Technology Collaboration Programme
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IEAGHG Technical Review
2021-TR03
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# IEAGHG Monitoring Network – Webinar & Virtual Discussion: Monitoring Expertise Showcase for Post-Closure Monitoring

IEA GREENHOUSE GAS R&D PROGRAMME

## International Energy Agency

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## ACKNOWLEDGEMENTS AND CITATIONS


This report describes a virtual panel discussion for the IEAGHG Monitoring Network held in January 2021. This report was prepared by Samantha Neades, IEAGHG with input from the panellists.

IEAGHG would like to thank the IEAGHG Monitoring Network Steering Committee for their efforts in facilitating this webinar:

- Charles Jenkins, *CSIRO*
- Frederick Gal, *BRGM*
- Jun Kita, *Marine Ecology Research Institute (MERI)*
- Katherine Romanak, *Bureau of Economic Geology at the University of Texas*
- Lee Spangler, *Montana State University*
- Rob Trautz, *Electric Power Research Institute (EPRI)*
- Susan Hovorka, *Bureau of Economic Geology at the University of Texas*
- Tom Daley, *Lawrence Berkeley National Laboratory*
- Ziqiu Xue, *Research Institute of Innovative Technology for the Earth, Kyoto (RITE)*
- Tim Dixon, *IEAGHG (Chair)*
- James Craig, *IEAGHG*
- Samantha Neades, *IEAGHG*

IEAGHG would also like to thank the panellists for their contributions to the event:

- Jonathan Ennis-King, *CSIRO*
- Yannick Bouet, *Modis*
- Fabrice Boesch, *Modis*
- Hadi Nourollah, *CO2CRC*
- Dave Johnson, *LI-COR Biosciences*
- Katherine Romanak, *Bureau of Economic Geology at the University of Texas*
- David Bomse, *Mesa Photonics*
- Nick Hoffman, *CarbonNet*
- Don Lawton, *University of Calgary / CMC*

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## Introduction

On the 26th January 2021, a virtual event was held for the IEAGHG Monitoring Network, an expertise showcase for post-closure monitoring. 63 attendees joined the webinar, in addition to 19 panellists and 2 IEAGHG support staff.

This was a little different from usual webinars, whereby the Steering Committee aimed for a more interactive and informal experience for the audience with a scenario-based exercise. Experts in the area of post-closure monitoring were invited prior to the webinar to propose how they would approach a post-closure monitoring plan for a given hypothetical $CO_2$ storage site. These hypothetical proposals were presented to the webinar audience (who were acting as the site developer) and following questions and discussion from the IEAGHG Monitoring Network Steering Committee, the audience was invited to vote on which technologies they would choose as a developer for this hypothetical site.

## Welcome

Tim Dixon, General Manager of IEAGHG, was the moderator for this webinar and welcomed all to the event. He noted that the Steering Committee chose this topic for the webinar as it is of interest because there are requirements for post-closure monitoring from various regulations, but there are no projects that have reached this stage yet; it's an area where thinking is currently being developed.

Steering Committee Panellists:

**Tim Dixon** (IEAGHG, UK)
**Susan Hovorka** (Bureau of Economic Geology at the University of Texas, USA),
**Charles Jenkins** (CSIRO, Australia),
**Lee Spangler** (Montana State University, USA),
**Jun Kita** (MERI, Japan),
**Frederick Gal** (BRGM, France),
**Tom Daley** (Lawrence Berkeley National Laboratory, USA),
**Ziqiu Xue** (RITE, Japan),
**James Craig** (IEAGHG, UK).

## Scene Setting & Scenario

Susan Hovorka (*BEG at UTexas*) introduced the hypothetical site scenario. She emphasised that the aim of the event was to learn about post-closure monitoring options, with an informal 'game' to engage panellists with the audience in thinking about $CO_2$ storage sites and measurement, monitoring and verification (MMV). This is a hypothetical site with some gaps in the information, in reality the site characteristics would be much better understood for storage projects and months of planning would have been done prior to making any sort of decisions on monitoring programmes. The hypothetical site scenario is described in figure 1, below. This 'site' will be injecting for 25 years, into 50 metre thick sandstone at a depth of 1.5km. The plume is planned for stabilisation at 100 years as shown in the blue area on the figure.

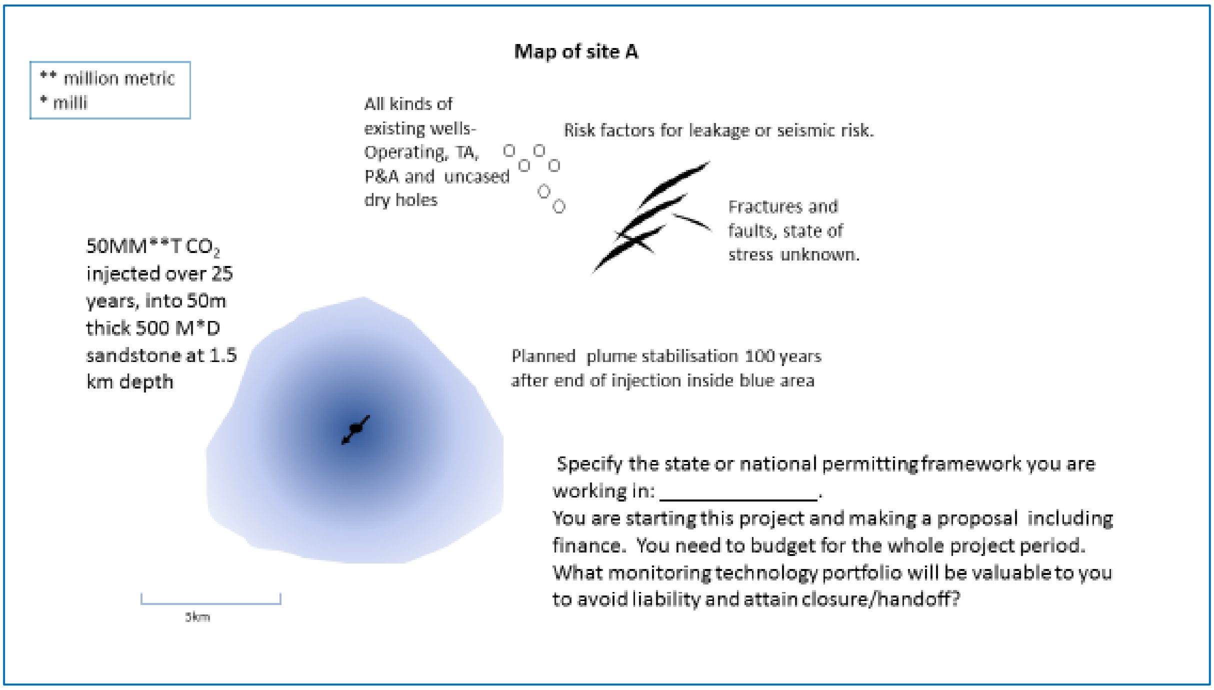


*Figure 1.* ***Hypothetical site scenario for the post-closure monitoring proposals***

## Pitches & Proposals

Proposals (also referred to as pitches) were received from seven international experts in post-closure monitoring. Their proposed approaches and techniques that could be considered for such a storage site are briefly described below.

It was emphasised again and by the panellists that this hypothetical scenario was not indicative of what would be looked at when choosing a real monitoring programme; this scenario is not indicative of a full site description. Effective and proper post-closure monitoring requires a full and detailed site characterisation, baseline knowledge and a lot of data from the area before a site is even approved.

**Jonathan Ennis-King** (*CSIRO*) introduced cross-well pressure tomography for long-term monitoring of $CO_2$ storage, developed by CSIRO and CO2CRC. Pressure tomography is looking at characterising reservoir properties from cross-well pressure response to water injection or production in a time-lapse sense, detecting $CO_2$ from repeat water injections before and after the $CO_2$ is in place. The pressure signal from each well is used to invert and reconstruct the reservoir properties along with the spatial location of the $CO_2$ plume in a tomographic sense. With this approach, having a baseline is key. For this specific 'site', this proposal would use pressure tomography as fence-line or sentinel monitoring to detect and locate anomalies that would trigger further investigation. Dynamic models will indicate the riskiest paths for unintended migration and wells would then be placed to detect consequential plume migration. Pressure tomography has a small surface footprint and is non-invasive, is easy to repeat, can be readily combined with other downhole monitoring and has low ongoing cost over long periods of time. A major cost with this technology would be the drilling of new wells (although existing wells may be able to be repurposed) and operational costs include the supply of water for injection and general maintenance of pressure gauges and wells.

**Yannick Bouet** and **Fabrice Boesch** (*Modis*) presented a plan focussed on atmospheric (using handheld mobile infrared cameras for surface leak detection) and biospheric monitoring, the latter using groundwater sampling and deep aquifer sampling for the study of micro-organisms. The deep groundwater bottomhole sampling tool can be deployed by wireline and is designed for micro-biological studies related to natural gas storage in freshwater aquifers. At a $CO_2$ storage site this could be used for monitoring of an aquifer above a caprock, ideally in a monitoring well down gradient of the $CO_2$ plume and can be repeated over time to monitor changes. The mobile camera works on the infrared spectrum where gases are strongly absorbed, so it's possible to see specific gases that are invisible to the naked eye. The camera has very good performance in finding the emission source quickly and provides the data in real time, so could be deployed to spot any anomalies. These technologies would work well in synergy with other tools used for post-closure monitoring.

**Hadi Nourollah** (*CO2CRC*) shared geophysical techniques used in reservoir, seal and environmental monitoring as investigated at the Otway project in Australia. Geophysical techniques relevant for monitoring at this hypothetical site have been performed by CO2CRC at the Otway site since 2005, with surface geophones and in 2021 have evolved to using fibre optics and SOV to provide more fit-for-purpose and cost effective techniques. Otway Stage 2C used a buried geophone array and fibre optics to provide forward modelling for a similar scenario as the hypothetical site being discussed at this webinar. Using these techniques, Otway Stage 3 offered better geophysical monitoring techniques that proved to reduce costs, have a lower footprint with remote monitoring, on demand continuous plume monitoring with a detection limit of less than 1000 tonnes. To address the seal capacity issue at the hypothetical site this proposal would use seismic sampling in conjunction with conventional technique of MICP (mercury injection capillary pressure) for calibration points and anisotropy to interpolate the capillary pressure, and therefore seal capacity.

**Dave Johnson** (*LI-COR Biosciences*) introduced an emissions monitoring system (flux system) for surface monitoring at $CO_2$ storage sites. Gas molecules are carried by eddies of wind and are either released or absorbed when mixed with the ecosystem. This system consists of a $CO_2$ gas analyser and a 3D sonic anemometer to measure the wind speed / direction. High speed measurements of $CO_2$ molecules in the wind can determine a net absorption or emission of $CO_2$ over a time period. Due to natural occurrences, ambient concentrations can vary 350 – 500 ppm in a single day, so a solution would be to measure the net difference in $CO_2$ molecules over a half hour window. Flux stations are widely used, are a proven method and using such eddy covariance techniques are the most direct and defensible way to measure fluxes in the air. Footprint mapping tools allow one to see where the emission is coming from, selecting areas of interest for detailing results for different geological formations.

**Katherine Romanak** (*Bureau of Economic Geology at the University of Texas, USA*) and **David Bomse** (*Mesa Photonics*) spoke about a process-based soil-gas approach for $CO_2$ leakage attribution. The method for this technology instantly separates and attributes various gas inputs, which is coupled with a measurement by Raman sensor which supplies smart data collection for continuous monitoring. This approach was looked at for the hypothetical site under the permitting framework of the California Resources Board Low Carbon Fuel Standard (LCFS), assuming a timeline of a 25 year project and 100 year PISC (post-injection site care). This approach will not 'find' leakage, but address long-term liability by attribution, by determining if any environmental change represents leakage from the project, by providing a direct and fast method to respond to any public allegation of leakage and with continuous monitoring in areas needing surveillance. The technique defines processes based on stoichiometry of reactions based on four simple gases; $CO_2$, $CH_4$, $O_2$ and $N_2$. The Raman spectroscopy measurement technology provides continuous monitoring capabilities, measures all four gases of interest simultaneously, is self-calibrating and needs no consumable supplies. The process-based soil-gas approach also inherently tackles some of the technically difficult LCFS requirements.

**Nick Hoffman** (*CarbonNet*) emphasised that MMV is extremely site-specific and monitoring should be risk-based, following an extensive site characterisation. One of the most important factors of a storage site is the injectivity; the thickness of the reservoir times the permeability and good initial injectivity is crucial to success and poor injectivity can lead to pressure issues. The Gorgon project is in a similar setting and injectivity zone as the hypothetical site being discussed in this webinar and so is a good analogue. At Gorgon, pressure monitoring and management are important. The Decatur project is another analogue to the hypothetical site, and taking learnings from these examples suggests that this hypothetical site would need: a full site characterisation prior to a go/no-go decision, repurposing of legacy wells in addition to new monitoring wells and is likely to need well pressure and temperature monitoring (fibre) and well microseismicity (DAS fibre). The annual MMV opex, site closure technical review and regulatory approvals would also need to be considered and factored into any project plans and budgets.

**Don Lawton** (*University of Calgary / CMC*) considered an approach under the Alberta (Canada) regulatory framework where a Closure Certificate can be issued by the Province (typically 10 years post-closure) providing that a monitoring programme satisfies several key criteria. This approach would undertake a 3D surface seismic survey over the area of interest immediately after closure and a repeated 3D surface seismic survey after 10 years post-closure. In addition, this approach recommends four instrumented observation wells at different offsets from the injection pads, where there would be continuous above zone pressure monitoring and DAS monitoring (including microseismic and VSPs) with well data used for reservoir modelling and history matching. The near surface would also need to be monitored with groundwater monitoring wells in the area of interest, using domestic wells where possible and annual sampling programmes unless anomalous results were found.

## Questions & Discussion

Following the seven 'pitches', the IEAGHG Monitoring Network Steering Committee and audience delved deeper into the approaches presented with several questions, prompting discussion between panellists and audience members.

The Committee explored further on the costs of some of the approaches. It was noted that onshore compared to offshore situations would be very different, but the ballpark figure of an approach such as cross-well pressure tomography would expect costs of a few million (perhaps 5 – 10) dollars per well. Of course, this is all very site-specific, and factors like whether you could repurpose existing wells would greatly impact the costs. In terms of the Modis deep groundwater monitoring, a single camera costs around €100,000 and the sampler around €50,000. The costs of the process-based soil gas approach are around US $60,000 for an installed sensor, with no consumable supplies and very little maintenance costs; the main costs are upfront and for installation.

In terms of water requirements for monitoring across the plume with cross-well pressure measurements, at Otway this injection has been around 200 tonnes a day over 6 hours per day, over 4 wells. The best resolution is on the scale of separation of the wells; the lines between where you're injecting water and where you're monitoring pressure are the most sensitive locations for plume detection.

The deep ground water monitoring tools (infrared cameras) are newer technologies and perhaps ones not as widely known but have many benefits. Detectable limits for the camera depend on the concentration, location (the distance from where you're trying to see the plume) and situational conditions (such as the weather), but is around 1000ppm of $CO_2$. The cameras have several options for deployment, they can be on a fixed setting for anomaly detection coupled with mobile cameras for further investigation and these could be mounted on drones, for example. For now, Modis are using these mainly as mobile cameras to detect gas leaks on surface installations, but there is flexibility with this technology.

The geophysical techniques approach was an interesting proposal regarding the caprock capacity and ability of the seismic to understand the problem over a large area, and would use seismic characteristics to describe the capacity of a shale caprock to indirectly measure the capacity of this caprock, which is being used at the Otway project where it ties in with other datasets to give a good picture of the subsurface situation. The idea is to use seismic to see what you have in the MICP sample of the caprock, then the more anisotropic the caprock the better a seal because the shale layers are more closely layered together. This information is then interpolated with the structure characteristics, and provides a static characterisation rather than dynamic monitoring of $CO_2$ – but this characterisation is taking place on demand, 24/7, so the sealing can be seen over time. Over time, seismic can keep being acquired over time to monitor any changes in the shale. In this context, it is crucial to do operational and post-closure monitoring and the seismic would be done more in the operational phase of a project.

The eddy covariance approach would first establish a baseline to know what the typical fluxes are in the environment and experiments (at CCS and controlled release sites) have shown that they can detect leaks from 1 to 300kg of $CO_2$ per day depending on the distance of the system from the site. It is harder to detect smaller sites from a long distance away, but then you would monitor and see a bigger area.

The process-based soil gas approach is flexible in that it can do both continuous and demand driven monitoring, which could depend on regulatory requirements of an area, for example some may require constant surveying near wells or faults. An ideal use for this approach would be to provide continuous monitoring in periods of remediation, where it can be confirmed that the signal is disappearing. The process-based technique is being used in some applications to the LCFS and the team have inputted into the LCFS CCS protocol. The method is not yet endorsed by regulators but this generic type of technology (attribution monitoring) is considered in the ISO standards for geological storage. There is a paper from Dixon and Romanak[1] which looks into these regulations.

It was recognised that post-closure monitoring approaches look at the response of the overall seal system to injection and the end of injection, with reservoir injectivity and fall off tests to demonstrate the aquifer is responding in a way consistent with the decay of the pressure of $CO_2$, dissipation of $CO_2$ into the aquifer and no evidence of seal failure. These need to be over a sufficient period of time, which will depend on the reservoir and seal quality, and if this period is over 25 years (for example) this would be a serious undertaking and that leads back to the question of was this site suitable for storage in the first place. If it's not suitable for monitoring, it's not suitable for storage. Ongoing pressure monitoring emphasises changes as the risk profile changes after closure. Pressure monitoring is critical but if there are no wells into the aquifer, then you need to measure within the injection well to provide a detailed and very comprehensive model of the subsurface seismic to properly characterise the site prior to project initiation.

Most of surface based solutions are post-leak, when the $CO_2$ has reached the surface. To account for this in official measurements, you would have to estimate how much has migrated out of the reservoir and this would be deducted from any storage credits (but this would be difficult to calculate). Leakage

[1] Dixon & Romanak, '**Improving monitoring protocols for $CO_2$ geological storage with technical advances in $CO_2$ attribution monitoring**', International Journal of Greenhouse Gas Control Volume 41, October 2015 https://doi.org/10.1016/j.ijggc.2015.05.029

is defined as $CO_2$ that fluxes across the ground surface and not out of the reservoir, and greenhouse gas accounting is concerned with the emissions reaching the air or water column, but that is where more work is needed – having deep monitoring methods to inform the near surface methods in real time. By the time it reaches the surface there has been a release, but this is why site characterisation is so important – to know the seal capacity, the pressure constraints etc., and injection / pressure could be managed to lessen the loss of $CO_2$.

## Audience Voting, Feedback & Discussion

The audience were given the chance to vote on which of the technologies or approaches they would choose if they were acting as the site developer of the hypothetical site introduced in this webinar. The precise results of the poll will not be reported in this report as it was only an informal way of engaging the audience and providing feedback to the Network Steering Committee.

There was some conversation about why some did not choose seismic. Perhaps some thought if there is a well-defined structure, seismic isn't needed – but this isn't the case, you need to know what is out of zone. In this hypothetical scenario, the presence of wells, fractures and faults is the reason why large scale seismic monitoring would in fact be needed. There is value in constant monitoring and having an on demand, remotely operable seismic to see if the plume is behaving as expected and to quickly detect any anomalies. We know the subsurface well but need to be prepared for any changes.

A broad view shared by many was that a site would probably be doing most of the above; there is no silver bullet for post-closure monitoring. Deep monitoring approaches are giving a detailed picture on what's happening inside of the formation and ensuring you have this picture, along with structural and well integrity, is crucial. Perhaps this explains why the surface processes were also less popular with the audience; the below surface geophysical techniques are key to ensure the integrity of the reservoir. However, shallow and surface monitoring may be needed as assurance monitoring, regulators may require sites to look for consequences (not leaks) to define the social licence. Responding to stakeholder concerns is going to be important. There has been one case where local landowners have suspected a leak but this was disproven by various methods[2]. What's key to remember is that geologic $CO_2$ storage is safe by design, and we design it to be safe.

Post-closure liability and costs is different in different regions. For example, in Alberta, during a storage programme there is a stewardship paid by the operator for tonnes stored and this funding is kept in case there is an issue to be remediated post-closure so the government / public does not have to pay. Similarly, in the EU the system requires an amount of money from the operator to the regulator for that purpose. False positives are an important issue to consider too; ideally, technologies should have a low false positive rate and this would be a serious consideration over long term post-closure.

Interestingly, there were a lot of differing thoughts on the approaches presented in this webinar which demonstrates that the understanding of the technologies and approaches for post-closure monitoring is still immature. The results of the voting gave more information on what needs to be looked into further and was a good mechanism to test and engage the audience.

[2] Romanak et al, '**Assessment of Alleged $CO_2$ Leakage at the Kerr Farm using a Simple Process-based Soil Gas Technique: Implications for Carbon Capture, Utilization, and Storage (CCUS) Monitoring**', Energy Procedia Volume 37, 2013, https://doi.org/10.1016/j.egypro.2013.06.326

## Wrap-Up & Summary

The webinar was concluded by Tim Dixon who thanked the panellists, Steering Committee and audience for their valuable input into the event. Many topics were looked into around the area of post-closure monitoring for $CO_2$ storage sites, and several key messages were drawn from the discussion:

- There is a wide range of available technologies that can be deployed for post-closure monitoring programmes, all of which have different merits,

- Post-closure monitoring is very site specific,

- Effective and proper post-closure monitoring requires a full and detailed site characterisation, baseline knowledge and a lot of data from the area before a site can be approved,

- It's important to do both operational and post-closure monitoring,

- Leakage is defined as $CO_2$ that fluxes across the ground surface and not out of the reservoir; greenhouse gas emissions accounting is concerned with the $CO_2$ reaching the air or water column,

- More work is needed on deep monitoring methods informing the near surface methods in real time,

- The subsurface is known well but operators need to be prepared for any changes,

- It is likely and recommended that monitoring programmes will use a variety of technologies that complement one another,

- Shallow and surface monitoring may be needed as assurance monitoring,

- Responding to stakeholder concerns is an important facet of monitoring programmes,

- Environmental liability differs in different regions,

- False positives are an important factor to consider when choosing technologies,

- Understanding of post-closure monitoring approaches is still immature,

- Geologic $CO_2$ storage is safe by design, and is designed to be safe.

## Previous Monitoring Network Meetings

The development of this discussion panel was prompted by the current travel restrictions due to the Covid-19 pandemic and was a follow-up webinar to the August 2020 Monitoring Network Webinar and Virtual Panel Discussion. For a copy of the report from the previous webinar, please contact tom.billcliff@ieaghg.org, quoting report number 2020-TR03. The 13th in-person meeting of the IEAGHG Monitoring Network was held on 20th – 22nd August 2019, hosted by the University of Calgary and for a copy of this meeting report quote number 2020-02. For more information on the IEAGHG Monitoring Network see https://ieaghg.org/networks/monitoring-network.

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

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