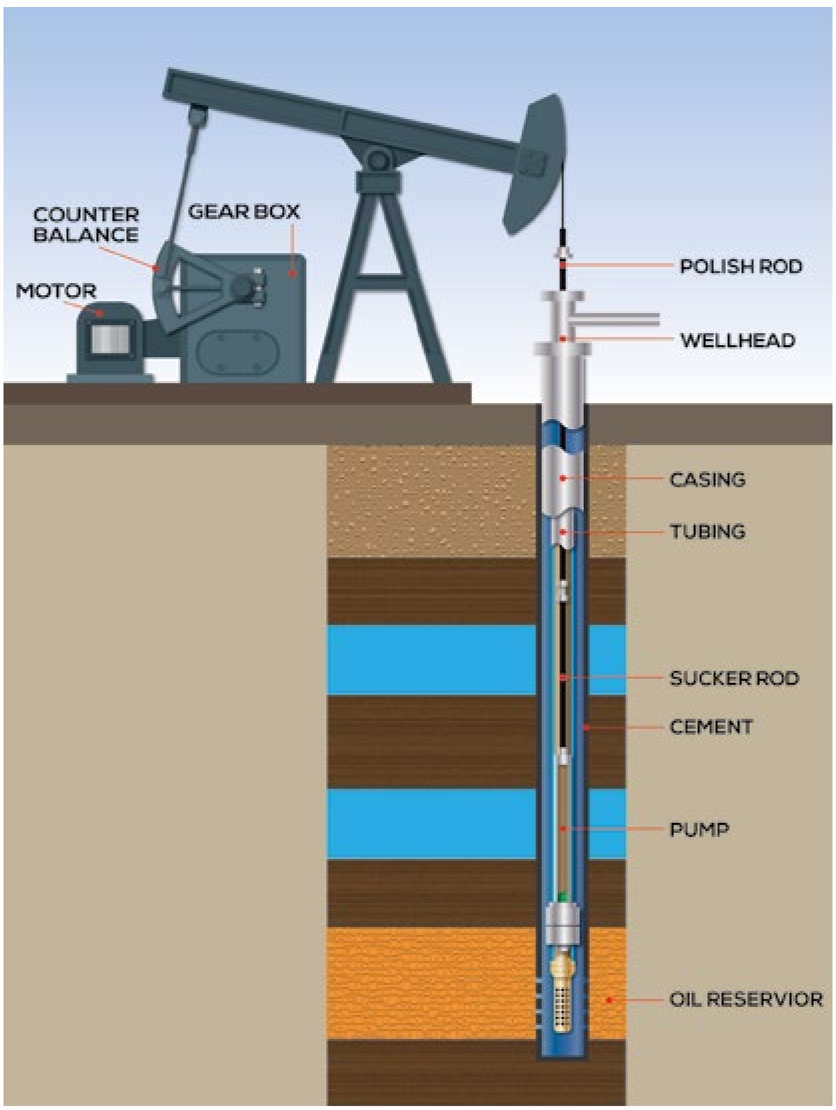


Figure 20. A standard oilfield wellbore, with a pump jack attached. This image is not to scale, and the wellbore stretches down at least 1000 metres into the ground. In a CCS well, the casings and tubing will also typically extend across all of this depth.

The WMP has shown that CO_2 can be safely stored in rock formations without affecting drinking water. Between the years 2000 and 2012, the WMP took water samples from drinking-water wells in the area above where CO_2 has been injected. The readings in the year 2000 acted as a "baseline" – this means that the readings from these wells showed us what the quality of the water was before injection of CO_2 began. These baseline readings were then compared with results that were taken at various points, years after the CO_2 injection began. The comparisons between water wells before, during and after injection have shown that no changes have occurred in water quality caused by CO_2 injected into the oilfield, and recorded minor changes in well water are likely from natural, seasonal or other causes. Well water in the area continues to meet provincial regulatory standards.

If leakage from a CO_2 storage project were to happen into groundwater, it would most likely occur through the wellbores. Wellbores are the holes drilled deep into rock formations like oil and gas reservoirs to both inject substances like CO_2 and bring to the surface materials like oil. Wells are cased in metal and cement, especially nearer to the surface, in order to protect drinking water. See Figure 20.

All operating wells are topped with a "wellhead" (see Figure 21) which remains in place during the production or injection life of the well until it is permanently closed (shut in). When a well is no longer in use, the well is "capped" and injected with high volumes of cement to fully seal it.

Figure 21. This CO_2 injection well has a wellhead that can be turned off, stopping injection. Wellbores that are not currently producing oil or being used for injection will have a wellhead such as this on the surface. Wells that are no longer in use will have their wellhead removed and will be cemented down the full length of the wellbore to ensure they do not allow for the upward movement of liquids and gases. All surface lines and equipment will be removed and the well will be permanently capped. (Photograph courtesy of Cenovus Energy)

Governments and industry have strict regulations about maintaining the integrity of oil and gas wells.

Q

32. Will topsoil be affected by CO_2 storage?

A

Nearly all soil contains naturally occurring CO_2, created by what are called "biogenic" processes – this means that the decaying of plant and animal matter leaves CO_2 in the soil. At the beginning of the WMP in 2000, soil gas samples were taken at various locations above the oilfield where the CO_2 was going to be injected. These readings showed a wide range of CO_2 in the soil (from 2% to 11%). The readings were then used as a baseline to compare with soil gas samples that continued to be taken at those same locations in the next 10 years.

Figure 22. Soil gas samples are taken in a field above the Weyburn oil reservoir. (Photograph courtesy of the PTRC)

A comparison of soil before and after injection showed that there has been no increase in CO_2 in the soil attributable to the storage of CO_2 in the Weyburn oilfield after 12 years of measurements; small fluctuations are part of seasonal cycles or variations in moisture.

Q

33. Will fish or wildlife be affected by CO_2 storage?

A

The WMP showed that CO_2 was not affecting either groundwater or soil in the areas where water and soil were tested above and near the oilfield. Fish would only be affected if the CO_2 entered groundwater, lakes, or rivers from deep in the earth. Likewise, animals would only be affected if CO_2 were leaking into the atmosphere or the soil. As indicated in the two previous questions, there is no evidence that leakage has happened, and the fish and other animals above the Weyburn oilfield have not been affected by CO_2 storage.

Q

34. Will land values be affected by CO_2 storage?

A

The Weyburn area and the City of Weyburn (population approximately 10,000) have not experienced a reduction in property values because of the injection of CO_2 in the Weyburn oilfield. The area has also benefited from "industrial tourism." Many national and international visitors come to tour the injection facilities and spend money on hotels and food while in the area.

Many issues affect the value of land and property. Economic conditions in in an area, and the location of a house or farm in relation to highways, railway lines and power transmission towers are just two of the factors that might adversely or positively affect the value of a property.

Some individuals and groups have suggested that CO_2 storage projects might adversely affect property values in a community where a project is being planned because of perceived problems such as potential leakage or increased industrial activity. However, the Weyburn area has benefited substantially from the CO_2 injection because the production life of the oilfield has been extended – and some property values above the injection zone and in the city have increased.

Figure 23. Visitors such as these, at Cenovus's Weyburn field, number in the hundreds – including scientists, regulators and politicians from around the world who want to find out about CO_2 storage. Industrial tourism has proven to be a boon to the local community, but as CCS projects become more common this international interest will decline. (Photograph courtesy of PTRC)

Unlike a CO_2-EOR project such as Weyburn, which results in additional oil production, a CCS project that is injecting CO_2 only for storage may not create the same direct economic benefit, aside from the potential of increased economic activity and employment during construction of the CCS infrastructure.

Concerns about increased traffic and the location of injection wells in a CCS project are real issues for a community to consider. These are concerns that should be discussed between project planners and individual land holders who may be affected before a project is put in place. If potential project impacts are identified and handled properly, property values should not be adversely affected by a CO_2 storage project.

Q

35. What are faults and fractures?

A

Fractures are discontinuities or "cracks" in rocks, caused by stresses within the earth's crust. Fractures are referred to as faults when the rocks on either side of a fracture have moved in different directions, causing displacement (offset) of the rock layers (see Figure 24). Faults and fractures can be simple or complex in geometry, may be open or closed, and therefore can form either channels for fluids to flow, or barriers where fluids get trapped. Oilfields are often created when a fault has helped to trap the oil in place.

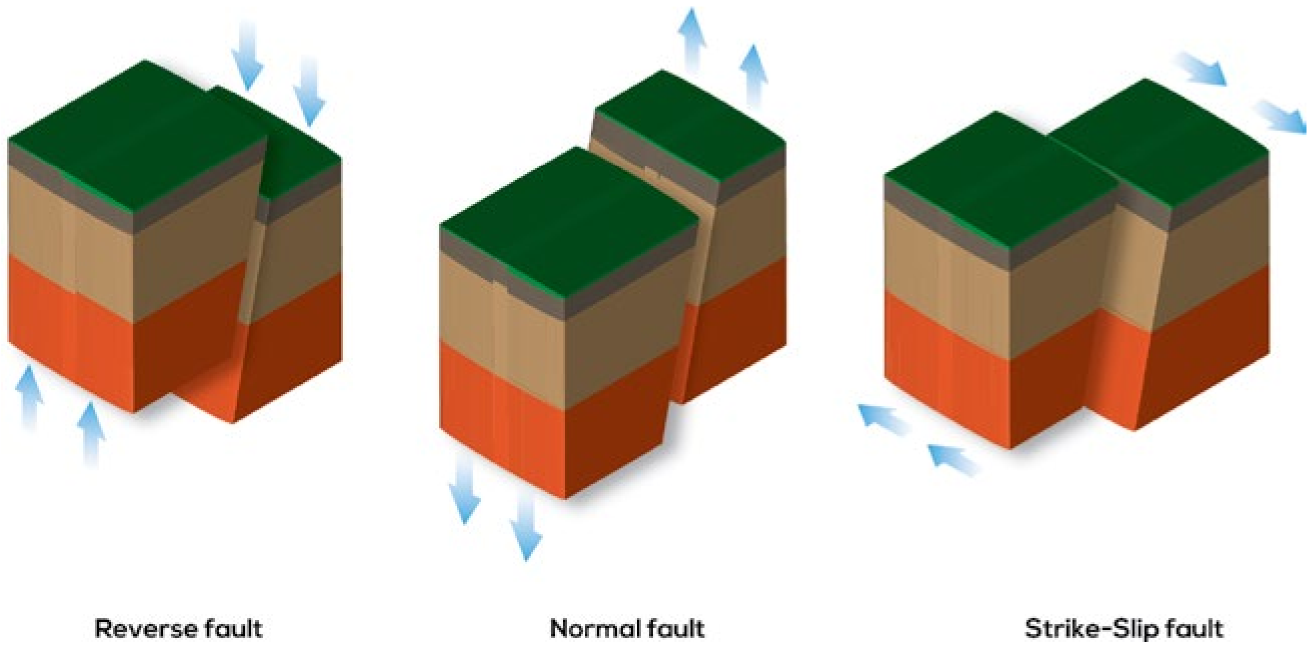


Figure 24. An example of the three basic kinds of faults. Image reworked from information provided by the US Geological Survey (http://soundwaves.usgs.gov/2009/11/fieldwork2.html).

An understanding of fractures in a storage reservoir or oilfield can help scientists predict how injected CO_2 will spread out and be contained. The nature of any fractures and faults in surrounding rocks needs to be understood so that safe containment of injected CO_2 can be assured.

For the WMP, characterisation of the oil reservoir and surrounding rocks was made possible through the collection of data and samples, and extensive research. This has allowed a comprehensive understanding of the distribution and nature of faults and fractures, showing that the existing faults and fractures at the Weyburn-Midale fields would not impair the fields' ability to trap and contain CO_2 or other fluids injected into the reservoir, just as the oil and gas have been contained for millions of years.

Q

36. Could injecting CO_2 underground cause an earthquake?

A

Just as with oil and gas extraction, the changes in pressure caused by CO_2 injection can cause extremely small earth movements in a process called "induced seismicity." With careful control of injection pressures and extensive reservoir management techniques that are employed as standard by the oil industry, risks of damage from potential induced seismicity are reduced to insignificant levels. In fact, these very low levels of seismicity can actually be very useful, allowing monitoring by geophysicists to provide further data on the safe distribution of CO_2 within the reservoir.

In the WMP, extensive monitoring of seismicity (which is more accurately termed induced micro-seismicity in this case) has shown that movement events are relatively infrequent and tiny in magnitude. Movements are not felt on the surface; in fact, some are so small they are barely measurable. Moreover, most of the monitored events have been associated with periods of water injection as opposed to CO_2. In the Weyburn oilfield, most of the micro-seismic events have occurred around the location of the production wells, meaning that the increased flow of oil and water in the reservoir may be responsible for these small events, not the CO_2. Depicted in Figure 25, the results obtained at the Weyburn field show that the recorded micro-seismic events are tens to thousands of times weaker than the weakest earthquakes that could be felt by humans at ground surface. Figure 26 provides context for the seismic activity at Weyburn.

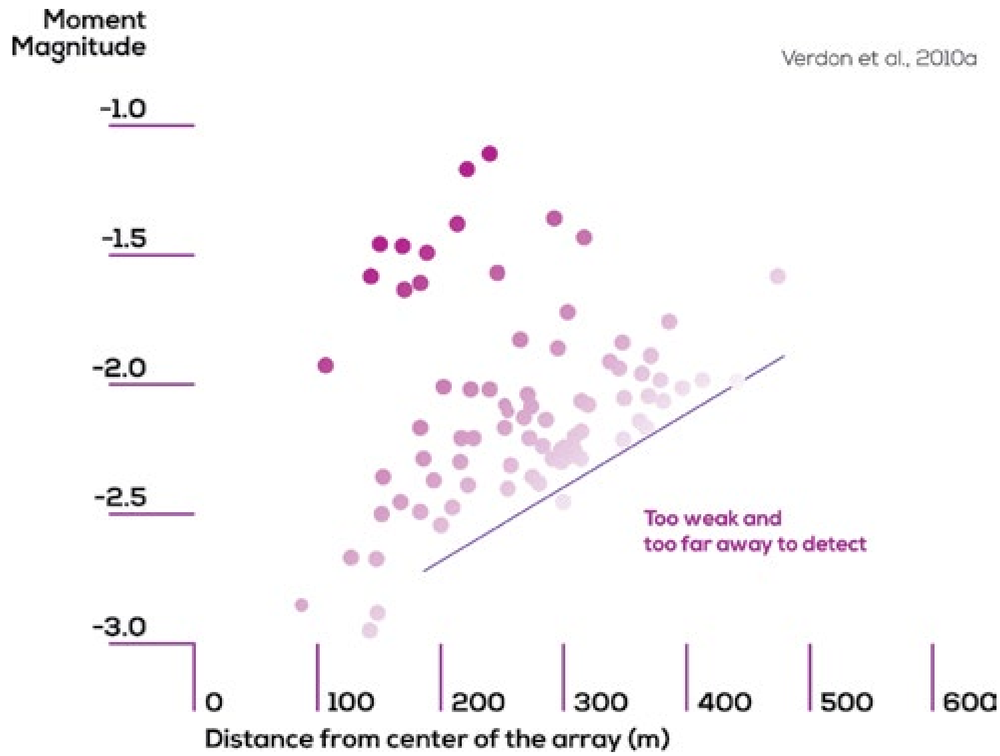


Figure 25. This figure shows the approximately 100 micro-seismic events measured at the Weyburn oilfield during the period of 2003 to 2007. (Courtesy Dr. Don Gendzwill, University of Saskatchewan)

Earthquake and Micro-Earthquake Comparison

Magnitude	Equivalent TNT Radiated Energy	Energy Comparison
+3	480 kilograms	Large potash mine earthquake
+2	15 kilograms	Small potash mine earthquake
+1	480 grams	10 ton trucks collide
0	15 grams	Jump off a tall building
-1	0.5 gram	30-30 rifle bullet
-2	15 miligram	Drop a large dictionary
-3	0.5 miligram	Break a small stick

Red = Weyburn CO_2 injection micro-earthquake sizes

Figure 26. A comparison of the micro-seismic events recorded at Weyburn versus larger measurements. Nothing at Weyburn was above -1.0. (Courtesy Dr Don Gedzwill, University of Saskatchewan)

Q

37. What if there is an earthquake near a CO_2 storage site?

A

Whether earthquakes are common in your part of the world or do not occur at all, when it comes to discussing CO_2 storage, people always ask about earthquakes.

CO_2 storage sites are characterised and investigated using technologies such as seismic imaging to identify their stability, and are selected because they are unlikely to be affected by an earthquake. The WMP chose a stable location to store CO_2 in an oilfield that contains no active faults, and in an area of North America that is not very seismically active.

Even in geologically active places on earth, like Japan or the west coast of North America, if an earthquake does occur it is highly improbable that a leak from the geological formations deep in the earth would occur. Both California and Japan have evidence to back this up.

California has many gas and oil deposits both on and off shore near seismically active faults and earthquakes. Some of these deposits are potential CO_2 storage locations – depending on their depth and availability of caprock – and have remained secure storage locations for oil and gas over many millions of years (including several decades of oil production and study) and hundreds of earthquakes. Some nearer-surface reservoirs have shown movement of oil and gas to the surface along faults, but any potential CO_2 storage locations would be characterised ahead of injection to identify these potential leakage routes and avoid them. As one of the more seismically active places on earth, with a sizable endowment of oil and gas, California can still safely store CO_2 underground provided the proper characterisation of potential storage sites takes place.

Another recent, specific example of an earthquake happening very close to an actual CO_2 storage site comes from Nagaoka, Japan. In 2004, a major earthquake measuring 6.8 on the Richter scale occurred a mere 20 kilometres away from a CO_2 injection site 1,100 metres below the ground. The injected CO_2 has been monitored by scientists before, during and after the earthquake and no leaks have been detected to date.

Q

38. What are wellbores and how do you maintain them?

A

Wellbores are the holes drilled deep into rock formations like oil and gas reservoirs to both inject materials like CO_2 and bring to the surface materials like oil. Wellbores are the routes through which oil moves upwards or CO_2 and other substances move downwards. They have cement and metal casings all the way down, especially nearer to the surface, in order to stabilise the wellbore, to provide pathways for fluid movement and the installation and retraction of instrumentation, to protect drinking water, and for other functions.

Wells are constructed to very high standards and can be effectively monitored. For example, pressure and temperatures can be monitored both inside the well casing and between the casing and the surrounding rock (in the annulus). Fluid samples can be obtained from within the reservoir as a further check against unexpected behaviour, and specialised monitoring tools can be lowered inside the well casing to measure the condition of the well to full depth. If imperfections are discovered in the casing or the annulus (which at most depths is filled with cement), standard procedures from the oil and gas industry can be used to repair (remediate) these imperfections. Figure 27 is an illustration of an injection well for a carbon storage project that shows some of the monitoring equipment that can be included.

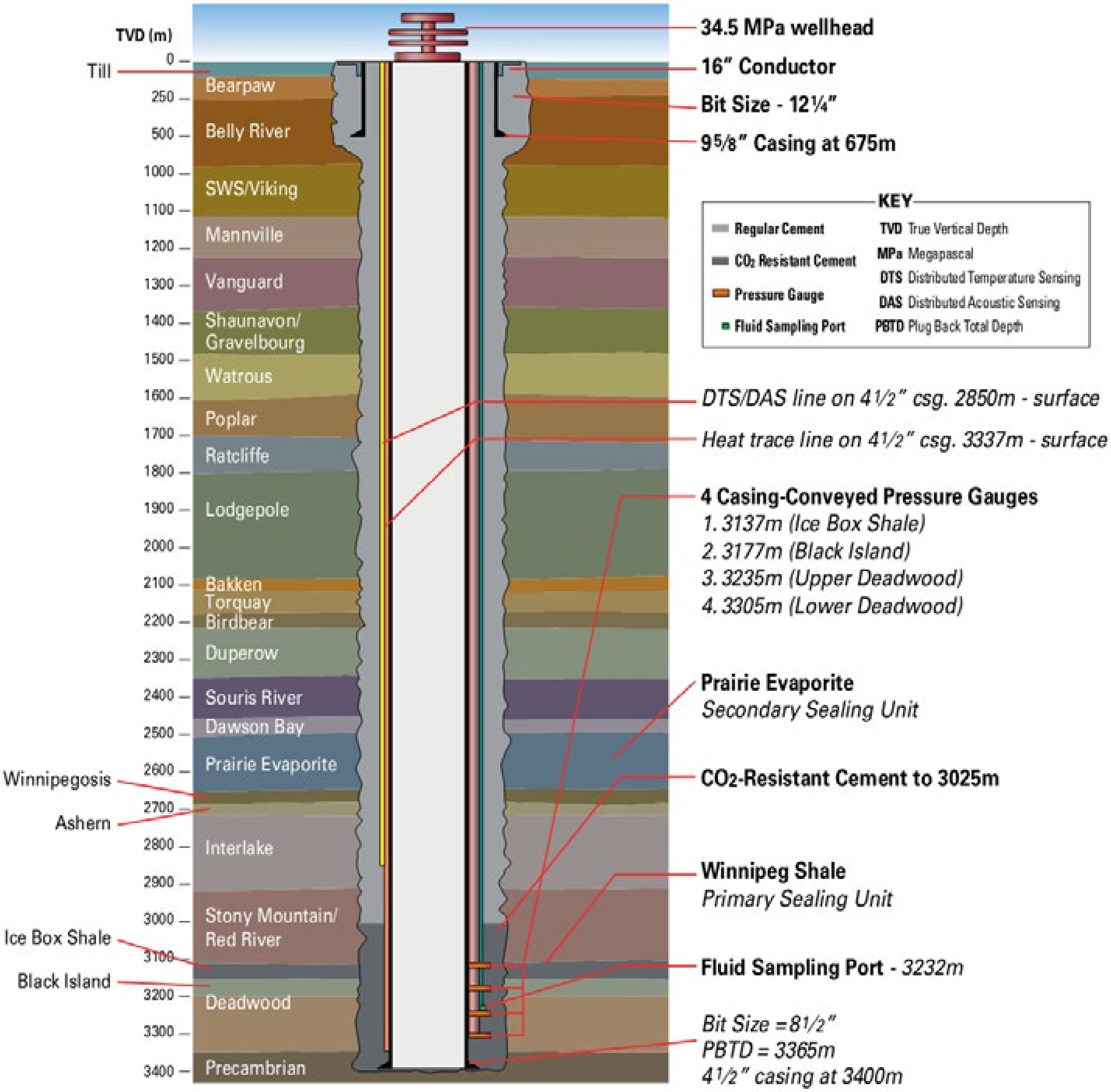


Figure 27. Some wellbores in CCS projects include various listening and measuring devices, such as this wellbore in a new Saskatchewan deep saline storage project called Aquistore. In this case the monitoring equipment in the wellbore helps to ensure that no CO_2 escapes to the surface. (Picture courtesy of PTRC's Aquistore Project)

The operators of the Weyburn and Midale oilfields have developed world leading expertise on the safe operation of wellbores where CO_2 injection is utilised at an industrial scale. Research in the WMP has demonstrated the safe, long term integrity of wells that are carefully constructed and monitored.

Q

39. How do you know that CO_2 pipelines are safe?

A

Pipelines, whether carrying CO_2, oil, natural gas (methane) or other compounds, are governed by regulations that have been established by governments. Pipeline operators are required to make their operations adhere to these regulations, and this is done increasingly through automated computer systems that can measure the pressures within pipelines, identify locations of pressure loss, and administer shut-down operations with speed and efficiency.

In the WMP, the Dakota Gasification Company (operators of the large pipeline that carries CO_2 to Canada from the United States) and both the Weyburn and Midale oilfield operators (Cenovus Energy and Apache Canada) employ computer monitored systems on their CO_2 pipelines, which help monitor pressure, flow rates and volumes. This ensures that leaks, should they occur, can be quickly found and fixed.

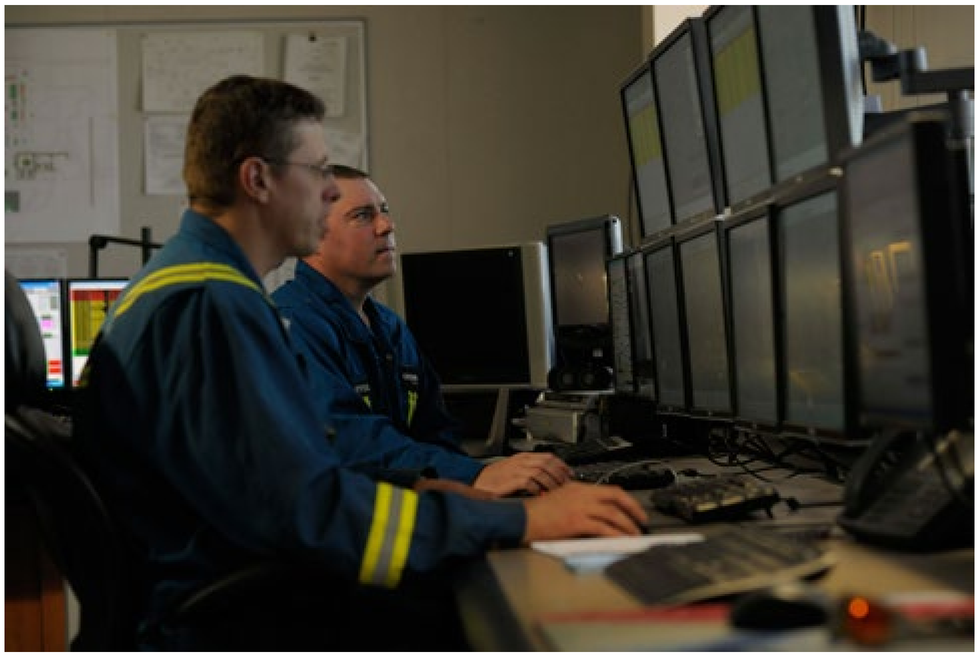


Figure 28. Staff at Cenovus's Weyburn oilfield monitor CO_2 pipelines using computers with advanced pressure and temperature technologies. (Photograph courtesy of Cenovus Energy)

Q

40. What if there is a leak of CO_2 from a pipeline?

A

A leak from a CO_2 pipeline is highly unlikely and even tiny leaks can be very quickly detected and dealt with. However, if a leak were to occur it could have several effects. A slow leak over time would in most cases be dispersed without health effects, provided there were no other substances in the pipeline that could be dangerous. However, because CO_2 is heavier than air, a slow leak of CO_2 into a low lying area in exceptional circumstances (like a day when there was no wind or air movement) could result in CO_2 accumulating in one spot to a dangerous level, leading to a potential hazard. However, such a leak would be very quickly detected and dealt with due to a decrease of pressure in the pipe.

A major pipeline rupture (caused by a puncture, for example) might cause an initial explosion because the pipeline is under pressure; persons close to the rupture could be injured by an explosion. Injury from the cold temperatures caused by the expansion of compressed CO_2 is also possible.

People who are stuck in a small space with concentrated CO_2 vapor would need supplemental oxygen, but under most weather conditions, the plume of emerging CO_2 would be very visible, because water vapor in the air would condense in the suddenly cold conditions. The CO_2 would emerge from the pipeline in a flow that would quickly turn solid once it came into contact with the air. This escaping CO_2 would dissipate slowly as the solid turned to gas. CO_2 is heavier than the air around it, and so it could collect in low lying areas, but CO_2 also dissipates easily to non-toxic levels in even minor winds.

Figure 29. The CO_2 pipeline from Beulah, North Dakota, to southern Saskatchewan is buried more than six feet deep to minimise the potential for ruptures. (Photograph courtesy of Dakota Gasification Company)

Most importantly, all modern pipelines (including those that supply CO_2 from North Dakota to Saskatchewan in the WMP) are monitored with advanced computer systems that sense pressure reductions in the pipeline and are able to stop the flow of gas very quickly at various points along the route should any potential pressure drop occur. There has never been an injury incurred, nor leak of CO_2, from the pipeline that feeds the Weyburn and Midale oilfields, and piping CO_2 across long distances is commonplace in North America.

Q

41. How much noise and disruption do storage projects cause?

A

Like any project involving construction and ongoing operations, CO_2 enhanced oil recovery and carbon capture and storage projects do have a visible presence in the communities where they are built.

Most of these disruptions are short lived, such as the construction of the CO_2 capture and compression facilities, the pipeline for transport of the CO_2, and the drilling of the injection and monitoring wells (Figure 30). Some aspects of such projects, however, will be continuous, including the physical injection and monitoring wells (although this presence is minimal – see Figure 31), a possible increase in traffic on nearby roads (this is particularly true in the case of EOR-CO_2 injection, since oil tankers and maintenance trucks are likely to be required) and some noise associated with the operation of compressors and wells.

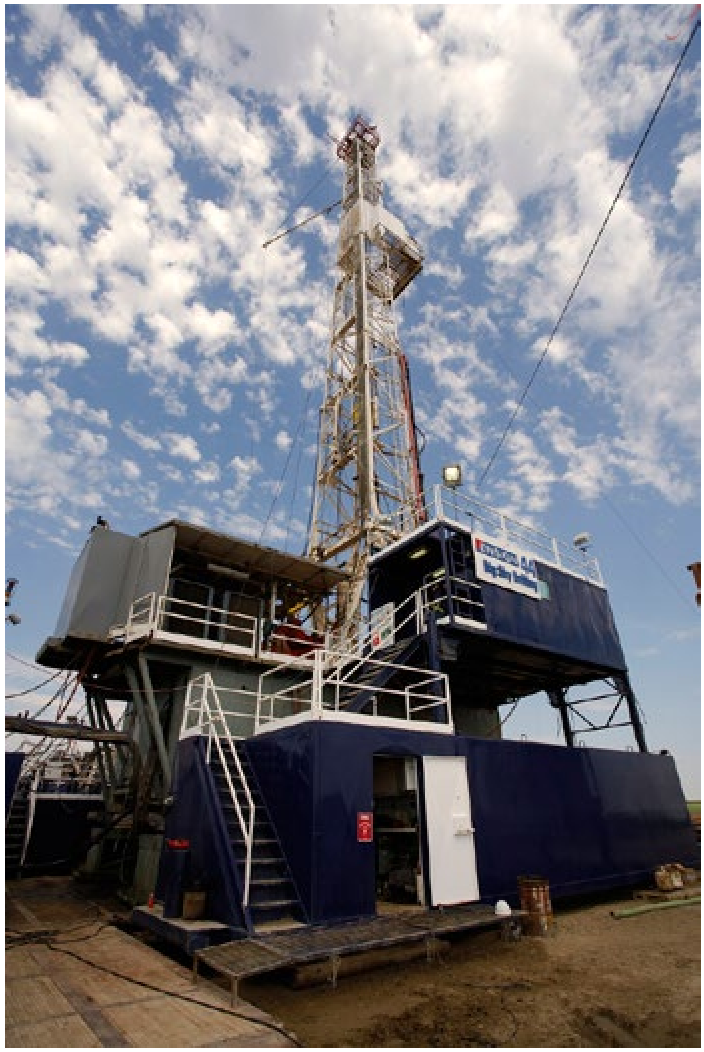


Figure 30. A drilling rig operating in the Weyburn area. Drilling is one possible disruption caused by CCS projects, but is usually completed in a relatively small time frame. (Photograph courtesy of Cenovus Energy)

In the case of CO_2 enhanced oil recovery, and the injection of CO_2 into the Weyburn and Midale oilfields in particular, the local community was used to industrial activity because of nearly 50 years of oil recovery in the area. Injection and production wells, the presence of trucks on rural gravel roads, and the operation of machinery are all well-known experiences. The oil companies work with the community to use as little land as possible when placing wells, landscape the locations, assure cattle grazing and agricultural uses are not disrupted, and keep up roadways in the areas. Permissions were sought ahead of time for accessing private land, and regulations are followed for the placement of wells and compressors away from dwellings to minimise the impact of noise.

The key is for project owners and planners to meet with communities and be forthcoming about what kinds of impacts can be expected from projects – both potential disruptions and potential benefits such as jobs, reduction in CO_2 emissions and economic improvements.

Q

42. How visible is a CO_2 storage facility?

A

Since CO_2 storage occurs deep underground, there is very little visible presence of a storage project on the surface. The pipe carrying the CO_2 will normally be buried, and the only likely visual evidence of the site will be the injection well(s). While CO_2 enhanced oil recovery operations will have many injection and producing wells, a storage project that is injecting CO_2 only into a deep saline formation, one or two injection wells are likely to be the only visible sign of the storage operation.

At the Weyburn oilfield, the presence of production wells (pumpjacks) is a common sight in the rural fields. The addition of CO_2 injection wells did not significantly change the landscape. Well sites are attractively maintained, and the injection wells are covered in beige fibreglass coverings to protect them from the elements and to help them to blend into the surroundings (see Figure 31). Pipelines are buried to a depth that allows for planting of crops and the grazing of livestock.

Figure 31. A pumpjack (production well) on the right, and CO_2 injection well, on the left (protected by a beige fibreglass covering) rest in a canola field in the Weyburn area. (Photograph courtesy of PTRC)

Q 43. If I own the mineral rights beneath my land, will I be paid for CO_2 storage?

A

The answers to this question vary and are determined by the regulations that govern CO_2 storage and mineral extraction in different countries. CO_2 is not a mineral, and so it is unlikely that the storage of CO_2 itself beneath a piece of land would lead to payment for the mineral rights holders. However, if CO_2 is being injected into an oil reservoir, leading to increased oil production, then the mineral rights holder would benefit depending on the royalty rate he or she has negotiated with the oil company. This is the case in the Weyburn and Midale oilfields, where increased oil production because of CO_2 injection has led to increased royalties for mineral rights holders.

Oil and drilling companies in Canada also pay for what is called “surface rights” access. If landowners do not own the mineral rights beneath their property, they may still be paid a (yearly) fee for the placement of a CO_2 injection well or oil production well on their property.

Storing CO_2 in a deep saline formation or non-producing oil/gas reservoir is a different matter. Since there is no oil or other mineral production arising from storage, the pore space used for storage is not likely to lead to payment for the mineral rights holder; in Canada, the only compensation will be for surface access and the placement of well(s). The Province of Alberta in Canada announced, in 2011, that pore spaces are not a part of mineral rights and belong to the government. But regulations related to pore spaces and mineral rights vary widely by country, and should be investigated before storage projects are planned.

Q

44. What if there is a leak of CO_2 underground?

A

Storage sites are carefully chosen and studied to ensure that the chance of CO_2 escaping from the storage reservoir(s) into surrounding rocks is very low. If any leakage were to occur, researchers have shown that CO_2 would almost certainly move along narrow pathways into nearby rocks through faults, fractures or deep wells. In the multiple layers of rock present above storage sites, CO_2 would have to pass through several more layers of sealing rocks to reach sensitive areas such as shallow groundwater or ecosystems, which are located a thousand metres or more above the injection zone.

WMP research has shown that significant leakage of CO_2 from the reservoir to potable groundwater in the shallow subsurface is very unlikely – even if the worst assumptions are made about the nature of rock layers and the condition of older wells that have been drilled into the oilfield. For the WMP, workshops were held with the local community and environmental experts in order to identify environmental assets of most concern, and assess possible impacts of any leakage. The results of these detailed assessments show that risks are low and can be effectively monitored and managed.

Q

45. What if CO_2 leaks 100 or 1000 years from now?

A

Geological time is measured in the millions of years, not just in hundreds or thousands. The naturally occurring CO_2 deposits that exist in the world – many of them in underground formations similar to the Weyburn and Midale oilfields – have remained stable and in place for tens of millions of years.

CO_2 storage sites are chosen for the ways in which they are similar to these exact sorts of natural storage sites. Any likely leaks of CO_2, in the long term, would be through the wellbores that human beings have drilled into these formations.

If these wellbores, or some other unforeseen feature of the storage location, cause the CO_2 to leak many years after the companies and people who injected the CO_2 are gone, plans are in place to assume responsibility for these storage sites and fix the problem. In 2011, for example, the Government of Alberta in Canada assumed what is called "long-term liability" for storage sites, meaning that the provincial government would be responsible for the maintenance of these sites after companies and people have come and gone.

Q

46. If there is a leak, who will be responsible for fixing it?

A

While different countries and jurisdictions may have different rules, generally speaking if there is a leak at an active CO_2 storage site, fixing the leak would be the responsibility of the operator. In the case of the Weyburn and Midale oilfields in Saskatchewan, both of the oil companies (Cenovus and Apache, respectively) are required to maintain wells, pipelines, and infrastructure at their oilfields according to regulations and laws put in place by the provincial government. A leak of CO_2, either from a pipeline or from the reservoir through a wellbore, would require immediate action from the companies, which have response protocols in place.

Once a storage site has been closed and a company is no longer operating the facility, different governments have different laws in place determining who is responsible for long-term safety and maintenance of CO_2 storage. In the province of Alberta, Canada, the provincial government has taken on long-term liability of stored CO_2 once a site is no longer active, and will be responsible for assuring that any leaks are fixed and that wellbores are maintained.

CONCLUSION

The IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project cannot answer all the questions that people may have about carbon capture and storage; as an adjunct to a CO_2-EOR (enhanced oil recovery operation) it offers insights primarily into the measurement and monitoring of injected CO_2. Having taken place in the geological formation with the largest single amount of injected manmade CO_2 in the world, and as a research project with extensive peer-reviewed results, the project can offer evidence of safe and secure geological storage of CO_2 and provide real data and scientific information for many of the public's most frequently raised concerns about CO_2 storage.

The questions and answers covered in this publication offer key information that will help readers understand the science, logistics, benefits and potential risks of CO_2 storage. Some readers may be new to the topic of CO_2 geological storage, while others may have had similar projects proposed near where they live and therefore be familiar with some of the issues. While some of the questions and answers contained here also touch upon aspects of the carbon capture and storage chain (deep saline formation storage, transport, capture technologies), other active projects offer more detailed information on these additional topics. Readers are encouraged to investigate websites for more information (http://www.globalccsinstitute.com and http://www.sequestration.org).

Carbon capture and storage, if it is to go forward globally in a significant way to help alleviate the potential impacts of climate change, requires a significant level of understanding and dialogue on the parts of industry representatives, government officials, policy makers, politicians and, most importantly, the general public. The Global CCS Institute and the Petroleum Technology Research Centre hope that this publication contributes to that dialogue and provides answers that will allow for CO_2 storage to succeed on its scientific and environmental merits.

If you are interested in finding out more about the scientific research conducted in the WMP, a copy of the full final report – ***Best Practices for Validating CO_2 Geological Storage: Observations and Guidance from the IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project*** – is available for sale from Geosciences Publishing (www.geosciencepublishing.ca). You may also contact the PTRC (info@ptrc.ca) for more information on ordering the book.

END NOTES

[1] Wilson, M. and M. Monea. Eds. *IEAGHG Weyburn CO_2 Monitoring and Storage Project Summary Report, 2000-2004*. From the Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, September 5-9. 2004. Volume III. Vancouver, Canada.

[2] Hitchon, B. Ed. *Best Practices for Validating CO_2 Geological Storage: Observations and Guidance from the IEAGHG Weyburn-Midale CO_2 Monitoring and Storage Project*. Geoscience Publishing. Sherwood Park, Alberta, Canada.

[3] http://www.epa.gov/climatechange/ghgemissions/global.html.

[4] Based on US EPA estimates, a passenger car emits a little over 5000 kg of CO_2 a year (5 metric tonnes). Twenty-two million tonnes of stored CO2, therefore, is equivalent to mitigating 4.2 million cars.

[5] Cook, J. et al. 2013 Environ. Res. Lett. 8 024024. Accessible at: http://iopscience.iop.org.

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