IEA GREENHOUSE GAS R&D PROGRAMME

CO_2 ENHANCED RECOVERY IN THE WEYBURN OIL FIELD: REPORT OF A WORKSHOP TO DISCUSS MONITORING

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SUMMARY

The Weyburn Oil field is operated by PanCanadian Petroleum and lies on the north western rim of the Williston Basin. It is 16km south east of Weyburn in southern Saskatchewan. Operations of the oil field began in 1954 and currently there are some 650 production and water injection wells in operation. The average daily crude oil production is 3300 m^3 (c. 20700 bbl/d). The Weyburn field produces about 10% of PanCanadian's total oil production. Over its lifetime the field has produced some 54 million m^3 of oil from primary and waterflood production. The field is currently in production decline having produced in excess of 26% of the estimated recoverable oil reserves.

PanCanadian announced in 1997 that it would develop an EOR project to extend the life of the Weyburn field by more than 25 years. The project will involve a CO_2 miscible flood, which is anticipated to extract an additional 122 million barrels or more of oil from the field. In miscible CO_2-EOR, the CO_2 mixes with the crude oil causing it to swell and reduce its viscosity, whilst also increasing or maintaining reservoir pressure. The combination of these processes enables more of the crude oil in the reservoir to flow to the production wells from which it can be recovered. Additional oil recovery of 10 to 15% or more of the original oil in place is often quoted as typical, but actual results vary considerably.

The CO_2 for the project will come from the Great Plains Synfuels plant in Beulah, North Dakota, operated by the Dakota Gasification Co. Construction of a 325-km pipeline, owned by the Dakota Gasification Company, has commenced with completion expected by early 2000. The pipeline will supply 95 million scfd[1] (2.7 million m^3/d) to the Weyburn field. There are a number of key features of this project:

- It involves the cross border transfer of CO_2 from the USA to Canada and so is, essentially, the first time there has been international trading of "physical" CO_2 for the purposes of emissions reduction.

- The CO_2 for the flood comes from fossil fuel use. There are 74 CO_2-EOR projects in the USA. In most cases the CO_2 is taken from natural CO_2 reservoirs such as Shells McElmo Dome field, principally because of its lower supply cost. There are only 4 sites that use anthropogenic CO_2 (from gas processing and fertiliser plants). Their total use accounts for some 13 million m^3 per day. The Weyburn project represents a significant increase in the use of anthropogenic CO_2 for oil production. With the establishment of the CO_2 gas pipeline infrastructure this will lead to an increased use of anthropogenic CO_2 in EOR projects.

The Petroleum Technology Research Centre estimates that 50% of the injected CO_2 will be locked up in the oil that remains in the ground. The other 50% will come to the surface with the produced oil; then it will come out of solution as the pressure drops and will be recovered, compressed and reinjected. In this way, the majority of the CO_2 purchased from Dakota Gasification and used in the project will be permanently stored underground. Over the 20-year lifetime of the project it is expected that some 19 million tonnes of CO_2 will become stored in the Weyburn oil field. In production terms the project will store some 85 m^3 of CO_2 per barrel of oil produced.

The Weyburn CO_2-EOR project provides a unique opportunity for developing an understanding of the way CO_2 is stored underground. By developing the understanding of the fate of CO_2 in the oil

[1] Standard cubic feet per day

reservoir, confidence in CO_2/EOR as a CO_2 storage option can grow. To develop the understanding of the fate of CO_2 in the oil reservoir an extended monitoring programme is required. It is considered that the Weyburn field has a number of key features, which make it an excellent opportunity to consider for a monitoring programme. These features include:

- It is a relatively shallow (1400m) field with excellent accessibility.

- The field has been extensively developed, which has resulted in a comprehensive understanding of the geology of the field and also the presence of numerous observation wells.

To take advantage of this opportunity a workshop was organised by Saskatchewan Energy and Mines, the IEA Greenhouse Gas R&D Programme and the University of Calgary. The workshop was designed to bring together the necessary experts to develop a monitoring programme for the Weyburn field. The workshop was held in Regina, Canada from August 25th to 27th 1999. Fifty-five experts attended to discuss monitoring and research opportunities. Participants in the workshop included representatives from Japan, Netherlands, Norway, USA and, Canada

On the first day of the workshop there was a field tour of the Weyburn oil field to allow the participants to gain an appreciation of the field characteristics. The tour included a presentation on the oil field itself and the planned CO_2-EOR project by field engineering staff from PanCanadian Petroleum, the field's operator. This was a followed by a tour of the field, control centre and oil production satellite facilities. On the morning of the second day, a number of speakers set the context for the workshop discussions through a series of papers, which covered the following topics:

- Canadian and Saskatchewan perspectives in EOR.
- Weyburn oil field geological and reservoir characteristics.
- The Weyburn oil field development history and EOR production plan.
- CO_2 supply to the Weyburn oil field.
- CO_2 EOR in a fractured carbonate reservoir environment.
- Scientific and technical monitoring of EOR.

The rest of the workshop comprised breakout sessions designed to discuss in greater detail the monitoring and research options and to discuss options for taking the project forward. Four expert groups were formed to discuss the monitoring and research options.

It was decided that a proposal for enhanced monitoring would be developed and that both PanCanadian and the participants in the workshop would review it. The Petroleum Technology Research Centre (a Regina based research group) would lead the drafting of this proposal with the input of a number of experts nominated by the workshop. The first draft of the proposal would be ready for discussion at another workshop to be held in Regina on October 5, 1999. The final proposal should be ready by early in 2000. This will then be circulated to potential funders and participants through the IEA Greenhouse Gas R&D Programme and other routes.

CO_2 ENHANCED OIL RECOVERY IN THE WEYBURN OIL FIELD REPORT ON A WORKSHOP TO DISCUSS MONITORING

1. WORKSHOP OBJECTIVE

A workshop was held in Regina, Canada between August 25^{th} -27^{th} to establish a programme for monitoring the CO_2-EOR flood planned for the Weyburn oil field. Fifty-five experts attended the meeting. The objective of the workshop was to identify the monitoring requirements and research priorities that would allow a monitoring and research programme to be developed, so that the potential for CO_2 storage as part of a CO_2 - Enhanced Oil Recovery (EOR) project could be fully understood.

2. BACKGROUND

CO_2 storage underground is attracting considerable interest worldwide as a means of avoiding continued release of CO_2 from anthropogenic sources with its consequences for global climate change.

One underground CO_2 storage project, which is now underway, is the Sleipner project in the North Sea. This is the world's first commercial-scale CO_2 storage project, has now been operating for over 3 years with in excess of two million tonnes of CO_2 now stored underground. The Sleipner West field, which is in the Norwegian sector of the North Sea, began production in 1996. The licensees of the field are Statoil (operator), Esso Norge, Norsk Hydro and Elf Petroleum Norge. A feature of the natural gas from the Sleipner West field is that it contains about 9% CO_2. This must be reduced to 2.5% for commercial sale. CO_2 is stripped from the natural gas in an amine scrubbing plant and then injected into a saline water bearing structure, known as the Utsira formation. The Utsira formation is a sand formation about 800 metres below the seabed.

As part of this activity, and to monitor the storage of CO_2, a demonstration project called the Saline Aquifer Carbon Dioxide Storage (SACS) project was established. The monitoring exercise, which is now underway, aims to determine the fate of the stored CO_2. The monitoring activity will include a series of seismic surveys of the Utsira formation, to determine how the CO_2 bubble is developing in the deep saline reservoir. The monitoring and research programmes for the Sleipner/SACS projects were developed at a workshop held in Trondheim in November 1997. The Trondheim workshop was organised by IEA Greenhouse R&D Programme (IEA GHG) and Statoil. Since the initial workshop, IEA GHG has played an active role in the SACS project and is disseminating the results of the project via its web page, newsletter and conference organisation activities.

An alternative option to CO_2 storage in underground reservoirs is CO_2 injection into an oil reservoir. This option has the potential to enhance oil recovery whilst also storing a significant proportion of the injected CO_2 underground. CO_2-EOR can be either miscible or immiscible depending primarily on the pressure of the injection gas into the reservoir. In miscible CO_2-EOR, the CO_2 mixes with the crude oil causing it to swell and reduce its viscosity, whilst also increasing or maintaining reservoir pressure. The combination of these processes enables more of the crude oil in the reservoir to flow freely to the production wells from which it can be recovered. Additional oil recovery of 10 to 15% or more of the original oil in place is often quoted as typical but actual results vary considerably. In immiscible CO_2-EOR, the CO_2 is used to re-pressure the reservoir and as a sweep gas, to move the oil towards the production well (see Figure 1 overleaf). A side benefit of CO_2 injection is that the CO_2 preferentially mobilises the lighter fractions of the oil, which slightly improves the quality of the produced oil.

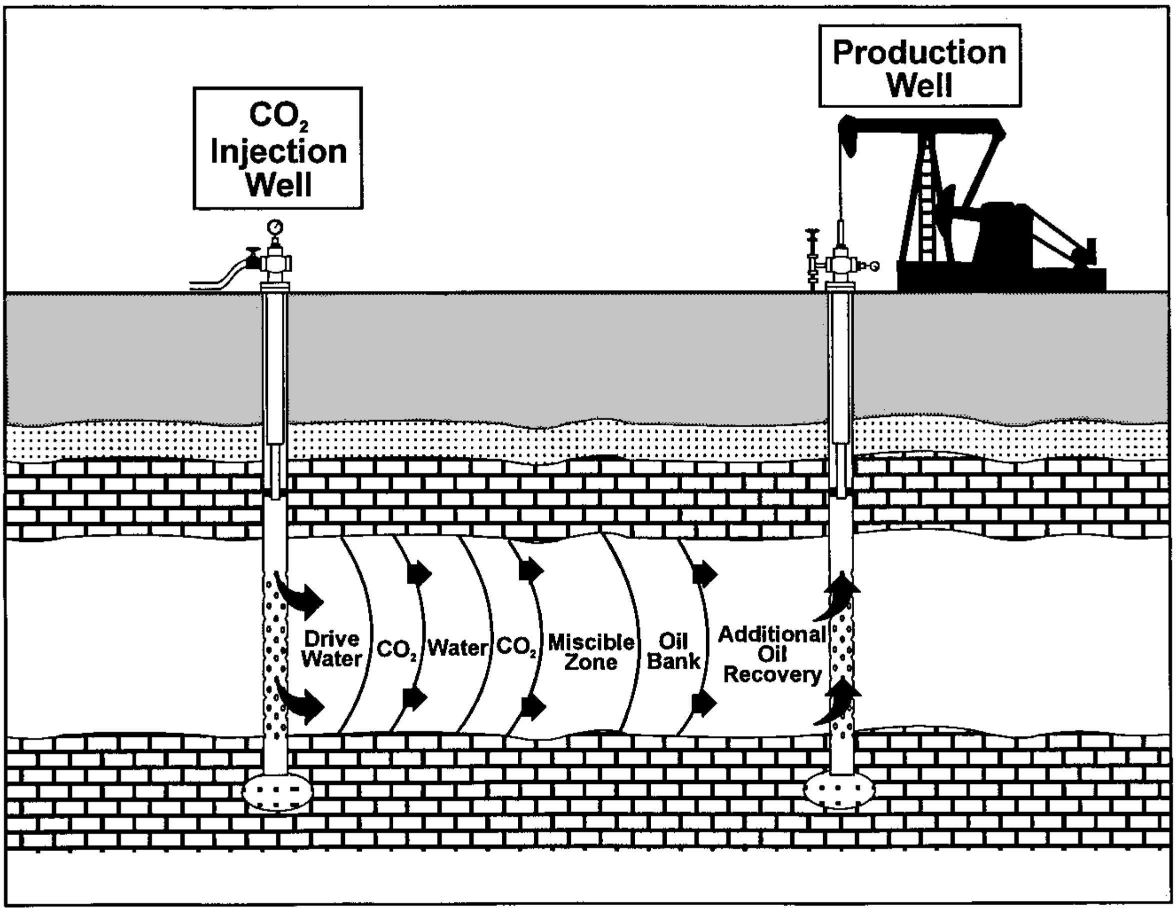

Figure 1 Schematic Diagram of a Miscible CO_2-EOR Flood

CO_2-EOR has been used extensively in the USA, with some 74 projects now operating. Most of the CO_2 comes from natural underground sources rather than from fossil fuel use. Also, most CO_2-EOR projects undertaken to date have been designed to minimise CO_2 losses in the reservoir since such losses represent an additional production cost. However, it is expected that interest in storing CO_2 as an integral part of the EOR process will develop in the future. If this is the case, there will be a need to determine how much CO_2 can be stored and the relative merits of storage versus enhanced oil production. In addition, the fate of the stored CO_2 will need to be determined.

The Weyburn field CO_2-EOR project offers an excellent opportunity to study the fate of the injected CO_2 and the benefits/disadvantages of storage over EOR in a field scale trial. Like the Sleipner project the Weyburn project offers an excellent opportunity to validate theory with practice and will be of interest to a great many organisations involved in this area of work.

For this reason the IEA GHG were pleased to be asked to be involved in the organisation of this workshop in co-operation with Saskatchewan Energy and Mines and the University of Calgary. IEA GHG brings experience from the Trondheim meeting and the SACS project to benefit the development of the Weyburn Monitoring Project.

3. THE WEYBURN MONITORING WORKSHOP

The Weyburn Monitoring workshop was held in Regina, Canada between August 25th- 27th. Fifty-five experts attended the workshop to discuss the monitoring and research opportunities. The list of attendees is given in Annex 1.

The first day of the workshop included a field tour of the Weyburn project area and a discussion of the project with field engineering staff from PanCanadian Petroleum (PanCanadian), the oil field operator.

The workshop itself began on Day 2, with a plenary session involving presentations on the Weyburn field, the CO_2 supply, and on scientific and technical aspects of monitoring. These presentations also included a description of the IEA GHG Programme by its Chairman, Kelly Thambimuthu. The rest of the workshop consisted of breakout sessions designed to discuss in greater detail the monitoring and research options and to develop the route forward. Four expert groups were formed to discuss the monitoring and research options.

3.1 Weyburn Field Tour

The workshop delegates were taken by bus from Regina to the Weyburn oil field and were given an overview of the oil fields geological and operational characteristics. In addition, the delegates were able to view the oil production and treatment facilities at the field satellites[2], the operations control centre and oil separation and treatment plants.

The Weyburn Oil field is operated by PanCanadian and lies on the northwestern rim of the Williston Basin. It is 16km south east of Weyburn in southern Saskatchewan (see Figure 2)

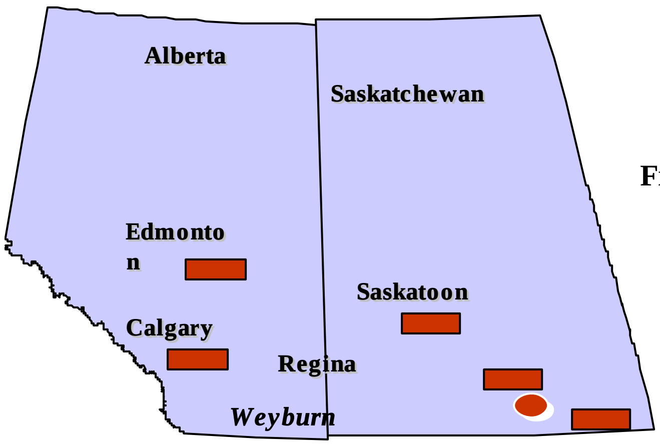

Figure 2 Schematic of Weyburn field Position in Canada

Operations of the field began in 1954, currently there are some 650 production and water injection wells in operation. The average daily crude oil production is 3300 m^3 (c. 20700 bbl/d). The associated gas from the crude oil production is separated, compressed and sent to a nearby plant at Steelman for processing. The treated crude oil enters a large market in eastern Canada and the northeastern USA. Inter-provincial pipelines carry oil from the Weyburn field to these markets. PanCanadian is the second largest oil and gas producer in Canada with annual sales of some $3 billion. The Weyburn field produces about 10% of PanCanadian's total oil production.

A review of the Weyburn Oil field, as presented to the delegates, is given in Annex 2.

[2] Several production wells serve small automatic treatment plants termed "satellites" which undertake primary treatment of the oil before it passes to the central treatment plant.

3.2 CO_2 EOR in the Weyburn field

PanCanadian announced in 1997 that it would develop an EOR project to extend the life of the Weyburn field by more than 25 years. The project will involve a CO_2 miscible flood, which is anticipated to extract an additional 122 million barrels or more of oil from the field. The CO_2 for the project will come from the Great Plains Synfuels plant in Beulah, North Dakota, operated by the Dakota Gasification Co. Construction of a 325-km pipeline, owned by the Dakota Gasification Company, has commenced with completion expected by early 2000. The pipeline will supply 95 million scfd[3] (2.7 million m^3/d) to the Weyburn field.

One unique feature of the Weyburn project is that it involves the cross border transfer of CO_2 from the USA to Canada. Whilst there are emissions trading projects being developed within countries such as Canada, the Weyburn project is essentially the first international project where physical quantities of CO_2 are traded for purposes of reducing climate change. The volume of CO_2 stored will be applied against the national accounts of the US and Canada, based on an agreement reached between Dakota Gasification and PanCanadian for volume sharing.

Another key feature of this project is that the CO_2 comes from fossil fuel use. There are 74 CO_2-EOR projects in the USA (see Figure 3 below). In most of these cases the CO_2 is taken from natural CO_2 reservoirs such as Shells McElmo Dome field, principally because of its lower supply cost. There are only 4 sites that use anthropogenic CO_2, taken from gas processing and fertiliser plants, accounting for some 13 million m^3 of anthropogenic CO_2 per day.

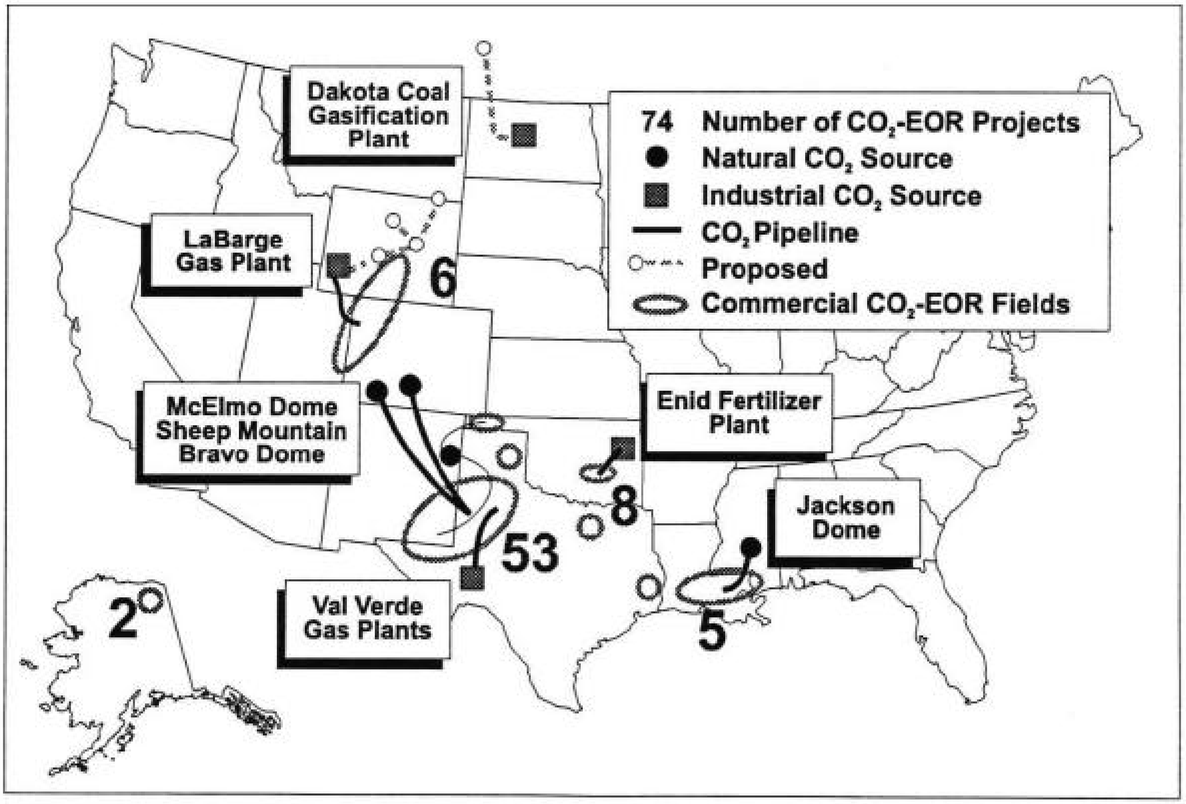

Figure 3 Commercial CO_2-EOR Projects in the USA.

The Weyburn project represents a significant increase in the use of anthropogenic CO_2 for oil production. With the establishment of the CO_2 gas pipeline infrastructure it is hoped that this will lead to an increased use of anthropogenic CO_2 in EOR projects in both the USA and Canada. The Petroleum Technology Research Centre estimates that 50% of the injected CO_2 will be locked up in

[3] Million standard cubic feet per day

the oil that remains in the ground. The other 50% will come to the surface with the produced oil, where it will come out of solution as the pressure drops and be recovered, compressed and reinjected. In this way, the majority of the CO_2 purchased from Dakota Gasification will be permanently stored underground. Over the 20-year lifetime of the project it is expected that some 19 million tonnes of CO_2 will become stored in the Weyburn oil field. In production terms the project will store some 85 m^3 of CO_2 per barrel of oil produced.

Detailed geological and reservoir simulation models of the Weyburn unit have been constructed to quantify the increased oil recovery from the injection of CO_2 into the oil-bearing rock. These models predict increased recovery from 13 to 19% as a result of CO_2 injection into production patterns covering approximately half of the surface area of the reservoir. These estimated recoveries are consistent with US floods where 15 to 25% of the original oil can be recovered by contact with a miscible fluid. The viability of a CO_2 flood in areas of the Weyburn field, or any other reservoir, is dependent on the following general conditions:

- The reservoir is continuous and is well sealed to prevent excessive solvent losses to other zones.
- The oil is miscible with CO_2 at acceptable and achievable operating pressures (if the pressure required for miscibility is too high there is a risk of exceeding the fracture pressure of the rock; fractures allow the CO_2 to bypass the trapped oil).
- The existing waterflood has managed to successfully maintain pressures so that significant quantities of CO_2 are not required to re-pressure the reservoir to attain miscibility (water is a considerably cheaper fluid for pressure maintenance than CO_2).
- The oil swells as CO_2 becomes miscible with it and the viscosity is reduced.
- The spacing between wells is optimised by in-fill drilling to allow efficient use of the CO_2 and to maintain effective flood control.

The Weyburn CO_2 Flood is designed to optimise the volumes of CO_2 required to produce the oil, since CO_2 represents the largest operating cost component of the project. Water is injected alternately with slugs of CO_2 to maintain reservoir pressure and push oil towards the production well. Under current waterflood recovery, it is estimated that approximately 30% of the oil would be recovered from the reservoir as shown in Table 1.

Table 1 History of Weyburn Unit

Discovered : 1954 Area: 52,000 acres Current Oil Rate: 3,067 m^3/d Number of active Wells: 963 total 534 vertical oil wells 138 horizontal oil wells (285 legs) 171 injection system	Sour Crude: 25-34º API[4] Low GOR[5]: 2% H_2S Depth: 1,400 m OOIP[6]: 223 million m^3 Cum. Prod. (12/98) 53.5 million m^3 Ultimate Waterflood Recovery: 30%

Enhanced oil recovery will add an incremental 19 million m^3 or more from the 75 patterns[7] that will be flooded over about 20 – 25 years. Ultimate oil recovery will increase to 34%. Enhanced oil recovery will, therefore, add substantially to the life of a field discovered in 1954 and currently in decline under waterflood production.

[4] Measured to American Petroleum Institute standard.
[5] Gas Oil Ratio
[6] Original oil in place.
[7] A pattern typically refers to a configuration of wells that is repeated across the field; for example you can have a five spot pattern which would which will include one injector in the centre and four producers in the corner locations.

Many of the oil fields in the Williston Basin, and indeed other sedimentary basins in the world, could use this EOR technique, substantially increasing the amount of greenhouse gas that could be sequestered. Capital requirements have been a major impediment to the use of CO_2 flooding. Recently, with the advent of new and improved drilling techniques and the extensive use of horizontal wells, the capital required for implementation of CO_2 EOR has been reduced by about 25% thus making it economically viable for some fields. In the specific case of the Weyburn Field, horizontal infill drilling has proved to be a profitable activity. Horizontal wells are drilled because of their incremental production under waterflood, rather than becoming part of the cost of the enhanced oil recovery project. In addition, the improved reservoir contact and sweep efficiency created by extensive horizontal drilling in the target area of the Weyburn Field makes enhanced oil recovery more predictable and more efficient, further improving the economics and reducing the risk involved in undertaking an expensive project

3.3 Plenary Session

The plenary session of the meeting consisted of a welcoming address by Malcolm Wilson of Saskatchewan Energy and Mines, who had been instrumental in bringing about the workshop. He was followed by Kelly Thambimuthu, Chairman of the IEA Greenhouse Gas R&D Programme, who gave a description of the IEA GHG Programme, described the Programme's purpose and intent, and discussed its possible role in projects such as this one.

These presentations were then followed by a series of papers, which are summarised below:

Canadian and Saskatchewan Perspectives on Enhanced Oil Recovery (Joint paper by Bruce Stewart of Natural Resources Canada and Roland Moberg of PTRC[8]). The presentation outlined the importance of the Weyburn CO_2-EOR project to Canada and emphasised the need to understand the process of geological storage of CO_2. Whilst, currently, CO_2-EOR projects aim to minimise gas losses (i.e. CO_2 storage underground), in the future this situation might change and CO_2 storage might be of benefit to project economics. The project is planned to have a 25-year life. What starts out now as an oil production project could end up as a CO_2 storage project.

Saskatchewan has considerable expertise in CO_2-EOR modelling and technical experience through the PTRC, a consortium of the University of Regina and Saskatchewan Research Council. All these capabilities are close to the proposed Weyburn CO_2-EOR project and are well placed to support the monitoring activity.

A detailed overview of the **Geological Conditions of the Williston Basin** in Southern Saskatchewan was given by a series of presentations by Chris Gilboy of Saskatchewan Energy and Mines, Julie Lefever of the North Dakota Geological Survey and Ben Rostron of the University of Calgary. The papers reviewed the geological conditions that led to the formation of the Weyburn oil field and reviewed the strata characteristics that comprise the Williston Basin as it is today.

Ray Hattenbach of the Dakota Gasification Company presented the next paper on **CO_2 Supply.** The paper outlined the details of the Great Plains Synfuels Plant owned by the Dakota Gasification Company. The plant, which is the first commercial, coal-fired synthetic fuels plant in the USA, began operation in 1984. The plant converts 184,000 tons of lignite into 3.54 million m^3 per day (125 MMscfd[9]) of pipeline quality SNG[10]. The plant also produces 1000 ST[11] of anhydrous ammonia and other chemical by-products.

[8] Petroleum Technology Research Centre
[9] Million standard cubic feet per day
[10] Synthetic Natural Gas
[11] Short tons

The plant is based on of Lurgi gasifiers that gasifier the lignite using oxygen and steam. The raw gas produced from the gasifiers is cooled, cleaned and then undergoes shift conversion followed by purification in a Rectisol plant. The clean purified fuel gas is then dried and compressed and dispatched from the plant via a pipeline for subsequent use. The Rectisol plant waste gas, which is rich in CO_2, is then dehydrated and compressed ready for entry into the CO_2 pipeline. The pipeline will be sized to handle the full flow from the plant (6.79 million m^3 per day that is 240 MMscfd). The pipeline will deliver some 95 MMscfd (2.83 million m^3 per day) of CO_2 to the Weyburn field; the remaining capacity will be available for use in other oil fields in Montana, Dakota and Southern Saskatchewan (Figure 4).

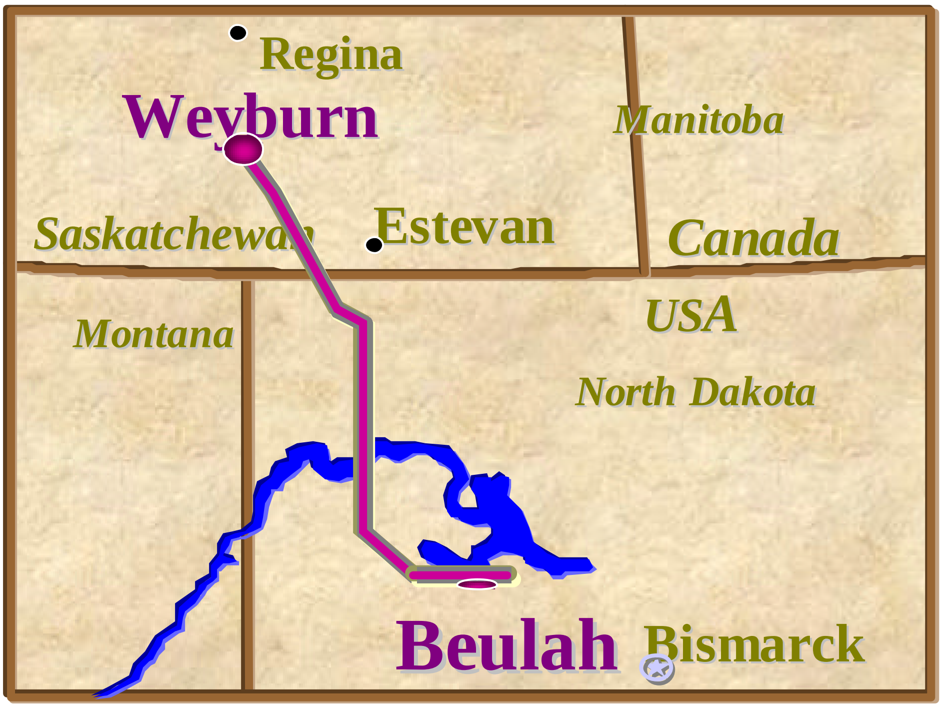

Figure 4. Schematic diagram of CO_2 pipeline to the Weyburn oil field from North Dakota
(Courtesy of PanCanadian)

Ken Brown and Sandy Graham of PanCanadian presented details of the **Weyburn Field Geological and Reservoir Characteristics.** Initial production (1955) involved the use of waterflood, which was followed by incremental vertical and horizontal well production to boost failing production starting in 1985 and 1995 respectively.

The main geological formations of the field were presented as well as typical well patterns used during the history of the field.

At the Weyburn field CO_2 will be injected into the permeable oil bearing rock strata through vertical and horizontal wells. The CO_2 is expected to migrate upwards, into the less permeable rock strata (the Marly), which has not been swept by the water flood. Water will then be injected through vertical wells to force the oil to the horizontal producer wells and help maintain reservoir pressure. Various options, such as CO_2 injection followed by water injection and combined CO_2/water injection, will be tested.

Ken Brown then continued with a presentation on the **Weyburn Development History and EOR Production plan**. PanCanadian carried out an extensive 5-year project evaluation before their announcement to proceed with the CO_2-EOR project. This evaluation included a study on Texan flood projects, a pilot and demonstration project at the Shell Midale Unit and a full facilities design. The evaluation also included extensive consultation with the Provincial government on the tax and royalty structure for the project, the owners of working interests in the field and an assessment of CO_2 supply options. Dakota Gasification was selected after a competitive tendering exercise with potential CO_2 suppliers. He summarised the status of the project as follows:

- Dakota Gasification Company is in the process of constructing the pipeline and installing the compressors, with completion expected by mid 2000.
- Pan Canadian had commenced the first phase of the development drilling programme
- Installation of the support facilities had also commenced.
- A consortium led by Colorado School of Mines will shoot a baseline 4D seismic survey. Later seismic shoots will allow, it is hoped, the CO_2 flood front to be monitored.
- In addition, PanCanadian had designed a tracer study to monitor CO_2 transmission in the reservoir.

The project was on target to begin CO_2 injection on 1st October 2000 but PanCanadian expected that the project could commence earlier.

Based on modelling studies, PanCanadian expect a boost in production of 15 000bbl/d[12] due to the miscible flood, with production peaking at 35 000bbl/d in 2009.

Two further papers were then presented by PTRC. The first was by Sam Huang on **CO_2 EOR in a Fractured Carbonate Reservoir Environment.** The paper summarised the benefits of CO_2 injection, and raised a series of questions about implementation. These questions included: what CO_2 injection pressure should be used, what purity of CO_2 was needed, what operating conditions should be used and how will rock fractures affect the CO_2 front in the reservoir Sam Huang then outlined the results of modelling studies undertaken to answer these questions. His main conclusions were that, in the Weyburn situation, the oil recovery potential looked promising even if the field was operated at near-miscible conditions as opposed to fully miscible conditions. Oil recovery would be sensitive to CO_2 flow rate and more detailed 2D and 3D modelling were needed to optimise CO_2 flowrates. He also noted that the incremental oil recovery with CO_2 injection was expected to be significant.

In the final plenary paper, Rafiq Islam of PTRC presented a review of **Scientific and Technical Monitoring of EOR**, examining the benefits that monitoring of the project could provide. Rafiq reviewed monitoring techniques that were available, including 4-D seismic and the use of permanent downhole seismic sensors. Emerging techniques included, electrical resistivity tomography, electromagnetics, ultrasound for local imaging, sound for wellbore fluid injection monitoring and laser/infra red for near wellbore monitoring.

Copies of those papers available at the workshop are given in Annex 3.

3.3 Results from the Breakout Groups

The delegates at the workshop were divided into 4 working groups covering the following areas:

- Measurement/Monitoring of Surface Activities - facilitator, Chris Wimmer , Saskatchewan Energy and Mines

- Subsurface Measurements - due to popularity this group was further divided into two subgroups. The first sub group was facilitated by Howard Loseth of SEM[13], the second by Larry Lechner of Saskatchewan Environment and Resource Management.

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[12] Barrels per day
[13] Saskatchewan Energy and Mines

- EOR/Sequestration Strategy - facilitator, Roland Moberg of PTRC.

Each group was given a series of questions to address. In addition, the groups were asked to discuss the organisational structure of the proposed project. It was considered to be important to design a program that would allow broad participation as well as providing useful information to all participants including the field operator, PanCanadian. The key additional questions to be considered included:

1. Who should participate?
2. Who will pay?
3. What do different partners want from the project?
4. Who will be project operator and how will the operator interact with PanCanadian?
5. What will be the role of the CO_2 supplier?
6. What will be the role and contribution of the IEA Greenhouse Gas R&D Programme?

Each group reported its findings to a plenary session (the findings of both sub-groups on sub-surface were collated). After discussion, an outline plan was developed for taking the monitoring project forward.

The findings of each working group are summarised below.

Working Group 1 - Measurement/Monitoring of Surface Activities

The objective of this working group was to address the fluid/gas inputs and outputs from the field, for example, CO_2 quality and quantity, water quality, oil analysis. The group agreed at the outset that a complete CO_2 mass balance needed to be developed of sufficient accuracy to allow the fate of CO_2 to be determined.

The group based its discussions on the following questions:

1. What are the input streams, how should they be measured and analysed (including frequency and accuracy of measurements)?
2. What are the output streams – how should they be measured and analysed (including frequency and accuracy of measurements)?
3. How does the measurement accuracy of the CO_2 input and the CO_2 output from the field associated with the oil produced compare, including any losses from the gas capture and recycle? This is a key to verification of storage.
4. What are the costs, sampling frequencies, sizes of samples, etc?

As prelude to the main discussions Ken Brown of PanCanadian outlined the monitoring programme that they intended to put in place. This input from PanCanadian was considered necessary to guide the work group's subsequent discussions. It was noted that the PanCanadian's monitoring programme had been designed to meet the field operator's needs, in terms of monitoring the production from the field as well as monitoring usage rates of water and CO_2 for contractual purposes. PanCanadian would undertake all measurements in accordance with the necessary industry standards; this could give a mass balance accuracy of no better than $^{+}/_{-}$ 10%. There was considerable discussion with regard to the accuracy requirements for the mass balance. It was concluded that to improve the accuracy significantly would require considerable additional cost and impact heavily on PanCanadian's activities. It was decided to leave this discussion until the final programme had been developed and then reconsider the issue of accuracy with Pan Canadian at that time.

The main input and output requirements were identified for the CO_2 mass balance. Those already covered by the PanCanadian monitoring programme were determined, which then served to identify those additional measurements that were required.

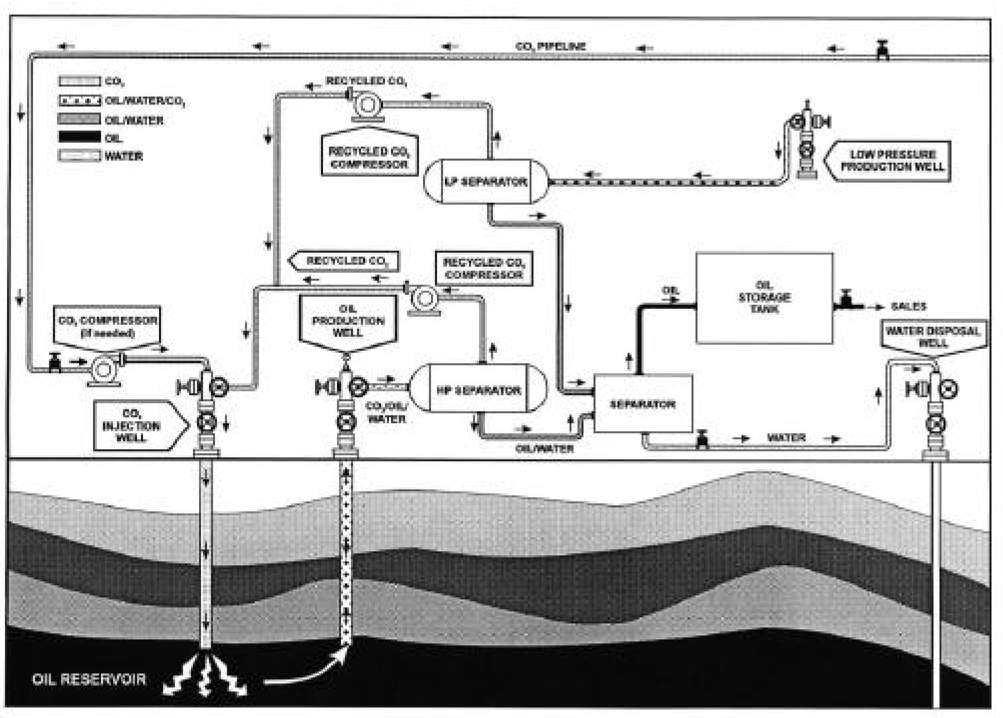

Figure 5 Typical CO_2-EOR Field Operation.

The input and output data included in the PanCanadian monitoring programme included:

<u>Inputs:</u>

1. CO_2

- Quality and volume of CO_2 supplied by DGC[14] measured for contractual reasons - continuous on-line analysis.

2. Water

- Some water chemistry data will be available
- Individual wellhead testing at satellites[15] will be undertaken to perform pattern mass balance

[14] Dakota Gasification Company
[15] A satellite refers to a facility where a number of flowlines come together for measurement of fluid rates and composition; typically you have a test and group test separator plus a bunch of switching valves to control the flow; these satellites can be managed either manually or be fully automated.

- Water injection rates will be monitored.

Outputs:

- All gas re-injected will be measured

The main additional requirements noted were:

- Pan Canadian were not monitoring closely the water chemistry in the field - this was considered essential to close the mass balance, since a significant proportion of the CO_2 may be present in the water.
- The gas and oil composition of the product needs to be measured.
- Solids monitoring needs to be undertaken at the treatment modules.
- The asphaltene content of the oil needs to be measured.

It was decided that sampling could be undertaken at representative patterns rather than over the whole field.

A main conclusion of the working group was that a baseline sampling exercise should be put in place as soon as possible to gain representative baseline data from the field before CO_2 injection begins. At this stage, this exercise could merely be an archiving process to allow subsequent data analysis to occur. Consideration, therefore, needs to be given to establishing a sample archive somewhere close to the field. Detailed consideration would need to be given to the sample storage procedures for each of the samples to be collected.

Other monitoring activities, to supplement the mass balance, included:

- 4D seismic
- Instrumentation of non-active wells (geophones, hydrophones)
- Passive seismic in abandoned wells
- Other sensing devices including, FHC[16] tracers, Doppler radar devices and placement of receivers to monitor the 3D seismic pulses were considered. Expansion/subsidence of the site was discussed as a possible monitoring tool
- Use of tracers, to tag the CO_2/water.
- Monitoring of nitrogen build up in the recycle gas.

Most of these techniques were discussed in more detail in Group 2.

[16] Flouro Hydrocarbon (FHC) tracers are generally used in secondary and tertiary oil recovery projects as a means of quantifying sweep efficiency and reservoir heterogeneity. They are relatively easy to measure accurately and at low concentrations using gas chromatography. Typically, a known quantity is injected in the injection during water or CO_2 injection well and then all of the surrounding production wells are monitored. The length of time before the tracer is detected, the concentrations, and the change in concentration profile with respect to time all yield information about the flow paths in the reservoir.

Working Group 2 - Subsurface Measurements

The group was asked to address how and where the CO_2 is stored in the reservoir.

The key questions to be addressed were:

1. Availability of baseline subsurface data? - Obtaining new baseline data required and avoidance of possible conflicts with the field operator.

2. Reservoir modelling - what model will be used? How will it be done and by whom?

3. Monitoring/modelling of physical and chemical reactions in the reservoir, including identification and verification? What measurement accuracy can be expected?

4. What remote sensing methods will be used? This is important for understanding storage and reservoir changes.

5. Are there intrusive sensors/tracers or other measurement options that should be considered?

6. What are the costs, sampling requirements, etc?

The group considered that the major task of the monitoring programme was to observe the expanding CO_2 interface. Monitoring was important in order to validate the computer simulations. Regular monitoring of the CO_2 storage operation would serve two purposes:

1) to confirm that CO_2 used for EOR is a safe and reliable CO_2 mitigation option

2) To supply data to validate reservoir simulation models which will be essential in planning future CO_2 EOR projects including where CO_2 storage is an integral part of the project.

The group concluded that one of the advantages of the Weyburn project was the wealth of data that is already available. The existing information that could be used to determine the present boundary conditions is as follows:

- Core samples - Extensive core material is available through SEM[17]. PanCanadian also has this data, as well as interpretations from the core analysis.

- Logs - Extensive well logs are also available from the SEM well files. As this field has been developed since the 1950s, the value of some of the old logs is questionable.

- Production data - Production data is available from SEM, or PanCanadian production accounting.

- Seismic - 2D and 3D seismic is available from PanCanadian. The seismic data is 3 or 4 years old. Interpretation of the data may be proprietary to PanCanadian.

- Fluid Samples - Fluid samples are available, particularly for oil, including API gravity and PVT analysis

- Pressures - Static reservoir pressure data is required to determine the pressure distribution throughout the reservoir.

- Geological Modelling - Modelling has been carried both in-house at PanCanadian and for PanCanadian by consultants. PanCanadian has spent a large amount of time and money

[17] Saskatchewan Energy and Mines

developing the models. While the data that is fed into the models is available in the public domain, the interpretation of the data in the model is proprietary to PanCanadian.

As discussed in Group 1, PanCanadian will have adequate data regarding the CO_2 volumes being injected into the reservoir and the volumes of CO_2 being produced once breakthrough occurs at producing wells. They would like a more proactive method of monitoring the flood front. Currently, PanCanadian plans to monitor the flood front by running 4D seismic on only two of the patterns (due to significant cost).

Figure 6 Production Wells on the Weyburn Oil Field.
(Courtesy of PanCanadian)

Monitoring should determine where the CO_2 front is, if any CO_2 is leaking out of the project area, and the coverage in the reservoir (conformance). Data from the injectors and production wells can be used in a material balance calculation for the reservoir. The volume of CO_2 injected minus the volume of CO_2 produced will give an indication of the amount of CO_2 that stays in the reservoir. The monitoring program should describe what is happening inside the reservoir.

In order to describe what is happening in the reservoir, a good definition of the conditions present in the reservoir prior to CO_2 injection is necessary. As indicated in the previous section, much of this information is currently available. The main area of information that may be lacking is an analysis of the current fluid conditions in the reservoir, particularly water (See Group 1 discussions).

In designing the 4D seismic, consideration should be given to permanently installed geophones. If seismic equipment changes significantly, mathematical matching would be an option. Some permanent downhole equipment could be installed, particularly in vertical wells due for abandonment and horizontal wells that are not scheduled to remain in use as part of the project. Cross well seismic was also thought to be worth considering.

The Group concluded that there might be some limitations to the applicability of the seismic techniques. There would be a small density difference between supercritical CO_2 and water that may make definition of the interface difficult. The reservoir may not be thick enough to provide sufficient detail. 4D seismic will only give aereal distribution; other mechanisms will need to be applied for vertical definition of the flood front. Therefore, there may be some merit in running 3D seismic before the 4D seismic program begins to get better vertical definition In addition, verification of geophysical characteristics through drilling, sampling and testing would help define a proper 4D program.

The CO_2 is delivered at high pressure but relatively low temperature, typically at a lower temperature than the temperature of the reservoir. There will be heat transfer from the reservoir to the CO_2. This factor must be incorporated into the model. The temperatures could be monitored by thermocouples installed downhole.

The CO_2 will interact with the oil, the water and potentially the rock. The reaction is typically more important for dolomite than limestone. Both dolomite and limestone are present in the oil field strata. The nature of these interactions needs to be established. The CO_2/carbonate chemistry related to this reservoir should be investigated through baseline chemical analysis. The CO_2 may cause dissolution of the reservoir rock, releasing fines that may lead to plugging. Scaling may also be an issue.

Bottomhole fluid sampling should be used in order to establish whether the CO_2 is travelling with the oil or the water. In addition, the samples may reveal the production of oil from previously unswept portions of the reservoir.

A significant portion of the group's time was spent discussing modelling the reservoir. The selection of an appropriate model will depend on the data available. Mineralogical data already available is likely sufficient to establish that part of the model. The model would be used to detect trends and predict changes in the reservoir. Future sampling (preferably downhole) would be used to verify the predictions. Water chemical data should be inserted in the model to interpret the reactions occurring in the reservoir as a function of time. The goal of the model design effort would be to develop a fully coupled fluid flow and geochemical model.

As the Weyburn project is quite large, perhaps a detailed study of a small area would be appropriate. An obvious choice would be the same two patterns that PanCanadian plans to use for the 4D seismic.

The sequestration portion of the project received significantly less attention in the group discussions. During the relatively short time required for the CO_2 flood (relative to geological time scales), the CO_2 reactions with the reservoir will not be as advanced as they would be over the longer term. The issue for sequestration relates to the tendency of the CO_2 to remain in the reservoir. CO_2 could migrate vertically through the rock as a gas, or as a result of casing leaks, so monitoring upper formations may be necessary. CO_2 may travel in the water and be carried out of the immediate project area.

Working Group 3 - EOR/Sequestration Strategy

The group needs to identify project balance between understanding EOR and the optimisation of oil recovery and CO_2 sequestration.

The key questions the group was asked to consider were:

1. Will the results be adequate to evaluate CO_2 storage as a priority outcome in the future?

2. What is the impact of maximising CO_2 sequestration on oil production and vice versa?

3. How would injection strategies change if CO_2 took on a real or implied value, what is the sensitivity of production/injection strategy to implied CO_2 price?

4. Will the result allow us to determine the long-term fate of CO_2 in the reservoir?

5. What is the role of bottom water in CO_2 sequestration?

The main conclusions from the group to the questions posed were:

1. **Will the results be adequate to evaluate CO_2 storage as a priority outcome in the future?**

   It is likely that the Weyburn monitoring project will, at least in a gross sense, determine the amount of CO_2 that can be stored in the reservoir. Clearly, this is a long-term process given that the CO_2 flood will be carried out over 25 years. When individual patterns are completed early on some indication of the answer should be available.

2. **What is the impact of maximising CO_2 sequestration on oil production and vice versa?**

   For any given area of the reservoir it is very unlikely that the operator would be able to maximise both the oil recovery and the amount of CO_2 that was sequestered. One way to deal with this conflict would be to differentiate between these objectives and carry out a pilot to learn as much as possible about CO_2 sequestration on a smaller scale.

3. **How would injection strategies change if CO_2 took on a real or implied value, what is the sensitivity of production/injection strategy to implied CO_2 price?**

   It was not clear that, if CO_2 sequestration took on an implied value, the economic optimisation of the Weyburn field would change to accommodate this. PanCanadian the field operator had not considered the future potential for CO_2 storage. All their economic analyses were based on increased oil production. As the licensor and operator of an oil field their primary interest was oil production as long as there was economically extractable oil to be produced. Obviously, the potential future value of CO_2 would determine how far the operator would go in sacrificing oil recovery for increased CO_2 sequestration. It was considered that in the absence of a regulatory or fiscal regime that Pan Canadian would not consider storage as a commercial exercise. Any CO_2 storage credits must exceed the revenue that could be gained from oil production and compensate for any additional field activities (such as well capping etc.,) that may be necessary to seal the field for CO_2 storage.

4. **Will the result allow us to determine the long-term fate of CO_2 in the reservoir?**

   It was considered likely that the CO_2 for the Weyburn field will stay within that geological structure given the existing trapping mechanism. However, if the project eventually was converted to a CO_2 sequestration project, there is a low likelihood that future generations could see carbonated water in Lake Winnipeg a few million years from now.

5. **What is the role of bottom water in CO_2 sequestration?**

   Recent work by SRC[18] indicates that significant volumes of CO_2 could be stored in bottom water reservoirs in Saskatchewan. The amount of CO_2 that can be stored depends on such factors as temperature, pressure, salinity, and impurities in the CO_2 stream.

At the final plenary session the facilitators for each working group presented the feedback from the four working groups on the additional questions. The consensus opinion was:

Who should participate? - Universities and other Canadian Governmental and Federal research bodies, interested research parties (US DOE, IEA GHG), other interested industrial parties. It was noted there could be potential conflicts of interest between the industrial partners and the field operator.

Who will pay? - Governments, research participants (cash or in-kind), industrial partners

[18] Saskatchewan Research Council

Figure 7 Oil Collection from Producer Wells at Central Automatic Treatment Satellite on Weyburn Field
(Courtesy of PanCanadian)

What do different partners want from the project?

It was considered that the answer to this question varied depending on the type of organisation involved. For instance:

- Governments could be looking for guidance for policy, information on what are the practical limits of CO_2 sequestration, verification of actual CO_2 sequestration i.e. is it permanently stored and what are the social costs, as well as job creation opportunities. All these points would be needed to gain the public to approval of the technique, to answer the questions such as is it safe and environmentally sound?

- Research institutions will be looking for contracts, opportunities for the development of expertise and credibility, opportunities to develop proprietary technology

- Industry could be looking for competitive advantage, proprietary knowledge, access to data to apply to their own fields and opportunities to develop marginal resources

- PanCanadian on the other hand will be looking to make profit from their investment, develop corporate expertise in the areas of CO_2 flooding and sequestration, gain additional information plus additional manpower to speed up the learning process. In addition, they would be looking for no-hassle monitoring, no additional costs, and minimum interference in the operation of the CO_2 flood and not to give away any competitor advantage freely or cheaply. The knowledge could be used by PanCanadian to improve later phases of the project, expand the project and to enter new EOR projects in the future.

- Dakota Gasification will be looking for publicity on the success of the CO_2-EOR project to fully utilize the capacity of their CO_2 supply system

Who will be project operator and how will the operator interact with PanCanadian?

It was concluded that the project operator should be PTRC who need to establish an early working relationship with PanCanadian and a clearly defined interactive management scheme.

What will be the role of the CO_2 supplier?

The CO_2 supplier does not have a direct role to play in the project, unless it wants one.

What will be the role and contribution of the IEA Greenhouse Gas R&D Programme?

IEA GHG can bring expertise and experience from its involvement in the Sleipner/SACS project to the table. It can bring about International co-operation through a legal agreement to cover international participation. It can help by disseminating the results of the project widely by using its existing dissemination channels.

Figure 8 Weyburn oil field control centre
(Courtesy of PanCanadian)

4. PROJECT FORMATION

The outcome of the workshop was a project team structure and an outline plan to take the project forward.

The project team would comprise:

Co-ordination:	Roland Moberg	PTRC
Geophysical:	Jim Brown	University of Calgary
Geochemical:	Bill Gunter	Alberta Research Council
Hydrogeology:	Ben Rostron	University of Alberta
Numerical Modelling:	Michael Stenhouse	Monitor Scientific
Experimental:	Sam Huang	Saskatchewan Research Council
Geology:	Fran Haidl	Saskatchewan Energy & Mines
Industry Perspective:	David Thomas	BP Amoco
Programme Advisor	John Gale	IEA GHG

The detailed monitoring proposal would be developed in the following steps:

1. A rough proposal would be shared with PanCanadian as early as possible (ideally on September 21st).

2. A revised proposal would then be developed that was acceptable to PanCanadian.

3. The proposal would be submitted to various potential funding parties.

4. The proposal would be reshaped based on committed funding levels

5. IEA GHG would assist in developing necessary legal agreements.

5. PROGRESS SINCE THE WORKSHOP

Since the workshop, an initial project outline has been developed, which was presented at the second meeting on the Management of Carbon Dioxide. This was held in Regina on the 5th October 1999. And is the third in a series organised by federal and provincial governments of Canada and industry. The aims of the meetings are to advance the development of, and examine the conditions of deployment for, technologies that cover the capture, transportation, and geological use and storage (capture-and-storage) of CO_2. The aim of presenting the project outline at this meeting was to gain an initial critical review from the Canadian scientific community.

The outline proposal will be discussed with PanCanadian at a meeting in Calgary on the 12th October. It is planned that this meeting will provide a definitive starting point for the Monitoring Project team lead by PTRC to work with PanCanadian to develop a programme that is acceptable to all parties concerned.

IEA GHG has begun to disseminate the results of the Weyburn Monitoring Workshop via its web site and newsletter, as well as external presentations, in order to develop international interest in participation.

ANNEX 1

Weyburn Monitoring Workshop Attendee List

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ANNEX 2

Weyburn Field Details

ANNEX 3

Plenary Session Papers

A3.1

IEA GHG Perspective

A3.2

Canadian and Saskatchewan Perspectives in Enhanced Oil Recovery

A3.3

Capture and Disposal of Carbon Dioxide from Coal Combustion

A3.4

Weyburn Unit Geological Reservoir Characteristics

A3.5

Weyburn CO_2 Flood - A Project for the Future

A3.6

S&T Monitoring of EOR