Climate change mitigation: Best practices based on a decade of applied research by the IEAGHG Weyburn-Midale CO₂ Monitoring and Storage Project

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Introduction
Despite the recent setbacks of cancelled projects, and in the continued absence of adequate economic incentives, widespread deployment of carbon dioxide (CO₂) capture and storage (CCS) remains an essential measure if continued global increases in fossil fuel consumption are to be balanced with curbs on emissions.

The scale of the challenge remains daunting – according to calculations by the International Energy Agency in 2009, approximately 150,000M.t of anthropogenic CO₂ will need to be captured and permanently stored in the subsurface by 2050 if CCS is to contribute approximately 20% of the emissions cuts necessary to stabilise atmospheric concentrations at 450ppm. To date, considerably less than 100M.t have been geologically stored.

Critics often refer to CCS as an unproven technology. In fact, all the elements of CCS (CO₂ capture, transport and storage) have been proven as technically viable at significant scale. On the storage side, the world’s largest example has seen in excess of 20M.t of anthropogenic CO₂ safely injected into the neighbouring Weyburn and Midale oilfields of southern Saskatchewan, Canada since 2000 and 2005 respectively. Operated by Cenovus Energy and Apache Canada, respectively, the CO₂ injection into these fields has facilitated successful enhanced oil recovery (CO₂-EOR) – resulting in substantial increases in oil production (Figure 1).

Midale experience
The CO₂ streams for both current CO₂-EOR operations are currently purchased from the Dakota Gasification Company’s synthetic fuel plant in Beulah, North Dakota, and are transported through a 332km pipeline across the US-Canada border. From April 2014, Cenovus Energy will also inject CO₂ sourced from SaskPower’s Boundary Dam Power Station – where the world’s first industrial scale, post-combustion CO₂ capture plant is under construction at a cost of over half a billion dollars.

Annual injection rates of newly purchased CO₂ are in the order of 2.4Mt per annum at Weyburn, and at present an approximately equal amount is being recycled and re-injected into the reservoir in a “closed loop”. In the Midale oilfield, the annual CO₂ injection rate is currently 0.2Mt, of which 0.2Mt is recycled. The reservoir common to both sites comprises a carbonate unit approximately 30m thick at 1.4km depth.

Applied scientific research into CO₂ geological storage, associated with these CO₂-EOR operations), was initiated by the Petroleum Technology Research Centre (PTRC) in 2000. In recognition of global significance to the demonstration of CCS, the research project received support from the IEA Greenhouse Gas (IEAGHG) R&D programme and a range of international sponsors, and became known as the IEAGHG Weyburn CO₂ Monitoring and Storage Project.

A first phase of research focused on the Weyburn field was completed in 2004 and culminated in the publication of a summary report released in conjunction with the 7th International Conference on Greenhouse Gas Control Technologies in Vancouver (Wilson and Monea, 2004). The subsequent round of research incorporated the Midale oilfield, hence becoming known as the IEAGHG Weyburn-Midale CO₂ Monitoring and Storage Project (WMP).

Research was largely completed by the end of 2011, enabling the 2012 publication of a Best Practices Manual (BPM) titled Best Practices for Validating CO₂ Geological Storage, which documented key technical lessons learned over the entire decade of research.

Monitoring and validating
The second phase of research centred on the technical objectives of assessing monitoring methods and validating CO₂ geological storage, building on earlier work which showed that a deep carbonate reservoir could securely store CO₂ in conjunction with an active CO₂-EOR project. Studies were undertaken by various Canadian and international organisations;
component research tasks were assigned to one of four “themes”, each co-ordinated and managed by one or two recognised experts in the respective field:

**Theme 1: Geological Integrity**
**Theme 2: Wellbore Integrity**
**Theme 3: Storage Monitoring Methods (Geophysical and Geochemical)**
**Theme 4: Risk Assessment**

Geological and hydrogeological characterisation are critical components of storage assessment, and need to be considered at a variety of scales, governed by the required storage capacity and constrained by the availability of data. Definition of the storage complex, ie the intended reservoir(s) and any surrounding strata that will contain the injected CO₂, including seals, requires detailed characterisation; but the importance of regional characterisation data is also a key element, given the likely scale of CCS projects and the emerging regulatory requirements for permanent storage integrity.

WMP researchers undertook exhaustive characterisation work at both local and regional scales (Figure 2), forming the framework for predictive modelling of storage performance and long-term storage security using a variety of approaches and modelling software codes. The WMP utilised both traditional reactive-transport (coupling of fluid flow with geochemistry) and novel invasion percolation approaches, and the successful application of these methodologies is described in the BPM. Assessments of storage capacity, linked to predicted mass partitioning of CO₂ between free phase, aqueous and mineral species, are also described.

**Monitoring types**

Monitoring of CO₂ geological storage can be broadly divided into two types: deep focused, for monitoring of CO₂ distribution in the storage complex, seal integrity and pressure evolution in response to injection; and shallow focused, for leakage detection and protection of sensitive environmental receptors such as shallow groundwater and eco systems.

The successful imaging of CO₂ distribution in the reservoir using 3D time-lapse seismic surveys (Figure 3) has been an outstanding achievement of WMP research, especially given doubts in the early stages of research planning that the technique would be applicable to Weyburn. Marked decreases in acoustic impedance have been observed near CO₂ injection wells, interpreted to result from a combination of CO₂ saturation and increased pore pressure.

To quantify CO₂ saturations, therefore, pressure effects need to be discerned. Semi-quantitative results on resolving saturation and pressure influences have been obtained in the WMP by constraining time-lapse changes in impedance with Weyburn-specific rock-physics data. A highly novel methodology employed in the WMP has been to integrate data from 3D seismic, reservoir geochemical monitoring and production/injection data using reactive transport modelling and geostatistical techniques. Application of amplitude-versus-offset-and-azimuth techniques to seismic data has provided a method for interpreting and mapping anisotropy in the caprock, with good correlation to core measurements.

**Seismicity**

Following installation of a geophone array in 2003, and with commencement of an adjacent injection well in 2004, passive seismic monitoring has recorded low occurrence and very low magnitude of induced seismicity, indicative of an absence of significant reservoir deformation. Induced seismicity is still perceived as a key leakage risk scenario for CO₂ geological storage, so this real-world data is of some significance. Monitoring of shallow 

Figure 2: Local and Regional Study Areas in the context of the Williston Basin, a thick accumulation of sedimentary rocks straddling the US-Canada border.

Figure 3: Plan views of the CO₂-EOR injection area at Weyburn, showing seismic amplitude differences for the upper part of the reservoir. Lines and dots indicate horizontal and vertical injection or production wells. The bright colours effectively map out the distribution of CO₂ in the reservoir.
similar pattern of CO₂ concentrations with the same relationship to O₂ and N₂ concentrations. Moreover, consistent measurements of the unstable Carbon-14 isotope provided definitive proof that CO₂ present in soil gas at the site originated entirely from recent, biogenic processes within the soil profile.

Conclusion
In conclusion, these investigations showed no evidence for any leakage from the CO₂-EOR operations; concentrations and isotopic ratios detected showed that CO₂ present in soil gas originated from recent natural processes within the biosphere.

Within the study region surrounding the oilfields, in an area of approximately 40km by 50km, more than 4,000 wells penetrate to reservoir depths. As would be expected in a mature petroleum province, these wells originate over many decades and have been constructed and abandoned to varying standards. Wells can therefore be considered to constitute a potential leakage pathway, and WMP research has invested significant effort into understanding the parameters most likely to affect well integrity and relating these to available historic records.

Leakage scenarios centre on cement placement in the annulus, de-bonding between casing and wall rock, and channelling in the cement. Research activities included an extensive field-based testing programme, with access to a 1957 well that has been exposed to CO₂ within the Weyburn field. In addition to standard cased-hole logging, the WMP commissioned the design of a specially adapted downhole tool to conduct pressure-transient testing of the cement sheath and to obtain core samples. These tests provided important information on the hydraulic characteristics and indicated generally sound integrity of the cement sheath.

The decade of active WMP research coincided with rapid evolution of risk assessment as part of a wider risk-management framework for CO₂ geological storage that is being incorporated into regulations in many jurisdictions. After initial considerations of storage-performance assessment, the WMP proceeded to consider risks to the wider environment using expert panels and in consultation with local stakeholders, including the public.

The incorporation of a biosphere risk assessment has been a novel aspect of the WMP risk assessment in comparison with other existing, industrial-scale CCS projects.

WMP research has shown that risks associated with geological storage in the Weyburn and Midale oilfields are low and compare favourably with most types of major industrial project.

In summary, CO₂-EOR operations at the Weyburn and Midale oilfields and allied WMP research have successfully demonstrated the safe operation and integrity of CO₂ geological storage at industrial scale. Much work remains to be done, though, in further demonstrating safe CO₂ storage at industrial scale in a wider variety of geological contexts.

PTRC is looking forward to making another contribution to this goal through the Aquistore site, which will be receiving CO₂ from Boundary Dam later this year and acting as a long-term buffer storage facility against fluctuations in both CO₂ supply and demand for EOR.

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References


DIARY
Works visit: Crossrail C315 Connaught Tunnel Project
3 July, 4pm. Connaught Tunnel, East London
This complex project involves modifying a disused Victorian railway tunnel to carry the new Crossrail trains on the section from Whitechapel to Abbey Wood in south-east London. The most challenging element involves converting the central brick and iron twin bore section of the 1878 tunnel back to a single bore tunnel.

Contractor Taylor Woodrow and client Crossrail have arranged a site visit to the site. Prior booking is mandatory and attendees will need to bring their own PPE consisting of hard hat, safety boots and orange hi-viz trousers and tops, plus safety glasses and gloves.

Contact: Andrew Kenyon, tel: 0779 556 6302 or email: andrew.kenyon@vinicconstruction.co.uk

Managing Landslide Risks on Major Onshore Oil and Gas Pipeline Systems
10 July, 6pm. Geological Society, Burlington House, London
This meeting of the Engineering Group of the Geological Society will also include the Engineering Group AGM.

Contact: Matthew Eynon email: matt@earthsciencepartnership.com

Thames Tideway Tunnels – project update
19 September, 6pm. ICE, London
The Thames Tideway Tunnel is the largest privately financed project in Europe. The “Supersewer” is needed to help tackle the 39Mt of sewage discharged into the tidal River Thames a year. After over two years of public consultation, the development consent application was submitted to the Planning Inspectorate in February.

Thames Water’s Phil Stride will give a presentation covering, among other things, the problem of sewage discharges to the river and the proposed solution; an outline of the technical challenges faced; the proposed delivery route for the construction; and the latest situation on procurement.

Contact: BIS secretary, tel: 020 7665 2229 or email: bts@ice.org.uk

Hidden Shafts – Investigations into Victorian Railway Tunnels across the UK
1 October, 6pm. ICE, London
This meeting of the British Tunnelling Society Young Members group will look at shaft construction on the Victorian railway network.

Contact: BTS secretary, tel: 020 7665 2229 or email: bts@ice.org.uk