**CONFIDENTIAL**

# CO2CRC OTWAY PROJECT

# ANNUAL EXPERT REVIEW OF MONITORING AND VERIFICATION PROGRAMME

*Report Number: 2009/TR4*

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## ACKNOWLEDGEMENTS AND CITATIONS

This report was prepared on behalf of the IEA Greenhouse Gas R&D Programme by Sarah Hannis of the British Geological Survey.

The report should be cited in literature as follows:

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Further information on the Programmes' activities or copies of reports can be obtained by contacting the IEA GHG Programme at:

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# CO2CRC Otway Project

## Expert Review of Monitoring and Verification Programme

### Executive Summary

The Australian Cooperative Research Centre for Greenhouse Gas technologies (CO2CRC) is conducting a $CO_2$ injection project in Australia. Known as the CO2CRC Otway Project this is the first project to inject and store $CO_2$ under Australian conditions. The project, which is of intermediate scale, will inject approximately 100,000 tonnes of $CO_2$ over a 2 year period. The $CO_2$ is be extracted from a nearby natural accumulation via an existing production well then transported via pipeline and injected into a depleted gas field (called the Naylor gas field). In support of the injection project, a detailed monitoring programme has been developed by the CO2CRC for the Otway Project. One year since the injection and monitoring operations commenced, the IEA Greenhouse Gas R&D Programme (IEA GHG) was invited by the CO2CRC to undertake an independent expert annual review of the Otway Project monitoring programme.

An international team of experts (from Canada, France, UK and USA) was assembled by IEA GHG which reviewed the monitoring progress for the Otway Project. The Otway Project is considered to be an important, first of its kind, $CO_2$ injection activity into an onshore depleted gas reservoir. The Otway Project therefore provides important experience in monitoring this type of reservoir, which is likely to be widely used globally for $CO_2$ storage. The Otway Project is also interesting in that it is a composite onshore demonstration project that includes many key aspects of $CO_2$ storage i.e. $CO_2$ production, transportation, injection, and storage, albeit at a small scale, in a single demonstration project. A further strength of the project is considered to be CO2CRCs ownership of the production and injection wells which will allow the research programme to proceed unencumbered by external operational requirements which should allow the Otway Project to deliver on range of research objectives.

Whilst this review does not correspond to any particular project milestones, it shows the success to date in the project implementation and monitoring methodologies and results. It is clear that the monitoring work gives an indication that the reservoir is performing according to predictions. Despite the challenges associated with a depleted gas reservoir environment with a small diameter monitoring well the monitoring approach has shown significant success. This intensive and integrated effort is a first demonstration of feasibility for a depleted gas reservoir in Australia and represents a significant contribution to world knowledge.

With respect to the Otway Project monitoring program, the expert review team considered that:

a) In general the capacity, reliability, accuracy of many elements of the monitoring processes, are being demonstrated in the year since injection commenced, although as might be expected for a pilot test some techniques suffered from equipment reliability issues.

b) Findings to date are consistent with model predictions about the injection stream (principally the $CO_2$ plume).

c) Although some techniques demonstrated understanding and appropriate handling of the uncertainties in the monitoring and verification (M&V), in general there was insufficient reporting of these.

d) The monitoring programme was technically sound. Some assurance techniques would benefit from more consideration on expected responses for potential leakage scenarios.

e) The overall Monitoring and Verification approach is comprehensive, fulfils the requirements and is achievable within the programme schedule.

Particular recommendations include:

- Due to the likely challenging nature of integrating the results of the components of the M&V programme, reviewers recommend efforts start as soon as possible.

- Regardless of possible plans for repeat injections, reviewers recommend strongly that a plan for post-injection monitoring is developed if it is not already in existence. Results from post-injection monitoring at pilot projects (for example at Nagaoka) can provide key evidence for long-term storage assurance.

- Where there has been equipment failure, this is analysed for any recommendations for future improved practice.

The features of the Otway Project test site (own $CO_2$ supply, pipeline and injection site) make it suitable for consideration as an international test site for MMV. As such it may be well placed to also consider injection into the overlying aquifer, with potential important research potential which may have wider usefulness for Australian and worldwide storage projects.

# CO2CRC Otway Project

## Annual Expert Review of Monitoring and Verification Programme

### 1. BACKGROUND

The IEA Greenhouse Gas R&D Programme (IEA GHG) has organised a number of expert reviews for research projects and programmes on $CO_2$ capture and storage. IEA GHG has been actively involved in a number of practical R&D projects that involve the monitoring of injected $CO_2$. In addition, IEA GHG also runs an international research network on monitoring. IEA GHG, therefore, has considerable expertise and the technical experience to conduct expert reviews for projects. IEA GHG connections in the field also mean that it is well placed to organise independent project reviews using internationally respected experts.

The Australian Cooperative Research Centre for Greenhouse Gas technologies (CO2CRC) is currently undertaking the Otway Project for the injection and storage of carbon dioxide ($CO_2$) under Australian conditions. The Otway Project site is located in south-western Victoria (Australia). The aim of the project is to demonstrate that approximately 100,000 tonnes of $CO_2$ can be safely extracted from a nearby natural accumulation via an existing production well then transported via pipeline and injected over a two year period into a depleted gas field (Naylor gas field).

Monitoring is a critical portion of any $CO_2$ storage project programme and provides assurance that the injected greenhouse gas stream is confined to and migrating as expected in the target formation. A detailed monitoring programme has been developed by the CO2CRC for the Otway Project. Prior to the start of injection and monitoring operations IEA GHG undertook an independent expert review of the monitoring and verification programme for the Otway Project on behalf of CO2CRC. The independent review (IEA-GHG report number 2006/TR4) was aimed to supplement the internal project reviews that had already been undertaken with the project's industrial partners.

This report produced by IEA-GHG forms an annual independent expert review of the project. It focuses on the last year's worth of data collected by the project and any interim results and findings. This is in accordance with CO2CRC's remit from the Australian Federal Government and does not coincide with any of the project milestones. As the project approaches completion, it is an opportunity to document findings so far and to stimulate scientific discussion to identify gaps in research. Another similar review is scheduled for after mid-2010 when injection for phase one is complete.

## 2. EXPERT REVIEW PROCESS

### *Aims and Objectives*

The aim of the international independent expert review of the Otway Project monitoring programme was:

1. To review the status and findings to date of the monitoring and verification work programme that is being conducted by the CO2CRC for the Otway Project according to the five questions (below) provided by the project operators and through scientific and technical discussion:

    a) Capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.
    b) Usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.
    c) Demonstrated understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.
    d) Any scientific or technical issues that require attention.
    e) Likelihood that the M&V programme will be brought to a successful conclusion.

### *Expert Review Panel*

The Expert Review of the Otway Project was organised by IEA GHG in co-ordination with CO2CRC. Tim Dixon from IEA GHG managed the review process and acted as the Chairman of the review panel.

A group of technical experts was assembled for the expert review primarily from research groups not directly involved in the Otway Project. The experts were selected so that their range of expertise covered the range of monitoring activities encompassed in the monitoring and verification programme for the Otway Project. The experts that participated in the expert review are listed below, and biographies are provided in Appendix 17:

| Expert | Affiliation | Expertise |
|---|---|---|
| Dr Susan Hovorka | Texas Bureau of Economic Geology | Monitoring programme development, tracers and geochemical monitoring |
| Dr Andy Chadwick | British Geological Survey | Geophysical monitoring, seismic interpretation and simulation studies |
| Dr Don White | Geological Survey of Canada | Geophysical monitoring |
| Dr Mark Raistrick | Senergy Ltd | Geochemical monitoring |
| Lee Spangler | Montana State University | Surface monitoring |
| Hubert Fabriol | Bureau de recherches géologiques et minières | Geophysical monitoring |
| Neil Wildgust | IEA Greenhouse Gas R&D Programme | Monitoring programme development |
| Sarah Hannis | British Geological Survey | Rapporteur |

***Expert Review Programme***

The expert review involved:

1. CO2CRC provided scientific papers on different aspects of the Otway Project monitoring and verification programme for expert review. These were provided to the experts two weeks prior to the meeting together a blank review form detailing the five questions (Appendix 1). These were assigned to members of the panel according to their areas of expertise. Each paper was reviewed by at least two experts.
2. Detailed scientific and technical feedback to the monitoring researchers was documented by the experts prior to the meeting and these were returned to the relevant CO2CRC researchers. In some cases responses to comments were returned prior to the meeting.
3. A meeting was held IEA-GHG on the 1st June at the AIST, Waterfront Centre, Tokyo, to conduct an expert review of the CO2CRC Otway Project.
4. The expert review team summarised and consolidated their responses to the papers during a closed discussion session in the morning. Experts discussed their detailed feedback given so far in light of the initial responses received from CO2CRC. Important points, questions, suggestions and comments were highlighted to discuss further with the CO2CRC team later in the day.
5. Individual discussions were held between members of the expert review panel and CO2CRC experts over lunch.
6. A group discussion covering each paper in turn with the relevant CRC researcher was conducted in the afternoon. In some cases this involved telephone conference calls to Australia.
7. A closed session of the expert review team was the held to review results, draw conclusions and make recommendations.

The detailed programme for the Expert Review meeting is given in Table 1.

**Table 1 – Expert Review Programme**

| Time | Session |
|---|---|
| **10.00 – 12.30** | **Introduction**<br>**Internal review** by Review team of Review team responses. (Closed session). *Order of papers reviewed:*<br>Atmospheric (Etheridge)<br>Geology (Dance)<br>Geophysics (Urosevic)<br>Micro-seismics (Siggins)<br>Naylor monitoring well – Overview (Underschultz)<br>Naylor monitoring well – U-tube sampling (Freifeld)<br>Naylor monitoring well – Deep water chemistry (Kirste)<br>Naylor monitoring well – Gas chemistry (Boreham)<br>Naylor monitoring well – Tracers (Stalker)<br>Naylor monitoring well – Wellbore seismic (Daley)<br>Pressure (Paterson)<br>Reservoir modelling (Xu)<br>Shallow aquifers (Hortle)<br>Soil gas (Schacht) |
| **12.30 – 13.00** | **Lunch** including discussion session with CO2CRC experts |
| **13.00 – 15.00** | **Discussion session** by Review Team with CO2CRC (Jenkins, Sharma, Etheridge). |
| **15:00-16:00** | **Discussion session by Teleconference** by Review Team with CO2CRC (Urosevic, Boreham, Paterson). |
| **16.00 – 17.00** | **Review team Final Conclusions.** (Closed session). |

**Table 2 - Papers reviewed by the Expert Reviewers**

| Referred to as: | Title of reviewed document | Authors | App. |
|---|---|---|---|
| **Atmospheric** | Atmospheric monitoring at the CO2CRC Otway Project: A progress report to the IEA GHG Monitoring Network | D.M. Etheridge, Z. Loh, R. Leuning, A. Luhar, L. P. Steele, C.E. Allison, P.B. Krummel, D.A. Spencer, S. Zegelin | 3 |
| **Geology** | Geological Characterisation of the Otway Project Pilot Site: What a Difference a Well Makes. | Tess Dance, Lynton Spencer and Josh-Qiang Xu | 4 |
| **Geophysics (surface seismic)** | Application of geophysical monitoring within the Otway Project | Milovan Urosevic, Roman Pevzner and Valeriya Shulakova | 5 |
| **Micro-seismics** | Shallow Micro-seismic Monitoring at the Otway site | A.F. Siggins | 6 |
| **Naylor monitoring well overview** | Geochemical and hydrogeological monitoring and verification of carbon | James R. Underschultz, Barry Freifeld, Chris Boreham, Linda Stalker, | 7 |

| | | | |
|---|---|---|---|
| | storage in a depleted gas reservoir: examples from the CO2CRC Otway Project, Australia | Josh Xu and Dirk Kirste | |
| **U-tube sampling** | The U-tube Sampling Methodology and Real-Time Analysis of Geofluids | Freifeld, Barry, Perkins, Ernie, Underschultz, James, Boreham, Chris, | 8 |
| **Deep water chemistry** | Geochemical modelling and formation water monitoring at the CO2CRC Otway Project, Victoria, Australia | Kirste, Dirk, Perkins, Ernie, Boreham, Chris, Freifeld, Barry, Stalker, Linda, Schacht, Ulrike and Underschultz, James | 9 |
| **Gas chemistry** | Monitoring of $CO_2$ geological storage in a depleted natural gas reservoir, CO2CRC Otway Project, Victoria: gas geochemistry | Chris Boreham, Jim Underschultz, Linda Stalker and Barry Freifeld | 10 |
| **Tracers** | Tracer Paper –The successful application of tracers to measure, monitor and verify breakthrough of sequestered $CO_2$ at the CO2CRC Otway Project, Victoria, Australia | Linda Stalker, Chris Boreham, Jim Underschultz, Barry Freifeld, Ernie Perkins, Dirk Kirste, Ulrike Schacht, Sandeep Sharma | 11 |
| **Wellbore seismic** | Report on Borehole Seismic Monitoring at Otway using the Naylor-1 Instrument string | Thomas M. Daley with Sandeep Sharma, Aleksander Dzunic, Milovan Urosevic, Anton Kepic, Don Sherlock | 12 |
| **Pressure** | CO2CRC Otway Project Pressure Measurements | Lincoln Paterson and Jonathan Ennis-King | 13 |
| **Reservoir modelling** | The Otway Project $CO_2$ Injection Reservoir Simulation Modelling | Josh Xu | 14 |
| **Shallow aquifers** | Baseline hydrological monitoring of deep and shallow aquifers & Baseline groundwater chemistry monitoring of deep and shallow aquifers | Allison Hortle, Patrice Decaritat, Dirk Kirste, Charlotte Stalvies | 15 |
| **Soil gas** | Soil Gas Monitoring: Baseline Surveys 2005-2008, first Assurance Monitoring survey 2009 | Ulrike Schacht | 16 |

# 3. RESULTS AND DISCUSSION

## 3.1 General comments on the review

The following comments summarises the review team's responses following review of the papers and discussion with the CO2CRC team during the one day review meeting. These reviews recognise that this is an annual review and does not correspond to a particular milestone. As such, many of the techniques are still in progress and either the reported results or subsequent analysis and interpretation may not have advanced to a point where some of the questions posed could be answered conclusively.

The papers are referred to in their abbreviated form. Table 2 lists these and which appendix the detail can be found in. A blank version of the review form is provided in Appendix 1.

Detailed scientific and technical comments have been omitted from this report as they are intended as specific feedback to the researchers and too detailed to report here.

**Atmospheric**

The review team was impressed by the monitoring and analysis of data collected to date and described the study as a 'trend setter' and 'a model for other M&V approaches'.

The atmospheric plan is comprehensive using both established and emerging technologies to measure a variety of gases and detect gas isotopes reliably and accurately. As stated in the original review of the monitoring programme (IEA report number 2006/TR4), multiple flux towers would be ideal if there were no cost constraints. However, with the single flux tower and strong coordination with existing regional atmospheric monitoring programs, data collected from this well designed study provides important information about the feasibility and best deployment of this method. With optimal conditions the sensitivity is likely to be comparable to the target leak rate for detection. The identification of significant background fluctuations and the detection of two anomalous non-leakage sources of $CO_2$ is a clear demonstration of the efficacy of this program.

The review team look forward to the results of the planned opportunity for a controlled release of some $CO_2$ to prove the reliability of detecting a leak using this technique.

**Geology**

The review team considered the site static geological model to be satisfactory. This is the essential starting point for dynamic simulation and history matching and the development of a coherent monitoring strategy

In general the improved geological model has contributed to predictive modelling which is in broad agreement with reservoir monitoring results since injection. However the reviewers stressed the importance of using monitoring results to either to confirm or update the static model predictions, particularly in light of the fact that breakthrough occurred slightly earlier than predicted (this is in progress). Although a range of base geological scenarios was considered to support predictive modelling, the review team would also have liked to have seen some consideration of leakage scenarios, characterisation of the caprock and discussion of the long term fate of injected $CO_2$. These were performed as part of the risk assessment initially, but it

would have been useful to see some consideration or link to previous work in this paper in order to show a wider view.

This case study gives an excellent example of the methodology for storage site characterisation and modelling which may be employed at similar large scale demonstration or commercial storage sites elsewhere.

**Geophysics (Surface seismics)**

The review team found the overall approach to be detailed and thorough. Much work had gone into the necessary preparation for these techniques including optimising data acquisition and quantifying data repeatability. Preliminary processing showed indications of time-lapse plume detection capability in the reservoir; however it was still too early in the analysis stage to arrive at any categorical conclusions.

The reviewers understand the challenge of imaging $CO_2$ in a depleted gas field using seismic and that data collected is still being analysed (and as such scores given in Appendix 5 reflect the lack of actual results presented in the paper). However, initial responses from the researchers showed that they have a good basis for the interpretation of the 3D data, including promising time-lapse displays. However, because of the interplay of pressure and saturation effects on the seismic response very careful analysis and interpretation of the results is required.

The main benefit of surface seismic (3D) is that it provides continuous imaging of the overburden with strong capability of detecting upward migration of $CO_2$ from the reservoir. As such the reviewers would like to see more effort in the assessment of sensitivity of detection of fluid changes in the overlying Paaratte Formation, which is important and achievable.

**Micro-seismics**

The reviewers were disappointed by the lack of technical information or documentation relating to any of the criteria in the questions presented in this paper. The 'poor' scoring (Appendix 6) reflects the fact that both the technique and the paper require improvement, not that the technique should not have been conducted. It is recognised that this technique is not mature anywhere in the world, so any data gathered may be valuable for further research and may have more significance in the future. This is good data to collect but the little data presented here needs more thorough analysis and explanation so that it is not subject to misinterpretation.

The reviewers understand that this monitoring technique has suffered due to field equipment failures and budget issues, or ideally this technique would have two or more stations (either surface or downhole geophones) to allow precision in locating events. Notwithstanding this, clearly stated objectives and whether any micro-seismic events were expected could be stated in the paper. Other suggestions include a graph showing the location and magnitude of events at depth and also an analysis of data pre- and syn- injection to show no significant changes over background. Results to date suggest that no micro-seismic activity has been detected either shallow or of deep origin relating to the $CO_2$ injection, however surface monitoring is likely only capable of monitoring larger events (e.g., fault reactivation).

More rigorous interpretation should be possible for this technique and could provide useful conclusions.

**Naylor monitoring well - overview**

The reviewers were impressed by this excellent clearly written overview paper on the various geochemical elements of the project. Shallow In situ pressure and geochemistry at the reservoir is important proof of concept for assessing dynamic response, reducing uncertainty and calibrating predictive models.

This is a strong component of the project. The data has been successfully collected and monitoring results have verified predictions about the injection stream, particularly the in situ fluid analysis. These monitoring processes are judged overall as excellent in the first year since injection.

**U-tube sampling**

The reviewers found this to be an excellent review of the methodology of U-tube sampling. The report details several deployments of U-tubes and explains the value of repeat sample collection which this tool allows. The actual results collected using this equipment are dealt with in another paper.

The Otway Project is making a useful contribution to technology innovation by successfully deploying the three U tubes.

**Deep water chemistry**

The review team found little evidence in the paper that this technique is providing significant results to date. However, additional supporting documents provided at the review meeting increased reviewer confidence that the authors have considered the subsurface and sampling and analytical processes in detail. Despite this, there is still insufficient explanation of expected rock-water-$CO_2$ reaction, and the magnitude of measurement uncertainty needed to evaluate whether this technique would be adequate for successful monitoring. Any interpretation of $CO_2$ breakthrough and related reactions will be enhanced by studying baseline conditions; in particular establishing the nature of the $CO_2$-water-rock system is in equilibrium prior to $CO_2$ injection.

The review team understands the challenge in interpreting measured geochemical data (potential reactions and modifications to chemical and isotopic compositions during sample collection in the downhole environment, transport to the surface and subsequent preservation, processing and analysis). Such challenges have been faced by all $CO_2$ storage projects with a geochemical monitoring component to date and many remain outstanding. Integration with rock composition is needed.

There is still potential for this aspect of the Otway Project monitoring and verification program to yield useful data and insights both for this site and at others.

**Gas chemistry**

The review team found this to be a good interim report. The injection stream breakthrough was clearly identified using chemical and isotopic measurements of injected $CO_2$ and introduced tracers. The measurements were conducted on samples collected biweekly via the successful U-tube system.

The multiple measurements of the injected $CO_2$ stream composition were useful for reducing uncertainty in the measurements, although more discussion of the background variation and analytical and sampling uncertainty would have been helpful.

This is a complex system in a complex setting. The technique has been quite successful, but some details remain to be explained in order to understand this situation more fully.

**Tracers**

Artificial and carbon isotope tracers have been successfully used to detect breakthrough of the injected well. It is expected and anticipated that tracers will continue to provide useful information on injection stream migration pathways.

There are still many complexities relating breakthrough and dependence of detection on sampling strategy. Reviewers received assurance that their recommendations to authors to consider the physical and chemical $CO_2$-tracer stream coupling, $CO_2$-water-rock reactions and the evolution of carbon isotopic composition will be looked at in a future report.

Reviewers look forward to these results. They recognise the importance of this work and publishing widely so that other sites may benefit from the results of these methods employed at Otway Project.

**Wellbore seismic**

The reviewers found this to be a good interim report which presented the purposes, limits and difficulties, and results to date. The authors recognised the challenge of using this technique for such a deep reservoir, with a small amount of $CO_2$ and as such the authors set modest goals despite the well designed system. Significant issues arose due to failure and deterioration of some of the instrumentation and large seasonal variations in the near-surface. The authors were also very aware of the uncertainties in the monitoring results appropriately taking them into account in interpreting the results. However they need to be clearer in the paper about what difficulties are due to tool failure and what are due to tool poor response due to attenuation because of residual gas in the reservoir.

VSP (vertical seismic profiling) monitoring to date has showed no detectable change at the reservoir level, consistent with the small amount of $CO_2$ (5000 tonnes) injected to the time of the May 2008 survey. The ultimate usefulness of this technique therefore remains to be established during subsequent surveys. As with the surface seismic, the reviewers would like to see some follow on about sensitivity of the geophysics to potential leakage into the overlying Paaratte Formation.

**Pressure**

This was a good basic description of methodology and demonstrated the technology. In situ pressure measurements from the down-hole pressure sensors, flow rate in injection well, surface pressure at injection and production wells provide essential data for input into the dynamic simulation models. It was unfortunate that the down-hole pressure sensors in the monitoring well didn’t survive.

The results could benefit from a little more analysis and attribution before publication, particularly demonstrating that it is being incorporated into history matching.

**Reservoir modelling**

A good interim result asking all the important questions, although more work still needs to be done. Pressure monitoring in the injection well and results from two out of three geochemical sampling points in Naylor1 showed good agreement with modelled predictions of the behaviour of the injected $CO_2$.

A few points lacking explanation in the paper were discussed at the review meeting. (CO2CRC author feedback in italics)

- Were any potential leakage pathways included in the model? *Yes two models of scenarios were modelled, but have not yet been written up.*
- Was the caprock (predicted geochemical or geomechanical integrity of seal) considered? *This was included in the geology and modelling and risk assessment.*
- Why did breakthrough occur slightly faster than predicted in the model? *A range of relative permeabilities were modelled. This probably is due to a higher permeability pathway than expected.*
- Did the model incorporate density stratification between CH4 and $CO_2$? *Yes, this was modelled as initially to be density stratification followed by gradually mixing and spreading through diffusion.*

Forward modelling of the depleted field and aquifer interaction and long term fate of stored $CO_2$ are essential for the risk assessment, and subsequent for monitoring and verification. This paper shows the models are on the right track to achieve this.

**Shallow aquifers**

This paper demonstrated a widely accepted sampling and analysis methodology over an extensive array of sampling stations contributing to the characterisation of major freshwater aquifers in Otway Project area. However, despite the large number of sampling points, budget restrictions required the use of available wells, which are not necessarily the best placed to achieve this. This means that the scenarios demand more thinking to understand the complexities. This study is descriptive only, and does little to attempt to use the aquifer data collection to explore what would happen to the aquifers if the containment should fail and $CO_2$, brine or methane leak into aquifers.

Monitoring in the aquifers above the storage reservoir has provided public assurance of drinking water protection and there is expectation that this would provide an indicator of any unexpected leakage into the aquifer.

**Soil gas**

Methods described are broadly accepted to be of a suitable sampling frequency and spatial coverage for an effective Monitoring and Verification programme. However it appears to have suffered from a lack of continuity of operator and early sampling problems. The authors are well aware of the significant background fluctuations due to ecosystem contributions and are

addressing the situation by extensive background sampling and detection of isotopes and other gases. The effort was also significantly hampered by seasonal restriction on surface access.

The review team would like to see more explanation of the process of how a leakage signal could be separated from the noisy background signal. There is insufficient analysis about what the data collected to-date actually means. The helium anomalies particularly require explanation or they could be subject to misinterpretation.

Soil gas sampling is an assurance Monitoring and Verification technique which is expected to help confirm that $CO_2$ is not reaching the surface.

### 3.2 Specific Recommendations

Several key components have not been reported yet, but appear in the programme and will complete a successful monitoring campaign. These are:

- Non- detection of migration into the Paaratte Formation via seismic and the sensitivity of that technique.
- Models confirmed by monitoring that there is no risk of reactivation of faults.
- Confirmation that as modelled, no $CO_2$ has moved downwards past the original gas-water contact (spill point).

A number of specific recommendations were made for the Otway Project to consider, from which the programme and other projects could gain further benefit. These included:

- Further work to assess whether the tracers would survive a long flow-path to surface.
- Further work on the $CO_2$-rock-water-methane system in reservoir, caprock and overburden.
- The reviewers would like to see the well-head pressure from the Naylor well substituted for downhole gauges if possible.
- The importance of published site specific documentation which can build toward a contribution of how to monitor a commercial project. It would be helpful to other projects if descriptions of problems and remediative actions were included.
- Where there has been equipment failure, this is analysed for any recommendations for future improved practice.

The expert review panel also made additional recommendations based on their experiences gained in other monitoring projects:

- Reviewers recommend efforts start now to integrate the results of the components of the M&V programme to ensure a stronger synthesis. The reviewers realise that it will be a challenge to ensure integration, particularly as for many of the components this is the first time results have been compared.

- Reviewers recommend strongly that a plan for post-injection monitoring is developed if it is not already in existence. This should be independent of the plan for a repeat injection. Real post-injection monitoring experience is very significant as regulators and policy makers struggle with considering requirements of “post closure care”.

## 4. CONCLUSIONS

An international team of experts has reviewed the monitoring plans and programme for the CO2CRC Otway Project. The Otway Project was considered to be an important first of its kind, $CO_2$ injection activity into a closely monitored onshore depleted gas reservoir. The Otway Project should therefore provide important experience in monitoring this type of reservoir, which is likely to be widely used globally for $CO_2$ storage. The Otway Project is also interesting in that it is a composite onshore demonstration project that includes nearly all the aspects of $CO_2$ storage i.e. $CO_2$ production, transportation, injection, and storage, albeit at a small scale, in a single demonstration project. A further strength of the project is considered to be CO2CRCs ownership of the production and injection wells which will allow the research programme to proceed unencumbered by external operational requirements which should allow the Otway Project to deliver on range of research objectives.

It is clear that significant advances have been made in implementing the initial stages of the monitoring programme. This review does not accord with any specific project milestones and as such in most cases only "preliminary results" are reported. There has been much groundwork, planning and deployment of monitoring equipment and recording useful data. This, and the lessons learned therein, should not be underestimated. Thus, the potential value and effectiveness of much of the monitoring effort has yet to be fully realised.

With respect to the Otway Project monitoring program, the expert review team considered that:

**a)** **In general the capacity, reliability, accuracy of many elements of the monitoring processes are being demonstrated in the year since injection commenced.** The reviewers recognise that the effectiveness of the monitoring done to date still has to be realised for some techniques. This is because injection and monitoring are ongoing, and there has been some equipment failure and adjustments to collect needed data. In general the reviewers are confident that with time and continued data collection, analysis and interpretation efforts, the effectiveness can be realised. The review team look forward to the publication of these results.

**b)** **The usefulness of findings to date in verifying predictions about the injection stream should not be underestimated. The reviewers have not yet seen results presented regarding other mobilised substances** (heavy metals, organics and displaced saline water). The reviewers recognise that the reservoir environment in a depleted gas well and with a small diameter monitoring well has challenges. Despite these, the monitoring approach has merit and has shown significant success in observing the initial evolution of the $CO_2$ plume in this mixed gas system. The direct methods of tracers and downhole sampling have detected $CO_2$ at this stage, succeeding in early goals of measuring breakthrough which has been successfully history matched. This intensive and integrated effort is a first demonstration of feasibility for a depleted gas reservoir in Australia and represents a significant contribution to world knowledge.

**c)** **Although some techniques demonstrated understanding and appropriate handling of the uncertainties in the M&V, in general there was insufficient reporting of these.**

**d)** **The monitoring programme was technically sound but that some techniques, particularly the assurance methods would benefit from more consideration of**

**responses to potential leakage scenarios.** These elements, since they attempt to prove a negative, are challenging and with increased thought focused on what perturbations would be expected should leakage occur, the technical value can be enhanced without additional data collection. The basis has been developed for further remote, non-invasive, methods e.g. seismic, to provide further assurance in due course.

f) **The overall approach is comprehensible and the sum of Monitoring and Verification components fulfil the requirements which were achievable within the programme schedule.** This suggests a high likelihood that the M&V programme will be brought to a successful conclusion, although for many techniques it was too early to document that such success has been attained.

Specific recommendations include:

- Reviewers recommend efforts start now to integrate the results of the components of the M&V programme to ensure a stronger synthesis. The reviewers realise that it will be a challenge to ensure integration. For many of the components this review is the first time results have been compared.

- Reviewers recommend strongly that a plan for post-injection monitoring is developed if it is not already in existence. This should be independent of the plan for a repeat injection. Post injection monitoring experience is very significant as regulators and policymakers grapple with considering requirements of “post closure care”.

- Where there has been equipment failure, this is analysed for any recommendations for future improved practice.

**APPENDIX 1** Blank review form

# The CO2CRC Otway Project - 2009 IEA GHG Review

| | |
|---|---|
| **Project Area (Paper Title):** | |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | |

For each paper allocated to the reviewer we would ask that the reviewer address five questions that have been provided by the project operators in order for them the meet the requirements of the review. The five questions are as follows:

A. Capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.
B. Usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.
C. Demonstrated understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.
D. Likelihood that the M&V programme will be brought to a successful conclusion.
E. Any scientific or technical issues that require attention.

For each question we would ask the reviewers to provide the following:

- **Rating:** We would ask the reviewers to choose a rating (Excellent, Good, Adequate, Poor, Very Poor) which best reflects how the area of the project in under review meets the question posed. By providing a rating it will allow direct comparison of how different reviewers view each part of the project.
- **Summary Findings (1-2 Sentences):** This summary provides a short description of why the project was given the rating it was. This summary should also include any key comments arising from the detailed scientific and technical comments.
- **Detailed scientific and technical comments:** The detailed scientific and technical comments provide the most important feedback from the review to the project operator. Accordingly as much detail as possible should be provided to justify and positive or negative statements made. It is expected that the key conclusions from the scientific and technical comments should also be reflected in the summary findings and the rating for the project area.

The feedback proved from the reviewers on these forms will provide the basis for discussions and final conclusions in the face-to-face component of the peer review which is to be held in Tokyo, Japan on the 1st of June 2009.

If you are unsure of what is required or have any questions about the project, please to not hesitate to contact the review chair: Tim Dixon, at Tim.Dixon@ieaghg.org.

## APPENDIX 2 Review team summary

| | |
|---|---|
| **Project Area (Paper Title):** | The CO2CRC Otway Project 2009 IE GHG Review |
| **Name of Peer Reviewer:** | Review team summary |
| **Date of Review:** | 25 May 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | | | | |

**Summary findings (1-2 sentences)**

Overview of program status and rationale for annual review

**Detailed scientific and technical comments**

The reviewers were pleased to be part of the review of early results of this excellent, challenging, real world study, and found it the review process to be valuable, seeing early results.

The overall approach is comprehensive and the sum of the M&V components fulfil the requirements [in the question].

The reviewers realise that for many of the components, this review is the first time results have been compared. It is probably obvious to researchers that a stronger synthesis will be made by integration. In particular, the soil gas and aquifer efforts should begin to share results and attempt to co-interpret data with each other and with the rest of the project.

The reviewers did not see a plan for post-injection monitoring as the injection stabilises, if one does not exist the reviewers recommend strongly that one be developed independent of the plan for a repeat injection. Post injection monitoring experience is very significant in terms of applications, as regulator and policy makers struggle with “post closure care”, and include history matching the predictive modelling. Some observations at this scale to extend beyond those collected at the short Frio test would be valuable. In particular, the standard diameter injection well is available post injection, which could open some options for logging, fluid sampling and other activities not available in the Naylor well.

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | x | | | |

**Summary findings (1-2 sentences)**

**Detailed scientific and technical comments**

The reviewers interpreted the injection stream to include the plume. The injection stream is well quantified.

The methods which detect $CO_2$ at this stage are the direct methods of tracers and downhole sampling. There are many assurance-driven methods, none of which have identified $CO_2$ leakage. The basis has been developed for further remote, non-invasive, methods e.g. seismic, to provide further assurance in due course.

With respect to mobilised substances (heavy metals, organics and displaced water), the work is not yet presented.

The reviewers would like to see more work to assess how conservative tracers are. They seem to perform well in cross well. Would they survive a long flow-path to surface, or could they be attenuated as fast as $CO_2$ or as fast as methane?

Would like to see more work on $CO_2$-rock-water-methane system. Is the reason for such simple geochemical response that there was no rock-water contact, or is it a relative permeability – wellbore effect (lots of reacted water in the formation, but not being pulled into sampler because of reduced permeability to water where $CO_2$ moved). Integration of water chemistry with lab analysis of cores from CRC-1 are needed

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | x | | | |

**Summary findings (1-2 sentences)**

The environment in a depleted gas reservoir and with a small diameter monitoring well has challenges. The approach has shown significant success in observing the initial evolution of the $CO_2$ plume in this mixed gas system, which is a significant contribution. The subsurface team in particular has faced uncertainties head on to create a robust program

**Detailed scientific and technical comments**

The site specific observations should build toward a contribution of how to monitor a commercial project. Even instrument failure is relevant, if this should occur in a regulatory setting, what would be done?

There was insufficient reporting of the analytical and sampling uncertainties, with some exceptions including in particular the atmospheric monitoring which dealt with this well.

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | x | | | | |

**Summary findings (1-2 sentences)**

The intensive and integrated effort should pay out for a first demonstration of feasibility for Australia, also a significant contribution to the world knowledge adding a case with monitoring in a depleted gas reservoir. Early goals of measuring breakthrough and geochemical changes have been measured and successfully history matched.

It will be a challenge to ensure integration of the components of the M&V programme. Reviewers recommend efforts start now.

**Detailed scientific and technical comments**

Several key components have not reported in yet, but appear in program, and will complete successful monitoring. These are:

- Leakage detection in the Paaratte via seismic – would this be sensitive and is no leakage measured?
- Modelled no risk from faults confirmed by micro-seismic or other measurements?
- Modelled no downward $CO_2$ (past original gas-water contact/spill point) confirmed?

Is there a wellbore integrity maintenance/monitoring program?

While providing some public assurance, as noted, the technical value of some elements is still to be demonstrated, for example micro-seismic, soil gas and aquifer monitoring programs, which seem to be descriptive, not focused on detection of leakage. These elements, since they attempt to prove a negative, are challenging, and should have enough effort (not necessary an additional field effort) put in to eventually say that if leakage occurred, we would expect to see this or that change. If such changes did not occur, we are able to deduce no leakage.

E. Please comment on any scientific or technical issues that require attention.

**Summary findings (1-2 sentences)**

Remaining significant question – is $CO_2$ /methane system adequately understood seems to be favourably answered. Uncertainties should be resolved, and this significant result published.

The reviewers reiterate the need for post injection monitoring to provide information on closure.

Better on seismic, know more about pressure conditions.

**Detailed scientific and technical comments**

The reviewers would like to see the well-head pressure from the Naylor well substituted for downhole gages – interpretable or not? Downhole pressure is an expensive fussy technology – researchers love it – is it required in commercial settings?

$CO_2$ water-rock interactions in reservoir, caprock, and overburden

## APPENDIX 3 Atmospheric

| | |
|---|---|
| **Project Area (Paper Title):** | Atmospheric Monitoring |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | 24 May 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X X | | | | |

**Summary findings (1-2 sentences)**

The atmospheric plan is very comprehensive using both established and emerging technologies to measure a variety of gases. Methods employed are reliable and accurate.

A careful and systematic approach to designing an atmospheric monitoring program. Set quantitative goal, and determined that direct measurement of $CO_2$ would be unlikely to achieve the goal, but that combinations of isotopes and tracers could achieve the needed unique signal.

The program design is good. Especially strong is coordination with existing atmospheric monitoring programs to provide regional background data. On site background data was acquired over multiple seasons and multiple years. Multiple gases and isotopic ratios are planned. Different sampling regimes are planned including sampling of well headspace gases. This is a very comprehensive program with strong technical expertise to ensure quality implementation.

The detection of two anomalous $CO_2$ sources which could be identified as not due to leakage is a clear demonstration of the efficacy of this program.

Impressive publication record.
Systematic and clear.

B Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X | X | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Atmospheric sampling is more of an assurance M&V technique rather than one that will provide information about plume evolution (history matching) or mobilised substances, so this is not the most applicable question for this part of the program. It will help confirm that $CO_2$ is not reaching the surface.<br><br>Deals with methane, assuming that it comes to surface without biodegradation. | | | | | |

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X X | | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Ecosystem contributions and non-leakage sources of $CO_2$ emissions can provide significant background fluctuations. The team is well aware of this and is addressing the situation by extensive background sampling and detection of isotopes and other gases.<br><br>Systematic, data rich way of looking for signal, magnitude of noise, seeking ways to increase signal to allow reliable detection. Should be used as a model for other M&V approaches<br><br>This study is a trend setter. | | | | | |

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | X | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| The program is well designed and nicely integrated with ongoing atmospheric measurements. This study is likely to be of particular use to the M&V community<br><br>Programme is already collecting data confirming that there is no major leak | | | | | |

E. Please comment on any scientific or technical issues that require attention.

| **Summary findings (1-2 sentences)** |
| --- |
| This is a very strong effort.<br><br>What can be done to confirm the detectablity of a leak? – Any chance of venting some $CO_2$ + tracer and seeing how reliably it could be detected? *[This is planned from Otway well – CO2CRC]*. |

# APPENDIX 4 Geology

| | |
|---|---|
| **Project Area (Paper Title):** | Geological characterisation of the Otway site |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | 26 May 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X X | | | | |

**Summary findings (1-2 sentences)**

The geological knowledge of the storage site was considerably improved by using up to date technologies (wire line logs, coring) in the new CRC-1 and the existing Naylor-1 wells. This helped largely to build the static geological model and allowed dynamic simulation with a high degree of confidence, which is the basis for performance assessment and building the monitoring program.

Update documenting systematically the added value provided by core, open hole logs , single well hydrologic test to a good geologic model

A geological model is not directly monitoring, but is necessary and helpful for history matching.
.
There is a tendency in GS to discount the value of good descriptive and quantitative data input into an injection scenario. This study provides this case. A good geological model is intrinsically the essential starting point for other monitoring techniques.

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X X X | | | |

**Summary findings (1-2 sentences)**

The dynamic simulation is based on the geological model, improving the latter is fundamental to obtain correct history matching and breakthrough predictions. The breakthrough time was 5 months, a little bit ahead of the predicted time (between 6 and 9 months).

Improved geological model has contributed to predictive modelling which is in broad agreement with reservoir monitoring results since injection. No information given about potential mobilisation of other substances.

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X X X | | | |

**Summary findings (1-2 sentences)**

With an improved geological model, uncertainties about heterogeneities in the reservoir were reduced, and the dynamic simulation allowed a better excellent history match with pre and post production data from the depleted gas field. Furthermore, prediction of the $CO_2$ plume direction and shape, and arrival times of the $CO_2$ at the monitoring well may now be regarded with a higher degree of confidence.

Excellent explanation of use of geologic data to reduce uncertainty. Need to consider further remaining interwell uncertainty

Range of base geological scenarios considered to support predictive modelling. However the approach has been undertaken in a deterministic fashion, by considering best/worst/most likely geological scenarios

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X X | | | |

**Summary findings (1-2 sentences)**

As said before, the static model is fundamental for dynamic simulation and history matching.
The geological model should be improved by history matching during the injection and post-injection phases. That is using the results from monitoring either to confirm the static model or to change it in order to fit predictions with observations.

Good static model data to input to numerical model to match the project results received to date

Difficult to address this question on the basis of the geological characterisation paper.

E. Please comment on any scientific or technical issues that require attention.

**Summary findings (1-2 sentences)**

"…The presented case study provides an [excellent] example of the methodology for storage site characterisation and modelling which may be employed at similar large scale demonstration or commercial storage sites elsewhere…"

Nice result

Assessment of remaining uncertainties including caprock characterisation, fault properties, distribution of wider aquifer properties and connectivity with depleted gas field, long term fate

| **Summary findings (1-2 sentences)** |
| --- |
| of injected $CO_2$ is needed. |

# APPENDIX 5 Seismics

| | |
|---|---|
| **Project Area (Paper Title):** | Application of geophysical monitoring within the Otway Project |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | May 25, 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X X | X | | |

**Summary findings (1-2 sentences)**

The seismic monitoring methods proposed here have the potential for capacity if their reliability, accuracy and effectiveness can be demonstrated. To date, studies have focused on data repeatability with some preliminary indications of monitoring capability.

Status of active (surface source) seismic surveys. Detailed and thorough review, providing information and interpretation of many aspects of seismic data collection and interpretation.

Work-to-date has focused on data acquisition tests and repeatability, both of which are very important.

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | | X X | X | |

**Summary findings (1-2 sentences)**

The data acquired to date and the subsequent analysis is not far enough advanced to have contributed directly to “verifying predictions”. It is premature to arrive at any categorical conclusions.

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X X X | | | |

**Summary findings (1-2 sentences)**

The primary uncertainty associated with this monitoring activity is whether the method will have the sensitivity to usefully monitor the location of the injected $CO_2$. The authors are aware of this and have suggested that the method may be most suited to detecting leakage.

Good assessment of the difficulty in making the wished-for measurements. Would like to see more effort in assessment of sensitivity of detection of fluid changes in the overlying Paaratte Formation, quite important and more achievable.

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X X X | | | |

**Summary findings (1-2 sentences)**

In terms of monitoring for leakage, the report documents modelling that shows the 3D seismic data have adequate sensitivity and thus will likely be successful. Early 3D time-lapse results look promising and suggest a credible time-lapse effect. The distribution of the time-lapse change is enigmatic. It does not appear to reflect the likely pressure change distribution which should be largest around the injection well (unless it had had sufficient time to relax before the seismic was acquired). Pressure changes due to buoyancy effects in the $CO_2$ layer beneath the gas cap would not appear to be sufficient to produce the observed seismic response. On the other hand, the observed time-lapse pattern could perhaps reflect saturation changes in the reservoir, particularly if $CO_2$ is displacing water rather than residual gas (bearing in mind the observed recovery in reservoir pressures prior to injection). All in all, further careful analysis is required to extract the true meaning of any observed time-lapse changes.

The likelihood of success of the VSP data for monitoring $CO_2$ in the reservoir is less certain at this stage.

E. Please comment on any scientific or technical issues that require attention.

**Summary findings (1-2 sentences)**

The work to date is solid having focused on optimising data acquisition, quantifying repeatability and investigating various ways of using the 3-component (vector) data. However, the ability to use either the surface or VSP data to monitor $CO_2$ has not yet been fully demonstrated.

*[Again, the peer review has come too early for proper evaluation of the geophysical programme. The*

**Summary findings (1-2 sentences)**

*latest results demonstrate that TL 3D surface seismic has (when done thoughtfully) the capability to surprise (on the upside). The $CO_2$ related TL effect over Naylor field is clear (barring a mistake in processing). Furthermore, VSP data analysis, particularly if further TL 3D VSP could be acquired at the end of injection (December 2009), is expected to produce even more definite answers. Finally, the last TL 3D surface will also firm up (or produce further surprise on) these results.- CO2CRC]*

A preliminary difference display was shown in the response, comprising energy change at reservoir level. At first inspection this looks like a credible time-lapse effect. The distribution of the time-lapse change is enigmatic. Further careful analysis is required to extract the true meaning of any observed time-lapse changes.

A craftsman-like and detailed piece of work - recognition as a successful effort.

## APPENDIX 6 Micro-seismics

| | |
|---|---|
| **Project Area (Paper Title):** | Shallow Micro-seismic Monitoring at the Otway site |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | May 22, 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | | X | X X | |

**Summary findings (1-2 sentences)**

Documentation relating to any of the above criteria is lacking.

Note that the 'poor' scoring refers to the fact that the technique and paper requires improvement, not that it should not have been done.

The shallow micro-seismic monitoring system initially deployed recorded mainly the on-site engineering activities and surface seismic weight drop surveys. The field equipment has suffered periods of down-time during 2008 due to equipment failures at the field site, consequently, a new system, more sensitive, has been installed.

Status of surface micro-seismic monitoring. Most of the events are located at the surface, attributed to site activities. Deep events are not considered significant

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X | NA | X | |

**Summary findings (1-2 sentences)**

The objectives of the micro-seismic monitoring are not stated in the report ($CO_2$ tracking, pressure-induced fracturing, safety to the public, security of $CO_2$, fault reactivation?). Thus, again it is difficult to assess in relation to the above criteria.

No link with any shallow micro-seismic activity and the $CO_2$ injection was detected during 2008

Not addressed

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | | | X X | X |

**Summary findings (1-2 sentences)**

Although magnitudes and locations of micro-seismicity are stated, there is no discussion of uncertainties in these measurements or results per se or in regard to the uncertainty relative to the larger M&V issue based on the information provided to the reviewers.

Errors of location of micro-seismicity do not appear in the reviewed document. What is the meaning of different symbols and colours in the location map and sections of slide 3?

Important technology, especially in an area of many faults, and some tectonic activity? This report needs to assess failure scenarios – for example stress modelling could be wrong and faults slip

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X | X X | | |

**Summary findings (1-2 sentences)**

Surface monitoring is likely only capable of monitoring larger events (e.g., fault reactivation, subsidence) and not reservoir events, given the depth.

During 2008, no micro-seismic activity was recorded, either shallow or of deep origin. The recording system was replaced by a new one, more sensitive and with lower power consumption

More rigorous interpretation should be possible, either pressure increase causing micro-seismic signal or no signal, because of low pressure increase, either would be a good conclusion.

E. Please comment on any scientific or technical issues that require attention.

**Summary findings (1-2 sentences)**

There is simply not enough information in this report. Most of the required technical information is missing.

Arial coverage of the surface array is too poor, it should be completed by two or more stations (either surface or downhole geophones), in order to increase precision in locating events. A location sensitivity analysis and a comparison with the recordings of the deep downhole hydrophones in Naylor-1 are missing in the presented document

It is good data to have, but it needs to be explained completely, so that it is not subject to misinterpretation.

## APPENDIX 7 Naylor monitoring well - Overview

| | |
|---|---|
| **Project Area (Paper Title):** | Naylor Overview - Geochemical and hydrogeological monitoring |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | May 22, 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X X | X | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| In situ pressure and geochemistry at the reservoir is key to assessing dynamic response and calibrating prediction models. These monitoring processes are judged overall as excellent in the first year since injection.<br><br>Overview of various geochemical elements of the project | | | | | |

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X X | | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Findings to date are excellent in their ability to verify predictions about the injection stream. Particularly the in situ fluid analysis, aqueous geochemistry and $CO_2$. | | | | | |

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X X | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| The in situ measurements greatly reduce the uncertainties in the M&V process as they are used directly to improve the prediction model and also provide a means of calibrating remote measurement techniques (e.g., seismic). | | | | | |

| **Rating** |
|---|
| Overview of all the techniques, not very detailed |

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X X | | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Successful to date. No reason to believe that this component of the M&V programme won't be successful overall.<br><br>It is a complex operation in a complex setting, so may not have a yes/no answer. Much of the data is successfully collected, and the wheels are rolling toward latching down conclusions | | | | | |

E. Please comment on any scientific or technical issues that require attention.

| **Summary findings (1-2 sentences)** |
|---|
| Strong component of the project. Only improvement that I could suggest would be complementary time-lapse logging to determine bulk physical changes that accompany the changes in reservoir $CO_2$ saturation. |

## APPENDIX 8 U-tube sampling

| | |
|---|---|
| **Project Area (Paper Title):** | The U-tube Sampling Methodology and Real-Time Analysis of Geofluids |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | May 22, 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Report details several deployments of U-tubes and explains the value of repeat sample collection this tool allows. | | | | | |

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | | NA | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Not addressed<br>This paper deals with the equipment rather than the results (which were dealt with by another team) | | | | | |

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Good mature explanation of the uses of this sampler, with case studies. | | | | | |

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| U tube has delivered its result. Following phases will be gas-lift, less challenging, still important | | | | | |

E. Please comment on any scientific or technical issues that require attention.

| **Summary findings (1-2 sentences)** |
|---|
| Technology seems mature. With the 3 tubes, Otway makes a contribution to technology innovation |

# APPENDIX 9 Deep water chemistry

| | |
|---|---|
| **Project Area (Paper Title):** | **Geochemical modelling and formation water monitoring** |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | 20 May 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | | | x | |

**Summary findings (1-2 sentences)**

No positive evidence that the technique is providing significant results to date. There is insufficient explanation of expected reaction. Needs to assess magnitude and measurement uncertainty to evaluate whether this technique would be adequate to detect these reactions.

Additional supporting data and explanation were provided in a supplementary document made available at the IEA GHG review meeting in Tokyo on June 1st 2009. This document provides increased confidence that the authors have considered the subsurface and sampling/analytical processes in detail. However there is still insufficient description and explanation of the expected and measured signal from $CO_2$, water ± rock reactions relative to background reservoir dynamics and/or analytical uncertainty

In my view there is still potential for this aspect of the Otway M and V program to yield useful data and insights.

Short report of minimal rock-water-$CO_2$ interaction during breakthrough, showing no changes in a calcite buffered system

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | | NA | X | |

**Summary findings (1-2 sentences)**

There is little evidence of well characterised $CO_2$-water-mineral reactions in the M and V data presented to date

Not in this report

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | | | X X | |

**Summary findings (1-2 sentences)**

There is no quantitative description of the analytical and sampling uncertainties

There is no consideration of the relationship between expected signal from $CO_2$-water-mineral reactions and measurement uncertainties

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X | X | | |

**Summary findings (1-2 sentences)**

Depending on magnitude of reactions once $CO_2$ and water and the formation are able to react, the M and V program may or may not be successful.

It is clearly challenging to interpret measured geochemical data because of the potential reactions and modifications to chemical and isotopic compositions taking place during sample collection in the downhole environment, transport to the surface and subsequent preservation, processing and analysis. Such challenges have been faced by all $CO_2$ storage projects with a geochemical monitoring component to date and many remain outstanding, so the detailed scientific comments should be seen as constructive criticism, designed to help progress knowledge, and applicable to other sites.

I fundamentally believe this result, that many systems are not very sensitive to introduced $CO_2$. however the data are not in yet from the field test to show that this is true for the Waarre

E. Please comment on any scientific or technical issues that require attention.

**Summary findings (1-2 sentences)**

Description of uncertainties and evaluation of magnitude of expected reactions, if these are much larger than uncertainties there is still potential in this M and V activity.

Any interpretation of $CO_2$ breakthrough and related reactions will be enhanced by studying baseline conditions; in particular establishing whether the $CO_2$-water-rock system is in equilibrium prior to $CO_2$ injection, and quantifying the effects of kill fluid with time.

The aqueous geochemistry and tracers should not be considered in isolation, understanding the interaction between $CO_2$, formation water and reservoir minerals and how this relates to the migration pathway for injected $CO_2$ is limited by considering the tracer data alone

Need to compare data collected with data modelled and explain.

| **Summary findings (1-2 sentences)** |
| --- |
| Recommend laboratory study of $CO_2$-water rock reactions using Warre core.. |

## APPENDIX 10 Gas chemistry

| | |
|---|---|
| **Project Area (Paper Title):** | Gas Geochemistry |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | 20 May 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | X | | | |

**Summary findings (1-2 sentences)**

Carbon isotopic signature of injected $CO_2$ allows clear identification of arrival of injected $CO_2$ at monitoring well. Difference between baseline and injected $CO_2$ sufficient for high confidence (although measurement uncertainties not yet described in sufficient detail). $CO_2$ concentration increase also suggests arrival of injected $CO_2$. Artificial tracers confirm injector-monitoring well communication

Reports percent $CO_2$ and isotopic composition at biweekly U-tube samplings. Also reports the details of wax management and compositions. It also reports U-tube performance in terms of lift.

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | X | | | |

**Summary findings (1-2 sentences)**

Injection stream breakthrough clearly identified using chemical and isotopic measurements of injected $CO_2$ and artificial tracers

Provides data on $CO_2$ methane composition and wax. We need to know what happens (if anything) when Waarre Sandstone reacts with $CO_2$ – lab result to compare to field?

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | X | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Multiple measurements of injected $CO_2$ very helpful as low uncertainty in injected stream composition 6.5 (n=13 s.d. 0.4),<br>Limited reporting and discussion of background/baseline variation in carbon isotopic composition of $CO_2$ and analytical/sampling uncertainty<br><br>Good interim report on $CO_2$ percent and stable isotopes | | | | | |

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | X | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| The carbon isotope measurements of $CO_2$ and tracer sampling via the U-tube system have been very successful at identifying the arrival of injected $CO_2$<br><br>This is a complex system in a complex setting, especially with one packer. Already has been quite successful, some details remain that need explanation | | | | | |

E. Please comment on any scientific or technical issues that require attention.

| **Summary findings (1-2 sentences)** |
|---|
| Reporting of uncertainty and baseline variations in carbon isotopic composition of $CO_2$<br><br>Need a lot more integration to figure out what is going on in this complex situation |

## APPENDIX 11 Tracers

| | |
|---|---|
| **Project Area (Paper Title):** | **Tracer Paper –The successful application of tracers to measure, monitor and verify breakthrough of sequestered $CO_2$ at the CO2CRC Otway Project, Victoria, Australia** |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | 24 May 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X X | | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Artificial and carbon isotope tracers successfully used, identifying migration pathway from injection to monitoring well<br><br>Tracer breakthrough occurred and was useful in identifying the injected $CO_2$. Complexities include complex reservoir fluids and complex well completions, as well field analysis | | | | | |

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X X | | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Tracers successfully identify migration pathway – no information on other mobilised substances | | | | | |

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | X | | | |
| **Summary findings (1-2 sentences)** | | | | | |

| **Rating** |
|---|
| Generally good, reporting of statistical variation in U-tube samples in particular SF6 awaiting CD4 reporting.<br><br>As a fairly completed activity, this test reveals a lot about uncertainties. Looking at the complexities of breakthrough and dependence of detection on sampling strategy over a porous media over 300 m should make us humble about detection of tracer at surface leakage points. Overall however a simple story –$CO_2$ arrived quickly at expected interval below methane cap (probably), and then underwent complex behaviour as the plume grew |

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X X | | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Every reason to expect that tracers will continue to provide useful information on injection stream migration pathways; would like to see more discussion on physical and chemical aspects of $CO_2$ stream tracer coupling<br><br>Tracer program already worked | | | | | |

E. Please comment on any scientific or technical issues that require attention.

| **Summary findings (1-2 sentences)** |
|---|
| Recommend consideration of potential with time for physical and chemical decoupling between $CO_2$ and artificial tracers in reservoir and overburden. Recommend here or elsewhere (if more appropriate) detailed consideration of $CO_2$ water rock reactions and evolution of carbon isotopic composition of $CO_2$ and other C-species (HCO3- and carbonate cements)<br><br>*[That will not be addressed in the current paper that you have reviewed. We certainly will be working together with the large body of results to address these questions in the next 6-12 months. – CO2CRC]*<br><br>Look forward to next result… |

# APPENDIX 12 Wellbore seismic

| | |
|---|---|
| **Project Area (Paper Title):** | Report on borehole seismic monitoring at Otway |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | May 25, 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X X | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| The downhole seismic instrument package is well suited to the monitoring task at this site (deep reservoir, small amount of $CO_2$). Significant issues have arisen due to non-performance of some of the instrumentation and large seasonal variations in the near-surface.<br><br>Status review of well-bore based seismic. Interim results report purposes, limits and difficulties, and results to date | | | | | |

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | | X. NA | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Monitoring to date showed no detectable change at the reservoir level, consistent with the small amount of $CO_2$ (5000 tonnes) injected to the time of the May 2008 survey. Ultimate usefulness remains to be established during subsequent surveys.<br><br>Not applicable | | | | | |

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | | X | | |
| **Summary findings (1-2 sentences)** | | | | | |

| **Rating** |
|---|
| The analysis to date is very cognisant of the uncertainties in the time-lapse monitoring results and is appropriately taking them into account in interpreting the results.<br><br>It would be good to see some follow on about sensitivity of geophysics to leakage into the Paaratte. |

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X | X | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Based on results to date, it is not clear whether the initial objectives of this component of the monitoring program will be successful.<br><br>This site probably did not provide the world's best chance for a demonstration of the power of well-bore seismic. So success is relative, to add to experience. | | | | | |

E. Please comment on any scientific or technical issues that require attention.

| **Summary findings (1-2 sentences)** |
|---|
| The design of the downhole monitoring system represents state-of-the-art. More work is required in establishing the most effective means of analysing the data (methodology and data horizons) and overcoming the source-side data non-repeatability.<br><br>Look forward to next result |

# APPENDIX 13 Pressure

| | |
|---|---|
| **Project Area (Paper Title):** | Pressure Measurements |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | May 22, 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X | X | | |
| **Summary findings (1-2 sentences)** | | | | | |
| In situ pressure measurements provide essential data for improving the dynamic simulation models. The methodology rates highly in regard to each of the above criteria.<br><br>Initial presentation of bottom-hole pressure gages, flow rate in injection well, surface pressure at injection and production well. | | | | | |

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X X | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Have significant potential for verification of simulation predictions. But, measurements in injection well (rather than monitoring well) is a limitation.<br><br>This is a good summary of the injection stream, a key input to modelling Needs more analysis and attribution to confirm that the data are clean, reliable, and ready to go. | | | | | |

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X | X | | |
| **Summary findings (1-2 sentences)** | | | | | |

| **Rating** |
|---|
| Accuracy of measurements is assessed. |

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X | X | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Apart from demonstrating the technology, it is not clear how these results are being integrated into the overall programme.<br><br>An interim report on key basic data. | | | | | |

E. Please comment on any scientific or technical issues that require attention.

| **Summary findings (1-2 sentences)** |
|---|
| This was a good initial test demonstrating the technology. Data needs to be incorporated into history matching. |

# APPENDIX 14 Reservoir Modelling

| | |
|---|---|
| **Project Area (Paper Title):** | Reservoir Simulation Modelling |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | 25/5/09 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | | X | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Updates model parameters, Rg .35, Rw .09 from end point saturations from core, hydrologic boundary conditions via connection to aquifer, updated production history, role of gas compressibility. Good model match | | | | | |

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X X | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Pressure monitoring in injection well and results from 2/3 geochemical sampling point results in Naylor1 are in good agreement with modelled predictions. Paper does not deal with substance mobilisation.<br><br>Interesting methane/$CO_2$ interaction. Would like to know more both from measurements and models.<br>How much does the probabilistically distributed interwell permeability impact the gas distribution? Needs more exploration. | | | | | |

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X | X | | |

| **Summary findings (1-2 sentences)** |
|---|
| Xu paper states main remaining uncertainty is the character and hydraulic connectivity of the aquifer. However understanding of **potential leakage pathways** to receptors is described elsewhere as very poor (Jenkins overview paper).<br>The paper did not mention potential leakage pathways, have they done this but not shown us? – Someone must've done a scenario of leakage.<br><br>An interim result is attacking all the important questions, more work to be done<br><br>Interesting methane/$CO_2$ interaction. Would like to know more both from measurements and models.<br>How much does the probabilistically distributed interwell permeability impact the gas distribution? Needs more exploration. |

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | X | | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Behaviour of injected $CO_2$ at present in broad agreement with predictive modelling. Ultimately successful verification strategy depends heavily on absence of $CO_2$ in overlying aquifer formation.<br><br>An interim result is attacking all the important questions, more work to be done | | | | | |

E. Please comment on any scientific or technical issues that require attention.

| **Summary findings (1-2 sentences)** |
|---|
| Lack of information on caprock characteristics, predicted geochemical/geomechanical integrity of seal. Forward modelling of depleted field/aquifer interaction and long term fate of stored $CO_2$, important for risk assessment, M&V.<br><br>More work needed, but this is on a very good path |

# APPENDIX 15 Shallow aquifers

| | |
|---|---|
| **Project Area (Paper Title):** | Shallow aquifers/Hydrological Monitoring |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | 24 May 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X | X | | |
| **Summary findings (1-2 sentences)** | | | | | |
| A rather extensive array of sampling stations (25) as well as species included in the analysis indicate a comprehensive program of hydrological modelling. Methodology used is widely accepted for accuracy.<br><br>Characterisation of major freshwater aquifers in Pilot area, Port Campbell and Dilwyn karst aquifers | | | | | |

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | | NA | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Monitoring aquifers above the storage reservoir provides assurance of drinking water protection and provides an indicator of any unexpected leakage into the overburden. The species selected are the ones likely to change as a result of increasing $CO_2$ levels.<br><br>No data about injection stream. | | | | | |

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X | | X | |
| **Summary findings (1-2 sentences)** | | | | | |

| **Rating** |
|---|
| The paper addresses this issue in some fashion, but inherent uncertainties in water analysis are perhaps smaller than in some other M&V methods.<br><br>The aquifer study is descriptive only, and does not attempt to determine what would happen to the aquifers if the containment should fail and $CO_2$+brine+methane leak into aquifers. |

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | X | | X | | |
| **Summary findings (1-2 sentences)** | | | | | |
| The survey needs to be better designed to produce the requisite public information. Need to know what are risks to water and how do we know that no risk is occurring. | | | | | |

E. Please comment on any scientific or technical issues that require attention.

| **Summary findings (1-2 sentences)** |
|---|
| Because of the small budget, available wells were used, but this is not necessarily the way that it should be designed. – There are a large number of sampling points, but not necessarily in the right place. Because of the use of available wells only, need to think more about the scenario.<br><br>As for soil gas, the analysis is descriptive, and immature |

# APPENDIX 16 Soil gas

| | |
|---|---|
| **Project Area (Paper Title):** | Soil Gas Monitoring |
| **Name of Peer Reviewer:** | |
| **Date of Review:** | 24 May 2009 |

A. Please rate and comment on the capacity, reliability, accuracy and effectiveness of the enhanced monitoring processes, as demonstrated in their operation in the year since injection commenced.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | | X | X | |
| **Summary findings (1-2 sentences)** | | | | | |
| Summer 09 data was not provided, but comments can be made on the basis of the overall plan. Methods being used are broadly accepted. Seasonal restrictions on surface access prevent the same locations from being sampled frequently enough.<br><br>Baseline and technique inventory for soil gas. Several He anomalies. Extensive methane and $CO_2$ production, mostly with young $C^{14}$ | | | | | |

B. Please rate and comment on the usefulness of findings to date in verifying predictions about the injection stream and other mobilised substances.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | | NA X | | |
| **Summary findings (1-2 sentences)** | | | | | |
| Soil gas sampling is more of an assurance M&V technique rather than one that will provide information about plume evolution, so this is not the most applicable question for this part of the program. It will help confirm that $CO_2$ is not reaching the surface.<br><br>No data about injection stream This is an assurance technique. | | | | | |

C. Please rate and comment on the understanding of the uncertainties in the M&V, and appropriate handling of these uncertainties.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | X | | X | |
| **Summary findings (1-2 sentences)** | | | | | |

| **Rating** |
|---|
| Ecosystem contributions can provide significant background fluctuations. The team is well aware of this and is addressing the situation by extensive background sampling and detection of isotopes and other gases.<br><br>There is a good understanding of the uncertainties.<br><br>This is a "by the book" soil gas survey for the main constituents of interest, $CO_2$, methane, $C^{14}$, He. It does not undertake to understand process or how leakage signal could be separated from background |

D. Please rate and comment on the likelihood that the M&V programme will be brought to a successful conclusion.

| **Rating** | | | | | |
|---|---|---|---|---|---|
| **Criteria** | Excellent | Good | Adequate | Poor | Very Poor |
| **Rating** | | | X | X | |
| **Summary findings (1-2 sentences)** | | | | | |
| The Soil gas portion of the M&V is well designed and implementation looks strong as well.<br><br>This survey is, in my opinion, not likely to provide the desired public information. The $CO_2$ concentration changes over time appear noisy; | | | | | |

E. Please comment on any scientific or technical issues that require attention.

| **Summary findings (1-2 sentences)** |
|---|
| Aspects of this program are well designed, but there appears to be some lack of consistency on the effort perhaps partly caused by surface access issues. The high He areas warrant additional investigation.<br><br>Follow up on high He areas<br>Model ambient $CO_2$ generation, then model a hypothetical leakage signal<br>Plot data already collected more rigorously |

# APPENDIX 17 Expert Reviewer Biographies

## Andy Chadwick

Andy Chadwick is a Principal Scientist with the British Geological Survey. He holds an MA from the University of Oxford and a DSc from the University of Durham, and has nearly thirty years' experience in most aspects of seismic geophysics and basin analysis.

He has been involved in $CO_2$ sequestration since 1998, in a number of major international projects including SACS, CO2STORE, CASTOR, CO2GeoNet and CO2ReMoVe. His work in this field has focussed on storage site characterisation and geophysical monitoring and verification. The latter has included detailed interpretation and modelling of the time-lapse (4D) seismic at Sleipner. He has also contributed to the development of alternative geophysical monitoring technologies such as microgravimetry.

He has contributed to special reports for the UK DTI on $CO_2$ monitoring technologies and site regulation, is a contributor to the IEAGHG web-based Decision Support Tool for site monitoring and has provided technical advice on $CO_2$ storage regulation issues to the UK and Australian governments and also to the government of Western Australia.

## Susan Hovorka

Susan D. Hovorka is a Senior Research Scientist at the Bureau of Economic Geology, Jackson School of Geosciences. She is the chief scientist of the Gulf Coast Carbon Centre, (**www.gulfcoastcarbon.org**) an academic-industry consortium seeking an economic basis on which to move forward on carbon sequestration. She holds a BA from Earlham College and a MA and PhD in geology from the University of Texas at Austin. Currently she is leading a team in a Frio Brine field pilot $CO_2$ injection and SECARB Phase II-and III large volumes tests to assess the cost, safety, and effectiveness of geologic sequestration as a mechanism for reducing atmospheric greenhouse gas emissions). She is also active on facilitating exchange between applied scientists and citizens, with a focus on pre-college students and teachers. Her background is sedimentology with application of hydrologic and two-phase flow processes.

## Don White

Don White is a Senior Research Scientist at the Geological Survey of Canada. He received his Ph.D. in Geophysics from the University of British Columbia. His research focuses on applications of seismology to mineral exploration, deep-crustal structure, and time-lapse monitoring. From 2001-2004, he was the theme leader for Monitoring and Verification during Phase I of the IEA Weyburn $CO_2$ Monitoring and Storage Project and continues as leader of the geophysical monitoring programme in Weyburn-Phase II. Recently, he participated on an external review of Japan's Nagaoka $CO_2$ injection and storage project.

## Tim Dixon

Tim joined IEA GHG in January 2008. He is responsible for ensuring IEA GHG activities provide the evidence-base to support the growing regulatory and policy developments for CCS.

From 2002 Tim worked in the UK Department for Business, Enterprise and Regulatory Reform – BERR (formerly Department of Trade and Industry - DTI) as Senior Policy Advisor, seconded from AEA Technology. He worked in the area of carbon capture and storage (CCS) and also cleaner fossil fuels, coal mine methane, and related international collaborations and agreements. As well as working on UK and EU regulatory developments for CCS, Tim led the DTI work on CCS and emissions trading (EU ETS and CDM), and represented the UK DTI in the work for the amendments of the London Protocol (1996) and OSPAR (1997) marine conventions to remove their prohibitions on $CO_2$ storage. Tim also worked on the CCS and cleaner fossil fuel initiatives for the UK's G8 Presidency and the EU-China NZEC Project for the UK's EU-Presidency in 2005.

Prior to BERR, in AEA Technology's ETSU at Harwell since 1995, Tim worked as Programme Area Manager for UK DTI's Cleaner Fossil Fuels and Carbon Abatement Programmes, Principal Consultant for International Emissions Trading, and Manager of DTI Renewable Energy Exports. Tim has also worked in Non-Destructive Testing in UKAEA, with a spell at Curtin University, Perth, Australia. Tim has an MBA from Oxford Brookes University (1997), a BSc Applied Physics from the University of Hull (1986), and is a member of the UK Energy Institute and the UK Environmental Law Association.

## Neil Wildgust

Neil joined IEA GHG in April 2008 and is responsible for co-ordination of IEA GHG activities relating to geological storage.

Neil previously worked for Eon UK, where from 2003 he was responsible for groundwater assessment and landfill permitting, and also maintained a technology tracking role for CCS geological storage issues. Neil has a BSc (Hons) in Geology from Southampton University in 1987, an MSc in Applied Environmental Geology from Cardiff University in 1998 and is a chartered geologist. After graduating in 1987, Neil worked for Lonrho as an exploration geologist in Mozambique and subsequently has had spells working for BP, RMC, Hyder Consulting, Geotechnical Engineering and Jacobs Babtie. His experience encompasses mining and quarrying, oil and gas, contaminated land assessment, landfill waste disposal and geotechnical investigation.

## Mark Raistrick

Mark Raistrick is a geologist and an expert in geological $CO_2$ storage monitoring. Mark's background includes hands on experience of operational geological $CO_2$ storage; collecting, and interpreting monitoring data, and developing monitoring tools at a number of $CO_2$ storage projects, including the IEA GHG Weyburn Project in Saskatchewan, Canada.

Since joining Senergy, Mark has advised UK and global clients on $CO_2$ storage site selection, storage monitoring, containment and operational risk assessment. Projects include both saline aquifer and depleted gas field storage site selection and characterization, basin screening, $CO_2$ enhanced oil recovery and CDM project planning.

## Lee Spangler

Lee Spangler is the Associate Vice President of Research at Montana State University where he directs the Energy Research Institute. He also directs two efforts related to geologic carbon

sequestration, the Big Sky Carbon Sequestration Partnership (one of 7 DOE funded Regional Partnerships) and the Zero Emission Research and Technology Centre (ZERT) which involves 5 DOE national labs and two universities. In this program Dr. Spangler lead the development of a unique field laboratory for testing detection technologies that has attracted international collaborators and will be the topic of a special issue of the Journal of Environmental Earth Sciences (formerly Environmental Geology, in preparation). He has served on the FutureGen Technical Experts panel and has been an instructor in the Carbon Sequestration Leadership Forum's Capacity Building Workshop Program.

## Hubert Fabriol

Hubert Fabriol obtained a PhD in Applied Geophysics at University of Pierre et Marie Curie, Paris, in 1977: "Development of a method of differential geomagnetic sounding and its application to the detection of geothermal energy sources in the Rhine graben". Hubert joined BRGM in 1983, and now manages the Underground and Cavities Risk Unit (30 persons). His involvement in $CO_2$ geological storage started in 1993 within the European project JOULE II. He participated to former EU projects (SACS, SACS2), and Weyburn Phase I. He is presently involved in FP6 funded projects (GRASP, CO2ReMoVe) and coordinates the project Géocarbone Monitoring, funded by the French Agency for Research. He assessed the French Ministry of Environment for the London Convention and OSPAR discussions on $CO_2$ sub-sea bed geological storage. He is presently member of the CSLF Risk Assessment Task Force. His areas of interest in $CO_2$ storage are monitoring, particularly passive seismic, electric and electromagnetic methods, and safety criteria.

## Sarah Hannes

Sarah Hannis is a geologist at the British Geological Survey. She has a first class honours MSci degree in Geological Sciences from Imperial College, London. At BGS she has worked mainly on UK and world mineral resources, investigating security of supply issues and providing advice on UK mineral planning policy. Recently she has been working on BGS carbon storage projects and contributing to the IEAGHG web based Decision Support Tool for $CO_2$ storage site monitoring. Previously she worked for Schlumberger as a reservoir evaluation wireline senior field engineer, logging oil and gas wells along the Louisiana coastline.