

ASSESSMENT OF THE LONG-TERM FATE OF CO₂ INJECTED INTO THE WEYBURN FIELD

System-Level Modeling of CO₂ Migration and Potential Impacts

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Abstract: CO₂ is being injected into a 1450-m deep oil reservoir located in Weyburn, Saskatchewan, Canada, for enhanced oil recovery. To complement this commercial activity, a major research project to study geological sequestration and storage of CO₂, known as the International Energy Agency (IEA) Weyburn CO₂ Monitoring and Storage Project, was launched in July 2000. Phase 1 of this project was completed in 2004. This paper discusses the long-term assessment of the fate of CO₂ in the IEA Weyburn Project, describing the underlying methodology as well as the modeling approach and the results obtained. The conclusion from the modeling predictions is that if the Weyburn CO₂ storage system evolves as expected, long-term geological storage of greenhouse gas CO₂ will be achieved.

Key words: Greenhouse gas mitigation, geological storage of CO₂, CO₂ migration, system-level modeling, long-term assessment, risk assessment, abandoned wells, environmental impacts.

1. INTRODUCTION

CO₂ from the North Dakota Gasification plant is being transported and injected into a 1450-m deep oil reservoir located in Weyburn, south Saskatchewan, Canada (Figure 1) for enhanced oil recovery (EOR). The operator, EnCana Resources of Calgary, Alberta, designed a total of 75 patterns (each pattern is ~1 km²) for this operation that is intended to last for approximately 34 years. To complement this commercial activity, a major research project to study geological sequestration and storage of CO₂, known as the International Energy Agency (IEA) Weyburn CO₂ Monitoring and Storage Project (henceforth called the IEA Weyburn Project), was launched

in July 2000. The first phase of this project (2000-2004) was sponsored by a number of governments and industrial sponsors from North America, Europe and Japan, including Natural Resources Canada (NRCan) and the U.S. Department of Energy. Planning for Phase 2 is already underway.

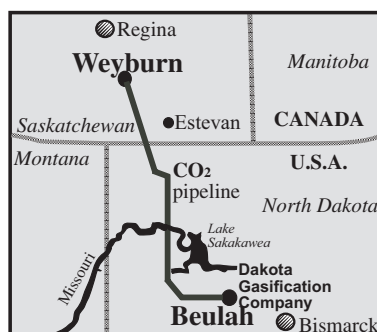


Figure 1. Location of the Weyburn field and the CO₂ pipeline from Beulah, North Dakota.

One of the objectives of the IEA Weyburn Project was to determine the long-term fate of CO₂ injected into the reservoir. Such a determination involves an evaluation of the potential for CO₂ to migrate to the environment via both natural and man-made (wellbore) pathways.

CO₂ storage projects are relatively few and so assessments associated with CO₂ storage are in their infancy. In the particular case of the IEA Weyburn Project, long-term (geological) storage of CO₂ is an additional benefit of EOR. However, safety studies for such storage of CO₂ are unusual in that they need to consider the evolution of natural systems over timeframes considerably in excess of those considered in industrial or engineering projects - typically several decades and rarely hundreds of years.

Many of the advances made in the last twenty years in the field of safety assessments for the geological disposal of radioactive wastes can also be applied to CO₂ storage (Savage, 1995). Similar to CO₂ sequestration, the final storage of nuclear waste requires an understanding of complex coupled physical-chemical-mechanical processes occurring over hundreds to tens of thousands of years. The spatial scales of both types of project are also similar.

This paper discusses the methodology applied to the long-term assessment of the fate of CO₂ in the IEA Weyburn Project, the modeling approach and the results obtained. A preliminary evaluation of the potential environmental impacts from releases of CO₂ to the biosphere is also described.

2. METHODOLOGY – SYSTEMS ANALYSIS FRAMEWORK

The Systems Analysis framework that was applied to the long-term assessment for the IEA Weyburn Project is based on the well-established methodology that has been, and still is, used widely and successfully in the field of radioactive waste management and disposal (Cranwell et al., 1982; Goodwin, 1991; Stenhouse et al., 2001). The basis of this approach is to develop a transparent and systematic treatment of the ‘system’ being assessed, as well as generating documentation that is auditable, should the need arise.

One of the first steps in the methodology is to define what is meant by the ‘System’ to be assessed. Figure 2 provides a schematic diagram of the basic components of a CO₂ storage system, *viz*:

- The **CO₂ storage reservoir** situated at depth, in this case the Weyburn field, within the
- **Geosphere**, which consists of a number of geological and hydrogeological units above and below the reservoir (units are not shown explicitly in Figure 2); and the
- **Biosphere**, the name given to the surface, or near-surface environment, where potential environmental impacts are normally evaluated.

The arrows shown in Figure 2 represent potential CO₂ migration pathways away from the reservoir. Two abandoned wells are also shown in this diagram, representing wellbores as potential (fast) pathways for reservoir CO₂ to migrate to the surface or near-surface. One of the major tasks of the IEA Weyburn Project was the detailed geological and hydrogeological characterization of the region around the Weyburn field, so that the main features of the geosphere, principally those representing potential pathways or sinks for CO₂, could be identified and incorporated in the migration modeling (see Section 3).

Having defined the ‘System’, the next stage of the process involved the identification of *scenarios*. Scenarios are defined as plausible and credible ways in which the Weyburn CO₂ storage system might evolve over decades to hundreds to thousands of years. One scenario was central to the modeling effort in Phase 1 - the Base Scenario, defined as “the expected evolution of the Weyburn CO₂ storage system”. Table 1 provides a description of the elements that constitute the Base Scenario. Other (alternative) scenarios were also identified, though not discussed here. The documentation of scenarios occurs primarily through the listing of relevant features, events and processes (FEPs) - those factors that can affect the CO₂ storage system.

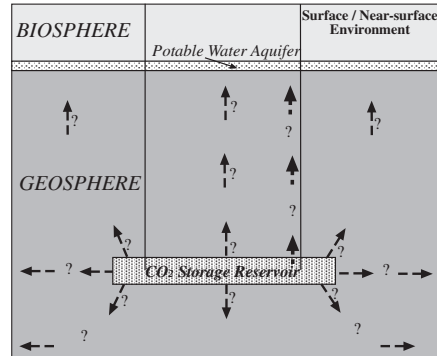


Figure 2. Schematic diagram of CO₂ storage system (cf. the more realistic representation shown in Figure 3).

Table 1. Key elements of the Base Scenario for the Weyburn CO₂ storage system.

Base Scenario

- **Modeling domain:** the Weyburn field (75 patterns) and the surrounding 10-km zone.
- **Time frame:** From the end of CO₂ injection to 5,000 years, or at which time 50% of the CO₂ in-place has migrated from the reservoir.
- **Caprock:** Based on existing information, the caprock integrity is not impaired; any fractures or discontinuities that exist are all isolated or sealed (see also abandoned wells).
- **Geosphere:** A series of aquitards/aquifers exist above and below the reservoir horizon; these formations may contain fractures and fissures.
- The System Model takes into account physical trapping features that have contained the oil/gas in the reservoir.
- Geochemical processes - *e.g.*, water chemistry changes, CO₂ removal (by solubility and ionic trapping), precipitation of carbonate minerals - occur in the aqueous phase of all aquifers.
- The Biosphere exists from the deepest potable aquifer, *i.e.*, extends to ~ 300 m below surface. It includes soil, surface water and the atmosphere as well as the flora and fauna that are found within these areas.
- **Abandoned wells:** All wells within the modeling domain are included and are assumed to have been abandoned according to current field abandonment procedures. This assumption includes wells that may have been abandoned previously according to different abandonment practices.
- Well seals will slowly degrade after abandonment. These seals consist primarily of the cement used to fill the annulus between casing and borehole, cement and metal plugs used to fill the casing bore, and the cap welded onto the casing ~ 4 m below ground surface.
- The metal casing will also degrade with time.
- FEPs that address storage and migration of CO₂ include hydrodynamics, buoyancy, geochemistry (precipitation / dissolution of minerals) and density-driven flow, dissolution of CO₂ in water and residual oil, and pressure-temperature changes occurring in the geological formations.

3. MODELING OF CO₂ MIGRATION FROM THE WEYBURN RESERVOIR

The modeling of CO₂ migration away from the storage reservoir was carried out in two stages, each of which is discussed separately below:

- Modeling of CO₂ migration away from the reservoir via natural pathways, i.e., through the geosphere; and
- Modeling of CO₂ migration through abandoned wells.

3.1 Modeling of CO₂ Migration Through the Geosphere

Figure 3 shows the model used as the basis for the long-term assessment of CO₂ migration in the geosphere. This geosphere model comprises a series of formations classified as either aquifers (exhibiting relatively high permeability) or aquitards (low permeability), and extends to ~10 km beyond the EOR region. The various ‘compartments’ of the model were identified as part of the detailed site characterization program. The geosphere also includes the reservoir (Midale Marly and Vuggy formations identified in Figure 3) beyond the EOR region.

ECLIPSE 300 (E300), a compositional simulator developed by GeoQuest/Schlumberger, was used as the modeling tool. Although not developed to specifically model CO₂ geological sequestration, one of the routines of the code is to simulate EOR employing a CO₂ flood. Key features of the code that are relevant to the modeling of CO₂ migration include equation-of-state capability to track the thermodynamic state of CO₂, which has low critical pressure and temperature, as well as the effect of the density gradient due to CO₂ dissolved in water.

The starting point for the long-term assessment modeling was the projected end of EOR activities, i.e., at 2034. Thus, results obtained from the reservoir simulation predictions for the end of the EOR period - in particular, the CO₂ in place, and pressure and fluid/component distributions within the field - were used as starting conditions for modeling CO₂ migration away from the storage reservoir. In order to avoid up-scaling problems between the reservoir simulation and long-term assessment models, the central area (75 patterns) of the Weyburn field had the same resolution in both models. Furthermore, pore volumes for the migration model were made identical to those of the reservoir simulation model. In the central area of the geosphere model (EOR region), the properties were replaced with the history-matched reservoir properties used in the reservoir simulation model.

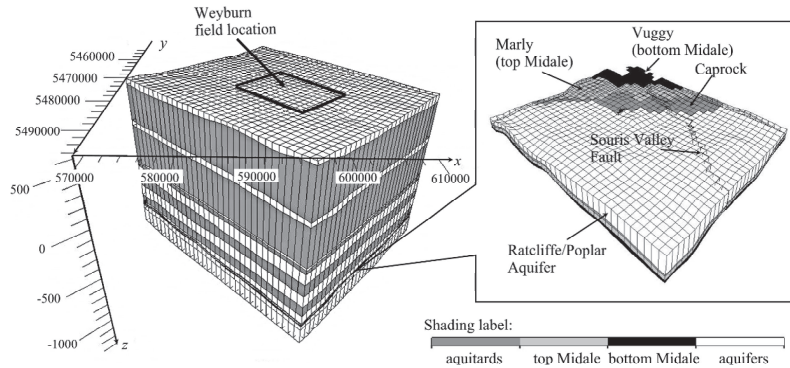


Figure 3. The model for assessing CO₂ migration within the geosphere. The x and y axes are UTM coordinates. The z axis is depth with respect to sea level in meters. Note that the vertical scale in the figure has been exaggerated.

Additional key input data were relative permeability and capillary pressure data for aquifers, aquitards, and reservoir rocks, obtained from a variety of sources. EnCana, the field operator, was the source of field data.

Key assumptions of the model included treating the fractured reservoir rock as an equivalent porous medium, with permeability values provided from field data as well as from history-matching results. This particular assumption may over-estimate mass transfer by ignoring diffusion into the rock matrix. In some cases, this is an important mass-transfer retardation process. Further details of the modeling assumptions, as well as input data and output results, can be found in Zhou et al. (2005).

Figure 4 displays the key results obtained from the long-term migration modeling. In this diagram, results are presented as the mass transfer rate of CO₂ (kg/day) out of the reservoir and into various regions of the geosphere, from 2034 up to 5,000 years after the end of EOR. Also shown in this diagram is the average oil phase pressure inside the EOR area, which has a major influence on CO₂ migration. The initially high pressure gradient across the boundary of the EOR region causes relatively fast mass transfer of CO₂, which subsequently slows down as the pressure decreases. The slight change in rate, reflected in an increase in lateral CO₂ migration at 1,000 years, is due to restoration of ambient pressure/flow field conditions.

To summarize the significance of the results shown in Figure 4, the cumulative amount of CO₂ removed from the EOR region is 26.8% of the initial CO₂-in-place at the end of EOR (~ 21 MT): 18.2% migrates into the geosphere *below* the reservoir, 8.6% migrates *laterally* (within the Midale formations), and 0.02% migrates to the geosphere *above*. No CO₂ reaches the biosphere, i.e., enters the lowest potable aquifer or any layer above, including the surface, over the 5,000-year period.

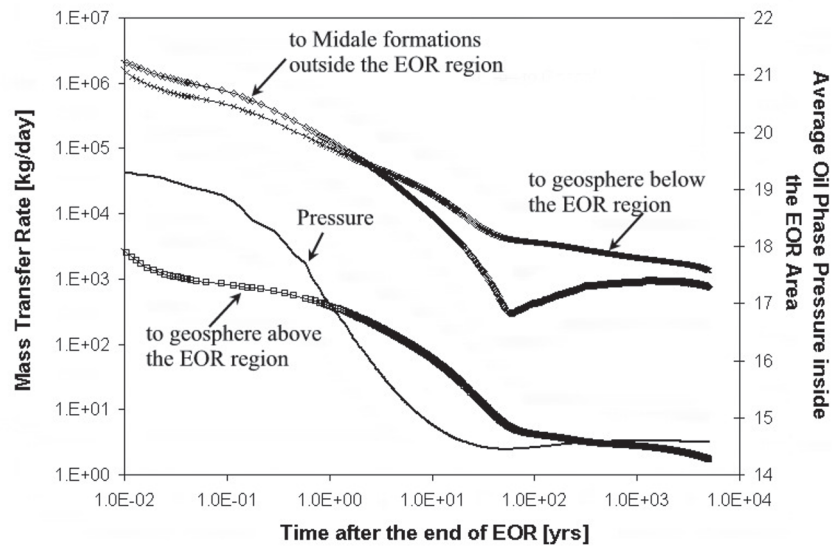


Figure 4. Time variation of CO₂ mass transfer rates (kg/day) into the geosphere, and oil phase pressure inside the EOR region (75 patterns) averaged over hydrocarbon pore volumes.

The substantial thickness of aquitards immediately above the reservoir (see Figure 3) is largely responsible for restricting the vertical movement of CO₂. In addition, sensitivity studies have demonstrated that key parameters affecting CO₂ movement include the caprock permeability and the ‘entry pressure’ (for entry of fluid into the caprock).

3.2 CO₂ Leakage Through Abandoned Wells

Thousands of wells exist within the study area, i.e., within the lateral extent of the system model. Thus, while CO₂ migration through the geosphere was treated deterministically, modeling of CO₂ leakage through abandoned wells was treated stochastically in order to address the substantial variability of these wells. This variability is reflected primarily in the heterogeneity of both the CO₂ distribution and the rock properties within the reservoir.

Stochastic treatment of CO₂ leakage through wells was achieved using a ‘Unit-Cell’ model (Figure 5). Using this model, the key assumptions were:

- Cement seal degradation corresponding to an increase in permeability from 0.001 mD initially to 1 mD at 100 years (cf. predictions from a supporting sub-task indicating such an increase in permeability but over a time period of 1,000 years rather than 100 years);

- No loss of CO₂ to fluid flow within the reservoir as well as within the formations surrounding the wellbore;
- Fast transport of CO₂ once it enters the open borehole, i.e., rapid ascent of CO₂ to the surface as gas bubbles.

Given the variability and uncertainty of key parameters used in the 'Unit-Cell' model, the above assumptions were considered to result in a conservative treatment, i.e., over-estimating CO₂ leakage.

Existing data (Yu, 1993) for fresh concrete used in low-level radioactive waste disposal systems show that this material is extremely restrictive to flow (the water phase becomes mobile at near unity saturation). The exceedingly high capillary pressure (>20 MPa at near unity water saturation) effectively blocks intrusion of non-aqueous phase fluids. While these properties are valuable to sealing performance, they may not be realistic for aged cement materials in wells. In the absence of corresponding data for aged cement, we used an estimated capillary pressure obtained by estimating the capillary pressure drop due to a permeability increase using existing data for fresh cement together with the permeability-porosity relationship found in Scheidegger (1974).

The 75-pattern EOR region was represented by 6,075 grids in the geosphere model (Figure 3). Of these grids, 287 were selected with a bias towards existing well locations, high CO₂-in-place, and high permeability values. Together, these selections correspond to a conservative treatment.

The 'Unit-Cell' model was activated for 287 simulations in which saturation, component concentrations, and permeability values in each of the 287 grids were used as input for individual runs. The results show a large range in leakage rates with the *maximum* leakage rate ranging from 0 to 0.016 kg/day. The time at which this maximum leakage rate occurred also varied significantly. Figure 6 shows the mean, 95%, and maximum leakage rates as a function of time obtained from these (287) runs, along with leakage rates vs. time from selected runs.

The variability in well leakage is also shown in Figure 7, which displays cumulative leakage of CO₂ via abandoned wells as a function of time. In general, the stochastic nature of reservoir conditions dictates stochastic behavior of leakage through abandoned wells across the study area.

However, when the cement permeability is low (≤ 1 mD), the ultimate control of leakage lies in cement permeability. When the permeability of cement is higher (e.g., > 10 mD), reservoir properties govern the rate and amount of CO₂ leakage. To confirm this conclusion, a few 'Unit Cell' runs were carried out using an increased cement permeability (10 mD) (Millidarcy: approximately equal to 10^{-8} m/s). In these cases, the results indicated an increase in both the leakage rates and cumulative leakage, but only by a factor of about two.

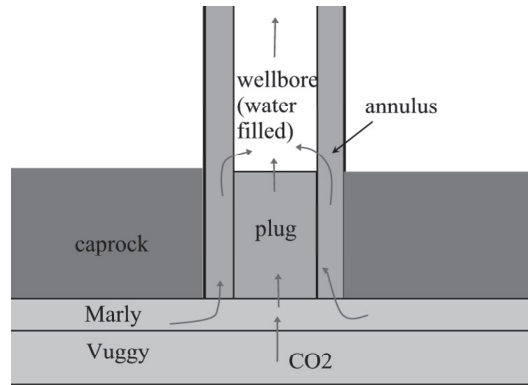


Figure 5. ‘Unit-Cell’ model for assessing the leakage of CO₂ via abandoned wells.

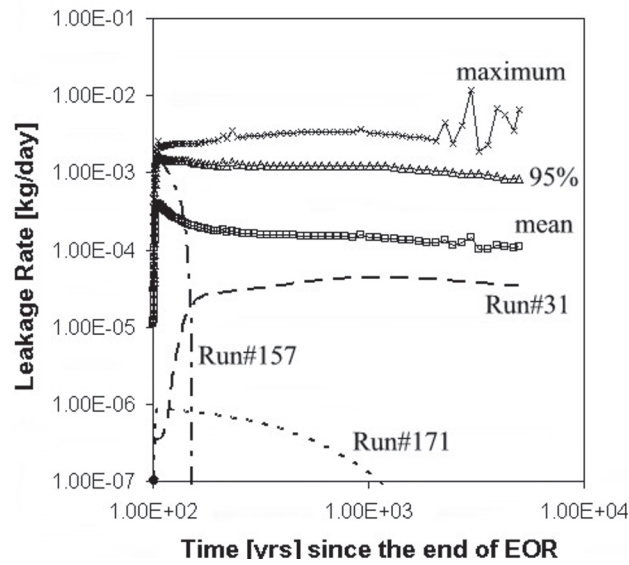


Figure 6. Stochastic results of CO₂ leakage rate as a function of time, predicted using the ‘Unit Cell’ model combined with a stochastic treatment. The diagram shows the results of a few selected runs. Note that the 5% result is off (below) the scale of Figure 6.

The combination of the *maximum* CO₂ flux through a wellbore (0.016 kg/day) with an estimated 1,000 wells over the 75-pattern area (currently ~824 wells), yields a total cumulative leakage of CO₂ of ~0.03 MT over

5,000 years. This total amount represents ~0.14% of the total CO₂-in-place (21 MT) at the end of EOR. This value is a highly conservative upper estimate, however, as it assumes that the maximum flux is maintained throughout the 5,000-year period for all wells, which is not supported by the observed results. Thus, a more representative value is the *mean cumulative leakage*, corresponding to less than 0.001% of the CO₂-in-place at the end of EOR.

4. POTENTIAL ENVIRONMENTAL IMPACTS FROM CO₂ LEAKAGE TO THE BIOSPHERE

In order to put the results obtained from well leakage modeling in some perspective, scoping calculations were carried out to address two potential environmental impacts:

- *Indoor air CO₂ concentration:* CO₂ leakage from an abandoned well (point source) directly into the basement or lower floor of a dwelling through cracks in the foundation. The maximum acceptable CO₂ flux from the wellbore was determined by the limiting CO₂ concentration in air (Health Canada, 1989).
- *Mobilization of trace metals into drinking water:* CO₂ leakage from an abandoned well directly into a potable groundwater, changing the water chemistry, which in turn promotes the release of a toxic trace metal (lead) into the water supply. The maximum acceptable CO₂ flux in this case was determined via geochemical modeling, taking into account an interim drinking water standard for dissolved lead (Langmuir, 1997).

Evaluation of the above cases indicated that the more restrictive example is CO₂ leakage into a potable aquifer, yielding a limiting CO₂ leakage rate of similar magnitude to the mean cumulative leakage described in the previous section.

Given that only scoping calculations were carried out, more detailed treatments of these environmental impacts are required, particularly in the case of trace metal release into drinking water, before making a definitive statement on an acceptable CO₂ leakage rate to the biosphere.

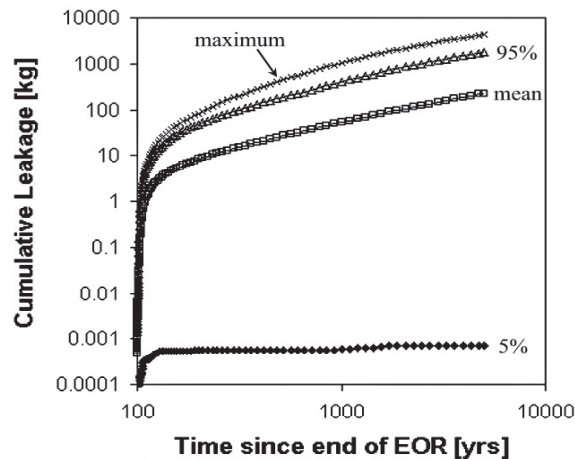


Figure 7. Stochastic results of cumulative leakages of CO₂ via abandoned wells.

5. SUMMARY

For the Base Scenario identified for the IEA Weyburn Project, modeling of CO₂ migration within the geosphere indicated that up to 75% of the initial CO₂-in-place (at the end of EOR) remained within, and in the vicinity of, the EOR region. No CO₂ enters the biosphere within the simulation period of 5,000 years.

Modeling of leakage via abandoned wells focused on the performance of degraded cement sealing combined with the variability of properties and CO₂ distribution in the reservoir. The conservative treatments incorporated in stochastic modeling provided upper bounding results indicating that the *maximum* possible leakage after 5,000 years is approximately 0.14% of the initial CO₂-in-place. However, the *likely cumulative leakage* after 5,000 years, however, is less than 0.001% of the initial CO₂-in-place.

These results mean that if the Weyburn CO₂ storage system evolves as expected, the goal of storing greenhouse gas CO₂ will be achieved. Future assessments should focus on alternative scenarios, including seismic activity, open wellbores, and human intrusions.

ACKNOWLEDGEMENTS

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