Developing a Monitoring and Verification Scheme for a Pilot Project, Otway Basin, Australia

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Abstract
The Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) has selected a site in the Otway Basin SE Australia, as a demonstration pilot project for all aspects of geosequestration of CO\textsubscript{2}. The Otway Basin with its natural CO\textsubscript{2} accumulations and many depleted gas fields, offers an appropriate site for such a pilot project. The goal of this pilot project is to demonstrate that CO\textsubscript{2} can be safely transported and stored underground. The constraints of risk assessment and established regulatory performance criteria over the different phases of the project, provide a framework within which a range of established direct and remote sensing technologies are deployed. These provide repeat assessments from a reservoir, containment, wellbore integrity, near surface and atmospheric perspective. The measurements involve seismic, microseismic, petrophysical well logs and geochemical sampling including tracer and isotope analysis, plus associated forward modelling. The areal consequences of CO\textsubscript{2} migration and trapping will be addressed through characterization of the hydrodynamic properties of the region. A network of soil sampling and atmospheric detectors is planned to provide a baseline against which anomalous sources of CO\textsubscript{2} can be distinguished from the storage reservoir CO\textsubscript{2} to the satisfaction of the community and regulatory authorities.

Keywords: monitoring, verification, risk, regulatory, geophysics, geochemistry, atmospheric

Introduction
The Otway Basin Pilot Project (OBPP) meets all five storage project attributes which are: proximity to source, storage capacity, containment, injectivity and environmental integrity. The commercial oil and gas tenements in the Otway Basin in Victoria, selected for the pilot project, are in an undeveloped CO\textsubscript{2} field (Buttress), which is the source of CO\textsubscript{2}, and a depleted gas field (Naylor), which will be the injection/containment site. The extracted and separated CO\textsubscript{2} stream will be transported by pipeline and injected into a new well; drilled down-dip of the existing well; into the depleted Waarre reservoir in the Naylor field at a depth of approximately 2000 metres. Characterization of the site has involved analysis of a large quantity of geological, geophysical and other regionally relevant data and the construction of static and dynamic reservoir models. The regional formations provide an excellent porous and permeable geological formation that will provide a highly suitable reservoir system for CO\textsubscript{2} storage. In summary, the site assessment results, indicating that the Waarre Formation is a suitable storage reservoir for CO\textsubscript{2}, conclude the following key attributes. There are no significant faults evident in the wells at the Waarre C level and there is a fairly uniform Waarre C thickness. The local and regional seals have contained a

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number of natural CO$_2$ accumulations in the eastern Otway Basin over geological time. The storage reservoir has enough porosity and permeability to be able to accept the injected CO$_2$ at forecasted rates. The injected CO$_2$ is predicted to move updip from the injector location and migrate to the crest of the fault block and accumulate below the residual methane gas cap in the vicinity of existing Naylor-1 well. The selected site has the major advantage of being onshore rather than offshore, allowing the project research teams to test and further refine the monitoring and verification techniques at a more accessible location.

**Monitoring and Verification Role in Geosequestration**

The goals of a monitoring framework is to provide a comprehensive set of information from direct measurements and remote sensing of the process of injection and storage of CO$_2$, such that we can appropriately document the complete storage process to establish the safe transport, injection, containment of CO$_2$ and the subsequent safe abandonment and restoration of the site. Within this function we must meet the requirements of the Regulatory Impact Statement 2004 from the Commonwealth Organization of Australian Governments (COAG) that for the purposes of monitoring and verification, a regulatory framework should:

- Provide for the generation of clear, comprehensive, timely and accurate information that is used to effectively and responsibly manage environmental, health, safety and economic risks and to ensure that set performance standards are being met; and

- Determine to an appropriate level of accuracy the quantity, composition and location of gas captured, transported, injected and stored and the net abatement of emissions. This should include identification and accounting of fugitive emissions

The range of monitoring and verification (M&V) technologies comprises an integrated framework of diverse methods and measurement systems crossing many disciplinary boundaries. We have categorized them by their means of measurement; either remote, or direct sampling, or by their domain of operation, of which there are three. The first is the sub-surface domain to monitor and verify the deep injection and migration behaviour of injected CO$_2$, from the surface or borehole. The second is the near-surface domain comprising sampling and remote measurements to verify the non-seepage to shallow zones and soils again from surface and borehole. Finally the atmospheric domain, comprising a baseline characterization of seasonal and diurnal variation of existing gas distribution and composition accumulated over suitable time which can be monitored by point source gas sampling, coupled with dispersion modeling or by spectral absorption and infrared detectors locally or by aircraft and satellite. The M&V technologies are deployed in a number of modes across the project lifetime. Monitoring can be categorized into baseline and operational monitoring. While verification monitoring consists of both subsurface and environmental confirmation of performance criteria.

**Pilot Project Risk Assessment**

A complete qualitative and quantitative risk assessment has been carried out to determine the overall suitability of the site for long-term storage. The risk of leakage from man-made leakage pathways resulting from the storage site itself, such as dissolution of the seal, are reduced by selecting sites with thick sealing formations such as the Belfast Mudstone. Fault reactivation after injection ceases is extremely unlikely as the pressure exerted on any fault by the CO$_2$ is likely to be less than originally existed when containing hydrocarbons. The OBPP site has multiple barriers to potable water aquifers and the modeling has shown that even in the unlikely event that escape from the primary storage site occurs, the CO$_2$ will be contained within the overlying reservoir formations. Leakage through wells is also a very remote possibility as the injection horizon is deep and multiple plugs will be placed in the well bore as part of the well decommissioning process.
Subsurface M&V planned for OBPP

The first task is to refine the uncertainties in reservoir properties. There has been a reasonable elapsed time between acquisition of the 3D seismic and the subsequent production and shut-in of the Naylor-1 well. There is residual gas within the Naylor reservoir with uncertainty as to the gas-water contact in Naylor-1. The presence of residual gas provides a significant challenge to direct detection of the CO$_2$ plume once it migrates out of the water zone after injection. More precise understanding of these properties will determine the monitoring options we have. Both Naylor-1 and Buttress-1 will be re-entered to establish gas water contacts with reference to a reservoir saturation log and the integrity of the cement bonds through casing and cement inspection logs. This will also provide an opportunity to test the viability of VSP methods being planned. A new injection well is planned to be drilled close to the observation well. Data gathering activities will include obtaining cores through the top seal and each of the Timboon and Waare formations, thus allowing for future laboratory testing. Openhole wireline logs and pressure measurements/flow samples from the reservoir will be taken as well. Pressure transient testing will be used to determine the hydrologic characteristics prior to injection of CO$_2$. The results will be used to modify the injection protocol, if needed. Once the casing has been run and cemented, the integrity of the seal will be assessed through running casing and cement inspection surveys. Downhole pressure and temperature gauges will be run to monitor injection conditions.

In favourable conditions surface and borehole seismic are important survey tools, as the geological formations and structures can be defined and quite subtle changes associated with the presence of the supercritical fluid can also be detected. We have forward modeled the expected seismic response [1] and predict the travel time differences associated with the CO$_2$ plume with the gas, to be of the order of 50 $\mu$secs, below the detectability of conventional acquisition. We studying in the laboratory the elastic response of the reservoir under different effective stresses and for sub and supercritical CO$_2$ together with methane in comparison to Gassman prediction [2]. With respect to this challenge we plan to carry out walkaway VSPs using a compressional and shear source together with multicomponent surface lines to tie back to the existing 3D seismic. These will provide the means to get higher resolution imaging and in particular allow us to infer fluid properties from elastic amplitude versus offset (AVO) data. In collaboration with Lawrence Berkely National Laboratories we plan to acquire and process travel time data to $\mu$sec accuracy. Opportunities to acquire time-lapse data before and after injection will be taken, and where practical permanent sensor array is being considered for both observation and injection well. In addition to these surveys, we plan to deploy both on surface and downhole, where practical, tiltmeters, microseismic and differential GPS sensors. This will provide the means to monitor the changes in stress state associated with the injection and detect or rule out any signs of reactivation of the bounding fault ahead of time. Comparisons before and after injection will be important to establish any departures from baseline.

Wellhead and downhole fluid sampling at the monitoring well will be carried out before, during, and after CO$_2$ injection. Both chemical and isotopic analysis will be made of fluids and gases. The changes in the elemental and isotopic compositions will be used to monitor the geochemical reactions occurring in the reservoir, and to establish the nature and amount of geochemical trapping of CO$_2$ [3]. The analytical results for tracers (both injected and natural) will be used to confirm the arrival of the CO$_2$ plume at the monitoring well. In addition, their relative retardation can be used to determine saturations in the region swept by the CO$_2$ plume, thereby showing the extent of gravity override versus uniform volumetric sweep. Tracers will also be used follow the movement of the injected carbon dioxide in the subsurface injection formation, and movement beyond and through the seal, into overlying aquifers, soil leakage and atmosphere [4].

The presence of naturally occurring subsurface CO$_2$ in the Otway sub-basin makes identifying the injected CO$_2$ more complex. A regional survey of the distribution, type and origin of existing CO$_2$
a will be carried out through an integrated program of soil gas sampling, hydrogeology, water chemistry and atmospheric measurements. Sampling will be carried out over a defined grid and repeated several times per year (to account for seasonal effects), before, during and after injection. The areal consequences of CO$_2$ migration and trapping will be addressed through characterization of the hydrodynamic properties of the region. The connectivity and fluid migration timescales of the potential and existing fresh water reservoirs will be established using available hydraulic head, well pressure and geological information. This will provide input into establishing fluid pathways, flow timescales and identifying flow barriers due to facies changes and faults. (Figure 1.)

A sentinel network of atmospheric monitoring equipment will be set up to provide the environmental background against which anomalous sources of CO$_2$ can be detected. The proposed location and layout of the Otway Project has some significant advantages for the assessment of possible impact of atmospheric monitoring. It is in a rural region with the coast only 4 km to the southwest. SW winds are prevalent. The short fetch across mainly pasture or lightly forested land will minimise the CO$_2$ concentration variations resulting from ecological exchange. The CO$_2$ source well (Buttress), and others sources of CO$_2$, and their associated infrastructure, which may release CO$_2$ and other gases, are downwind of the proposed geosequestration well while SW winds prevail. The Cape Grim Baseline Atmospheric Pollution Station, (a WMO Global Atmosphere Watch station, operated jointly by CSIRO and the Bureau of Meteorology) has monitored atmospheric composition for decades and can be used as a baseline reference. A CO$_2$ analyser system (LoFlo [5]), which provides high precision continuous CO$_2$ measurements, will be used. CO$_2$ arising from well and storage site will be determined using atmospheric dispersion analysis [6]. This technique requires measurements of CO$_2$ and tracer gas concentrations up- and down-wind of the source plus an understanding of the dispersion at small scales (tens to hundreds of metres, influenced by micrometeorology) to larger scales (several kilometers, influenced additionally by mesoscale and synoptic winds). The CO$_2$ of magmatic origin can also be distinguished by its enriched $^{13}$C isotopic content compared to that derived from ecological exchange, biomass burning and fossil fuel. The injected CO$_2$ will also be marked by detectable tracers.
Pilot Project Phasing and Operations

In discussion with the appropriate government regulatory authorities [4] the project work scope has been divided into four project phases which reflect the focus of the project on storage and related monitoring activities. Each phase completion is approved through verification of performance against objectives:

Phase 1A Pre-Injection (i) Establish injection and migration models and uncertainties

Phase 1B Production and Injection (1) Environmental impacts within regulatory bounds
Injection/Migration within model prediction bounds

Phase 2 Post Injection (1) Verified stable plume within model prediction. (2) Appropriate decommissioning certificate(s) from the authorities

Phase 3 Post Closure (1) No evidence of injected CO$_2$ within specified period.

Phase 4 Longer Term (1) No evidence of injected CO$_2$ within specified period.

The role of monitoring and verification of performance for Phases 1A, 1B and Phase 2 will require a continuum of high intensity monitoring activities comprising the complete suite of subsurface technology to predict, measure and verify performance of injection and migration with pre-injection baseline data sets for reference. Phase 2 will see post injection closure of the Buttress well and decommissioning of the surface facilities. M&V tasks will be ongoing in the Naylor site to validate the transition criteria to Phase 3. The validation that the plume is now stable will come from log based measurements showing no evidence of CO$_2$ in the overlying formation beyond secondary containment. In addition fluid samples collected from existing deep water wells should show no evidence of the injected CO$_2$. There are four such wells. Soil and air samples collected in the proximity of the Naylor-1 and Naylor-2 wells should also show no evidence of the injected CO$_2$. Phase 3 is focused on public assurance and monitoring for long-term storage security. It is planned to augment a program of water well monitoring by the local water authority by testing soil samples from these wells for evidence of the injected CO$_2$. If no evidence of the injected CO$_2$ is detected in 2 years, this phase can transition into Phase 4. Monitoring for Phase 4 will continue to focus on public assurance through the augmented testing program in the deep wells as described.
above. Again, where there is no surface evidence of injected CO$_2$ for a further 2 years, this phase can terminate.

**Conclusion**

A pilot project has been planned to comprehensively test all phases of a large scale geosequestration project. The planning for this project has been based on a detailed geological evaluation and the planning for monitoring the disposition of the CO$_2$ has been carried out with reference to public and regulatory safety requirements and a thorough and rigorous risk assessment of the containment. The project also addresses near-term and long-term monitoring issues raised by the necessary time of containment and the transitional phases are approved against performance objectives verified by analysis of the acquired data. The monitoring will comprise established technology, but will also be used as a test for innovative technology. The project offers a unique set of circumstances to implement and demonstrate an integrated range of downhole and atmospheric sensing technologies to ensure successful long term storage and provide public assurance of the safety of the project.

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**Reference List:**


