PART IV

ACTIVE CO_2 INJECTION SITES

Monitoring Strategies and System Evolution of
Active, Man-Made Carbon Dioxide Storage Sites

THE IEA WEYBURN CO_2 MONITORING AND STORAGE PROJECT

Integrated results from Europe

J.B. Riding

British Geological Survey, Keyworth, Nottingham NG12 5GG, UK

Abstract: The IEA Weyburn CO_2 Monitoring and Storage Project has analysed the effects of a miscible CO_2 flood into a carbonate reservoir rock at an onshore Canadian oilfield. Anthropogenic CO_2 is being injected as part of an enhanced oil recovery operation. The European research was aimed at analysing long-term migration pathways of CO_2 and the effects of CO_2 on the hydrochemical and mineralogical properties of the reservoir rock. The long term safety and performance of CO_2 storage was assessed by the construction of a Features, Events and Processes (FEP) database which provides a comprehensive knowledge base for the geological storage of CO_2. The pre-CO_2 injection hydrogeological, hydrochemical and petrographical conditions in the reservoir were investigated in order to recognise changes caused by the CO_2 flood and to assess the fate of the CO_2. The Mississippian aquifer has a salinity gradient in the Weyburn area, where flows are oriented SW-NE. The baseline gas fluxes and CO_2 concentrations in groundwater and soil were also studied. The dissolved gas in the reservoir waters has allowed potential transport pathways to be identified. Experimental studies of CO_2-porewater-rock interactions in the Midale Marly unit have indicated slight dissolution of carbonate and silicate minerals, but relatively rapid saturation with respect to carbonate minerals. Equivalent studies on the overlying and underlying units show similar reaction processes, but secondary gypsum precipitation was also observed. Carbon dioxide flooding experiments on samples of the Midale Marly unit demonstrated that porosity and gas permeability increased significantly and calcite and dolomite were shown to have undergone corrosion. Hydrogeological modelling indicates that if any dissolved CO_2 entered the main aquifers, it would be moved away from Weyburn in an E-NE direction at a rate of *c.* 0.2 metres per year due to regional groundwater flow. Analysis of reservoir fluids proved that dissolved CO_2 and CH_4 increased significantly in the injection area between 2002 and 2003 and that solubility trapping accounts for the majority of the injected CO_2, with little apparent mineral trapping. Twelve microseismic events were recorded and these are

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provisionally interpreted as possibly being related to small fractures formed by injection-driven fluid migration within the reservoir. Pre- and post-injection soil gas data are consistent with a shallow biological origin for the measured CO_2. Isotopic ($\delta^{13}C$) data values are higher than in the injected CO_2, and confirm this interpretation. No evidence for leakage of the injected CO_2 to ground level has so far been detected.

Key words: CO_2 injection; geological storage of greenhouse gases; enhanced oil recovery; geoscientific monitoring; safety assessment studies

1. INTRODUCTION

The IEA Weyburn CO_2 Monitoring and Storage Project was a collaborative initiative involving workers from North America and Europe and was co-ordinated by the Petroleum Technology Research Centre (PTRC) in Regina, Canada. The project has studied the geological sequestration of CO_2 during a commercial enhanced oil recovery (EOR) operation at the Weyburn oilfield, Saskatchewan, Western Canada. EnCana Resources (formerly PanCanadian Resources) began injecting a 95% pure CO_2 stream into the oil reservoir, the Midale Beds, at Weyburn during September 2000. At the conclusion of this EOR operation, it is anticipated that over 20 million tonnes of anthropogenic CO_2 will have been permanently and safely sequestered in these Mississippian strata, which are *c*. 1.4 km underground. Hence, greenhouse gas emissions will have been significantly reduced as part of a cost-effective industrial operation. The principal objective of the monitoring project was to enhance scientific knowledge pertaining to the underground sequestration of CO_2 associated with EOR using several different techniques in geoscientific monitoring. Another major strand to this work has been the promotion of international collaboration on carbon management research between scientists in Canada, the USA and Europe. The results from this project will help guide policy makers on carbon management issues. The European project team comprises nine organisations and was co-funded by the European Commission (EC).

2. THE GEOLOGY OF THE WEYBURN OILFIELD AND THE CO_2-EOR OPERATION

The Weyburn oilfield is in south-east Saskatchewan, Canada (Figure 1a) and lies in the north-eastern part of the Williston Basin. It was discovered in 1954, is now operated by EnCana Resources and covers some 180 square kilometres of prairie. Medium gravity sour crude oil (25 to 34 degree API) is produced from the uppermost Midale Beds (Charles Formation), which represent a transgressive-regressive cycle and comprise a succession of upwards shoaling, shallow marine carbonate-evaporite sediments of Mississippian (Early Carboniferous) age. The Midale Vuggy unit is a succession of highly fractured and permeable vuggy, heterolithic limestones that were deposited in relatively deep water. This unit is overlain by the cryptocrystalline dolomites of the Midale Marly unit, which represent shallow water conditions (Wegelin, 1987). The Midale Marly unit contains the majority of the remaining oil reserves and is the target for the miscible CO_2 flood (Figure 1b).

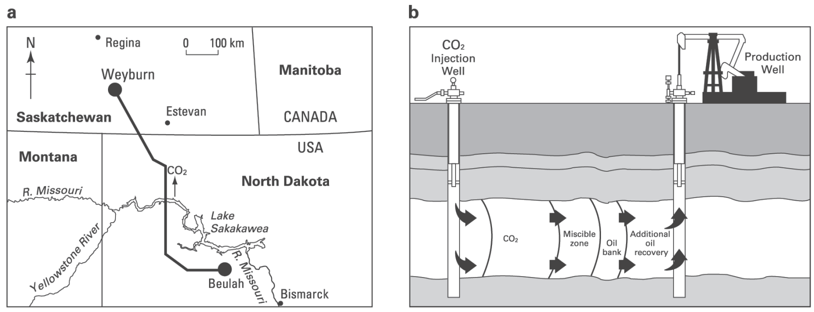

Figure 1. (a) location of the Weyburn oilfield and the route of the CO_2 pipeline. (b) how a miscible CO_2-EOR flood produces incremental oil; at the Weyburn unit, the depth to the reservoir unit is *c*. 1400 m.

Since 1964, water injection has been used as a secondary oil recovery strategy and has efficiently swept incremental oil from the Midale Vuggy Beds due to the high permeability of this unit. The water flood helped the field to achieve its peak production in 1965. The field was revitalized in 1991 by the drilling of horizontal wells. The Midale Marly Beds are less permeable and CO_2 injection is an effective method of extracting oil from this unit. This is because CO_2 is an excellent solvent and dissolves into the oil, thereby simultaneously reducing viscosity and increasing volume. The reduced viscosity makes the oil flow more easily and the swelling of the CO_2-rich oil enhances reservoir pressure. It is anticipated that this CO_2-EOR operation will extend the life of the Weyburn oilfield by the production of 130 million barrels of incremental oil (Figure 1b). The injection of CO_2 was started in September 2000 as Phase 1A and the initial injection rate was 5000 tonnes per day. Injection was originally in 18 patterns of nine wells, each at the west end of the oilfield. The CO_2 flood has been extended in a south-easterly direction and the ultimate aim is to flood 75 patterns in phases over the next 15 years. The CO_2 used is a purchased by-product of coal gasification and supplied to Weyburn through a 320 km long pipeline from the Great Plains Synfuels Plant in Beulah, North Dakota, USA that is operated by the Dakota Gasification Company (Figure 1a) (Stelter, 2001).

3. THE EUROPEAN PART OF THE IEA WEYBURN CO_2 MONITORING AND STORAGE PROJECT

The scientific tasks of the European research on the Weyburn oilfield are divided into three Work Packages (Riding et al., 2003). The scope and principal conclusions of each of these Work Packages are given in this section. This research was aimed principally at studying the potential long-term migration pathways of CO_2, and the effects of CO_2 on the hydrochemical and mineralogical properties of the reservoir rock at Weyburn. These are largely controlled by the regional geology, hydrodynamics and hydrochemistry of the aquifer systems.

3.1 Work Package 1 – Long-Term Safety and Performance of CO_2 Storage

The aim of this Work Package was to use systems analysis to provide a framework into which data can be integrated to give an assessment of the safety and reservoir integrity of CO_2 injection at the Weyburn oilfield. Features, events and processes (FEPs) describing the behaviour of CO_2 in the subsurface were used to describe and evaluate the storage concept and as a method of assessing all potentially significant factors. A generic FEP database for the geological storage of CO_2 has been developed. Natural analogue data obtained through the EC co-funded NASCENT project were also incorporated. The selected FEPs were included for their relevance to the long-term safety and performance of the reservoir, after the injection of CO_2 has been completed and the injection wells have been sealed. However, some FEPs pertaining to the injection phase have been included. The database contains some 200 FEPs arranged in a hierarchical structure that has eight categories. Each has a text description with references to the literature and discussion of its relevance to long-term performance and safety. The database is internet-enabled and incorporates hyperlinks to many other relevant information sources and is fully searchable. The generic (i.e. non Weyburn-specific) FEP database is available at http://www.quintessa-online.com/CO_2/. It is therefore a comprehensive knowledge base for the geological storage of CO_2. Potentially important scenarios for the future evolution of a geological storage system were also considered. These scenarios need to be addressed in system-level models for the assessment of performance and safety. The use of the FEP database as an audit tool to evaluate the completeness of such models has been demonstrated. Deterministic and probabilistic performance assessment methodologies have been investigated to determine the long-term fate of CO_2 in the geosphere and biosphere.

3.2 Work Package 2 – Definition of Baseline Hydrogeological, Hydrochemical and Petrographical Conditions

The aim of this Work Package was to define the pre-CO_2 injection hydrogeological, hydrochemical and petrographical conditions in the Weyburn reservoir at both local and regional scales (Riding et al., 2003). A full understanding of these baseline conditions has allowed the recognition of changes resulting from the CO_2 flood and assessing the fate of the injected CO_2. To place the Weyburn oilfield in its regional context, the geological structure, hydrogeology and water chemistry were first compiled at the basin scale. The study then focused on a smaller area, centred on Weyburn. The geological structure of the area is a southward/south-westward-trending monocline. The Mississippian aquifer has a steep salinity gradient in the Weyburn area, where brines are concentrated in the south and are associated with Devonian evaporites. Salinity values in the north reflect previous dissolution of Devonian evaporites. The overall up-dip flows are dominantly oriented south-west to north-east. This is an important factor when investigating potential upward CO_2 migration and chemistry of water mixing by flooding.

The baseline chemistry of the aquifer systems was assessed at a regional scale and included analytical data from the Weyburn oilfield. Geochemical modelling has indicated the main *in-situ* chemical characteristics of the Mississippian reservoir fluids at Weyburn. Dissolved organic acid anions do not have a significant effect on the alkalinity; by contrast, sulphide concentrations may represent >60% of the total alkalinity. The reservoir waters are largely in thermodynamic equilibrium with respect to anhydrite, barite, calcite, dolomite and a silica phase. Dissolved aluminium may be controlled by clay minerals and/or K-feldspar.

Baseline mineralogical data have also been analysed to assess the initial chemical environment and to identify core material within the CO_2 flood area for use in hydrothermal experiments. Experimental geochemical studies on core samples from the first CO_2 flooding area have been carried out to ascertain key fluid properties. A further aspect of the baseline studies was to determine the pre-injection regional gas fluxes and concentrations in both groundwater and soil. The former has improved understanding of fluid-flow pathways throughout the Weyburn oilfield. A variety of dissolved and free gases and elements have been analysed. These help to determine the baseline water-rock interactions and allow potential rapid transport pathways to be identified.

Part of this task was to investigate whether soil gases and groundwater analyses can be used to identify the position of near surface features that may connect with the reservoir at depth. Seismic profiles were examined for faults, which may conduct gases and liquids above the reservoir, however none, which outcrop, were found. Consistent with this, the soil gas anomalies measured at Weyburn do not follow linear trends. The CO_2 distributions reflect both the origins and natural reactions that typify modern biogenic CO_2. The majority of the minor CO_2 anomalies may therefore be explained by anthropogenic or near surface phenomena. There is no correlation between these CO_2 anomalies with the injection wells or CO_2 pipelines. Furthermore, the expected seasonal variations in CO_2 flux data have been discerned. For example, measurements taken in September 2001 proved lower than those measured in July 2001 due to seasonal variations in soil humidity, vegetation and agricultural activity.

3.3 Work Package 3 – Define Changes to Baseline Hydrochemical, Hydrogeological and Petrographical Conditions Resulting from CO_2 Injection

Work Package 3 sought to assess the impact of injected CO_2 on the baseline conditions, especially reservoir geochemistry, mineralogy, fracture generation and fluid flow pathways (Riding et al., 2003). Experimental geochemical studies of CO_2-porewater-rock interactions investigated dissolution/precipitation reactions between CO_2, Midale reservoir rocks, the caprock, borehole cement and porewaters under reservoir conditions. The data were used in the geochemical modelling to show how mineral saturation changes when CO_2 is injected into the Midale Marly unit. It was found that the effects of CO_2 injection into Midale beds gave rapid reactions with variable amounts of carbonate mineral dissolution, some precipitation of gypsum and slow reactivity of aluminosilicate minerals. The Midale Vuggy samples proved the most reactive with etching of surfaces giving minor secondary porosity and secondary gypsum. By contrast, few observable mineralogical changes were observed in the Midale Marly samples. The Midale Evaporite caprock samples were altered slightly more than the Midale Marly lithologies and include some gypsum precipitation. The injection of CO_2 appears to have had little impact on the strength of the two cement types tested. Three CO_2 flooding experiments were completed on Midale Marly samples. Sample porosity and gas permeability increased significantly. Calcite and dolomite both underwent significant corrosion and some disintegration was observed. Anhydrite and gypsum were also corroded, whereas alkali feldspar, celestine and fluorite appeared to be unaffected. Mass balance calculations indicate a consistency between sample weight loss and the amounts of dissolved Ca^{2+} and Mg^{2+}.

The geochemical evolution of the Weyburn site has been achieved in an integrated study comprising field sampling, experimental studies and predictive geochemical modelling. It was determined that dissolved CO_2 in reservoir fluids increased 10-fold in the phase A1 injection area between 2002 and 2003; dissolved methane (CH_4) also increased significantly. Solubility trapping accounts for the majority of the injected CO_2, with little apparent mineral trapping. Regional scale hydrogeological modelling indicates that subsurface water flow is oriented south-west to north-east. Some contrasts in density and aquifer dips in the Weyburn area however, cause modifications to this principal direction. Should CO_2-charged groundwaters migrate from the reservoir succession, and the material were incorporated into the main aquifers, it is predicted that dissolved gas would only be moved 25 kilometres away from Weyburn in an east to north-east direction after 100,000 years.

Microseismic monitoring was undertaken to map hydraulic-induced fractures that have been stimulated by injection/EOR activities. Twelve microseismic events with magnitudes of -2.3 to -1.7 were recorded at 300 to 400 m from the observation well. Operations in a nearby well were shut down during ten of these events, hence this microseismicity is interpreted as possibly being related to the formation of small fractures produced by injection-driven fluid migration within the reservoir. The results of comprehensive soil gas surveys between 2001 and 2003 indicate shallow biological origins for the measured CO_2. Seasonal variability in the soil gas values and limited $\delta^{13}C$ isotopic data support this interpretation. There is no evidence so far of any leaks of injected CO_2 at the surface.

4. CONCLUSION

The Weyburn oilfield has proven to be an outstanding natural laboratory for the study of CO_2 storage; this is based on its comprehensive well/field data, the extensive core material and the accessibility of the site. The European part of the IEA Weyburn CO_2 Monitoring and Storage Project has derived significant scientific knowledge related to a commercial miscible CO_2-EOR operation. The structure of the research is intended to serve as a model, which can be applied to other CO_2 storage operations. Furthermore, the results from this project should help guide policy development on the abatement of greenhouse emissions from energy generation using underground storage. This project has also been notable for the many successful international collaborations which have taken place within the large project team. These have been both intra-European and transatlantic collaborations.

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