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Geochemical and hydrogeological monitoring and verification of carbon storage in a depleted gas reservoir: examples from the Otway Project, Australia

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Introduction

A significant class of carbon dioxide (CO2) storage site anticipated to be utilized early in deployment of commercial Carbon Capture and Storage (CCS) is "depleted hydrocarbon reservoirs". These sites provide the advantage of being relatively data-rich and having the demonstrable containment security of the previously held hydrocarbon reserves. The Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) Otway Project in Australia is the first intensely monitored pilot site for CO_2 storage in a depleted gas reservoir. The project was planned in three broad stages. The first stage commenced in 2004 with site selection and characterization, development of an operational plan for the production transport and injection of CO_2, the design of an extensive monitoring and verification (M&V) program, and extensive baseline sampling. The second stage began with the start of injection in late March 2008 of a roughly 80:20 mol% CO_2:CH_4 gas mixture being produced from the nearby Buttress Field, compressed on surface, then transported 2.25 km in an underground pipeline and injected into the depleted Naylor Gas Field at a rate of up to 1000 tonnes per week. By July 2009, some 60,000 tonnes of CO_2 mixed gas had been stored. Extensive monitoring of both the reservoir and shallow subsurface has been conducted during this stage two. Finally, stage three will consist of long term post injection monitoring and decommissioning of the surface equipment.

Site Characterisation

The Naylor Gas Field (5.4 BSCF of 2P OGIP) was developed with a production completion of the Waarre-C Formation in the Naylor-1 discovery bore. Gas was produced from May 2002 until October 2003. An increasing water cut and an intraformational barrier (the Waarre-B) led to the setting of a casing patch across the Waarre-C and new perforations in the deeper Waarre-A level which produced until June 2004 when the well was shut-in due to water influx. A small gas cap remained in the Waarre-C of the Naylor structure with residual methane saturation of about 20% below the post-production gas-water contact (2039.5 m drill depth from the rotary table, or "mRT").

An analogue model of a braided fluvial system (Dance et al., 2008) was used to help generate a range of facies distributions with associated rock properties for the initial static geological model. In parallel, the regional hydrogeology was characterised (Hortle et al., 2008). This allowed the dynamic reservoir model to be conditioned with an extensive aquifer in hydraulic

communication with the Naylor Field, resulting in a good history match with the Naylor production history. The dynamic reservoir model was used to forecast the movement of CO_2 within the Naylor structure over the anticipated injection period and site the planned CRC-1 injection well (Xu and Pathmanathan, 2007). A travel time of about 6 months was targeted for the CO_2 injected at CRC-1 to migrate to the Naylor-1 observation well.

The CRC-1 well was drilled 300 m downdip from Nayor-1 in February-March 2007. New data (cores, cuttings, wireline pressure testing, fluid sampling, petrophysical logs and mud gas samples) facilitated an update of both the static and dynamic models. The updated geological model (braided fluvial but with more of a marine influence) was used to select a perforation interval in CRC-1 that would maximize the likelihood of a migration pathway communicating updip to the level of the current GWC.

Baseline Sampling

An assurance monitoring program (Hennig et al., 2008) was developed to demonstrate CO_2 containment to the regulators and the local community. Shallow and deep groundwater, soil gas, and atmospheric monitoring were conducted for 2 years prior to injection to establish the baseline conditions. Groundwater levels for 6 nearby monitoring and potential future water supply bores completed in shallow and deep aquifers are monitored and logged hourly. Groundwater samples are obtained biannually from 21 shallow and 3 deep water bores and analyzed for detailed geochemistry, dissolved gas content and isotopes (Caritat et al., 2008). Soil gas samples were initially taken biannually but subsequently reduced to yearly sampling during the summer months (Feb-Mar). It was determined that in winter the soil gas is swamped with shallow biogenic CO_2 (Hennig et al., 2008).

The baseline sampling of the subsurface reservoir gases revealed the supply CO_2 to be isotopically distinct from the CO_2 at Naylor-1. This enabled the CO_2 to be used as a natural tracer, however, no such distinction was found in the carbon isotopic composition of CH_4 or wet gas components (Boreham et al., 2008). Baseline soil gas samples have highly variable concentrations and isotopic signatures with a wide range of magmatic to biogenic origin (Watson et al., 2006). As a result, it was determined that the CO_2 to be injected at CRC-1 could not be uniquely identified from the natural variations of CO_2 already in the area if there were to be a seepage. To remedy this, tracer compounds at appropriate concentrations were added to the injected CO_2 gas mixture.

Monitoring and Verification Design

For assurance monitoring, the same groundwater, soil gas, and atmospheric monitoring surveys and equipment used to characterise the baseline conditions were continued during and post-injection. At reservoir level, a combined geochemical and geophysics integrated bottom hole assembly (BHA) was designed. In addition to the imaging provided by the surface and down-hole geophysics sensors and the monitoring of formation pressure changes with down-hole pressure-temperature gauges, geochemical sampling was planned to: a) provide physical evidence of the CO_2 arrival at the intended location within the Naylor structure; b) provide a measurement of the travel time for the injected gas between the CRC-1 and Naylor-1 wells; c) provide a timing and thus an injection volume for the filling of the depleted gas reservoir; d) measure the partitioning of the injected gas between the existing water and CH_4 phases; e) provide a measure of the tracer compound concentrations and partitioning; f) provide a measure

of the isotopic composition and mixing of the injected and in-situ CO_2; and, g) provide a measure of the formation water chemistry evolution with gas injection. These outputs are also intended to provide valuable calibration and validation of the static and dynamic reservoir models and the geochemical reaction path model. These desired scientific outcomes preclude the collection of geochemistry samples at the wellhead since the change in pressure and temperature between the reservoir and the wellhead allow for the fractionation of isotopic compositions and the degassing and subsequent change in chemistry of the liquid samples. To meet the requirements for minimally altered fluid samples, a multilevel downhole U-Tube sampling system (Freifeld et al., 2005) was deployed.

The BHA has a custom designed inflatable packer that was used to seal off the wellbore above the top of the Waarre C casing patch. Above the packer are 3 three-component and 8 single-component geophones used for microseismic monitoring and seismic reflection surveys, respectively. Below the packer are 3 geophones and 3 hydrophones for performing high resolution travel time measurements. Three U-Tube sampling ports are located in the borehole at: a) the CH_4 gas cap at 2028.8 mRT; b) just below the post-production GWC at 2041.8 mRT; and, c) deeper in the water leg at 2046.3 mRT. Unfortunately, the two pressure-temperature gauges in the BHA immediately failed, probably from water shorting the electrical connections. To compensate, wellhead pressure gauges were installed on all 6 of the U-Tube ¼ ” SS lines.

Operations

The operational mode commenced on the 18th March, 2008, with the continual injection of mixed gas into the CRC-1 well. Three tracers, CD_4 (2 kL), Kr (20 kL) and SF_6 (312 kg), were co-injected over a 2-day period on 4th and 5th April 2008 (Stalker et al., 2008). Numerical simulation established that the optimal time for the addition of tracers was after the injection of 1000 tonnes of the CO_2 mixed gas, which allowed dissolution of the various components at the leading-edge of migration through the Waarre C reservoir (Stalker et al., 2008). During normal operation, gas and water samples are collected weekly.

During sampling, a major operational challenge involved the build-up of hydrocarbon ‘wax’ at the supply and monitoring wells. The wax precipitating in the plant and equipment was characterised in the laboratory to be dominated by a homologous series of *n*-alkanes that initially maximised at *n*-C_{27} (Boreham et al., 2008) with a melting point of ~40°C. At Buttress-1, simply raising the produced fluid temperature with a hot water bath and using a heating tape provides an adequate level of preventative maintenance. At Naylor-1, a solvent delivery and retrieval system involving Solvesso-100™ has proven successful in flushing wax from the U-tube sampling lines.

Preliminary Results

Between the samples taken on June 27th and July 17th 2008, U-Tube 2 showed a slight drop in pH, a slight increase in dissolved CO_2 content, and an increase in the carbon isotopic composition of CO_2. In addition, U-Tube 2 showed the arrival of minute amounts of all three tracer compounds. U-Tube 2 subsequently displayed a consistent rise in CO_2 mol% with an abrupt increase in CO_2 mol% between August 7th and 22nd 2008. Here, it began transitioning from a N_2-assisted lift of formation water to a self-lifting gas, corresponding to the movement of the GWC to below the U-Tube 2 check valve intake. From mid-September 2008 to mid-February 2009, CO_2 contents in U-Tube 2 have consistently remained between 52–59 mol%. The deeper U-Tube 3 started transitioning to self-lifting gas in early November 2008, following the

cumulative injection of ~30,000 tonnes of mixed supercritical fluid. However, the transition to gas-lift occurred over a more extended period compared with U-Tube 2, with solely self-lift gas produced after mid-December 2008. Over the same period, the response of U-Tube 1 has remained comparatively subdued. The CO_2 content in U-Tube 1 stayed relatively low until U-Tube 3 transitioned to gas lift, when the CO_2 content in U-Tube 1 rose to ~21% (Fig. 1).

The aqueous samples from U-Tube 2 and 3 both showed a drop in pH coincident with the increased dissolved CO_2 content consistent with buffering by calcite. However, there was no corresponding increase in HCO_3^- and Ca^{2+} to the degree predicted by geochemical modeling. This suggests that either the injected CO_2 has not had significant contact with the formation water and that the observed changes in aqueous geochemistry are local, occuring near the supercritical CO_2 front or reservoir heterogeneity is preferentially moving un-reacted CO_2 through the lower part of the gas saturated zone (Kirste et al., 2009).

Comparisons will also be made between the pre-injection numerical simulations and estimated storage capacity for the depleted gas reservoir and the observations at the Naylor-1 wellbore. The Otway Project represents the first extensively monitored CO_2 storage in a depleted gas reservoir. The site characterization and definition of the initial static and dynamic models allowed for the design of the infrastructure to deliver results within the project timeframe. An integrated M&V program was developed and deployed to maximise data acquisition and quality. Injection to date of 60,000 tonnes has successfully been emplaced in the target reservoir and the CO_2 has migrated into the intended storage structure around the monitoring bore. The geochemical sampling program has defined the breakthrough of dissolved then supercritical CO_2 with the added tracer compounds within the design parameters of the test. Ongoing sampling will provide more valuable data into the future.

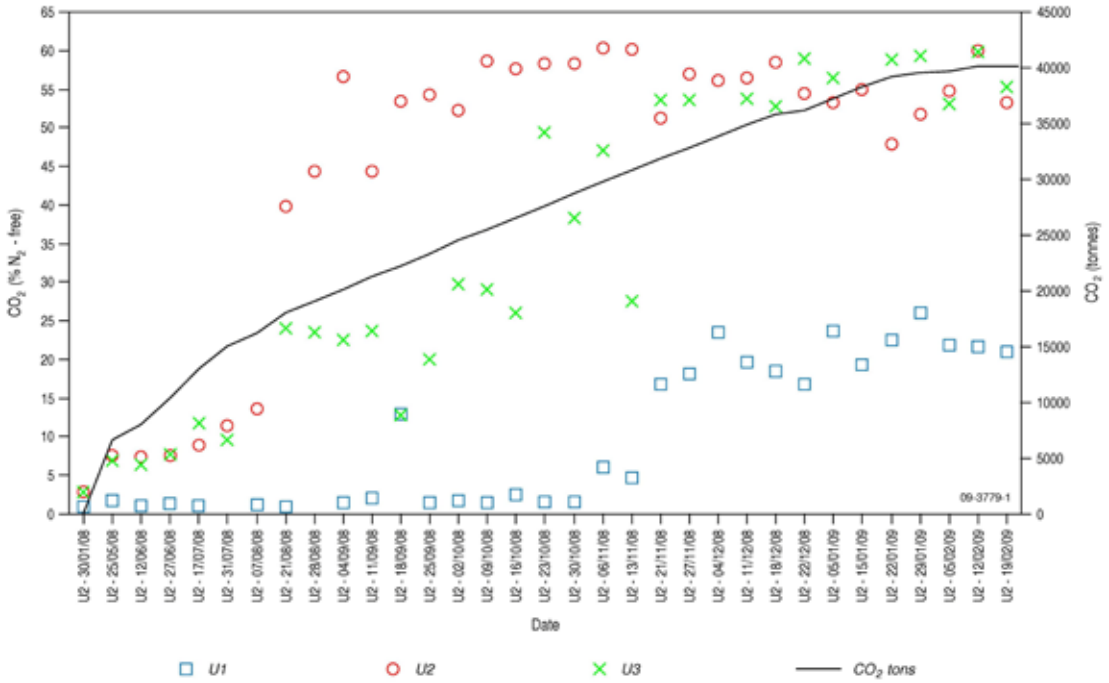

Figure 1. Time series of a) CO_2 content (% as N_2-free basis) of samples collected from U-tubes at Naylor-1 well, and 2) cumulative tonnes of mixed supercritical CO_2-CH_4 injected into at CRC-1 well.

Conclusions

The CO2CRC Otway Project is reaching 18 months injection and has successfully demonstrated the storage of over 60,000 tonnes of CO_2 mixed gas. Geochemical sampling at the Naylor-1 observation well has detected tracer compounds and measured isotopic composition of the gas chemistry that conclusively demonstrate the injected mixed gas has migrated into the Naylor structure as predicted by numerical simulation. Further monitoring of the site will continue to provide valuable data to help calibrate the static and dynamic models and provide assurance of containment.

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References:

Boreham, C. J., J. Chen, and Z. Hong, 2008, Baseline study on sub-surface petroleum occurrences at the CO2CRC, Otway Project, western Victoria. Eastern Australasian Basins Symposium III, Sydney, 14–17 September, 2008, p. 489–499.

Dance, T., L. Spencer, and J. Q. Xu, 2008, Geological characterization of the Otway pilot site: what a difference a well makes. 9th International Conference on Greenhouse Gas Technologies (GHGT-9), 16 - 20 November 2008, The Omni Shoreham Hotel, Washington DC. Extended Abstract.

de Caritat, P, D. Kirste, and A. Hortle, 2008, Pre-injection baseline of groundwater composition and levels in the CO2CRC Otway Project area, Victoria, Australia. CO2CRC Research Symposium. Queenstown, New Zealand.

Freifeld, B. M., R. C. Trautz, K. K. Yousif, T. J. Phelps, L. R. Myer, S. D. Hovorka, and D. Collins, 2005, The U-Tube: A novel system for acquiring borehole fluid samples from a deep geologic CO_2 sequestration experiment. J Geophys. Res., v. 110, B10293, doi:10.1029/2005JB003735.

Hennig, A, D. Etheridge, P. de Caritat, M. Watson, R. Leuning, C. Boreham, D. de Vries, D. Sherlock, and S. Sharma, 2008, Assurance Monitoring in the CO2CRC Otway Project to demonstrate geological storage of CO2: Review of the Environmental Monitoring Systems and Results Prior to the Injection of CO2. APPEA Journal, v. 48.

Hortle, A., J. Xu, and T. Dance, 2008, Hydrodynamic interpretation of the Waarre Formation Aquifer in the onshore Otway Basin: Implications for the CO2CRC Otway Basin Project. 9th International Conference on Greenhouse Gas Technologies (GHGT-9), 16 - 20 November 2008, The Omni Shoreham Hotel, Washington DC. Extended Abstract.

Kirste, D, E. Perkins, C. Boreham, B. Freifeld, L. Stalker, U. Schacht, and J. Underschultz, 2009, Geochemical modelling and formation water monitoring at the CO2CRC Otway Project, Victoria, Australia Submitted to the 24th International Applied Geochemistry Symposium, 1-4 June, 2009, Fredericton, N.B., Canada.

Stalker, L., C. Boreham, J. Underschultz, B. Freifeld, E. Perkins, and S. Sharma, 2008, Geochemical monitoring at the CO2CRC Otway Project: tracer injection and reservoir fluid acquisition. 9th International Conference on Greenhouse Gas Technologies (GHGT-9), 16 - 20 November 2008, The Omni Shoreham Hotel, Washington DC. Extended Abstract.

Watson, M., C. Rogers, and C. Boreham, 2006, Initial soil gas sampling results: OBPP and associated natural CO_2 accumulations. CO2CRC Research Symposium. Hunter Valley Australia. 14-16 November.

Xu, J. and M. Pathmanathan, 2007, The Otway project reservoir simulation study. CO2CRC Research Symposium. 6-8 November. p. 49.