IEA Greenhouse Gas R&D Programme

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 CO₂. 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-CO₂ greenhouses gases. This helps to put in perspective the potential of capture and storage of CO₂.

The IEA GHG Weyburn CO₂ Monitoring and Storage Project

IEA GHG assisted in the establishment of the Weyburn CO₂ 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 CO₂ 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. Copyright © EnCana Corporation. All rights reserved.
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 Cl
- 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)
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INTRODUCTION

There are many ways to mitigate the emission of greenhouse gases, one of which is the long-term storage of carbon dioxide (CO₂) underground. The subject of this report is a large-scale commercial pilot project in Weyburn, Saskatchewan, Canada, where CO₂ 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 CO₂ 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 CO₂ 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, CO₂, 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. CO₂ must remain underground for possibly thousands of years if the geological storage of CO₂ 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 CO₂ for long periods of time. For example, McElmo Dome in the USA contains up to 283 billion m³ (10 trillion cubic feet) of CO₂. The dome has 44 wells that produce CO₂ at individual rates up to 3 million m³/day (100 mmcf/d). The dome currently supplies CO₂ for a number of major EOR projects in Texas.

The safety of geological storage of CO₂ 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 CO₂ stored.
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 caprock, 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

<table>
<thead>
<tr>
<th>Storage option</th>
<th>Global capacity</th>
<th>% of emissions to 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depleted oil and gas fields</td>
<td>920</td>
<td>45</td>
</tr>
<tr>
<td>Deep saline reservoirs</td>
<td>400-10,000</td>
<td>20-500</td>
</tr>
<tr>
<td>Unmineable coal measures</td>
<td>40</td>
<td>2</td>
</tr>
</tbody>
</table>

3
In summary, depleted oil and gas fields have a number of attractive features as CO₂ 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 CO₂.

Thus, the underground storage of CO₂ used for EOR is one of the most promising and economic ways to effect the geological storage of CO₂.
The Weyburn project aims to assess the technical and economic feasibility of CO₂ storage in geological formations, particularly oil reservoirs. The overall objective is to predict and verify the ability of an oil reservoir to store CO₂. The work has focused on understanding the mechanisms of CO₂ distribution and containment within the reservoir and the degree to which CO₂ can be permanently stored. The expertise obtained could be used when selecting other CO₂ 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 CO₂ 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 organizations. 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 m³/day (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 m³ 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, CO₂ injection began in 2000. EnCana agreed to have the commercial oil recovery project second as a demonstration project for CO₂ storage in an oil field. Weyburn has all the key elements required for a sizeable demonstration project for CO₂ storage, which are:

- It is a large-scale EOR programme in a partially depleted reservoir;
- A man-made source of CO₂ 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.
CO₂ INJECTION

In late 2000, CO₂ injection was initiated at an initial injection rate of 2.69 million m³/d (or 5000 t/d) into 19 patterns. The CO₂ 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 CO₂ to the Weyburn field (see Figure 3).

In addition, CO₂ injection and recycle facilities have been installed in the Weyburn field. By 2002, the rate of CO₂ injection in the Phase 1 area increased to 3.39 million m³/d (6300 t/d) including 0.71 million m³/day (1320 t/d) of CO₂ recycled from oil production. The CO₂-EOR has contributed over 788 m³/d (5000 barrels/d) to a total daily production of 3240 m³/d (20 560 barrels/d) for the entire Weyburn unit, and this will grow with time. As of May 30, 2003, cumulative CO₂ injected was 1.90 billion m³ (3.5 million t). The EOR plan for 2003-2008 includes expanding the CO₂ flood into a total of 75 patterns, with about 10.8 billion m³ (20 million t) of injected CO₂ anticipated over the lifetime of the project.

Figure 3: Location of the Weyburn field and the CO₂ pipeline from North Dakota
The figure highlights some key features of the project:

- It involves the cross border transfer of CO₂ from the USA to Canada and so is, essentially, the first time that there has been international trading of ‘physical’ CO₂ for the purposes of emissions reduction;
- The CO₂ for the EOR comes from fossil fuel use. The Weyburn project represents a significant increase in the use of man-made CO₂ for oil production. The establishment of the CO₂ gas pipeline infrastructure will lead to an increased use of man-made CO₂ in EOR projects.

CO₂-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.
The IEA GHG Weyburn CO₂ 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 CO₂ 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 CO₂ 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 CO₂. 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 CO₂ or impact the distribution and fate of any CO₂ 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 CO₂ 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 CO₂ 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.

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.

![Figure 4: Relative position of the system model within the overall regional study area of the project (Wilson & Monea 2004).](image-url)
PREDICTION, MONITORING AND VERIFICATION OF CO₂ MOVEMENTS

The focus of the second theme was how the monitoring of the movement of CO₂ in the reservoir and to identification of any effects (physical or chemical) of injecting CO₂. The specific objectives were to:

1. Test and improve conventional predictions of CO₂ flood movement in the reservoir;
2. Assess the nature and rate of the chemical reactions that are the mechanisms for long-term storage of CO₂ within the reservoir;
3. Observe the response of the reservoir to flooding with CO₂;
4. Develop and demonstrate methods for monitoring the CO₂ flood; and
5. Determine the distribution and security of CO₂ within the reservoir.

Knowledge of the reservoir in the CO₂ 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 CO₂ flood. Initial predictions of how the CO₂ 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 CO₂ injection process and characterize the reservoir between boreholes.

Monitoring and Verification

Monitoring entails observing the physical and chemical effects of the CO₂ injection on the state of the reservoir system with a focus on tracking the spread of CO₂ 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 CO₂ in the subsurface.

Production data sampling is the primary means of monitoring the effects of CO₂ 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 CO₂.
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.
**Geochemical Monitoring**

The injected carbon in the CO₂ 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 CO₂ could be traced by chemical analysis of the produced fluids. Artificial tracer gases were also used to monitor the movement of CO₂ through the reservoir.

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

1. Injected CO₂ 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 CO₂ 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 CO₂. Soil gas sampling is designed to detect injected CO₂ that may have escaped from the reservoir and percolated to the surface. Sampling and analysis of gas above the injection site found fluxes for CO₂ and O₂ 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 CO₂ from depth.

In this theme, the ability of seismic and geochemical sampling methods to monitor physical and chemical changes in the Weyburn reservoir induced by CO₂ injection has been demonstrated. Both methods are capable of determining the areal distribution of CO₂ within the reservoir, although at different levels of detail.
CO₂ STORAGE CAPACITY/ DISTRIBUTION, PREDICTION AND APPLICATION OF ECONOMIC LIMITS

The role of Theme 3 in the assessment of CO₂ storage was to demonstrate the technical and economic feasibility of sequestration of CO₂ in geological formations, primarily oil reservoirs. A unique methodology for reservoir simulation has been developed that can assess the CO₂ storage capacity of a large-scale CO₂-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 CO₂ 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 CO₂ storage project reaches its economic limit. Finally, work from this theme provided important information for the risk assessment of potential CO₂ leakage and migration in Theme 4. Thus the scope of Theme 3 encompassed three major areas:

1. Prediction of CO₂ storage capacity;
2. Prediction of CO₂ 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 CO₂ in the Weyburn oil system was studied to determine if the conditions required for miscibility of the injected CO₂ with the reservoir oil change with continuing field operation. This could affect both oil recovery and the CO₂ 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.

CO₂-coreflood laboratory experiments were conducted to determine the impact of the changing composition of oil and recycled gas on oil recovery and CO₂ 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 CO₂ (see Figure 5). The long-term (1 000 – 10 000 years) chemical impact on CO₂ 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.

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 CO₂ 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 CO₂ storage capacity and distribution in the Weyburn reservoir.

A comprehensive economic model was developed to compare the relative merits of incremental oil recovery and CO₂ 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 CO₂ storage. The model provides users with the ability to evaluate the preliminary economics of a specific CO₂ storage opportunity for a specific CO₂ supply source, a specific CO₂ transportation system, and a specific CO₂ storage project. It means that the impact of CO₂ 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 CO₂ 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 CO₂ would remain trapped in the reservoir;
- Predicting the future movements of the CO₂ within the reservoir;
- Discovering potential risks of CO₂ 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.
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 CO₂ 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 CO₂ 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 CO₂. The studies have highlighted the significant capacity of the geosphere region surrounding the reservoir to effectively store CO₂ and prevent its migration to the biosphere. The Weyburn project delivers a credible assessment of the permanent containment of injected CO₂ as determined by formal risk analysis techniques, including long-term predictive reservoir simulations.

Figure 7: CO₂-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 CO₂ 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 CO₂.

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 CO₂. Soil gas sampling above the injection site found no evidence so far for the escape of injected CO₂. Theme 2 demonstrated the ability of seismic and geochemical sampling methods to monitor physical and chemical changes in the Weyburn reservoir induced by CO₂ injection. Both methods can determine the distribution of CO₂ within the reservoir.

The storage capacity of the Weyburn field was estimated in Theme 3. It was found that 45.15 million tonnes (Mt) CO₂ could be stored in the entire reservoir. Of this, 22.65 Mt CO₂ 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 CO₂ 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 CO₂ at Weyburn.

The fate of CO₂ within the geosphere and the man-made pathways was assessed in Theme 4. Geochemical fluid sampling allowed researchers to track the CO₂ in the reservoir. Seismic surveys were able to detect the changes in the reservoir that result from CO₂, so as a result, the movement of CO₂ in the reservoir can be ‘seen’. The numerical simulations showed that over 5000 years, in an extreme and unlikely case of well failure, essentially 100% of the CO₂ 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 CO₂ 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 CO₂ 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 CO₂. The geosphere region surrounding the reservoir can effectively store CO₂ and prevent its migration to the biosphere. The Weyburn project delivers a credible assessment of the permanent...
containment of injected CO\textsubscript{2} as determined by formal risk analysis techniques, including long-term predictive reservoir simulations.

The risk assessment modeling showed that CO\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{2} sinks above the primary storage zone.
CO₂-EOR has the potential to facilitate the storage of millions of tonnes of CO₂, which would otherwise have been emitted as result of human activity. The CO₂ used becomes a purchasable commodity, and once carbon credits are awarded for the CO₂, 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 CO₂ 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 CO₂-EOR. Although it represents a large capacity for CO₂ storage, it is not sufficient, in terms of both total capacity and site availability to meet all of the needs for mitigation of CO₂. Thus other storage options may also be required. These could include the injection of CO₂ 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 CO₂ storage is introduced, the economic impact of EOR with CO₂ 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, CO₂ 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 CO₂ storage. Currently, about 6000 tonnes of CO₂ is injected each day (as a gas at the Earth’s surface this amount of CO₂ 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 CO₂ will be stored over the lifetime of the planned EOR project. However, the capture, compression and transport of the CO₂ produces some CO₂ itself, so the final amount stored must account for the CO₂ produced in the process. Thus, the net CO₂ 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 CO₂-EOR and storage represents a capacity of about 638 Mt CO₂.

From Phase 1 it has been concluded that EOR works well as a storage mechanism for CO₂. There are several technologies and techniques, such as 4D seismic surveying, which allow CO₂ to be observed and tracked in the reservoir. Performance assessment, using reservoir modeling and simulation has shown that the reservoir will contain safely the CO₂ for as long as it is necessary to dissolve all the CO₂ 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.
BIBLIOGRAPHY
