Planning multi-parameter/multidimensional monitoring of CO_2 storage, using the Otway Basin Pilot Project as an example.

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Abstract

The Australian Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) is proposing to inject 100,000 tons of CO_2 in a large scale test of storage technology in a pilot project in South Eastern Australia called the Otway Basin Pilot Project (OBPP). The Otway Basin with its natural CO_2 accumulations and many depleted gas fields, offers an appropriate site for such a pilot project. An 88% CO_2 stream will be produced from a well (Buttress) near to the proposed depleted gas reservoir (Naylor) intended for storage. The goal of this pilot project is to demonstrate that CO_2 can be safely transported and stored underground. The monitoring and verification framework has been developed to monitor for the presence and behaviour of CO_2 in the sub-surface reservoir, near surface and atmosphere. A range of technologies will address risk areas identified by a rigorous process of risk assessment and subsequently verify conformance to clearly identifiable performance criteria. These criteria have been agreed in conjunction with the regulatory authorities to manage the project through all phases addressing responsibilities, liabilities and to provide assurance of safe storage to the satisfaction of the public at large. Many aspects of the proposed monitoring will be discussed and this paper will provide an overview of the whole plan, with emphasis on the atmospheric monitoring strategy, as this is unique in its approach to other projects around the world.

An extensive range of established direct and remote sensing technologies deployed on surface and in the borehole have been planned for repeat assessments from a reservoir, containment, wellbore integrity, near surface and atmospheric perspective. These involve seismic, microseismic, petrophysical well logs and geochemical sampling including tracer and isotope analysis, plus associated forward modelling. The presence of naturally occurring subsurface CO_2 in the Otway area makes it more difficult to identify injected CO_2. A regional survey of the distribution, type and origin of existing CO_2 will be carried out through soil gas sampling. 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 time scales of the potential fresh water reservoirs will be established using all available (and appropriate) well pressure and geological information.

Introduction

The commercial oil and gas leases (tenements), in the Otway Basin in Victoria, selected for the pilot project, are in an undeveloped CO_2 field (Buttress), which is the source of CO_2, and a depleted gas field (Naylor), which will be the injection/containment site (figure 1.). The extracted and separated CO_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 the collection 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_2 storage. In summary, the site assessment results, indicating that the Waarre Formation is a suitable site for CO_2 storage, conclude the following key attributes of the site. There are no significant faults evident in the wells at the Waarre C level; there is a fairly uniform Waarre C thickness. The local and regional seals have contained a 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 rates forecast. 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.

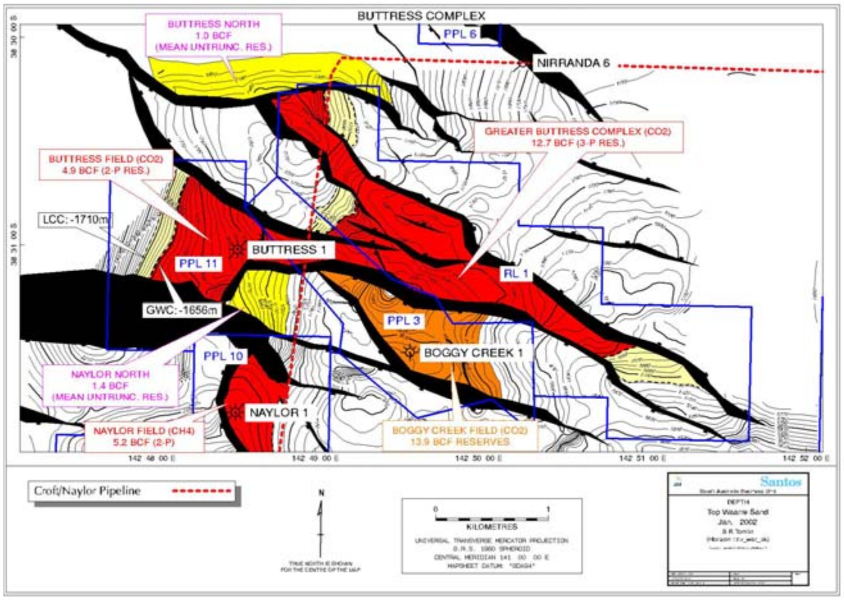


Figure 1. Top Waare Sand Structure Map

Pilot Project Risk Assessment

A comprehensive risk assessment has been undertaken for all stages of the OBPP before commencing CO_2 injection. A systematic approach has been taken to risk assessment for the OBPP considering both the engineered and natural systems. The engineered systems consist of the wells, the plant, the gathering line while the natural system includes the geology, the reservoir, the overlying and underlying formations and the groundwater flow regimes. Under the qualitative risk assessment approach, a listing of the potential risks, their specific issues and potential consequences was created. Mitigation measures were then defined to bring the risk levels down to acceptable levels. This was supplemented by a quantitative risk assessment (QRA) wherein mathematical probabilities through Monte Carlo simulation were assigned to specific risk events and simulations run to consider the range of impacts.

The qualitative assessment is developed through a "risk register" designed to cover all aspects of the project. The initial Planning and Pre-Implementation register consists of items largely related to the uncertainties associated with the planning of the project, such as regulatory approval, long term liability, project execution management, material availability, funding, land owner agreements and public acceptability. The second Implementation Risk register deals with production, processing, transportation, drilling and injection risks, as well as personnel and decommissioning risks. These have well established procedures developed within the oil and gas for over seventy years. Extensive geoscience work done suggests that the source and sink are able to meet the project demands with high certainty. The area is not new for petroleum-type activities and there are several production wells, a gas injection and storage site and processing plants in the immediate vicinity of the project site that have been working safely for years and that are accepted by the local community.

The last Long Term and Containment risk register provides a means to assess long-term containment needs through an evaluation of the potential natural and man-made leakage pathways, their likelihood of being activated, and an assessment of the amount and duration of any leaked volumes. Natural pathways include permeable zones in seal, faults either existing or caused by regional over-pressurisation or earthquakes. Incorrect mapping of the migration direction and exceeding filling the reservoir beyond spill point can also be causal in allowing the CO_2 to migrate beyond its intended area. This risk is minimal as Naylor is a depleted oil/gas field which has previously held more fluids than are being injected and probably for many millions of years. The risk of leakage from most man-made leakage pathways such as wells can be easily managed this is standard activity in the oil and gas business. There are also multiple barriers between the storage reservoir and shallow water aquifers.

The quantitative risk assessment follows the RISQUE method (Bowden et al, 2004), which is a systematic process that uses a formal group of experts to provide quantitative judgments that are incorporated into a risk analysis and management framework. The basic approach to this process is to characterize and quantify risk both in terms of likelihood of identified risk events and also their consequences. The risk assessment approach integrates current best practice risk assessment methods with best available information. The "expert panel" assesses all available information against a list of containment risk issues. This list is used consistently for different sites, and hence provides a means to quantitatively compare different sites for containment risk. The list consists of quantitative leakage risk of permeable zones in seal, faults, wells, leakage via seal, regional scale over-pressurisation, local scale over-pressurisation, CO_2 exceeding spill point of the storage site, earthquake - induced fractures, incorrect modelling of migration direction, unintentional over-filling of the storage site, well-head, pipeline, or compressor failure.

Overall, the risk analysis demonstrates that the OBPP has all low risk events with minimal consequences. 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 barriers (plugs) will be placed in the well bore as part of the well decommissioning process

Monitoring and Verification Role

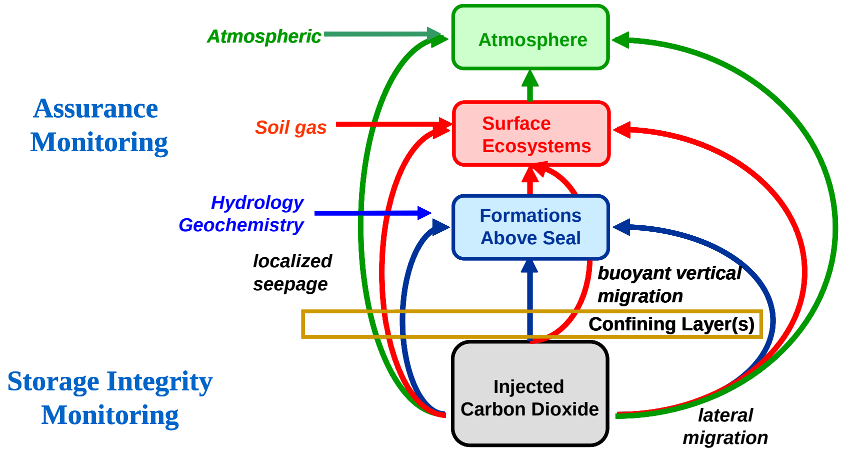
The goals of a monitoring framework is to provide a comprehensive set of information from direct measurements and remote sensing of the process of injection and storage of CO_2, such that we can appropriately document the complete storage process to establish the safe transport, injection, containment 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 infra red 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.



Modified from: http://web.princeton.edu/sites/cmi-aquifers/

Figure 2. Monitoring and Verification Domain of application

Pilot Project Phasing and Regulatory Performance Indicators

In discussion with the appropriate government regulatory authorities 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 assessed by verification of performance against objectives:

- Phase 1A Pre-Injection
    - Establish injection and migration models and uncertainties
- Phase 1B Production and Injection
    - Environmental impacts within regulatory bounds
    - Injection/Migration within model prediction bounds
- Phase 2 Post Injection
    - Verified stable plume within model prediction.
    - Appropriate decommissioning certificate(s) from the authorities
    - Wells decommissioned as per regulation

    - Sites restored as per regulation
- Phase 3 Post Closure
    - No evidence of injected CO_2 within specified period.
- Phase 4 Longer Term
    - No evidence of injected CO_2 within specified period.

The role of monitoring and verification of performance for Phases 1A, 1B and 2 will require a continuum of high intensity monitoring activities. The transition from one phase to another will be dependent on engineering determinants, which will be well defined. Phase 2 will see post injection closure (or sale) 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 evidence of injected CO_2 for a further 2 years, this phase can terminate.

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/fluid 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 (Li et al, 2006) and predict the travel time differences associated with the CO_2 plume with the gas, to be of the order of 50 μsecs, 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 (Siggins, 2006). 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 μsec 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 (Perkins et al, 2006). 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. It is expected that each tracer will uniquely partition between the aqueous, supercritical CO_2 phases. If the partitioning between the phases is appropriate, the tracer may act as a precursor to the injection stream and provide an early signal of movement. A number of chemical tracers are currently being evaluated for injection [3] in the supercritical carbon dioxide stream with detection limit, suitability, availability and health and safety as the primary concern.

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.

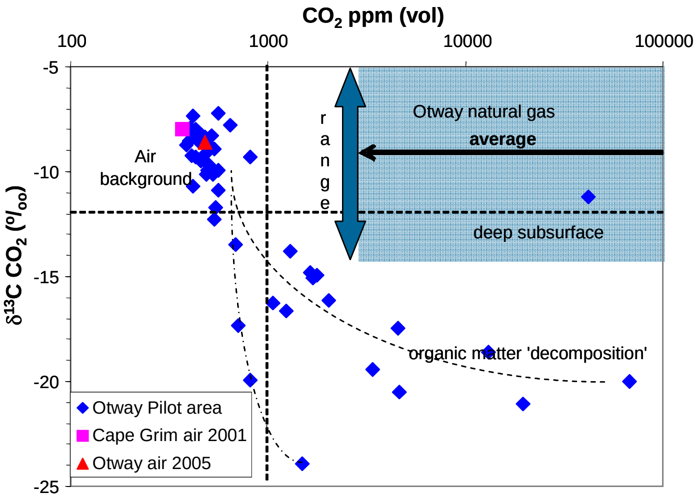


Figure 3. Soil sampling showing predominant biological signature

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 (Francey et al 2003), 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 (Hurley et al, 2005). 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.

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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