

Role of Enhanced Oil Recovery in Carbon Sequestration The Weyburn Monitoring Project, a case study

*K. Brown (ken_brown@pcp.ca),
PanCanadian Petroleum Limited)
150 - 9th Avenue S.W., P.O. Box 2850, Calgary, Alberta T2P 2S5*

*W. Jazrawi (Waleed_Jazrawi@pancanadian.ca)
Petroleum Technology Research Centre
6 Research Drive, Regina, Saskatchewan S4S 7J7*

*R. Moberg (Moberg@src.sk.ca)
Petroleum Technology Research Centre
6 Research Drive, Regina, Saskatchewan S4S 7J7*

*M. Wilson (Mwilson@sem.gov.sk.ca)
Petroleum Technology Research Centre
6 Research Drive, Regina, Saskatchewan S4S 7J7*

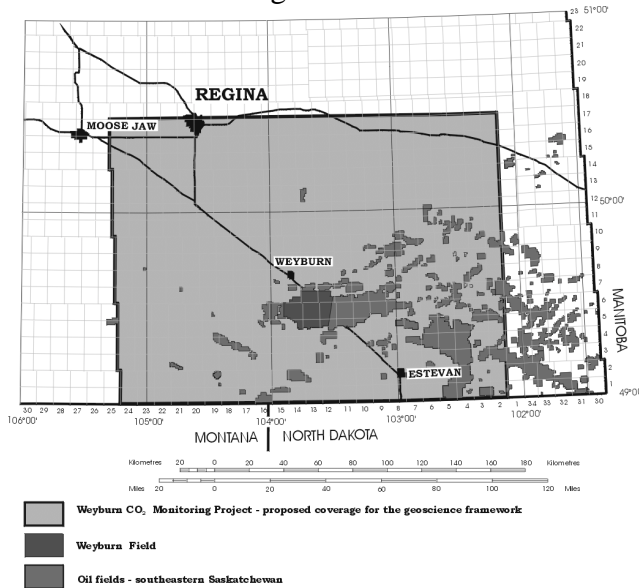
Abstract:

Injection of CO₂ into a carbonate oil reservoir in southeastern Saskatchewan, Canada, began on September 22, 2000. Prior to the start of injection, substantial baseline data were obtained from the field. This baseline data include extensive seismic work (3D-seismic, VSP, cross-well and single-well seismic) and geochemical sampling. The monitoring project will evaluate the distribution of CO₂ in a carbonate reservoir and will determine the chemical reactions that are occurring within the reservoir between the CO₂ and the reservoir rock and fluids.

The ultimate goal of the monitoring project is to verify the long-term storage capacity of an oil reservoir, with particular emphasis on reservoir integrity. Understanding how CO₂ moves within and interacts with the reservoir fluids and minerals will allow a determination of total reservoir capacity should CO₂ storage become the ultimate goal. On a short-term basis, the monitoring will identify new, cost-effective ways to track the path of CO₂ in any oil reservoir.

The paper discusses the Enhanced Oil Recovery Project, the progress of the CO₂ flood, and the goals of the Monitoring Project. Particular emphasis is placed on understanding how the monitoring project will help determine the capacity of oil reservoirs to retain CO₂ for the long-term.

Figure 1



Introduction:

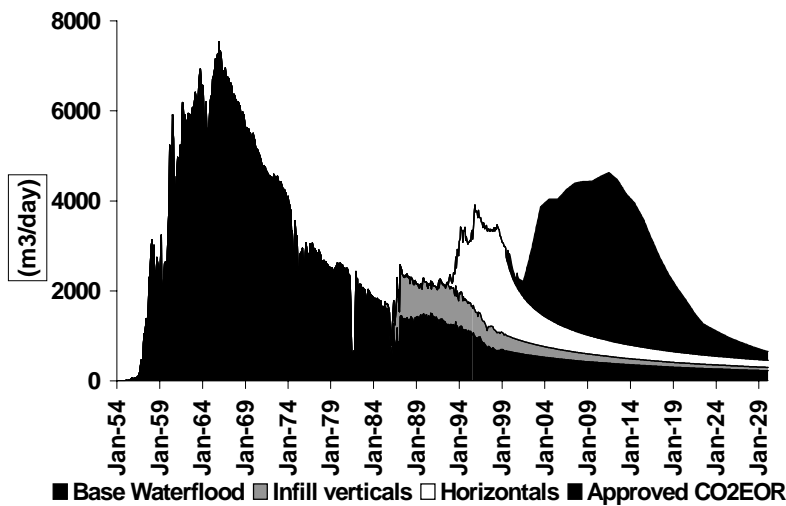
Weyburn Field is a major oil field in southeastern Saskatchewan, Canada. The oil is located in a carbonate reservoir of Mississippian age with an upper seal of anhydrite.

Initial oil in place is estimated at approximately 1.4 billion barrels, making this a significant field by world standards. Weyburn Field was discovered in 1954.

Following unitization, waterflooding commenced in 1962. Some reversal of the production decline (figure 2) was

achieved in the nineties with a primarily horizontal infill drilling program. To maintain high production rates, however, an enhanced oil recovery process was required - CO₂ was taken as the solvent of choice.

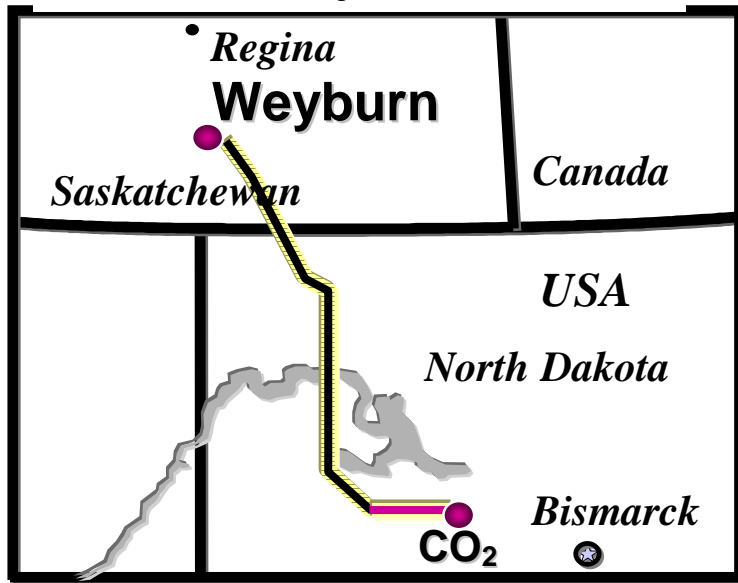
Figure 2



An estimated 34% of the oil in place will be recoverable under waterflood. In excess of 80% of this oil has already been produced according to government statistics. Incremental production with injection of CO₂ is estimated to be in the order of 15% of initial oil in place, in the area of the field to be flooded. This will produce an additional 130 million barrels (21 million m³) of oil over the anticipated 25 year life of the tertiary recovery project.

PanCanadian Resources Ltd. (PCR) is the operator of Weyburn Field. Reaching the decision to move ahead with a commercial project projected to cost in excess of \$1 billion cdn was achieved without any pilot scale testing. Instead, PCR made use of the results of two CO₂ flood pilots operated by Shell Canada in the late eighties and through the nineties in Midale Field, a lateral extension of the same geologic reservoir, together with extensive reservoir study and modeling. The pilots and modeling, in concert with an

Figure 3



innovative fiscal structure negotiated with the resource owner, the Province of Saskatchewan, allowed this project to proceed.

The CO₂ is produced from a coal gasification facility located at Beulah, North Dakota. CO₂ purity is in the order of 96%, with traces of H₂S, hydrocarbons and nitrogen in the stream. The CO₂ is compressed to approximately 2200 psi and fed into a 330 km pipeline

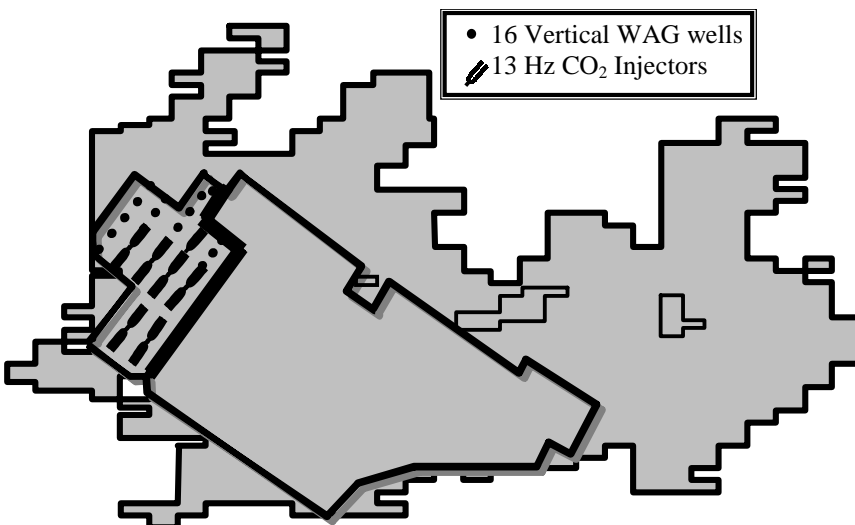
terminating at Weyburn Field. There is no additional pumping required along the pipeline. The CO₂ is delivered in supercritical condition at 2175 psi.

Injection of CO₂ into the reservoir began September 22, 2000. Due to commissioning problems, PCR has only been able to inject 50 million scf/d (2500 tonnes) instead of the design equivalent of close to 100 million scf/d (approximately 5000 tonnes/day) at time of writing.

CO₂ will be injected into a limited portion of the field (figure 4), which encompasses a total of 75 inverted nine-spot patterns converted to line drive. The area to be flooded contains approximately 60% of the oil reserves of Weyburn Field. In the first phase of injection, 17 patterns are targeted. New phases will be added as recycled CO₂ becomes available for expansion. At the time of writing, injection had proceeded without problem. There had been no injectivity issues and no response seen at any of the production wells.

Within the phase 1 area (figure 4 identified by well locations), there are a total of 29 injection wells, forming the line drive. Sixteen of these injection wells are vertical and

Figure 4



thirteen are horizontal wells. There are also four observation wells in the area, two of these are horizontal. Over the planned life of the field under tertiary recovery, it is expected that some 18 million tonnes of CO₂ from the Dakota Gasification Plant in North Dakota will be injected into the field. Unless a buyer can be found for the CO₂

stored in the field, no blow-down phase will be utilized allowing for permanent sequestration of the CO₂. On a net basis, gross CO₂ purchased from Dakota Gasification less the equivalent CO₂ released by the generation of electricity to power compressors (both at Beulah and recycle compressors at Weyburn), the equivalent of approximately 14 million tonnes of CO₂ will be prevented from reaching the atmosphere. For the produced oil, on a life-cycle basis, it has been estimated that CO₂ production at end use will be two-thirds that of oil produced in a conventional fashion.

Baseline Studies:

Weyburn is an excellent candidate for monitoring and verification of sequestration in an oil reservoir. The prime rationale for this statement is that it was possible to obtain a full suite of baseline data from the reservoir prior to first injection of CO₂.

In Weyburn Field, over 1000 wells have been drilled and more than 600 of these wells have been cored. The geophysical logs from these wells are available as part of a public database, as are the cores. In addition to the core and log data, all the production (gas, oil and water) and injection data taken since the discovery of the field are also readily available. Weyburn has probably the best historical database of any field in the world. Additionally, access to all wells and surface facilities is complete and easy. The field has been extensively modeled by PCR prior to making the decision to proceed and as part of developing the strategy for field operations under CO₂ flood. All of this information will be made available to the international research team undertaking the monitoring study.

Monitoring Program:

The monitoring program has been broken into the following key tasks. These tasks are as follows:

1. Sample collection
2. Preparing the geologic framework
3. Geochemical analysis
4. Geophysical analysis
5. Long-term assessment of risk and reservoir integrity

This is an extensive monitoring program designed to extend over a four year period. While four years does not cover the life cycle of CO₂ injection into the Phase 1 area, expected to be about eight years, it was estimated to be a reasonable period over which to collect and analyze data from the project. In addition to allowing samples and data to be collected over an extended period, the timing allows for experimentation requiring lengthy time periods to be undertaken and, also, allows sufficient time for graduate students to participate in the research. One of the goals of the project will be to help develop expertise in the area of CO₂ tertiary oil recovery; this is achieved through student training.

In addition to the extent of the project in terms of time and scope of study, the project engages a truly international research team. The researchers forming the team include European, U.S. and Canadian experts. This enables the project to take advantage of expertise in both the Williston Basin itself together with expertise in the various technical components of the program listed above. The researchers also form important links to other major studies, such as the StatOil CO₂ injection to the Utsira formation in the North Sea and various geologic studies of aquifer potential.

Sample Collection:

Sampling of produced fluids and gases is supervised by the field staff of PCR in cooperation with researchers from the University of Calgary. Analysis of the samples is being undertaken primarily at the University of Calgary although other research agencies are engaged in this exercise. The analytic results are then transferred to other research teams within the project requiring this data. Fluid samples will be collected on a regular basis to allow effective monitoring to proceed.

Preparing the Geologic Framework:

A key element of understanding the integrity of the reservoir as a storage location for greenhouse gas is to understand the broader geologic framework within which the reservoir is located. The proposed study (see figure 1 for the area to be covered by the geological framework study) includes the development of an enhanced understanding of the depositional history of the basin, as well as post-depositional events, particularly the reactivation of zones of weakness within the Precambrian basement during Phanerozoic time.

More specifically, the geological work will study the reservoir itself, the upper and lower seals of the reservoir, and potential leakage channels to overlying formations. Surface geochemical work will seek to identify migration paths to surface; the use of remote sensing techniques to identify the surface expression of fracture systems that may possibly be conduits for gas migration will also be used. Overlying regional aquifers will be examined as possible lateral migration paths within the basin.

An important part of the geological study will be the hydrogeology, examining the fluid chemistry and flows within the basin. This will identify both flow directions and flow rates as well as zones where cross-formational flow occurs. A full understanding of formation mineralogy and the chemistry of the fluids will determine reaction rates and the potential for permanent storage of greenhouse gases that migrate across formational boundaries into adjacent aquifers.

As part of its geological history, it should be noted that this portion of North America was subject to glaciation. Deglaciation occurred some 15-20,000 years ago, leading to a reduction in stress and possible reactivation of structural features in the recent geologic past. From a reservoir perspective, early production and consequent depressuring of the reservoir followed by repressuring with conversion to waterflood in the sixties may have had some impact on the structure within the reservoir and the overlying seal.

Geochemistry:

The geochemical portion of the monitoring project will determine the interactions of the CO₂ with the fluids and rock matrix within the reservoir. Baseline samples have been collected to ensure data availability prior to first injection of CO₂. This will provide the basis against which further sampling and analytic work can be compared.

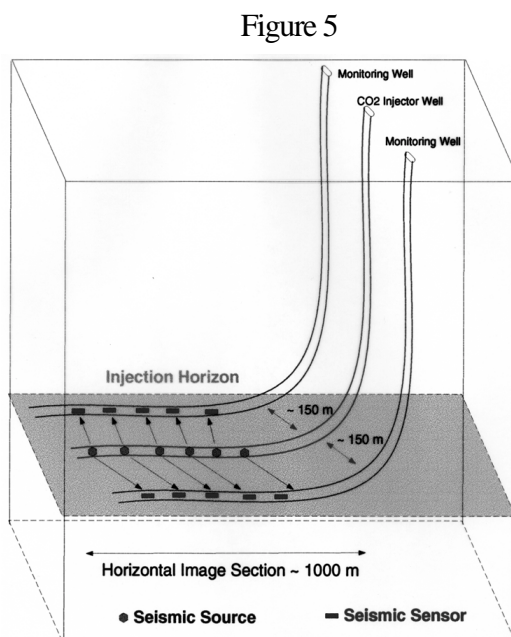
The geochemical analysis will evaluate the isotopic composition of the carbon (as carbon dioxide) stream at the production wells. This will determine the source of the carbon as being from the coal-based new CO₂ supply or as a result of release from the carbonates or fluids in the reservoir. In this way, the carbon will act as a tracer, indicating when the purchased CO₂ arrives at the producing well.

The geochemical analysis will also evaluate the reaction kinetics with reactive minerals in the formation. Both short and long-term reaction kinetics will be evaluated as a means of determining the stability of the CO₂ in the reservoir over the long term. In particular, some of the finer-grained sediments within the reservoir may well provide the mineralogy for more permanent storage of the CO₂ in the reservoir. The information determined by analysis will be used in geochemical simulators for simulation of sequestration stability. Empirical testing will determine surface reaction kinetics with minerals in the reservoir as well as extended, elevated temperature tests in cores taken from the Weyburn reservoir.

The upper reservoir seal, an anhydrite, will be examined and its stability in a changed chemical environment within the reservoir will be determined.

Geophysical Analysis:

As part of the CO₂ Enhanced Oil Recovery project, PanCanadian Resources Ltd., undertook a 3D 3-component geophysical survey of the phase 1 injection area. The intent will be to repeat this survey at intervals in an attempt to use conventional seismic techniques to monitor the CO₂ front in the project area. The challenge is substantial with a relatively thin reservoir (20-27m) at a depth of about 1450m being the target of detailed seismic monitoring. In addition, a smaller area was identified within the Phase 1 area for more detailed analysis. Within this area, a 3D 9-component geophysical survey was undertaken.



Preliminary analysis of the 3D 9-component data has been undertaken, using the compressional (p-wave) seismic data. Data quality from this survey is good, with interpretation possible down to the basement. The coincidence of structural features in the Mississippian with underlying features suggests basement control and periodic reactivation of zones of weakness in the basement. These

structural trends are potentially lines of weakness that could allow for leakage from the reservoir over time. These zones could allow leakage to surface or cross-formational movement of gases.

In addition to the more conventional surface seismic techniques, several other geophysical surveys were undertaken. These include the use of Vertical Seismic Profiling (VSP) from surface to a horizontal well in the reservoir. In addition, cross-well seismic between parallel horizontal wells (figure 5) and single horizontal well seismic programs were also run. It is hoped that these techniques will provide significantly finer resolution within the reservoir and help identify the movement of the CO₂ front in the reservoir.

Risk Assessment:

The ultimate goal of this monitoring and research program is to determine the integrity of the reservoir over an extended period of time. The results of each of the above phases, together with an assessment of possible future land-use changes in the area, will be modeled to determine the long-term storage capacity and integrity.

Currently, reservoirs undergoing CO₂ flooding are monitored only to the extent of optimizing oil recovery. The mechanisms at play in the reservoir, the paths of CO₂ through the reservoir, possible leakage over time, and total storage capacity are not typically studied in these reservoirs. Weyburn offers the only current opportunity to undertake such an extensive study of factors critical to determining storage integrity over time periods of interest to government, regulatory authorities and the public.

Conclusion:

Many of the features of the Weyburn reservoir are unique. The work in the monitoring study is, however, sufficiently generic that the methodology prepared for the risk assessment will be applicable in a broad sense. The monitoring study will also identify the most effective ways of assessing the motion of CO₂ in the reservoir and understanding the optimization of CO₂ storage as opposed to necessarily optimizing oil recovery alone. Understanding CO₂ movement will help to provide the information necessary to develop strategies to improve sweep efficiency within the reservoir. While not discussed in the text of this paper, one of the goals of this study is to study mobility control in the reservoir. Effective injection strategies, including the possible use of mobility control techniques, will improve sweep efficiency and potentially increase the volume of reservoir holding CO₂.

While injection has only just begun, initial indications are that there are no immediate injectivity issues. Prior to injection beginning, it was possible to collect a full suite of geochemical samples for analysis and to undertake a number of geophysical surveys using a variety of techniques. The data quality appear to be good from these programs. When this newly collected data are combined with the existing databanks available in Saskatchewan, it should be possible to determine with some confidence the longer-term consequences of greenhouse gas injection into the subsurface and the integrity of storage.

The conclusion of the study will be an assessment of the integrity of the reservoir and its ability to store CO₂ over the longer-term. The risk analysis will evaluate the potential for leakage, migration paths this leakage may take and future land-use changes that may impact on reservoir integrity.