IEA GHG Weyburn
CO_2 Monitoring & Storage Project

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IEA Greenhouse Gas R&D Programme

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This report has been produced by the IEA Greenhouse Gas R&D Programme (IEA GHG). IEA GHG is an international collaboration of governments and industries from many countries with several linked objectives:

- To identify and evaluate technologies that could be used to reduce the emissions of greenhouse gases arising from the use of fossil fuels;
- To disseminate the results of those evaluations;
- To identify targets for research, development and demonstration, and promote the appropriate work.

IEA GHG was established in 1991 and, since then, its main focus has been on capture and storage of CO_2. It has also examined a wide range of other technologies, including carbon sequestration in forests, renewable energy sources (biomass and wind energy) and methods for reducing emissions of non-CO_2 greenhouses gases. This helps to put in perspective the potential of capture and storage of CO_2.

The IEA GHG Weyburn CO_2 Monitoring and Storage Project

IEA GHG assisted in the establishment of the Weyburn CO_2 Monitoring and Storage Project by helping to organise with the Petroleum Technology Research Centre (PTRC) and University of Regina the inaugural meeting held in Regina, Canada in September 1999. The project has been managed by PTRC in coordination with EnCana the Weyburn oil field operator. IEA GHG supported the technical programme of the project and hence has allowed its name to the be used in the project title. Also, during the course of the project, the IEA GHG Programme undertook a formal expert review of the work underway.

The first phase of the project started in July 2002 and added a research component to the CO_2 flood underway at the EnCana Weyburn oil field. The project was a major international cooperative exercise with a budget of $40-million (Canadian) and involvement of 15 industry and government sponsors and 25 research and consulting organisations from several countries.

Front cover image: EnCana pumpjack operating near Weyburn, Saskatchewan.

The main sponsors were :

Governments:

- Natural Resources Canada (NRCan)
- United States Department of Energy (US DOE)
- Saskatchewan Industry & Resources (SIR)
- Alberta Energy Research Institute (AERI)
- European Community
- Petroleum Technology Research Centre

Industry:

- EnCana Corporation
- SaskPower
- Nexen Inc.
- Total
- Chevron Texaco (now Chevron Corporation)
- BP
- Dakota Gasification Co.
- TransAlta Utilities
- Engineering Advancement Association of Japan

The research providers were :

Canada:

- EnCana Corporation
- Saskatchewan Industry & Resources
- Saskatchewan Research Council
- University of Alberta
- University of Calgary
- University of Saskatchewan
- University of Regina
- J.D. Mollard and Associates Ltd.
- Alberta Research Council
- Geological Survey of Canada
- Hampson Russell
- Rakhit Petroleum Consulting Ltd.
- ECOMatters
- Canadian Energy Research Institute
- GEDCO Inc.

United States:

- Lawrence Berkeley National Laboratory
- Colorado School of Mines
- Monitor Scientific CI
- North Dakota Geological Survey

Europe:

- British Geological Survey (UK)
- Bureau de Recherches Geologiques et Minieres (BRGM, France)
- Geological Survey of Denmark and Greenland (GEUS)
- Istituto Nazionale de Geofisica e Vulcanolgia (INGV, Italy)
- Quintessa Ltd. (UK)

CONTENTS

INTRODUCTION

There are many ways to mitigate the emission of greenhouse gases, one of which is the long-term storage of carbon dioxide (CO_2) underground. The subject of this report is a large-scale commercial pilot project in Weyburn, Saskatchewan, Canada, where CO_2 is injected into a mature oil reservoir and stored underground. Essentially, the project is a field demonstration of carbon storage in the subsurface, which has been made possible by adding a research component to a CO_2 enhanced oil recovery (EOR) programme. Chapter 1 introduces the principles of underground storage and the practice of enhanced oil recovery. Chapter 2 covers the origins and location of the Weyburn project. The four research themes are described in Chapter 3. The results that have been identified are relayed in Chapter 4. In the final chapter the conclusions are reported and the results and implications of Phase 1 of the Weyburn Project are put in context.

GEOLOGICAL STORAGE

The main options for storing CO_2 underground are in ageing and depleted oil and gas reservoirs, deep saline reservoirs and unmineable coal seams (Figure 1). In the case of oil and gas reservoirs, CO_2, a by-product of hydrocarbon use, is essentially returned to formations that already contain hydrocarbons. The process of geological storage means that the injected greenhouse gas (GHG) either remains trapped and sealed in the reservoir or it may react chemically with the reservoir rocks and fluids to become part of the reservoir itself. This is known as geological storage. CO_2 must remain underground for possibly thousands of years if the geological storage of CO_2 is to be an effective way to avoid climate change.

Geological storage is thought to be safe for a number of reasons. Most importantly many of these formations have retained oil, gas or water in isolation from surrounding rocks for millions of years. In addition, there are many examples of sites that have stored large volumes of pure or almost pure CO_2 for long periods of time. For example, McElmo Dome in the USA contains up to 283 billion m^3 (10 trillion cubic feet) of CO_2. The dome has 44 wells that produce CO_2 at individual rates up to 3 million m^3/day (100 mmcfd). The dome currently supplies CO_2 for a number of major EOR projects in Texas.

The safety of geological storage of CO_2 will rely on the application of appropriate operational practices, regulations, monitoring and materials. The economics of geological storage depend largely on the type of reservoir being used. When storage is combined with enhanced oil recovery, as described in the next section, value is added to the process. In all storage cases, a major economic driver would be created if credits could be claimed for the CO_2 stored.

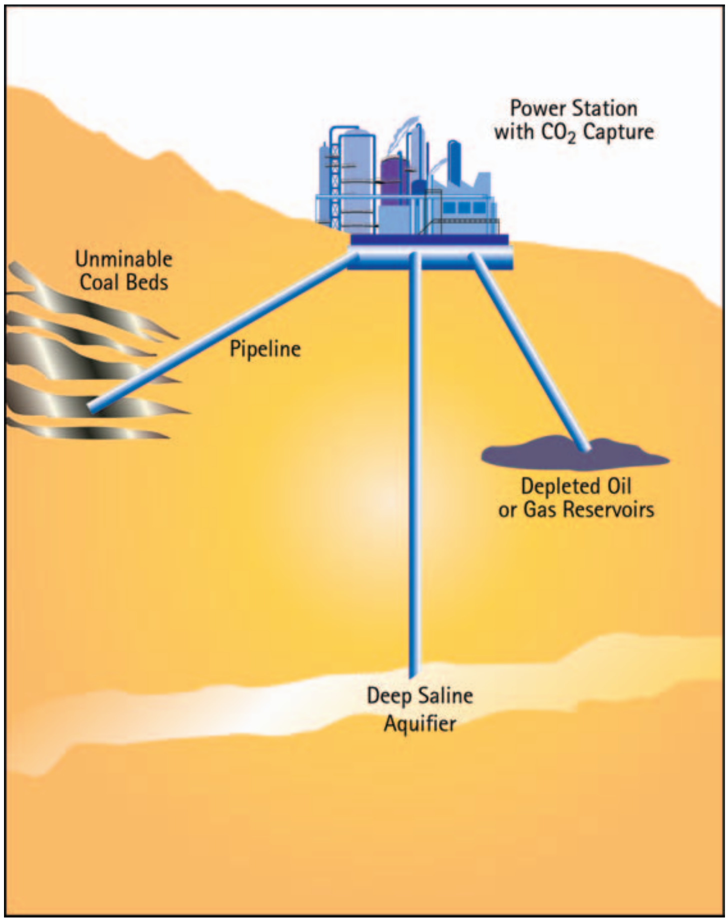


Figure 1: Options for the geological storage of CO_2
(Image ©IEA GHG)

The implementation of geological storage as a means of mitigating climate change has a number of advantages:

- Geological storage is close to being ready for immediate implementation on a global scale, unlike many other mitigation options;
- It would be relatively simple to implement, in terms of technological feasibility;
- Some of the economic drivers are already in place and the framework for developing others has been established in the Kyoto Protocol;
- Geological storage has the capacity to effect a large and swift impact on GHG emission reductions.

ENHANCED OIL RECOVERY

Oil and gas reservoirs consist of porous rocks covered by impermeable cap rock, which is often dome shaped in a location that prevents further migration (loss) of hydrocarbons. After more than a century of intensive petroleum exploitation, thousands of oil and gas fields are approaching the ends of their economically productive lives. CO_2 can be used in a process known as enhanced oil recovery (EOR) to recover more oil. In most oil fields only a portion of the original oil in place is recovered using standard petroleum extraction methods. For example, primary oil recovery (pumping the oil with no-pressure artificial membrane), and secondary, where the field is flooded with water to maintain pressure, will recover some 20-40% of the oil originally found in the reservoir. EOR has the potential to increase an oil field's ultimate recovery of oil up to 60%, and extend the oilfield's life by decades.

When the CO_2 is injected for EOR (Figure 2) it contacts oil that cannot be produced conventionally and causes it to swell and become less viscous. If the subsurface rock is thought of as sponge-like with pores containing the oil, then the swelling of the oil helps to push a portion of the oil out of the pores. The reduced viscosity then improves the flow of oil to the production wells. This technique called CO_2 – EOR is well established. If the CO_2 used is then stored in the oil reservoir, EOR has the potential to become an environmentally attractive option as well as an economic one. The Weyburn project explores and tests the theory for the long-term storage of CO_2 used in EOR.

Currently, CO_2 is injected underground in many EOR projects. For example, about 33 million t/y of CO_2 is already used at more than 74 EOR projects in the USA. Of the 74, only four sites use CO_2 from man made sources. Most of this CO_2 is extracted from natural reservoirs, but some is captured from natural gas plants and ammonia production. In addition, much of the technology for the transport and storage of gases is well established and in widespread use. Large volumes of CO_2 are routinely transported in pipelines.

The global potential for the storage of CO_2 in depleted oil and gas fields and other underground resources at a cost of less than 20$/t of CO_2 stored are shown in Table 1. The estimates are made by the IEA Greenhouse Gas R&D Programme (IEA GHG 2001) and are shown in comparison with projected total emissions between 2000 and 2050, according to a "business as usual" scenario (the IPCC's IS92a projection).

Table 1 Global potential of CO_2 storage in the geosphere

Storage option	Global capacity	
	$GtCO_2$	% of emissions to 2050
Depleted oil and gas fields	920	45
Deep saline reservoirs	400-10,000	20-500
Unmineable coal measures	40	2

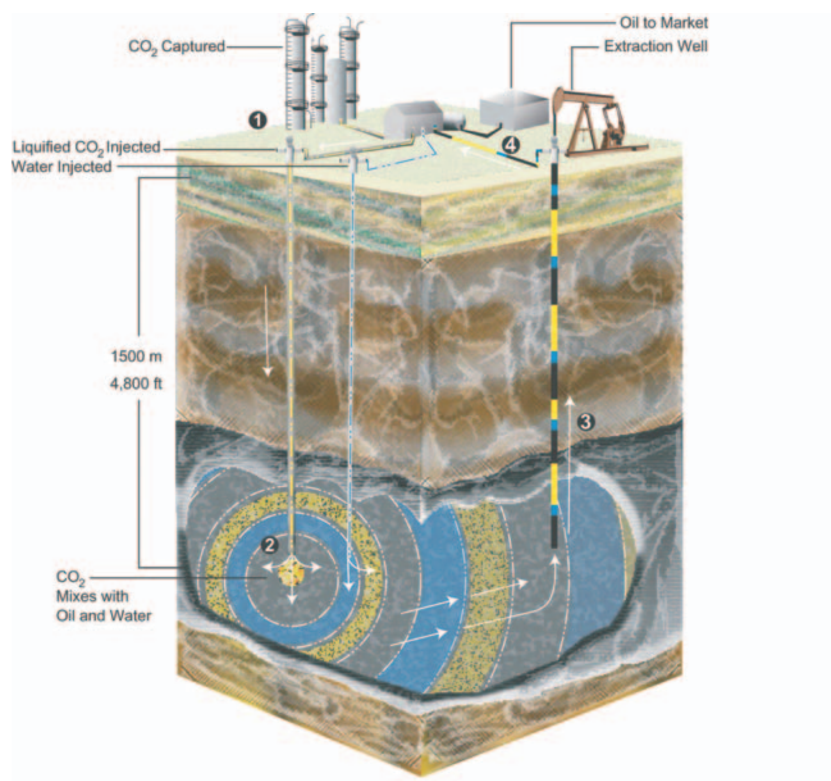


Figure 2: The Weyburn Midale Project schematic (courtesy of PTRC).
1) CO_2 is captured from the Dakota Gasification Plant in Beulah, North Dakota. CO_2 is then liquefied by compression and transported 320-km via pipeline to the Weyburn and Midale oilfields, where it's injected, along with water, 4 800 metres underground into a depleted oil and gas reservoir.
2) Oil absorbs injected CO_2, which causes the oil to expand. Combined with water injection, CO_2 injection increases reservoir pressure and oil fluidity enabling oil to escape from rock pores and flow more readily toward production wells.
3) Oil, CO_2 and water are extracted. A significant amount of CO_2 remains safely stored underground.
4) The extracted CO_2 and water are separated and re-injected. The oil (which conventional methods leave underground) is ready to be processed.

In summary, depleted oil and gas fields have a number of attractive features as CO_2 storage reservoirs (IEA GHG 2001):

- Exploration costs would be small;
- The reservoirs are proven traps, known to have held liquids and gases for millions of years;
- The reservoirs have well known geology;
- There is the potential to re-use some parts of the hydrocarbon production equipment to transport and inject the CO_2.

Thus, the underground storage of CO_2 used for EOR is one of the most promising and economic ways to effect the geological storage of CO_2.

THE WEYBURN PROJECT

The Weyburn project aims to assess the technical and economic feasibility of CO_2 storage in geological formations, particularly oil reservoirs. The overall objective is to predict and verify the ability of an oil reservoir to store CO_2. The work has focussed on understanding the mechanisms of CO_2 distribution and containment within the reservoir and the degree to which CO_2 can be permanently stored. The expertise obtained could be used when selecting other CO_2 storage sites. In this chapter the origin and organization of the Weyburn project are outlined and the oil field is described.

ORIGINS

In 1998, a Canadian oil and gas corporation (then PanCanadian Petroleum Limited, now EnCana Corporation) announced plans to implement a large scale EOR project in an oilfield near Weyburn, Saskatchewan, Canada, using CO_2 captured from a coal gasification power plant. This provided a chance to demonstrate and study a large-scale geological storage project and to provide the data to evaluate the safety, technical and economic feasibility of such storage.

In 1999, IEA GHG sponsored a planning workshop in Regina, Saskatchewan, in response to this remarkable opportunity. Experts in climate change, reservoir engineering, EOR and geology attended the workshop, as well as representatives of several government organizations interested in sponsoring the research and representatives of various research organisations. The newly formed Petroleum Technology Research Centre (PTRC) was also represented. The PTRC is a collaborative organisation founded by the University of Regina, the Saskatchewan Research Council, Natural Resources Canada and Saskatchewan Industry and Resources. The PTRC was founded with the aim of facilitating and managing industry-supported EOR, oil and gas research for Western Canadian oilfields. The University of Regina and the Saskatchewan Research Council are among the research groups providing the research effort. The PTRC provides a management structure that brings together individual projects to form larger research programmes with more comprehensive and long-term goals. The PTRC was considered ideal to manage the Weyburn storage project, due to its ability to bring objectivity to the program and to recruit some of its best researchers globally. As a result of the IEA GHG workshop, a plan and management structure for the storage project was formed. The research team was formed soon after, and collection of the initial baseline data began in 1999. The research project was funded by the provincial governments of Saskatchewan and Alberta, the federal governments of Canada and the USA, the EU and a number of private sector corporations operating inside and outside Canada.

LOCATION OF THE WEYBURN OILFIELD

The Weyburn oilfield lies on the northwestern rim of the Williston Basin, 16 km south east of Weyburn. The oil field began operation in 1954 and currently there are about 650 production and water injection wells in operation. Average daily crude oil production is 2 900 m^3/d (about 18,200 barrels/day). The Weyburn field produces about 10% of EnCana's total oil production. Over its lifetime the field has produced some 55 million m^3 of oil from primary and water flood production. The field is in production decline, having produced more than 25% of the estimated.

In order to keep the field viable, CO_2 injection began in 2000. EnCana agreed to have the commercial oil recovery project second as a demonstration project for CO_2 storage in an oil field. Weyburn has all the key elements required for a sizeable demonstration project for CO_2 storage, which are:

- It is a large-scale EOR programme in a partially depleted reservoir;
- A man-made source of CO_2 is available;
- It has a reservoir appropriate for storage;
- There was an opportunity to collect a baseline dataset.

In addition, the Weyburn site has a vast and publicly accessible collection of historical records dating back to the discovery of the field, an advantage which is not available for many other potential storage sites. The Province of Saskatchewan is unusual in that it has long required operators to provide records of operational and well histories and the Province has archived roughly 600 cores from the field as well as all the geophysical logs and other relevant information. All this data was made available to researchers and it provided a thorough historical dataset in addition to the pre-injection baseline dataset.

Operations at EnCana's Weyburn oil field in south eastern Saskatchewan, Canada.

CO_2 INJECTION

In late 2000, CO_2 injection was initiated at an initial injection rate of 2.69 million m^3/d (or 5000 t/d) into 19 patterns. The CO_2 for the Weyburn EOR project is produced in the Great Plains synfuels plant in Beulah, North Dakota, USA, which is operated by the Dakota Gasification Company. They have constructed a 325 km pipeline, which will supply the CO_2 to the Weyburn field (see Figure 3).

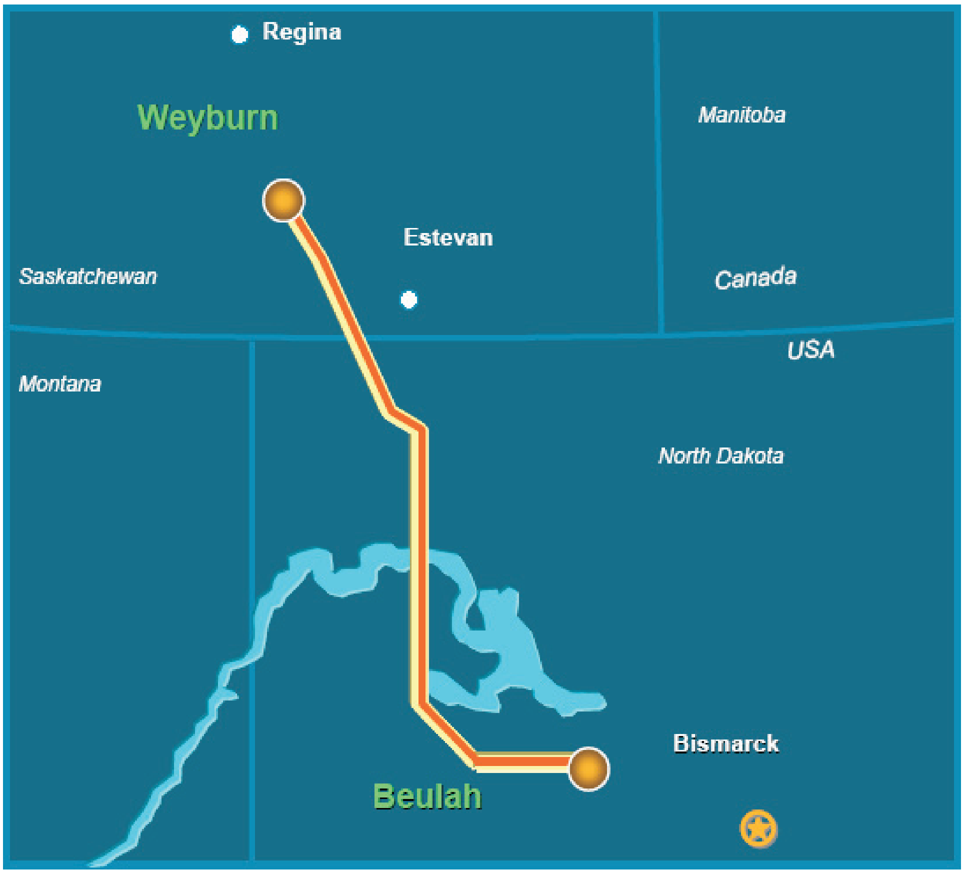


Figure 3: Location of the Weyburn field and the CO_2 pipeline from North Dakota

In addition, CO_2 injection and recycle facilities have been installed in the Weyburn field. By 2002, the rate of CO_2 injection in the Phase 1 area increased to 3.39 million m^3/d (6300 t/d) including 0.71 million m^3/day (1320 t/d) of CO_2 recycled from oil production. The CO_2-EOR has contributed over 788 m^3/d (5000 barrels/d) to a total daily production of 3240 m^3/d (20 560 barrels/d) for the entire Weyburn unit, and this will grow with time. As of May 30, 2003, cumulative CO_2 injected was 1.90 billion m^3 (3.5 million t). The EOR plan for 2003-2008 includes expanding the CO_2 flood into a total of 75 patterns, with about 10.8 billion m^3 (20 million t) of injected CO_2 anticipated over the lifetime of the project.

The Weyburn facility where the main CO_2 pipeline comes in from Beulah, North Dakota. ©Image courtesy of PTRC

The figure highlights some key features of the project:

- It involves the cross border transfer of CO_2 from the USA to Canada and so is, essentially, the first time that there has been international trading of 'physical' CO_2 for the purposes of emissions reduction;
- The CO_2 for the EOR comes from fossil fuel use. The Weyburn project represents a significant increase in the use of man-made CO_2 for oil production. The establishment of the CO_2 gas pipeline infrastructure will lead to an increased use of man-made CO_2 in EOR projects.

CO_2-EOR is projected to increase the Weyburn oilfield production. It also means that the oilfield will remain viable for another 20 years and will produce an additional 130 million barrels of oil.

RESEARCH THEMES

The IEA GHG Weyburn CO_2 Monitoring and Storage Project is a successful example of international collaboration between industry and research organisations, with researchers participating from Canada, the USA and four European countries. The goal was to make use of some of the most qualified researchers to ensure the quality of the scientific work undertaken. In addition, the IEA GHG engaged a team of international experts to undertake an expert review of the project in 2003, as part of maintaining the quality of research.

The research was divided into 81 separate subtasks. These were categorized into four major themes to cover the areas essential to a comprehensive study of the reservoir and of geological storage in general. A leading expert in the area of each theme was appointed to lead the research groups working under each theme. For example, the European research component was guided by the British Geological Survey. The four themes are described in the following sections.

GEOLOGICAL CHARACTERIZATION OF THE GEOSPHERE AND BIOSPHERE

A suitable geological setting for the long-term storage of CO_2 must have certain characteristics, including:

- Effective trapping mechanisms;
- Competent bounding seals,
- Hydraulic isolation from overlying aquifers,
- An appropriate hydrogeological regime; and
- Minimal potential pathways for the rapid migration of CO_2 along faults or fractures.

The Weyburn reservoir was investigated to determine how well it meets these criteria. The investigation included examination of the geosphere in the Weyburn area by a variety of methods to determine the integrity of the geological system for long-term storage of CO_2. A 200 x 200 km area, centred on the Weyburn field, was studied, to map the stratigraphic distribution and extents of reservoirs, seals, regional aquifers, and aquitards from the Precambrian basement to the ground surface (see Figure 4). The results provided the framework for extensive characterization of the subsurface fluid flow regime, which greatly influences the eventual distribution of injected CO_2 or impact the distribution and fate of any CO_2 leaking from the storage site. Tectonic features and basin structures were studied using seismic, high resolution aeromagnetic and other remotely sensed data. These studies were used to evaluate potential CO_2 migration in the study area. The near-surface hydrogeological environment was also described to determine topography, drainage basins, and the distribution of shallow aquifers. An integrated 3D geological model was constructed for an area extending 10 km beyond the limits of the CO_2 injection area. The geological model, which describes the natural system, serves as the basis for a more comprehensive System Model that includes anthropogenic attributes, such as well bores and production parameters. It is used for numerical risk and performance assessment modeling. The original model shows the status of the site prior to injection of CO_2. The model could then be compared with subsequent data when used in other research themes.

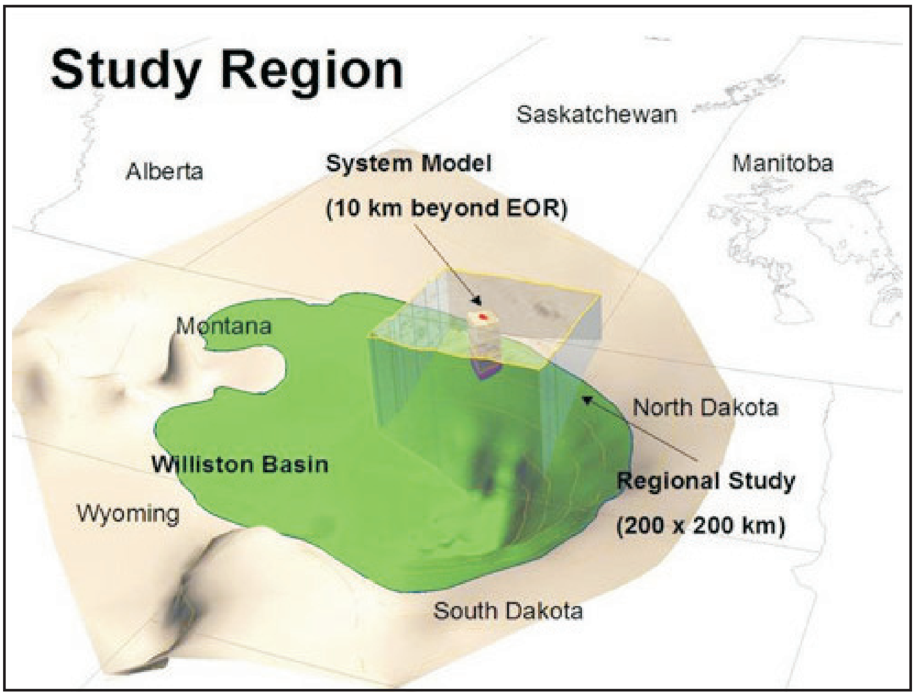


Figure 4: Relative position of the system model within the overall regional study area of the project (Wilson & Monea 2004).

The results showed that the Weyburn field is in a tectonically quiet region. Most faults and fracture zones in the greater region are localized disturbances. Larger scale features were also observed, and one fault identified in this study was included in the geological model used in risk assessment. Although the trace of this fault may be observed in strata overlying the reservoir, it appears that it has not compromised reservoir integrity in the last 50 million years. Thus the geological setting of the Weyburn oil pool is considered to be highly suitable for the secure long-term storage of CO_2.

Primary seals enclosing the reservoir were observed to be sound and exhibited only rare discontinuities, most of which formed shortly after deposition, and showed essentially no detectable evidence of fluid conductance. In general, all the aquifer flow is laterally confined within regionally continuous aquifer units. The lack of cross-formulation flow in the Weyburn area indicates that formation fluids, and any injected fluids such as CO_2, tend to stay within their respective aquifers.

In general, the work arising from the geological characterization of the Weyburn site indicates that geological storage of CO_2 in hydrocarbon reservoirs is a viable and promising technique for the mitigation of CO_2 emissions to the atmosphere.

PREDICTION, MONITORING AND VERIFICATION OF CO_2 MOVEMENTS

The focus of the second theme was how the monitoring of the movement of CO_2 in the reservoir and to identification of any effects (physical or chemical) of injecting CO_2. The specific objectives were to:

1. Test and improve conventional predictions of CO_2 flood movement in the reservoir;
2. Assess the nature and rate of the chemical reactions that are the mechanisms for long-term storage of CO_2 within the reservoir;
3. Observe the response of the reservoir to flooding with CO_2;
4. Develop and demonstrate methods for monitoring the CO_2 flood; and
5. Determine the distribution and security of CO_2 within the reservoir.

Knowledge of the reservoir in the CO_2 injection area is based on 50 years of production data and a large number of well bores and associated geological and geophysical logging data. Reservoir characteristics from this historical information formed the basis for designing the plan for EOR through a CO_2 flood. Initial predictions of how the CO_2 flood would progress were based on flow simulations using an existing reservoir model of the Weyburn field. A variety of seismic and geochemical sampling methods have been subsequently used to monitor the CO_2 injection process and characterize the reservoir between boreholes.

Monitoring and Verification

Monitoring entails observing the physical and chemical effects of the CO_2 injection on the state of the reservoir system with a focus on tracking the spread of CO_2 within, and potentially outside, the reservoir. An extensive effort was made to acquire robust baseline measurements against which all subsequent monitoring surveys could be compared. The project is made unique by this aspect and the extensive knowledge provided by the well-based monitoring that is done in the regular course of EOR operations. Verification is the substantiation of the interpreted monitoring results to allow reliable estimation of the volume and distribution of CO_2 in the subsurface.

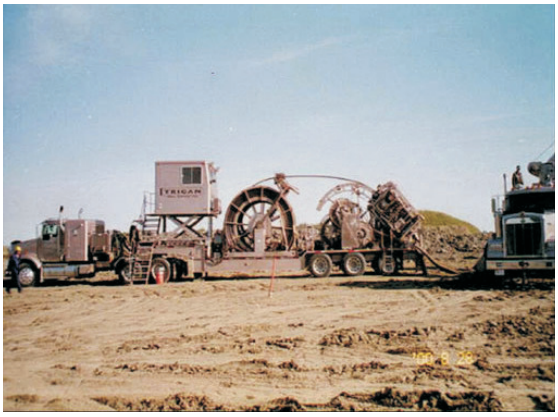
Production data sampling is the primary means of monitoring the effects of CO_2 injection at the reservoir. This sampling provides data that comprise regular sampling of downhole pressures as well as the volumes of injected and produced reservoir gases and fluids. Additional monitoring methods that have been implemented at the Weyburn field include:

1. Measurements of changes in reservoir fluid chemistry;
2. Imaging changes in the seismic properties of the reservoir;
3. Passive recording of microseismic activity in the reservoir; and
4. Sampling of surface soil gas for traces of leaking CO_2.

The monitoring effort is designed to document as much of the dynamic reservoir response as possible. Baseline static characterisation of the reservoir, including porosity, permeability, fracture systems and fluid distribution, prior to injection is important in planning the flood and anticipating how it will proceed. Baseline measurements also provide the reference against which all subsequent monitoring surveys can be compared. The goal is to track the saturation and distribution of CO_2 within the reservoir, after initiation of flooding, assess the interaction of CO_2 with other reservoir fluids, determine pressure variations, identify off-trend flow so that the injection process can be adjusted if necessary, and ensure the security of CO_2 within the reservoir. Monitoring also provides a means of verifying the volume of CO_2 that resides within the reservoir. Efficient and complete access to the reservoir volume and avoidance of premature flow-through of CO_2 to producing wells is important, whether the ultimate goal is either EOR or storage of CO_2.

Seismic Monitoring

Seismic monitoring was used to record any seismic activity that may have resulted from the injection of CO_2. Three dimensional seismic surveys were conducted at regular intervals, beginning before the start of CO_2 injection. The progress of the CO_2 in the reservoir was observed by comparing the seismic surveys over time. This also allowed observation of any changes in the reservoir resulting from the CO_2. This technique is known as 4D or time-lapse seismic surveying (3D seismic with time being the fourth dimension). The surveys were taken at one year intervals with surveys at baseline plus one year and baseline plus two years. The time-lapse seismic response proved highly sensitive to the presence of low levels (5-10 molar %) of a CO_2-rich component and less sensitive to increases at higher saturations. This allows confident identification of the CO_2-front, but makes accurate seismic-based volume estimation difficult.



Seismic monitoring : the truck that carries the coil-tubing used to deploy the seismic instrumentation down the borehole.
© Image courtesy of PTRC

Geochemical Monitoring

The injected carbon in the CO_2 has a different isotopic composition from the carbon of the reservoir rock and fluid, which means it has a specific isotopic signature that allows it to be identified. So the injected CO_2 could be traced by chemical analysis of the produced fluids. Artificial tracer gases were also used to monitor the movement of CO_2 through the reservoir.

Geochemical sampling of production fluids has identified short-term chemical processes in the evolution of the reservoir fluid geochemistry:

1. Injected CO_2 dissolves in the reservoir brine;
2. Carbonate minerals dissolve in the reservoir; and
3. There is an increase in the total dissolved solids in reservoir brine.

These processes show good spatial correlation with the highest CO_2 injection volumes of the Phase 1 area and with the seismic anomaly maps.

The geochemistry of produced oil, gas and brine has been regularly monitored and analysed for a broad range of chemical and isotopic parameters to infer injection-related chemical processes within the reservoir and to track the path of injected CO_2. Soil gas sampling is designed to detect injected CO_2 that may have escaped from the reservoir and percolated to the surface. Sampling and analysis of gas above the injection site found fluxes for CO_2 and O_2 within the range of that for natural soils and comparable to an off-set reference location, indicating that there is no evidence so far for escape of injected CO_2 from depth.

Soil gas survey being conducted at Weyburn. © Image courtesy of PTRC

In this theme, the ability of seismic and geochemical sampling methods to monitor physical and chemical changes in the Weyburn reservoir induced by CO_2 injection has been demonstrated. Both methods are capable of determining the areal distribution of CO_2 within the reservoir, although at different levels of detail.

CO_2 STORAGE CAPACITY/DISTRIBUTION, PREDICTION AND APPLICATION OF ECONOMIC LIMITS

The role of Theme 3 in the assessment of CO_2 storage was to demonstrate the technical and economic feasibility of sequestration of CO_2 in geological formations, primarily oil reservoirs. A unique methodology for reservoir simulation has been developed that can assess the CO_2 storage capacity of a large-scale CO_2-EOR operation. The approach began with detailed fine-grid single-pattern simulations and concluded with a coarse-grid simulation of the entire area to be flooded for EOR. In addition, a CO_2 storage economic model has been developed that takes carbon taxes and credits into account. The model can provide a credible assessment of the point at which a CO_2 storage project reaches its economic limit. Finally, work from this theme provided important information for the risk assessment of potential CO_2 leakage and migration in Theme 4. Thus the scope of Theme 3 encompassed three major areas:

1. Prediction of CO_2 storage capacity;
2. Prediction of CO_2 distribution within the reservoir; and
3. Prediction of economic limits to storage.

A broad range of investigations was performed to achieve this diversity of aims.

Phase behaviour of CO_2 in the Weyburn oil system was studied to determine if the conditions required for miscibility of the injected CO_2 with the reservoir oil change with continuing field operation. This could affect both oil recovery and the CO_2 storage capacity. The investigations involved the periodic collection and analysis of oil samples from different wells in the reservoir. Overall, the phase behaviour tests established that the miscible or near-miscible conditions needed for successful EOR from the Weyburn field were being maintained.

CO_2-coreflood laboratory experiments were conducted to determine the impact of the changing composition of oil and recycled gas on oil recovery and CO_2 movement. Oil samples were collected from the field for these tests. In general, it was found that the effect of natural permeability variations between cores overwhelmed the effect of differing oil composition.

Geochemical modeling was used to make long-term estimates of the volume of trapped CO_2 (see Figure 5). The long-term (1 000 – 10 000 years) chemical impact on CO_2 sequestration through dissolution and precipitation of minerals locally in the Weyburn field and regionally was predicted using geochemical models in conjunction with thermodynamic and kinetic data. The findings were used to identify whether or not permanent sequestration occurs in the basin by the precipitation of carbonate minerals.

The primary mechanism for CO_2 trapping and storage was phase trapping – that is trapping supercritical CO_2 as a separate phase. This would be enhanced by geochemical reactions occurring in the reservoir. Additional storage of CO_2 would occur through:

- solubility trapping - storage by dissolution of the gas in the water;
- ionic trapping – storage as the carbonate, bicarbonate and other ionic species in the water;
- mineral trapping – precipitation of new phases containing CO_2 in their structure.

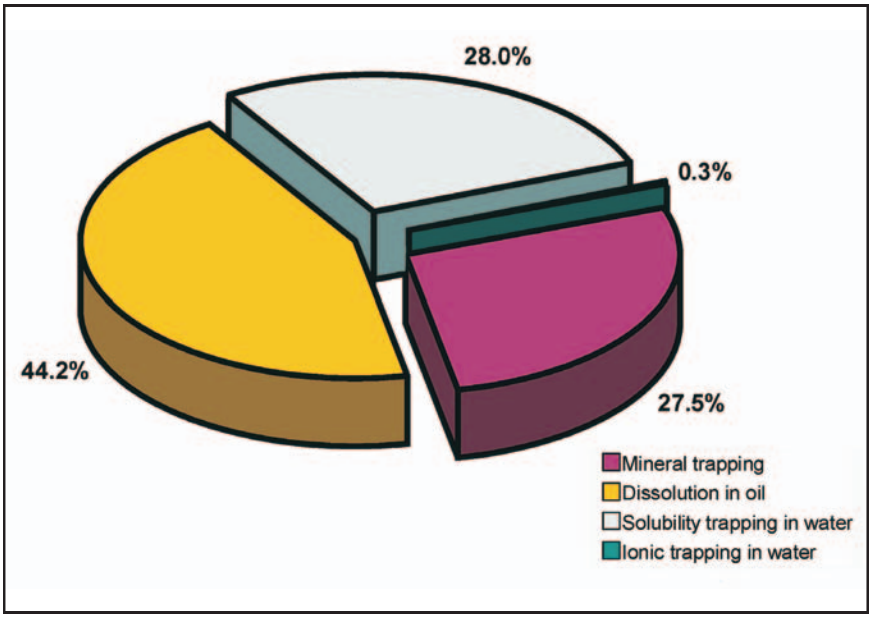


Figure 5: Preliminary estimation of CO_2 distribution in the Weyburn reservoir after 5000 years based on geochemical modelling of 75-pattern simulation EOR base case prediction (Wilson & Monea 2004).

The maximum potential amount of trapping in each flow unit could be estimated using details of the porosity, the volume of each of the flow units, and the reactions determined by the modeling efforts. These results were integrated over the entire reservoir to yield a total of about 45.15 million tonnes (Mt) with 22.65 Mt CO_2 stored through solubility, 0.25 Mt stored through ionic trapping and 22.25 Mt CO_2 stored through mineralogical trapping mechanisms. The plan was to inject about 20 Mt CO_2 as part of the EOR process, thus the Weyburn reservoir has excess storage capacity.

These estimates of storage capacity are for the long-term case and are based on a number of assumptions. The most critical assumptions were that there was just sufficient supercritical CO_2 for reaction in each of the flow units and that complete or significant reaction of the silicate minerals would occur over 5000 years. However, this was not the case. Based on the CO_2 storage capacity of 23.2 Mt for the baseline scenario, about 10.25 remains in the oleic phase, 6.50 Mt is dissolved, 0.07 Mt is stored through ionic trapping in the aqueous phase, and 6.38 Mt is stored through mineral trapping. It is predicted that there would not be a free supercritical CO_2 gas phase present in the reservoir after 5000 years.

The reservoir simulation model, which was validated by both laboratory-scale and field-scale simulation, has been successfully used to predict the CO_2 storage capacity and distribution in the Weyburn reservoir.

A comprehensive economic model was developed to compare the relative merits of incremental oil recovery and CO_2 storage for the project. The model was used to conduct economic analysis/sensitivity studies and assess the impact of economic limits on oil production and CO_2 storage. The model provides users with the ability to evaluate the preliminary economics of a specific CO_2 storage opportunity for a specific CO_2 supply source, a specific CO_2 transportation system, and a specific CO_2 storage project. It means that the impact of CO_2 credits, penalties and associated tax applications can be evaluated for each of the capture, transportation and storage modules and the sensitivity of the results to various economic parameters can be examined.

LONG-TERM RISK ASSESSMENTS OF THE STORAGE SITE

Primarily, the fourth theme had an environmental focus – to establish whether or not the CO_2 injected into the reservoir leaks to the biosphere, and if it does, could the leakage impose any environmental risk. Data and models from the previous themes were used in simulations and models to look at and assess the risks associated with the storage project. This work included:

- Determining how long the CO_2 would remain trapped in the reservoir;
- Predicting the future movements of the CO_2 within the reservoir;
- Discovering potential risks of CO_2 leakage from the reservoir to shallow potable water zones, the surface soil and the atmosphere.

The Weyburn "system" is very complex. The main components are the geology of the reservoir and overlying and underlying layers, varying well types, groundwater flow regimes and fluid characteristics (see Figure 6). A rigorous and formal systems analysis approach was used to manage this complexity. A list of features, events and processes was developed to assist in identifying the processes that could be relevant to the evolution or performance of the system. The evaluation of the list, led to a description of how the System might evolve over the 5000 year timeframe of the performance assessment. It formed the basis for a description of how the system may be *expected* to evolve, the base scenario, in the far future and other scenarios that describe alternative, but feasible futures. Performance assessment in Phase 1 focussed mainly on the base scenario.

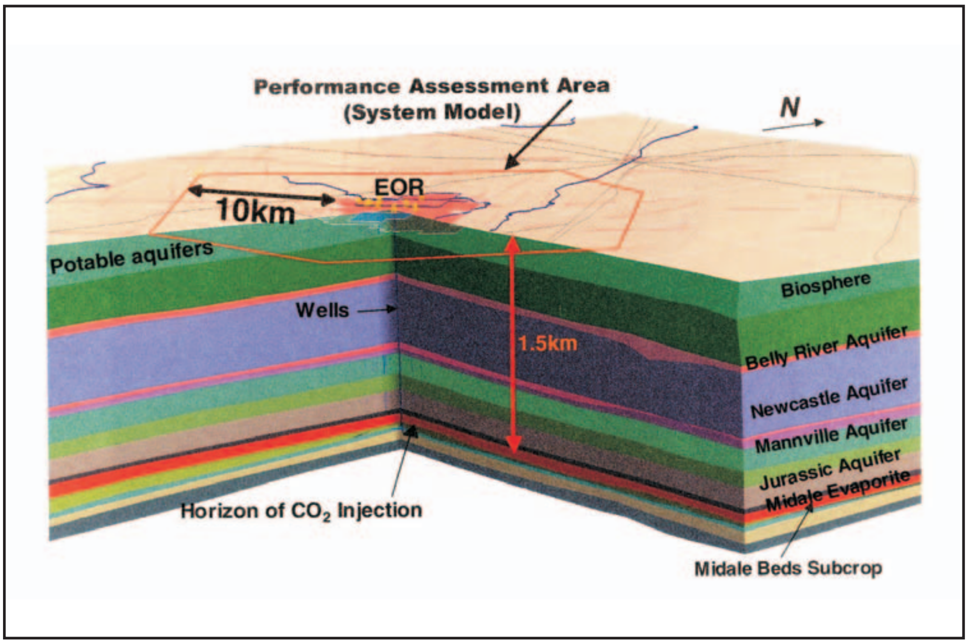


Figure 6: Diagrammatic representation of the system model consisting of the Weyburn Reservoir (EOR area), overlying and underlying geological layers, wells and the biosphere (Wilson & Monea 2004).

Simulations were conducted for a time period of 5000 years to provide an initial understanding of CO_2 migration – the process and parameters that may be important to modeling its long-term fate. These early studies highlighted the importance of processes such as CO_2 diffusion in the oil phase, phase saturation distribution at the end of EOR, groundwater velocities within the reservoir zone, and the strong interplay between the coupled processes of pressure-driven flow, density-driven flow, and diffusion.

The risk assessment included assessing the long-term integrity of the reservoir seal, the integrity of the injection and production wells, and the potential risk of human intrusion. Two primary methods of risk assessment were used. The first, deterministic risk assessment provided estimates of the various risks associated with specific variables. The second, probabilistic risk assessment, provided a distribution of the risk across the variables. Both methods were used to develop a model to predict the performance of the reservoir in containing the CO_2.

The fate of CO_2 within the geosphere and the man-made pathways was assessed by deterministic and stochastic approaches. Cumulatively, after 5000 years, the total amount of CO_2 removed from the EOR area was 26.8% (about 5.6 Mt) of the initial 21 Mt CO_2-in place at the end of EOR, of which 18.2% (3.8 Mt) moved into the geosphere below the reservoir, 8.6% (1.8 Mt) migrated laterally in the Midale reservoir outside the EOR area, and 0.02% (0.088 Mt) moved to the geosphere above the reservoir (see Figure 7). No CO_2 enters the potable aquifer system over the 5000 year period. The mean cumulative leakage through abandoned wells was estimated to be less than 0.001% of the CO_2-in place at the end of EOR. The results imply that there is a 95% probability that 98.7-99.5% of the initial CO_2-in place will remain stored in the geosphere for 5000 years. The likelihood of movement beyond this time period is very low.

The ultimate objective of the long-term risk assessment research tasks was to assess the performance and ability of the Weyburn reservoir to store CO_2 securely. Performance, by design, includes both engineering and safety aspects, and so the performance assessment also had a role in identifying the risks associated with the geological storage of CO_2 within the Weyburn reservoir. All performance assessment studies conducted within Phase 1 support the conclusion reached by the geological studies, that the geological setting at the Weyburn field is highly suitable for the long-term subsurface storage of CO_2. The studies have highlighted the significant capacity of the geosphere region surrounding the reservoir to effectively store CO_2 and prevent its migration to the biosphere. The Weyburn project delivers a credible assessment of the permanent containment of injected CO_2 as determined by formal risk analysis techniques, including long-term predictive reservoir simulations.

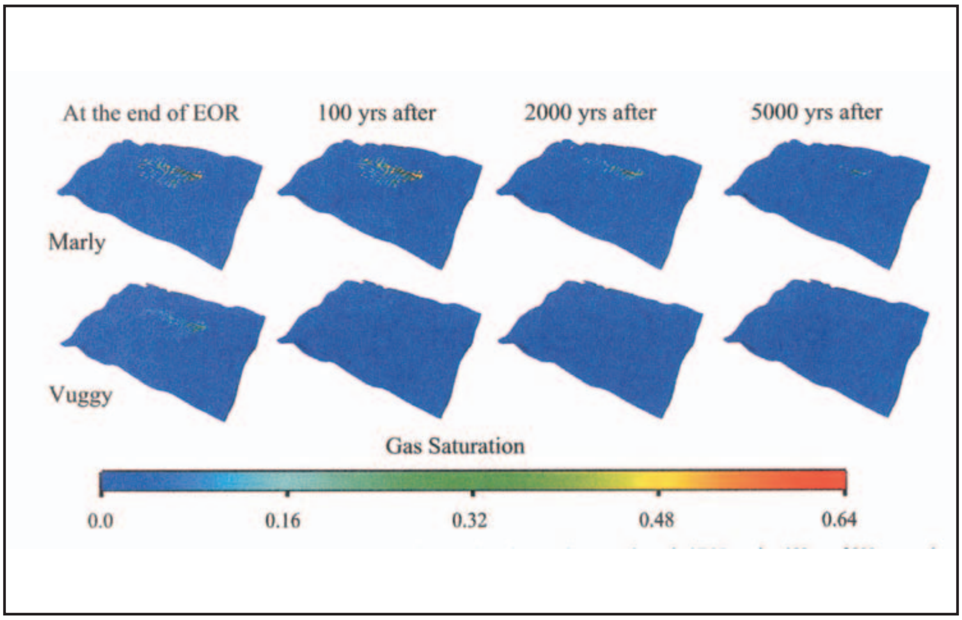


Figure 7: CO_2-rich gas phase movement in the Midale (Marly and Vuggy) layers at the end of EOR, and at 100 years, 2000 years and 5000 years after the end of EOR (Wilson & Monea 2004).

RESULTS

Theme 1 found that the Weyburn field is in a tectonically quiet region. Primary seals enclosing the reservoir were sound. The lack of flow in the Weyburn area indicates any injected CO_2 would tend to stay within its respective saline aquifer. In general, the geological setting of the Weyburn oil pool is considered to be highly suitable for the secure long-term storage of CO_2.

In theme 2 the geochemistry of produced oil, gas and brine was regularly monitored and analysed to identify chemical processes within the reservoir and to track the path of injected CO_2. Soil gas sampling above the injection site found no evidence so far for the escape of injected CO_2. Theme 2 demonstrated the ability of seismic and geochemical sampling methods to monitor physical and chemical changes in the Weyburn reservoir induced by CO_2 injection. Both methods can determine the distribution of CO_2 within the reservoir.

The storage capacity of the Weyburn field was estimated in Theme 3. It was found that 45.15 million tonnes (Mt) CO_2 could be stored in the entire reservoir. Of this, 22.65 Mt CO_2 would be stored in solution, 22.25 Mt would be stored by mineralogical trapping mechanisms and the final 0.25 Mt would be stored by ionic trapping. As the plan to inject about 20 Mt CO_2 as part of the EOR process, it was concluded that the Weyburn reservoir has excessive storage capacity. Thus, the reservoir simulation model has been used successfully to predict the storage capacity. Thus the reservoir simulation model has been used successfully used to predict the storage capacity and distribution of CO_2 at Weyburn.

The fate of CO_2 within the geosphere and the man-made pathways was assessed in Theme 4. Geochemical fluid sampling allowed researchers to track the CO_2 in the reservoir. Seismic surveys were able to detect the changes in the reservoir that result from CO_2, so as a result, the movement of CO_2 in the reservoir can be 'seen'. The numerical simulations showed that over 5 000 years, in an extreme and unlikely case of well failure, essentially 100% of the CO_2 will remain stored underground. Of this, 84.1% will remain where it was injected, in the Midale reservoir and adjoining regions, 11.9% will seep into the geosphere below the reservoir, 3.8% will migrate into the geosphere above the Midale reservoir, and only 0.2% will seep to the biosphere above. Five thousand years was chosen as the time limit with the expectation that essentially all the CO_2 will be dissolved by that time, effectively precluding any further movement upwards.

The long-term risk assessment research of Theme 4 assessed the performance and ability of the Weyburn reservoir to store CO_2 securely. The results of the performance assessment studies agree with those of the geological studies, that the geological setting at the Weyburn field is highly suitable for the long-term subsurface storage of CO_2. The geosphere region surrounding the reservoir can effectively store CO_2 and prevent its migration to the biosphere. The Weyburn project delivers a credible assessment of the permanent containment of injected CO_2 as determined by formal risk analysis techniques, including long-term predictive reservoir simulations.

The risk assessment modeling showed that CO_2 will never reach or penetrate overlying saline water zones through geological formations, nor will it reach either potable water zones closer to the surface or the ground surface above the storage reservoir. Identified wellbore leaks can usually be repaired by using understood techniques that are already available to the industry.

In summary, the project found that the CO_2 will be safely contained and that its storage can be economic. Geological settings such as the Weyburn reservoir appear to be highly suitable for the long-term storage of CO_2. A good geological description of the reservoir and a large surrounding area was developed which showed that the regional geology provides multiple containment zones. Should CO_2 leak past the primary sealing caprock, which is unlikely, there are a number of other zones with sealing capacity to act as vertical migration barriers and several saline aquifers to act as CO_2 sinks above the primary storage zone.

CONCLUSIONS

CO_2-EOR has the potential to facilitate the storage of millions of tonnes of CO_2, which would otherwise have been emitted as result of human activity. The CO_2 used becomes a purchasable commodity, and once carbon credits are awarded for the CO_2, the process will add value to storage as opposed to representing additional costs. In addition, although there is a great drive to find alternative sources of energy the world is highly dependent on fossil fuels for energy and will remain so for at least several decades. Storage of CO_2 used for EOR is thus doubly appealing as it allows more oil to be produced while reducing the greenhouse impact of the oil combustion.

While storage with EOR is currently the most economic form of geological storage, not all reservoirs are amenable to CO_2-EOR. Although it represents a large capacity for CO_2 storage, it is not sufficient, in terms of both total capacity and site availability to meet all of the needs for mitigation of CO_2. Thus other storage options may also be required. These could include the injection of CO_2 into more fully depleted oil and gas reservoirs and into deep saline aquifers. These other storage options will require an economic incentive, such as carbon credits, to become viable.

Until carbon credits or another economic incentive for CO_2 storage is introduced, the economic impact of EOR with CO_2 storage can be measured only in terms of incremental oil production. This is production that results directly from the application of a new recovery technique, such as in this case, CO_2 flooding. Before long, the dominant form of oil production at the Weyburn field will be incremental production, based on current production and the predicted level of production if EOR had not been applied.

The ultimate impact of the Weyburn project is anticipated to be significant, in terms of CO_2 storage. Currently, about 6000 tonnes of CO_2 is injected each day (as a gas at the Earth's surface this amount of CO_2 would fill a cube of almost 150 m length on each side). About 6 million tonnes has been stored to date. It is predicted that up to 26 Mt of CO_2 will be stored over the lifetime of the planned EOR project. However, the capture, compression and transport of the CO_2 produces some CO_2 itself, so the final amount stored must account for the CO_2 produced in the process. Thus, the net CO_2 stored will be about 20 Mt. This is the equivalent of removing 6.7 million cars from the road for 1 year. The success and the storage capacity achieved at the Weyburn field, implies that the total number of Western Canadian oil fields with a potential for CO_2-EOR and storage represents a capacity of about 638 Mt CO_2.

From Phase 1 it has been concluded that EOR works well as a storage mechanism for CO_2. There are several technologies and techniques, such as 4D seismic surveying, which allow CO_2 to be observed and tracked in the reservoir. Performance assessment, using reservoir modeling and simulation has shown that the reservoir will contain safely the CO_2 for as long as it is necessary to dissolve all the CO_2 in fluids (brine and oil) in the reservoir.

Phase 1 identified the most effective technologies for monitoring, verification and prediction of CO_2 behaviour in depleted oil reservoirs. It also highlighted the strengths and weaknesses of these technologies.

In summary, geological storage has the potential to store safely massive amounts of CO_2, and it is a technology that is ready and available to be implemented on a wide scale. The process is economic when combined with EOR. Geological storage with EOR has been demonstrated to be effective on a large commercial scale. Phase 1 of the IEA GHG Weyburn CO_2 Monitoring and Storage Project conducted on a mature oil field in Canada has demonstrated the safety of geological storage with EOR, as well as its economic and technical feasibility. Policy, regulations and international standards will need to be developed before geological storage can be developed on a wide scale. An essential part of the process will be to apply a standardized "toolkit" to assess, implement and operate storage projects and to monitor and verify independently the CO_2 stored. The IEA GHG Weyburn Project is an important step in this process. It will allow governments and corporations around the world to collaborate on storage programmes and will allow operators and investors to acquire carbon credits under the Kyoto Protocol. Phase 2 will focus on developing the geological storage toolkit and the scientific foundation for policy and regulatory development.

The ultimate deliverable from the first phase of the Weyburn project is a credible assessment of the permanent containment of injected CO_2 as determined by formal risk analysis techniques, including long-term predictive reservoir simulations.

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