Technology Collaboration Programme
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IEAGHG Monitoring Network Meeting Report

Technical Review 2023-TR05

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IEA GREENHOUSE GAS R&D PROGRAMME

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About IEAGHG

Blazing the way to net zero with leading CCS research. *We advance technology to accelerate project development & deployment.*

We are at the forefront of cutting-edge carbon, capture and storage (CCS) research. We advance technology that reduces carbon emissions and accelerates the deployment of CCS projects by improving processes, reducing costs, and overcoming barriers. Our authoritative research is peer-reviewed and widely used by governments and industry worldwide. As CCS technology specialists, we regularly input to organisations such as the IPCC and UNFCCC, contributing to the global net-zero transition.

About the IEA

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate is twofold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy. The IEA created Technology Collaboration Programmes (TCPs) to further facilitate international collaboration on energy related topics.

IEAGHG Monitoring Network Meeting

8th-9th August 2023

Baton Rouge, Louisiana, USA

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Executive Summary

The IEAGHG Monitoring Network aims to assess new technologies and techniques in the monitoring of CO_2 storage, determine the limitations, accuracy and applicability of monitoring techniques, disseminate information from research and pilot storage projects around the world, develop extensive monitoring guidelines for the different sub-categories of geological storage; oil and gas fields, unmineable coal seams, and saline aquifers covering the differing conditions and reservoir properties encountered globally as well as to engage with relevant regulatory bodies.

Co-hosted by Louisiana State University's (LSU) Petroleum Engineering Department and the Gulf Coast Carbon Center (GCCC) in Baton Rouge, Louisiana, this was the 14th in-person meeting of this IEAGHG research network and for the first time in the Network's history, the event was split into two separate themes to reflect the importance and timeliness of not only technical knowledge but also regulatory issues. Day 1 encompassed a technical deep-dive into developments in monitoring techniques, methods and processes and day 2 encouraged regulators and technical experts to ruminate on the details of regulatory topics that need addressing in the CO_2 monitoring sphere.

This meeting aimed to determine the limitations of CO_2 storage monitoring technologies available today, facilitate the exchange of ideas and experiences in monitoring, and promote the development of improved designs and implementation of monitoring guidelines. Technical sessions involved presentations from international experts and discussions on areas such as fibre optics, low-cost monitoring for subsurface seismic and non-seismic methods, offshore environmental monitoring, terrestrial monitoring and automation and integration of MMV. The regulatory-focused day delved into framing the problem, environmental aspects, requirements and societal considerations of monitoring.

The conclusions from the first day included: noting the significant advances in geophysics, adding maturity to plume monitoring; with carbonate geology - monitoring advances and needs are specific to this geology; there are strong tools for marine monitoring and attribution of seabed leakage; what monitoring is needed depends on what is needed by different users, e.g. environmental risk, accounting, business risk – trespass, liability for incident, allegation, economic risk, public acceptance/assurance; noted AUV developments and that small USV are commercial; combining permanent and/or mobile (on demand) – keep focussed on why and the value; hubs may have different CO_2 stream compositions with monitoring implications. Recommendations included: that developments in monitoring should be acceptable by regulators; development of traffic lights for monitoring measurements to trigger responses using weight of evidence and multiple lines of evidence; need for public data on CO_2 in overburden; it would be good to have a global database on environmental parameters.

The highlights of the regulatory day included: that looking into US Class I well permits and data provides much useful information and learnings for Class VI; speeding up the closure process would be very site specific and still determined by the regulator; and there was great input from regulators, particularly the Louisiana Department of Natural Resources. The workshop identified unmet needs which included: public communications; updating regulations and guidance to include technology/technique developments; more case studies on wellbore integrity and there would be benefit from having a test site; monitoring strategies for wells that cannot be re-entered; clearer metrics on groundwater monitoring for response to allegations; groundwater to take brine into account, as well as CO_2; how to better handle pressure space; delineate the area of review based on pressure and corrective action; brine monitoring; whose responsibility is induced seismicity due to pressure space interactions?; non-well based pressure monitoring; better fault characterisation – barrier, transmission, monitoring strategies; how to define the offshore “area of review” and pressure management; and to reach out better to journalists and social media.

Day 1: Technical Deep Dive

Session 1: Fibre Optics & Low-Cost Monitoring for Subsurface Seismic

LBNL Mont Terri project on fault system monitoring, Yves Guglielmi, Lawrence Berkeley National Laboratory

This presentation summarised work done at the Mont Terri Underground Research Laboratory. The lab is nestled into a clay layer underneath a highway in Switzerland, and the test facility runs fault injection experiments in a caprock analogue. Varying fibre optics are used to measure pore pressure, displacement, and strains to compare to seismic waves and to validate an active seismic technique (Continuous Active-Source Seismic Monitoring, or ‘CASSM’) for time-lapse imaging of fluid leakage in low-permeable fault affecting a caprock. The goal of this LBNL work is to validate CASSM and see if it tracks fault movement and answer the following questions: (1) Can we observe changes in seismic velocity? (2) Can we track leakage pathways? and (3) Can we inverse velocity changes into changes in fault effective stress or strain?

The fault was activated by injecting into the fault zone (~370 m deep) at a constant flow rate and was monitored to capture how the fault initiates and propagates. The first arrivals of P-waves were clearly observed, but the S-wave phases could not be seen due to the strong attenuation in the rock and fluid coupled instrumentation. The results show that the normal displacement estimated from the seismic response (δV_p) is consistent with local fibre optic measurements. This experiment has high implications for assessing information on aseismic and/or inter-seismic fault processes and on fracture/fault healing/sealing.

In conclusion, the validation of an active seismic imaging technique can bring indirect 4D information on fault activation and leakage in volumes between wells. Additionally, in having calibrated time-lapse images versus fault strain three perspectives emerge: that identifying the stress regime and gradient is critical in determining fault leakage direction, there may be large contrasts in fault opening spatial distributions which may be related to variations in fault thickness, and that there is significant residual deformation related to shear-induced damage. The next experiments will involve the injection of CO_2 dissolved in water.

DAS technology trials at Quest, Marcella Dean, Shell

Shell’s Quest CCS facility is a fully integrated, commercial-scale CCS facility in Canada which has stored over 1 million tonnes of CO_2 per year since 2015 (a total of over 8 million by March 2023). There are two fibre optic technologies deployed at this site: Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing Vertical Seismic Profiling (DAS VSP). DTS monitors temperatures along the wellbore with fibre optic cables cemented on casing. Warm-back analysis shows no evidence of any anomalies that could indicate loss of containment. DAS VSP also uses fibre optic cables cemented on casing and surface sources for imaging. The CO_2 plume near the wellbore can be seen based on the changes in acoustic impedance as CO_2 displaces brine. Observation of the differences in the time-lapse VSP images, baseline vs. current, shows containment and conformance of the injected CO_2 at the Quest site. Though the maximum subsurface offset from the well imageable is between 800-1000m, it can monitor containment along the injector well for the entire project lifetime. DAS VSP has been shown to be a robust time-lapse technology for CO_2 storage monitoring.

Current investigations for lower cost methods to image between injection pads are considering Helically Wound Cables (HWC). HWCs utilise wound fibres to almost eliminate broadside insensitivity and suppress noise as the cable is below most of the effect of ground roll. Combining HWC + a Virtual Source (VS) with DAS VSP can offer a good fit-for-purpose solution for imaging a CO_2 plume.

Another trial comparing DAS microseismic monitoring with downhole geophones revealed that it sees around 70% of the events the geophones can detect. DAS STA/LTA did not validate events well and an RMS-based method performed better instead. Estimations of the hypocentral distance between DAS and geophones were similar, but for some events, DAS suggested they were occurring closer to the well. DAS overestimated the magnitude for small events, and geophones overestimated magnitudes for larger and far events.

In summary, DTS can be used to verify containment via warm-back analysis. DAS VSP has been demonstrated to be a valuable monitoring option that reduces the need for repeat surface seismic surveys, especially early on. The method is valuable for confirming containment and conformance within the range of the imaging area. A new potential method using HWC can increase the imaging area in combination with DAS VSP. Finally, DAS microseismic has been demonstrated to be a lower cost monitoring option even in an active injector.

Borehole-DAS monitoring of a leakage-like CO_2 injection, Stanislav Glubokovskikh, Lawrence Berkeley National Laboratory

Stage 3 of the Otway project in Australia uses Surface Orbital Vibrators (SOV) and DAS for cost-effective, continuous, and automated monitoring with a decreased acquisition footprint to study the seismic detectability and trackability of a small leakage from commercial storage. Compared to conventional systems, DAS / SOV is temporally dense and spatially sparse.

This work simulated CO_2 leakage from the injection zone ~1.5 km deep (below a previous injection zone). 9 SOVs were used to track the plume and for validation, along with a 4D VSP. The SOV/DAS was able to pick the plume contours before the VSP seismic was acquired and was also able to capture the evolution of the CO_2 plume, which intersected the fault. Observed effects include the softening of the formation because of the CO_2, remobilization of the previous CO_2 injection plume, and seismicity triggered by CO_2 flow, not just pressure.

The multi-well DAS monitoring system provides high SNR (signal-to-noise ratio), angular coverage, and channel number, and can provide clear seismic images of a tiny plume. DAS amplitude within the plume enables repeat sonic logging for free and is a sensitive tool for microearthquake monitoring (though calibration of the amplitude is needed). Overall, it is an excellent monitoring system if you can afford deep wells. Points were made that the interaction and chemical response between the CO_2 and fault gouges should be considered further as most of the focus was on the pressure plume.

CaMI updates and concepts around sparse monitoring, Don Lawton, Carbon Management Canada

Various sensors are used at the CaMI station in Calgary, Canada, to evaluate monitoring systems at different radial distances to an injection into the overburden. Monitoring methods included Electrical Resistivity Tomography (ERT), DTS, VSP (geophones and DAS), large-scale VSP & 3D seismic surveys, and large-scale walkaway VSP (geophones and DAS). Decision making for optical fibres in wells for VSP surveys depend on geoscience (monitoring data quality), engineering (well integrity), and cost. VSPs can image the plumes mostly in the early days of the injection program, and 3D images can be used up to approximately 10 Mt of injection; thereafter it may become too costly. Sparse nodes are applicable for monitoring at large-scale beyond 500 Mt. Four SADAR® arrays are deployed at CaMI at different distances to refine performance understanding. The SADAR receiver, combined with a HyFold plasma source, maximises the signal-to-noise, frequency, azimuth, and real-time processing as a passive seismic monitoring system.

The main lessons from this site highlight the importance of understanding certain monitoring strategies are more / less applicable at different stages and should be chosen depending on the coverage, resolution, and cost. Examples include InSAR (reflectors), 3D seismic, soil sampling, groundwater, well pressure/temperature/fibre, walkaway VSP, well logs (RST), microseismic (geophone / DAS), electromagnetic, gravity, sparse nodes, and Electrical Resistivity Tomography (ERT).

Session 1 **Discussion**

There was a question to speakers if anyone had looked at the end-point CO_2 phase, in terms of geochemistry, after vertical/horizontal migration of the plumes because of the different cycling that carbon goes through. The Quest facility has done extensive reactive transport modelling and emphasises that these interactions are site-specific and recommends studies be done in each location.

Regarding a question about how equipment or monitoring systems may change over time to reconcile legacy data and evolve with the implementation of new equipment, it was noted that this is an ongoing question that is being studied and was recommended to perhaps stick to simple seismic data that would be applicable long-term.

These monitoring systems are also critical to increase confidence in closure. History matching models and predictions to the outcome helps validate understanding of operations. It is also critical to monitor pressure and not just the CO_2 plume, but it was noted that DAS cables can be used to see pressure responses. Additionally, recommendations for monitoring above the seal included above-zone pressure monitoring, measuring the strain over the whole overburden, and being cautious with added penetrations into the seal to monitor pressure.

Session 2: Non-Seismic Methods

Motivation and rationale for down-selecting MMV Technology Selection at Quest, Simon O'Brien, Shell

The Quest project started in 2015, injecting into a very secure geological site ~2000m deep, ~17% porosity, ~1000 mD permeability, with multiple thick continual seals. Quest risk managers recognise that measurement, monitoring and verification (MMV) technology selection at any project should be risk-based, site-specific, and adaptive with a focus on containment, conformance, confidence, and cost. MMV success depends on reliable early warning and effective mitigation actions.

At the Quest site, groundwater monitoring was utilised, gathering 2 years of baseline data and landowner wells were sampled regularly but ultimately phased out. Although there would be indications around the wellbore caused by a CO_2 leakage, the first indications will be downhole. InSAR evaluations since 2016 noted general subsidence over the whole observation area with no anomaly related to injection sites. The data shows less than estimated deformation. While data will be continually acquired, they will not be processed and InSAR will be used as a ‘contingency technology’. Microseismic technologies were used to understand the potential feasibility of Surface Nodes and DAS fibre optics as tools capable of low-cost, reliable, and effective seismicity monitoring. Surface node stations were deployed within a 10 km radius to compare to and integrate with data from the downhole geophone array. Time-lapse VSPs were used pre-injection in 2015, then in 2016, 2017, 2019, and 2021. The signals indicate that the plume size is consistent with modelling results. Results suggest perhaps they do not need all of the 3D seismic data, but is still good as a contingency.

The Quest MMV Plan concludes that there needs to be a focus on addressing key risks and eliminating or reducing those that do not affect decision-making. The focus should be on well integrity and near the wellbore, and the selection of technologies at similar storage projects would benefit from taking on a tiered approach, understanding that certain technologies are a better fit during different phases of a project. In this presentation, Tier 1 data provides continuous monitoring near well-bore and serves as an early warning system. Tier 2 data provides periodic monitoring near the wellbore, and Tier 3 data provides longer timeframe risks and contingent data that can be analysed in case of Tier 1 / 2 triggers, serving as conformance data.

It was noted that in the case of groundwater sampling, there is wide variability in samples and that baselines are hard to define. However, they can still be used to alleviate concerns, hence it is necessary to have enough data to account for seasonal variability.

Real-time wellbore monitoring for early leakage detection, Dr Takayuki Miyoshi, RITE

This presentation summarised the usage of Distributed Fibre Optic Strain Sensing (DFOSS) for well integrity monitoring, leakage detection in a shallow aquifer, and observing the injection profile to see if DFOSS is capable of early leakage detection.

Fibre cables are located behind the casing and the DFOSS uses Rayleigh scattering measurements, i.e. frequency shifts in response to strain and temperature changes. The cables proved to be capable of real-time monitoring, and were able to see the temperature change from water and cement slurry injection, confirming well integrity. Multiple water injection tests in the Japanese field confirmed that they were able to detect strain increase at the injection intervals, allowing estimation of the injection profile, and to see a pressure breakdown at the intervals which indicated water migration to the above zone from the injection intervals.

Through these tests, they concluded that DFOSS monitoring is capable of detecting early leakage. It was noted that while the system would be able to detect a problem, it may not be able to spot the location of the issue since the cable is linear and trying to monitor a 3D wellbore.

Novel Monitoring at the CO2CRC Otway International Test Centre, Australia, Charles Jenkins, CSIRO

Different monitoring tools are deployed at the Otway test centre to emphasise the need to bridge the gap in technology which considers both cost and complexity. This is needed because large-scale operations will be spatially big, last a long time, rely on non-structural trapping, and will not need to be always monitored everywhere. In these circumstances, operators can use monitoring that is informed by risk assessments to monitor what is consequential. For example, 4D seismic and logs cannot be taken frequently, but offer quality information. Pressure/temperature gauges can be taken frequently but offer low information content. At the Otway test centre, continuous seismic monitoring is conducted with DAS-SOV, pressure tomography detects broadly the same areas of CO_2 saturation as seismic, and more passive methods from earth tide monitoring.

In conclusion, there may be a need to sacrifice fidelity for increasing the frequency of monitoring. These well-based methods (i.e. pressure inversion, earth tide interpretation, acoustic logs from seismic, DAS-SOV, and pressure tomography) enable focused monitoring of at-risk areas and add an extension to the toolbox of monitoring tools adapted for large-scale, low-risk storage.

A concern was raised that these middle-ground technologies may offer more data and questions than you want to answer. In response, it was stated that the data acquired was not for advertisement but more about having the data available when asked, increasing confidence with stakeholders and the public.

Pressure and Temperature Monitoring of CO_2 Storage Operations, Mehdi Zeidouni, LSU

This presentation highlights the usage of pressure and temperature monitoring at geologic storage sites. The objective of this monitoring is to meet regulatory requirements whilst maximising storage efficiency, which must consider timeframes (pre-injection, injection, post-injection), radius of information (wellbore, near-wellbore, reservoir, beyond reservoir), and designs (green vs brownfield, onshore vs. offshore, deep vs. shallow).

Pressure monitoring strategies include active vs. passive monitoring, in-zone vs. above-zone monitoring, single-well vs. multi-well, and single-shot vs. time-lapse. Various pressure tests can be used to identify critical information such as the relationship between the deviation time and the plume boundary, the estimation of the size and location of the CO_2 plume, the estimation of the mobilities and extents of the plume and dry-out region, and the characterization of faults and fault transmissibility. Additionally, leakage into an above-zone interval, near-wellbore permeability loss, storage capacity/efficiency, and the time of CO_2 arrival at observation wells can be observed, although you may / may not be able to use it because the mobility change must be great to detect the arrival of CO_2.

Temperature is controlled by: (1) barothermal effects (Joule-Thompson, 'JT' and adiabatic), (2) heat of dissolution, (3) heat of vaporization, (4) heat advection, and (5) heat conduction. Temperature monitoring is effective and can estimate the CO_2 profile through warmback analysis, observe the arrival of CO_2 and monitor the above-zone area for leakages due to the JT effect. Halite precipitation was a cause of loss of injectivity, but the average reservoir pressure increase was minimal and halite damage was close to the wellbore.

Monitoring CO_2 Injection and Storage in Carbonates (MRCSP), Neeraj Gupta, Battelle

In this presentation, several snapshots were provided of different projects highlighting the uncertainties around injection into carbonate reservoirs. Carbonate geology heterogeneity challenges encompass uncertainty in reservoir continuity, storage capacity, plume migration, and pressure response. Typical systems are affected by fractures, hydrothermal migrations, vug and porosity development, and geologic changes that are hard to discern with seismic data. However, carbonate systems offer large storage potential across the US which include the MRCI region (Illinois, Michigan, Appalachian Basins which have proven injectivity and capacity), MRCSP Michigan Basin, AEP Mountaineer Plant, Weyburn and Zama fields, Wabash Valley Indiana, and more.

Across the different projects, characterization efforts included analysing seismic, well logs, core samples, injection tests, and utilisation of existing knowledge. Injection and monitoring operations included the analysis of reservoir pressure, temperature (DTS), groundwater chemistry, CO_2 injectate, soil gas, PNC (pulsed neutron capture) logging, borehole gravity, VSP-geophone, VSP-DAS, cross-well seismic, microseismicity, and InSAR (satellite radar).

Ultimately, characterisation is the biggest ally. While injection and monitoring in carbonates is feasible, there must be a detailed understanding of geology and reservoir behaviour. Pressure and temperature are the primary monitoring options, which can also support modelling and validation of the geology. Incorporation of uncertainty and preparation for contingency plans in case of unforeseen responses are advised. Lastly, seismic techniques do have some challenges such as resolution, noise, repeatability, and site-specificity.

Session 2 Panel Discussion: 'How to use these techniques in a commercial environment'

The session began with discussions on how to 'downselect' monitoring tools. There was a recognition that there would be demands from stakeholders and regulators for tools that may or may not be needed, but ultimately, monitoring tools should be selected based on risks and those tools that can protect the operator/project from ongoing natural carbon cycles and changes.

One suggestion for increased transparency and monitoring confidence was to create a traffic light system in which parameters are defined to indicate when injections are still safe and secure, when they should be paused / further assessed, and when they should be completely stopped (i.e. red – stop, green – go). It was recognised that Europe already has these systems to a degree.

A concern was brought forward about the precision of gauges. It was noted that drift issues are common, and discrepancies in measurements caused by external effects should be minimised, but these issues seem mostly unavoidable. Continuous recalibration is therefore needed.

Panellists commented on the possible future and commercial use of fibre optics as technologies are improving and changing rapidly. Fibre optics are useful for proving and validating any models or predictions in the long term to help build confidence. Additionally, it was acknowledged that fibre optics cannot be done everywhere, so specific areas should be targeted based on risk and on the location based on the plume depending on what information is wanted.

Session 3: Offshore Environmental Monitoring

Methodology to deploy shallow-focused subsea CCS technologies, Charles Jenkins, CSIRO

This work involving offshore monitoring in Gippsland, SE Australia, began around a decade ago, in a shallow dynamic marine environment. The main objectives of the project include distinguishing CO_2 release signatures from similar naturally occurring ones (signal-to-noise problem), determining the level of CO_2 release that would be associated with environmental impact at a range of scales (characterising impacts), and distinguishing changes resulting from other drivers and pressures in multiple-use zones from the activities of CCS operations (attributing impacts). Acoustics, for example, are very sensitive sensors, but there is a lot of data and very high variability from the abundance of lifeforms. Other sensors include both fixed and ship-borne sensors and they implemented seasonal deployment and retrieval.

For an example, a chemical sensor was discovered with marine life growth over it, which was common in this environment. It was found that developed sensor packages could be permanently deployed to survive both summer growth and winter storms and despite the complexity and variability of the environment, spatially small leakages of CO_2 produce distinct, rapidly variable signatures. Acoustic signatures are great at detecting even very small leakages from CO_2 bubbles and from fish, but data volume is an issue.

In the assessment of environmental impacts, high variability in abundances of lifeforms was observed, so instead, a reference site was established well outside any area of likely impact. Environmental DNA (eDNA), DNA released from organisms, was found to be promising and show changes in sediment communities, but the environmental values are an ongoing evaluation. Finally, cabled observatories use fibre optics and cables to create grids on the seafloor with the same concept as pipelines which provide power and comms to floating and sea-bed sensors.

In summary, the Gippsland offshore project permanently deployed sensor packages to monitor the marine environment, identified impact at the eDNA level, and designed a range of cabled observatories at a modest cost. Detailed reports will be available in the *International Journal of Greenhouse Gas Control.*

Marine monitoring - learnings from the North Sea, Jerry Blackford, Plymouth Marine Laboratory (PML)

This presentation summarizes learnings from STEMM-CCS – on modelling characterisation and methodological trials, the Green Sand project – on monitoring in practice, and ACTOM – on strategies and support tools. The North Sea is bordered by seven countries and is a busy region with complex currents and strong tidal signals.

The STEMM-CCS controlled CO_2 experimental release in shallow sediments 120m deep to test methods and validate models to detect, characterise, and quantify the CO_2. Different systems were ranked based on deployment attributes and monitoring processes. The Greensand project ran trials with various monitoring tools to make recommendations for monitoring in practice in marine environments. The ACTOM project provides a Decision Support Tool which allows operators to design efficient monitoring programs and demonstrate the effectiveness of these to regulators and stakeholders.

In summary, acoustics and chemical monitoring are clear winners, but they must be deployed close to the seabed. They are complimentary of each other, covering each other's weaknesses, and offer lower costs for offshore monitoring. Fixed platforms (landers) are best for long-term monitoring of high-risk areas, and mobile platforms (AUVs) are best for monitoring the whole area. This work recommends that in-well monitoring should use pressure and temperature; targeted monitoring of relict wells should use landers equipped with active acoustics and multivariate chemical sensors; wide area monitoring should use AUVs; and there should be spot or 2D monitoring of the overburden.

The selection of monitoring tools should consider the trade-offs between highly sensitive yet expensive, low-environmental-impact systems capable of detecting releases at the kg-scale that may have no impact on MT scale storage, and less sensitive yet affordable, high-impact systems with the capability to pick up 100T scale releases that could undermine long-term storage.

The process-based CSEEP Attribution Method: towards application in the shelf off South Texas, Katherine Romanak, GCCC, BEG at UTexas for Abdirahman Omar, NORCE

Variability in the environment is a key challenge that must be conquered for environmental monitoring at CO_2 storage sites. The process-based attribution method considers the stoichiometry of many variables, not just the $CO_{2,}$ to determine what processes are creating the CO_2 concentrations, whether natural or anomalous. This method works well onshore, but the higher variability offshore caused by variations in salinity pressure, and temperature makes the process more complex. For example, at the Tomakomai Project in Japan, a month of routine data collection produced a measurement outside of the threshold and caused a false positive for leakage. This showed that one year of baseline data is not enough to capture the full variability of naturally occurring processes.

The new Cseep method considers all the processes in the marine environment that would alter the natural CO_2 concentration in the seawater. A mathematical correction can be applied to the DIC for each of the processes that are considered. The method was developed at the STEMM-CCS controlled release project where scientists were able to tighten up the scatter in the DIC data, reduce the natural variability, and therefore clearly pick out the leakage anomaly. This indicates that a process-based approach is more accurate than concentration-based ones because it accounts for natural variability.

Thus, a process-based, C_{seep} method allows for characterization, attribution, and quantification of the major naturally occurring processes vs. CO_2 seepage. It is flexible but requires more upfront data collection. Additionally, most of the seepage remains within the sediments, requiring measurements to be taken close to the seafloor.

Geophysical-geochemical data integration: CO_2 deep storage formation vs. migration, transport and cycling, Richard Coffin, TAMU-CC

To confirm efficient storage, there is a need to be able to look at the CO_2 and know where the source is; however, finding and attributing leakage at or near the seabed is extremely difficult due to the complex, fluctuating, and overlapping nature of fluid, solid, and gas geochemistry in the marine environment. There may also be existing shallow structures that could serve as avenues for migration, which raises the question of whether they merit routine monitoring for assurance. In this presentation, field data, geology, seismic profiles, geochemistry, and biogeochemistry are integrated to study coastal ocean sediment carbon cycling applied to CO_2 migration.

A suite of technologies was introduced to enhance characterisation and risk assessment at CO_2 storage sites under development in basins where marine seepage is a concern. These technologies encompass fluid flow structures, such as pockmarks and chimneys, which can indicate areas of past or ongoing fluid flux. Additionally, the suite includes high-resolution 3D / 4D seismic imaging for detailed subsurface visualization. Controlled source electromagnetics are utilized to map resistivity, providing images of free gas and other features. The suite also includes heat flow measurement, enabling the detection of temperature anomalies. Lastly, piston coring is employed to gain geochemical insights into carbon cycling. This technique offers valuable information about the origin, processes at work, and fate of CO_2 in shallow sediments.

It is important to be able to know the source of the CO_2 in the case of a leakage, however, as the CO_2 migrates, it can change and go through different phases as it picks up different compounds from chemicals or other micro-organisms which makes this a complicated matter. There is an opportunity at many sites today to pull samples and evaluate the geochemical data. Integration of geochemical and geophysical data during site characterization can be used to evaluate the potential of a site to retain CO_2 over long >1000-year time scales.

Session 3 **Discussion**

There was a question if there was a threshold in the marine environment beyond which operators should act for mitigation. It was noted by the panellists that although there may be a need for more stringent assurance in the early days, marine life is ultimately rarely impacted by leakage. Around 80% stays in the sediment (as seen, for example, in the Gippsland work) and the pre-existing high variability in marine environments mean that the organisms living in them were rarely impacted by changes in pH or other variables caused by the presence of CO_2. If anything, there should be more consideration towards public perception to assuage their fears less they shut the project down.

Session 4: Near-Surface Monitoring, A Panel Discussion ‘Challenges in assessing surface signals & integration of subsurface data to inform action at the surface’

The focus of this panel discussion session was to address how and to what extent monitoring/routine monitoring should occur at the near surface as well as to assess the adequacy of deep well monitoring while still meeting regulatory requirements.

Monitoring marine systems presents numerous challenges, encompassing factors such as the significant environmental variability, the uncertainty regarding the composition of migrating CO_2 once it makes its way to the surface, and the unpredictable pathways that potential leakages might follow. These complexities make relying on point source measurements impractical for leakage, and while remote measurements might identify anomalies, the problem of attributing these anomalies to specific causes persists, especially as anomalies become more frequent due to the effects of climate change.

From a regulatory perspective, it is important to know when there is a leakage, to quantify the size of the leakage, and to assess the environmental impacts. Therefore, attribution and setting up a success metric is critical. Some of the tools for this included sensors, process-based stoichiometric analysis, and geochemical analysis by evaluating isotopes. These tools, while informative, cannot be used alone and should be used as a part of a bigger toolkit.

It was advised to implement leakage sensors only when there is a cause to do so because pre-emptively placing these sensors often flag natural fluxes and read as false positives. Additionally, it was recommended to have a kit pre-published and ready to be used in the case that there are anomalous activities to properly attribute any strange activities that may be a cause for public concern. In the offshore, bubbles seem to be the heroes.

The outcome of this discussion was the recommendation to initially prioritise deep monitoring to assess the project's progress. Then, it was suggested to have an attribution planning kit prepared so that in the event of an environmental issue, one can refer to the kit to determine whether a leakage is the cause or not. If yes, environmental assessment and accounting/reporting are required.

A final comment made brought forward concerns about the movement of the plume not necessarily because of the fear of surface leakage, but because of the competition of pore space and trespassing into unpermitted land or another project, as well as the potential to displace brine or contaminate the groundwater. Further considerations need to be made to better define 'leakage' and in delineating CO_2 containment vs. containment of all reservoir fluids.

Session 5: Automation and Integration of MMV

The Smart AUVs project, Ivar-Kristian Waarum, NGI

The National Norwegian Geotechnical Institute has a history of using different tools for marine monitoring which includes acoustic and chemical sensors – all of which are stationary sensors on the seabed. Monitoring devices are expensive to deploy, operate, and then service and redeploy. This presentation offered AUVs (Autonomous Underwater Vehicles) as an alternative and explores if Smart AUVs can be used to sense specific features – such as a leakage – to alter and change paths in an adaptive way rather than following a pre-programmed path.

This project to combine Smart Technology with AUVs was split into five work packages. The first defines the scope of different emission scenarios relevant to several applications. The second concentrated on modelling and simulating leakage scenarios. Work packages 3 & 4 – creating algorithms and planning for adaptive operations – centres around programming the AUVs for detection, quantification, and characterisation of greenhouse gas seepage before moving on with the rest of the programmed path. The final work package demonstrates AUV decision autonomy through field demonstrations. This would allow more measurements to be taken at a place where there is suspected seepage and find the plume area from the frequency of the points taken.

Deep learning accelerated monitoring data assimilation, Bailian Chen, Los Alamos National Laboratory

This presentation highlights lessons learned from the SMART (Science Informed Machine Learning to Accelerate Real Time Decisions in Subsurface Applications) Initiative to use science-informed machine learning for real-time visualization, rapid prediction, and real-time forecasting. The goal is to develop tools to assist in better decision-making to answer the questions: Is the project safe? Will/Where will the project leak? Will it cause induced seismicity? Where should I locate the wells? Where is the CO_2 now?

Software tools employ machine learning (ML) to integrate monitoring data into subsurface forecasts more rapidly than current physics-based data assimilation or history matching. The ES-MDA (Ensemble Smoother Multiple Data Assimilation) was deemed an effective approach, able to accelerate the data assimilation and reduce the uncertainty when comparing the calibrated data to history matching and forecasting. Other workflows use different methods for model reduction/parameterisation and proxy modelling.

Critical components and challenges for ML-based data assimilation include model reduction, inverse modelling, proxy modelling, and type of observational data. The limited amount of data related to CCS poses a challenge, but there are major successes in reducing uncertainty with current algorithms. However, the limited amount of data still poses a significant challenge.

How BP is accelerating technology to deliver sustainable seismic, Ted Manning, BP

Sustainable seismic focuses on delivering improved data with low carbon emissions and low environmental impact (e.g. line clearance on land or lower sound emissions in marine), for affordable yet high-quality data. Key elements include nimble (small, light, portable) sources and receivers, and autonomy.

For land, handheld sources and receivers were shown to image CCS reservoirs on the onshore US – indicating that low-cost, high-density seismic can be affordable and sustainable. In practice, these nimble sources and receivers (nodes) were deployed with only a few people and showed that very weak sources were sufficient and near-surface geology tested. Multiple sources are needed for better quality, and a source efficiency study is ongoing. These are unlocking surface seismic images for storage (CCS, H) and Geothermal.

For marine seismic, autonomy and robotics are being trialled to automate high inventory seabed recording with less sound exposure, from either smaller airgun arrays or moving marine vibrators. Large Uncrewed Surface Vessels (USVs) can rapidly deploy Autonomous Underwater Vehicle (AUV) gliding swarms (up to 1000s) at once, to provide faster, low-cost, low-emission surveys. Gliding nodes will avoid vessel entry to wind farms or exclusion zones and move crews onshore improving safety exposure. Ocean Bottom data is suitable for high-resolution near-surface images (CCS) and deep imaging. In many use cases, however, fewer AUVs may be sufficient for effective monitoring.

Sustainable seismic challenges the historical view of seismic cost and quality. 3D quality seismic will improve reservoir characterisation and screening, which should reduce risk for CCS projects to rapidly get to closure phase.

Gippsland work with sail drones: capabilities & data analysis, Andreas Marouchos, CSIRO

This presentation discusses the use of sail drones at the CSIRO Gippsland project. Sail drones were used in addition to conventional observing methods to investigate natural variability. There was an emphasis that autonomy is the future of ocean operations with a focus on persistence, localisation, and scale. The aims and objectives with ASV / USV (unmanned surface vehicle) deployments were to investigate the retrieval of spatiotemporal structure from different sampling patterns, to analyse for high-frequency anomaly detection rates and spatiotemporal variance structure of background noise, to capture several wind reversals in wind direction and alongshore currents, and to provide information on seasonal and between year spatial variability.

The CO_2 sensors performed within specs and the acoustic systems were comparable to full bioacoustics systems and were able to detect plumes. It was noted that there was high variability daily, seasonally, and interannually. Some learnings from the project were that regular calibrations are essential, management of the chain of custody is important, station keeping capability on USVs is critical, and machine learning algorithms can significantly improve the prediction of baseline signals. Additionally, bioacoustics have proven to be effective though work is ongoing. There is real-time capability for bioacoustics and both manned and unmanned platforms should be considered in a cost-benefit-capability framework.

Considerations on USVs include early collaboration on sensor integration, management of data bandwidth, strong collaborative relationships with regulators, and implementation of adaptable policies to keep pace with the rapidly evolving technology.

Session 5 **Discussion**

There was a small discussion on distinguishing the signatures between fish presence and gas seepage. There was also a question on the repeatability and cost-effectiveness between fibre optics and deploying the AUV swarms. It was noted that ultimately, one measurement from a single tool was not enough. Everything must be calibrated, and tools are best used in conjunction to be complementary with each other.

Session 6: Conclusions and Recommendations from Day 1

Conclusions

The presentations from day 1 showed significant advances in geophysics, adding maturity to plume monitoring through the integration of different types of fibre optics, SOVs, sparse monitoring, multi-physics, and better pressure measuring. There were added details in the fault failure systems at Mont Terri, advances in assessing monitoring needs specific to Carbonate geology, and summaries of tools for marine monitoring and for attribution of seabed leakage. Acoustics and bubbles were determined to be winners. Pressure was noted to be a proxy for risk.

Participants learned about advances in AUVs and USVs. Small USVs especially are now commercial and reflect a trend of moving away from old, expensive asset types. New technologies are instead trending towards utilizing resident / permanent tech in conjunction with mobile/temporary (on-demand) tech. Resident systems have an issue with utilization and are more difficult to upkeep, which may be a deterrent when compared to mobile systems which allow for more flexibility. However, these distributed assets are rapidly changing, and the selection of these tools should focus on the needs of the project and not on the newest, most elegant type of technology. An additional criterion to consider for these tools is the selection between sparse and dense datasets. Information comes at the cost of sensors and complications may arise with data analysis and collection.

It was established that there needs to be an intersection of monitoring between technology, regulation, and economics depending on the needs of users. The monitoring tool selection is site-specific and will reflect the priorities of the user, which encompasses regulatory compliance, environmental risks, accounting, business risks (i.e. trespass, liability, allegation, economic risks), and public acceptance/assurance. Analysing the selection of monitoring tools at a location starts with understanding the reasons why specific tools were chosen.

Future considerations of monitoring tools should keep in mind the issues and complications with data transfer, data analysis, and reactivity in real-time and plan on how to deal with situations when there is a big hub project with different CO_2 sources.

Recommendations

Day 1 recommendations started with asking regulators to accept the rapidly evolving field of monitoring technologies in order to be more flexible and not prematurely exclude any specific tools. Additional suggestions were made to set goals for creating a traffic light system through the utilisation of a suite of technologies that can trigger further evaluation or mitigation when they collectively signal an issue. It should be noted that the EU already has regulations for this. Final recommendations emphasise the need for more public data on CO_2 in the overburden and for a global database on environmental parameters.

Day 2: Regulatory Perspective

Many of the presentations given on day 2 went over topics presented on day 1 to a technical audience but aimed at a higher level to help inform regulators in the audience and those not necessarily well-versed in the intricacies of monitoring CO_2 storage. For brevity, some of the below summaries are shortened so as to not repeat information already provided in the above synopsis of day 1 of this meeting.

Session 1: Framing the Problem

Panel Discussion: US vs EU vs Australia Approach, Tim Dixon (IEAGHG), Ian Havercroft (GCCSI), Eva Halland (Norway), Laura Sorey (DNR)

Panellists from Australia, Norway and Louisiana joined this discussion to compare monitoring needs across different countries. Tim Dixon presented the international background, that the IPCC Greenhouse Gas Inventory methodology (2006) recognises that all storage sites are different and hence require a measurement-based approach. Ian Havercroft covered Australia and Southeast Asia, Eva Halland covered Norway and the EU, and Laura Sorey covered U.S. regulations. Questions for panellists included: (1) How do regulators decide if monitoring plans are sufficient? And (2) How will monitoring be used to get to closure?

Regulations regarding CCS in Australia are split between the commonwealth and several states. The regime that regulates CCS in Australian commonwealth waters is the Offshore Petroleum and Greenhouse Gas Storage Act developed in 2006 to amend the existing Petroleum Licensing regime. Applicants for a permit in these waters must develop site and environmental plans. The site plan details the monitoring and focuses on demonstrating the suitability of the site and on how risk was reduced. The Commonwealth minister must be convinced of the monitoring plan's ability to demonstrate that "significant events in the reservoir will be detected in a timely fashion to enable any necessary mitigation and remediation activities" These plans are reviewed every five years. What this means for closure is that the operator can transfer the site and long-term monitoring to the Australian government provided that the necessary conditions are met. One part of the application to obtain a site closure certificate entails submitting a report that shows ongoing monitoring and models of the injectate throughout the life of the project. At the end of a fifteen-year period, the certificate holder can apply for a declaration to conclude the liability for the storage site. Long-term monitoring, which is now undertaken by the government, implements the monitoring plans developed by the operator.

In Norway and the EU, monitoring tools are used to compare modelled behaviour, identify irregularities, follow the migration, detect leakages, and update the assessment of short- and long-term integrity of the storage complex. Monitoring plans shall be updated no less frequently than every five years, and there is a minimum monitoring period of 20 years after the final shutdown, with exceptions. After this, the site and all monitoring plans are handed over to the state, and the information must indicate safe storage and stabilisation of the CO_2. The regulations do not specify which technology or methodology, so the monitoring tools used to build confidence after closure must be smart, cost-effective, site-specific, and tailored to the risks.

In the U.S., the EPA (Environmental Protection Agency) holds authority, but states can apply for primacy for more specific monitoring plans; specific state regulations are still ongoing. A key question for operators is 'how do you get representative monitoring data and what do you want to do with it?'. Monitoring plans should use the best available strategies that make sense for the site, addressing the specific risks, and update throughout the life of the project. Having a representative set of data and a plan for navigating any deviations is critical. To get to closure, operators must submit a Post Injection Site Care (PISC) Plan with a minimum of 50 years of monitoring after injection. Reduction of the 50-year period must be made with the EPA whether the state has primacy. Monitoring plans must ultimately ensure the protection of the Underground Source of Drinking Water (USDW).

It was recognised that in European projects, there is higher confidence in the technology and that many discussions focused on financial assurance. In Louisiana, some training came from the operators or technical groups, but there is established expertise in well integrity and monitoring operational conditions with other well types.

What we have learned from UIC permits, Sue Hovorka & Angela Luciano, GCCC, BEG at UTexas

The Underground Injection Control (UIC) program under the U.S. EPA has historical experience with injection activities which focuses on non-endangerment of the underground drinking water. Class VI for carbon dioxide injection was added to the program in 2010 and has heritage in Class I – hazardous and non-hazardous waste – and Class II – pre-refinery oilfield waste. Class I has most of the parts of Class VI, and injection falloff tests are the extent of monitoring of injection formations. Class I and Class II both have similar traits which helped build Class VI, but Class VI has specific monitoring to account for multi-phase flow, the buoyant injectate, CO_2 reactivity, geo-cellular modelling, plume tracking, and more.

Data available from Class I permits shows success in most wells over the course of many decades. The permit applications are data-dense, include information on porosity, permeability, and injectivity from core samples, well logs, and falloff tests, and have applications for Class VI purposes. The wells show that there is relatively low-pressure build-up with several exceptions caused by grain composition in South Texas, skin, and well management, and it was found that Miocene formations tend to have higher injectivity when compared to Oligocene formations.

Other types of data available in Class I permits include formation salinity, well construction, financial assurance, remediation plans, and more. Extracting information from the permits requires help in digitizing the data to help build confidence in Class VI.

Session 1 **Discussion**

There was a brief discussion on plume stabilisation. Laura Sorey with the DNR said it means it is no longer migrating and will not encroach on areas where it may pose as a containment risk. Tim Dixon noted that regulations in the EU stated that they are 'evolving towards' long-term stability.

Monitoring well requirements and expectations in the U.S. state that end zone monitoring is required, but the specifics are not defined. There may be either direct or indirect monitors, but there must be some degree of pressure measurement that is justified.

Session 2: Tools

Pressure and temperature monitoring to address regulatory requirements, Mehdi Zeidouni, LSU

This talk focussed on the information extracted when monitoring, including information in the wellbore, near-wellbore, reservoir, and beyond the reservoir. Pressure can be monitored actively – at the injection well - and passively – in response to the injection at another location.

Various methods of pressure monitoring allow the identification of different features. Passive monitoring in the above zone can identify if there is a point source leakage or linear leakage, allowing identification of not only the leakage features but also the location of the leakage. Several active monitoring methods allow detection of the edge of the plume boundary, analysis of near-well bore, size of the plume, characterization of the fault, estimation of the storage capacity, and more. Temperature is much more complex but is effective for injection profiling, spotting the arrival of CO_2, and detecting leakage.

Review of results of groundwater monitoring comparing different projects, Sue Hovorka, GCCC, BEG at UTexas

This presentation asks 'how can we use the groundwater monitoring data to contribute to the storage project best?'. Groundwater monitoring data has limited capabilities but has value in dealing with incidents or allegations of damage to the groundwater.

Analysis of existing data from some groundwater monitoring examples observes complex geochemical mixing signals with no leakage trend found. It was concluded that there needs to be many more data points – decades worth – to detect any leakage trend. One project focused on sampling leakage indicator species that can leave behind fingerprints. In conclusion, reliance on groundwater monitoring for detecting leakage should be limited, but the data can be used to prove readiness and the data collection for natural variability can continue into the start of the project. It can be useful to utilise forward modelling

/ physical testing of aquifer rock and water response to CO_2 / brine leakage and use targeted analysis of indicator chemical species. Finally, the major value of this monitoring comes as protection to the operator in case of an incident or allegation.

New directions in monitoring onshore and offshore, summary of DAS & DTS, Charles Jenkins, CSIRO

This presentation summarises some discussions from Day 1 from the perspective of a consumer using DAS and DTS. When using DAS, you must adjust well design to use fibre optics on the casing to cement in place, which can be a delicate process. Once in place, it serves as a seismic receiver, like a geophone, which provides data every 5 meters, or as frequently as needed. Acoustic and temperature data is readily available, providing rich and large volumes of information.

Opportunities of continuous monitoring, Charles Jenkins, CSIRO

Marine monitoring at the Otway project found that acoustics were sensitive to bubbles and leakage but required analysis to distinguish actual leakage from fish. Machine learning is valuable for sorting noise from patterns like when fish predictably vanish at night. The use of DAS-SOVs at the Otway project site allows for unobtrusive, permanent, and continuous seismic monitoring. Earth tides show an impact on the pore pressure with only the nearby rock modulus as a free parameter. These continuous monitoring tools provide large datasets but require deep understanding to filter out the noise.

These tools can fill in the gap between high-value and low-frequency data like 4D-seismic vs. high-frequency data with lower information content. These permanently deployed sensors may be less informative but provide more frequent measurements which enable focused monitoring of at-risk areas.

A comment from the audience voiced some concerns about data density, record keeping, archiving, and the frequency of how many times the data had to be reviewed. From experience, however, it was noted that the amount of redundancy in each data sample allowed for rather quick interpretation and detection of anomalies. As for recordkeeping, there is the precedent of other well monitoring data and ultimately, regulators would have to wait and determine which makes the most sense.

Session 2 **Discussion**

There was a question on how regulators can apply pressure and temperature data for leakage monitoring and on the quantity of gauges that would be required to ensure adequate surveillance. It was emphasized that the applications and number of gauges ultimately depend on the risk and on what the goal for the site-specific analysis was. Different pressure monitoring tests provide information at different regions, and the number of gauges should be determined after establishing a baseline for an unacceptable threshold of pressure/temperature change (or of any other indicators). It was also noted that pressure gauges can be used in tandem with fibres and be complimentary, but fibres were not able to completely replace pressure gauges.

Tools and techniques for monitoring the above-zone interval and artificial penetrations when the well was unable to be re-entered were discussed. It was noted that above-zone monitoring is a common practice from natural gas storage projects and that when CO_2 leaves the reservoir, the pressure should show as a pressure increase in the above-zone monitoring interval. When the well can be re-entered, CO_2 leakage shows up as a temperature drop.

A concern was voiced about the cementing job and cement integrity when placing fibre cables. It was unclear what risks do or do not exist, but ultimately it was noted that there are trade-offs that should be discussed between the risk of a bad cement job and the risk of a less rigorous monitoring plan. The balance of risk is a discussion to be had with regulators to figure out levels of tolerable risk. However, the number of successful projects with successful fibre-optic installations lend it confidence.

Session 3: Environmental Aspects

Effective monitoring in a complex environment (onshore), Katherine Romanak, GCCC, BEG at UTexas

Effective monitoring is defined in this presentation as monitoring that satisfies the objectives of the regulation with clearly defined success metrics to provide assurance. The main objectives of regulations are either environmental protection or greenhouse gas accounting. Historically, the protocol for detecting leaks or anomalies has been through gathering baseline data and monitoring the CO_2. However, naturally produced CO_2 in the biosphere is increasing due to climate change and therefore baseline methods may result in false positives; the risk of false positives is greater than the risk of leakage, and false positives put projects at unnecessary risk. Searching for leakage will result in the discovery of many anomalies due to climate change, so attributing the source of the anomalies is critical. Attribution methods should have clear thresholds and be easily communicated.

Process-based soil gas ratios were offered as a solution as they use geochemical relationships to identify key processes using natural respirations rather than concentration comparisons. Ratios provide stakeholder-friendly monitoring, capture long-term changes in respirations, and do not require long-term data collection. In conclusion, monitoring in a complex environment requires smart monitoring, not more, and taking a process-based type of approach will give more accurate and stakeholder-friendly monitoring results compared to concentration baseline monitoring. Recommendations include de-emphasising routine environmental monitoring to avoid false positives, monitoring only when there is a reason to look based on deep well-based signals, and having an attribution plan ready to be used when the need arises.

Effective monitoring in a complex environment (offshore), Jerry Blackford, PML

When dealing with monitoring for leakage in marine environments, two primary aspects to look out for are bubble plumes and chemical changes. The latter includes pH, DIC, bicarbonate, and carbonate, but there is more focus on pH. There are two technologies favoured offshore; the first being acoustics monitors to detect bubbles and the second is chemical sensors to detect dissolved CO_2.

Like the onshore environment, there are naturally occurring variations offshore that may be mistaken as a false positive. Bubble releases and chemical changes near the seabed are commonplace, so distinguishing these from actual incidents requires the utilisation of smart anomaly metrics. This includes identifying bubble streams that were not there before and examining departures from natural co-variation relationships (like CSEEP detailed on day 1) which require in-depth, sometimes site-specific knowledge of multivariate trends.

This presentation discussed the ACTOM Decision Support Tool, which was created to allow operators to design efficient monitoring programs based on the risks and inputs from the user under different scenarios. It was argued that more than sufficient understanding and technology is available to allow high-quality environmental monitoring of offshore CCS, and this shouldn't be seen as any barrier to deployment. When making decisions for monitoring strategies, operators should keep in mind the trade-offs between highly sensitive, expensive strategies which maximise assurance and less sensitive, cheaper strategies that increase the risk of false negatives.

Monitoring background seismicity, offshore Norway (HNET), Philip Ringrose, Equinor

This presentation discusses the baseline seismicity assessment for CO_2 leakage in the Horda Platform region (North Sea) which will house the Northern Lights project. The Northern Lights area is close to an area with natural seismic activity and has been monitored with permanent reservoir monitoring systems, onshore broadband, ocean bottom sensors, and fibre-optic cables on the seafloor. The objectives are to analyse natural seismicity, to differentiate between induced & natural seismicity, and to understand the potential for induced seismicity.

Throughout the project, they were able to lower the magnitude of earthquakes that could be detected, integrate offshore geophones with onshore sensors, work on automatic detection systems, and were able to understand the stress state better.

It was concluded that the risk of induced seismicity is very low, but building trust and transparency with the public to avoid associations with false positives is critical. The innovative part of the project was in demonstrating that the existing data and targeted offshore deployments could achieve sufficient seismic detection. Future work includes the use of velocity models and DAS fibre as well as the development of response protocols. Additionally, there will be a push for establishing the need for higher quality seismic data for naturally occurring earthquakes in regions where it is not uncommon.

Session 3 **Discussion**

It was discussed that traffic light systems are an effective site screening method that can help with communication but defining exact parameters and thresholds must be better developed with consideration to site-specific differences. Additionally, it was noted that a significant finding from the marine leakage study was the minimal impact caused by CO_2 leakage.

There was a question on what kinds of information should be routinely put out to the public. It was noted that the type of data would depend on what helps build confidence in the project and that a key aspect of communication involves the usage of a trusted community member.

Session 4: Societal Considerations of Monitoring

Determinants of public perception about monitoring and why perceptions matter, Darrick Evensen, University of Edinburgh

This presentation summarizes findings about public perceptions of carbon storage as a part of the development of a CO_2 storage research facility in the United Kingdom. This facility will research monitoring technologies as well as social attitudes to hosting Net Zero infrastructure.

It was found that in this region, there is very low knowledge of carbon storage, ranging mostly from 'nothing at all' to 'heard, but know nothing'. There is higher than average support for carbon capture from industries, waste-to-energy, DACCS, hydrogen, and power while BECCS has the lowest support as a source for capture. Specific to sentiments about monitoring, it was discovered that more people thought organisations would monitor poorly, but 'not know' was the most common response. People who think monitoring will be done poorly have less trust in the government. Analysing predictors of monitoring views found that income and education did not indicate much while political orientation indicated that left-leaning groups have more scepticism. Additionally, people who felt more responsibility for climate change felt that monitoring would be done well. Finally, the groups that stated that monitoring would be done poorly had more environmental concerns and would be more likely to actively oppose a project. Groups who said monitoring would be done well associated CCS as a climate solution and were likely to support it.

In conclusion, it was found that there is a lack of knowledge about monitoring organisations, trust should be placed in other organisations as a proxy, socio-demographics showed little variation, and people with poor views on monitoring were more likely to actively oppose. It was recommended that there should be increased awareness of monitoring organisations, organisations should show independence from the government, and safety assurances should be delivered from trusted sources.

Communication for monitoring and risk and the Gulf Coast communities survey, Katherine Romanak, GCCC, BEG at UTexas

This presentation summarises work done as a part of the ACTOM project which analysed legal and regulatory, societal, and technical interplays among CCS. Major challenges were noted to be technical and socio-economical. For stakeholders, too technical geologic discussions can seem esoteric, and the lack of trust in industry combined with Hollywood views of risk pose as challenges. Questions of this research focus on the roles of technology in reassuring the public and on how complex vs. simple monitoring approaches are accepted.

Texas, Louisiana, and Florida locals were sampled for a survey. Two groups – high science and low science orientation – were identified based on attitudes towards science, climate change beliefs, need for cognition, and science media consumption. Both groups preferred simple monitoring, but the low-science orientation group was primarily influenced by who brought the message, showing higher levels of trust when the source of information was from the community.

Moving forward, the new Texas Louisiana Carbon Management Community ('TXLACMC') project will focus on utilising universities to serve as local community members who can help with outreach and share the message regarding CCS projects in the Gulf of Mexico.

Quest and Atlas community engagement and monitoring, Simon O'Brien, Shell

Effective community engagement and getting ahead of the messaging were identified as key business enablers at the Quest project. Key tactics in Quest's stakeholder engagement program involved hosting open houses, Quest café meetings, and community coffee sessions to discuss the program and listen to concerns from different community groups. Additionally, a community advisory panel was established to bring together community members – volunteers from council members, firefighters, high school students, etc. – to answer any questions about the project or monitoring programs.

Ultimately, building stakeholder relationships is critical. Engaging early and meeting on their terms helps alleviate concerns and create deep relationships. Lessons from this presentation highlight the importance of hearing concerns and accepting them as legitimate, meeting stakeholders on their terms where they are comfortable, developing consistency, and engaging with people whom the community trusts.

It was noted that when sharing monitoring plans and assessments with the community, it was important to share the right amount of data because sharing too much made the project seem dangerous due to the extensive precautions involved in the project.

Environmental Justice and Clean Energy Infrastructure, Clark Miller, Arizona State University

Enabling a just transition for carbon capture utilisation and sequestration is needed to ensure the flow of benefits to disadvantaged communities. There are many different facets of environmental justice and policy, and different types of public groups would be interested in different aspects.

Justice issues in carbon capture do not only exist in the infrastructure needed for the project itself but also in the relationship between those activities and the larger set of activities that receive offsets and credits from the CCS activities. Addressing the specific concerns of various groups is necessary, and monitoring fits into this discussion in that it can help provide reassurance to some audiences. These groups include regulators, investors, and Justice 40 regulators and activist groups. Other groups, such as those concerned with environmental risks from continued fossil fuel usage, land tenure, and those with mistrust towards project owners/regulators, may find monitoring to be less valuable.

Ultimately, while monitoring can engender greater confidence and establish credibility, the social credibility of messaging through trusted community members is important. Additionally, monitoring programmes should understand the audience and address the concerns of the specific type of public. Finally, designing monitoring systems should aim to reduce the chance of human fallibility causing avoidable problems.

Session 4 **Discussion**

There was an emphasis on noting the importance of understanding regional/local attitudes and values. While there were relatively few differences noted in the UK survey, there may be more discrepancies in the U.S.. Regarding the discussion on fallibility, a point was made that issues resulting from human error can be dealt with as long as there is transparency and communication in owning up to the mistakes and in remediating them.

Additionally, there was a comment noting the generational attitudes towards CCS due to opposition to fossil fuels. It was recommended that there should be an effort to improve the messaging and decouple CCS from fossil fuels.

Session 5: ‘Getting to Closure’, A Panel Discussion

This was led by Sue Hovorka, Charles Jenkins, Frederik Gal and Rob Trautz. The first part of this session discussed the tools available to help build confidence in getting to closure, and if they were sufficient to face any issues that may occur. For example, pressure tests can help map the CO_2 plume after closure to ensure stabilisation of the plume. However, whenever applying these tools, it should be kept in mind that they are all site-specific and utilization should meet the needs of the risks.

Why are there differing monitoring timelines in different countries?

There was a discussion on the different time frames required per country to get to closure. There is a risk assessment at the end of injection, which is 20 years or less in the EU if you can demonstrate that there is no risk to the containment and no reason to continue monitoring. In the U.S., there is deep concern about the risks from the presence of artificial penetrations, and as stated by Laura Sorey, having a longer closure period of 50 years is needed when considering the high risk of leakage pathways provided by the wells. It was noted that there was less concern about vertical migrations caused by failures of the caprock, the composite confining systems, or from other vertical paths caused by stair-stepping or faults, because there is more certainty in the geology when compared to artificial penetrations.

When might we have to extend the observational period?

A hypothetical scenario was raised to figure out under which circumstances should the observational period be extended. To describe the first scenario, it was noted that observed models and real data gradually converged with fewer errors over time. In cases where this alignment did not occur, it would justify the need for an extension since the reservoir is not behaving as expected. On the other hand, reservoirs that were performing very well may also warrant an extension since there was no reason to discontinue injection.

The observational period may also be extended if the well was interfering with other projects e.g., Class I hazardous wells or salt caverns. After some time, it is more than likely that the available 'sandbox' for injection projects will become crowded and managing the locations of all these injection wells will be critical. The final scenario concerns depleted fields, which is a completely enclosed reservoir which does not dissipate pressure. This may result in a continued increase in the column height as the CO_2 continues to rise.

Can we speed up the closure process?

It was recognised there was a tendency for operators to want to submit an alternative timeline before any injection even began. There was a strong suggestion to set up good monitoring plans first with good models before jumping ahead to see how quickly they can move the liability to someone else.

How would we close projects that have to pull out early?

Another hypothetical scenario was raised to discuss how wells that pull out early would deal with prematurely ending the project. Laura Sorey with LA DNR noted by that time, the operator would have enough monitoring data to provide the alternative timeline. The operator would either be hooked into the 50-year timeline or walk away in which case the state would take over monitoring and continue to get money from the operator as needed.

The discussion session wrapped up on the note that as injection projects commence and models are calibrated, there is increased confidence in how long it takes for the plume to stabilise. The strategies and tools currently in place are sufficient in being able to meet any problems that may arise.

Session 6: Unmet Needs, the closing session

Day 2 ended with a discussion on unmet needs in monitoring for CO_2 storage, drawing strongly on the audience for their views on what the regulators need from the monitoring community and how this can be facilitated. This was led by Tim Dixon, Sue Hovorka, Charles Jenkins and Laura Sorey.

It was noted that there is often a lack of effective and early outreach as well as strategies for outreach towards communities in the face of already existing bad perceptions, along with a noted mismatch between technical and regulatory demands that should be amended by improving the regulatory guidance.

Additional case studies are needed to investigate wellbore integrity by deliberately inducing failures and then repairing the issues. These studies could identify which monitoring tools are effective in detecting leaks and analyse the methods employed to remediate the wellbore, along with better above-zone monitoring and provision of monitoring strategies for wells that cannot be re-entered.

There should be clearer metrics on groundwater monitoring for responding to potential allegations of leakage, and groundwater monitoring must take brine into account along with the CO_2.

There should be better handling of pressure space and the managing of multiple projects that could interfere with each other. Of use may be a study into better delineation of the area of review based on pressure and corrective action, with a consideration for a risk-based assessment that focuses on non-endangerment of the USDW and brine monitoring.

More consideration is needed of the risk of induced seismicity due to the pressure space in the presence of multiple projects, and whose responsibility this is. A starting point would be case studies and looking at examples of large-scale water injection projects, for example, US injection projects and their communication of risk.

Another unmet need is non-well based methods which may be of use for brine and/or pressure monitoring. Better fault characterisation is also needed so that projects and regulators are not surprised by barriers that cause a decreased compartment, and to develop monitoring strategies to avoid cross-fault, along-fault, and up-fault transmissions.

More is needed looking into an offshore area of review, and regulations on overboarding brine onto the seafloor and related pressure management. Of importance here is seeing clear rules and communication for overboarding water onto the seafloor that is consistent in both state and federal waters.

Finally, of utmost importance was advanced and consistent outreach to journalists and social media on the topic of CO_2 storage monitoring and particularly with the development of new storage projects.

IEAGHG would like to thank the Monitoring Network Steering Committee for their input over many months to help construct the agenda for this meeting, the hosts at LSU (Mehdi Zeidouni and Janet Dugas) for their hard work and diligence in bringing together the event logistics, and the co-host Sue Hovorka of the GCCC, and finally to Angela Luciano of GCCC for her efforts in writing up the meeting report on behalf of IEAGHG.

IEAGHG Monitoring Network Steering Committee 2023

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David Alumbaugh	- LBNL
Mehdi Zeidouni	- PETE at LSU *(co-host)*
Janet Dugas	- PETE at LSU *(co-host)*

Annex 1: Meeting Agenda

IEAGHG Monitoring Network Meeting:
'Monitoring, Commercialisation & Regulatory Developments'

Cook Conference Center, Louisiana State University, Baton Rouge, Louisiana, USA

8th – 9th August 2023

ieaghg

LSU
Craft & Hawkins Department of Petroleum Engineering

GCCC GULF COAST CARBON CENTER

Sponsored by:

ExxonMobil AIR PRODUCTS

DAY 1: TECHNICAL DEEP-DIVE --- IN-PERSON ONLY ---		
Welcome		
08:00 – 08:10	Welcome from IEAGHG	IEAGHG
08:10 – 08:20	Welcome from hosts, LSU & GCCC	LSU & GCCC
Session 1: **Fibre Optics & Low-Cost Monitoring for Subsurface Seismic**		
08:20 – 08:35	LBL Mont Terri project on fault system monitoring	Yves Guglielmi, LBL
08:35 – 08:50	'DAS technology trials at Quest'	Marcella Dean, Shell
08:50 – 09:05	'Borehole-DAS monitoring of a leakage-like CO_2 injection'	Stanislav Glubokovskikh, LBL
09:05 – 09:20	'CaMI update and concepts around sparse monitoring'	Don Lawton, Carbon Management Canada
09:20 – 09:45	Discussion	
09:45 – 10:15	Break	

Session 2: **Non-Seismic Methods**		
10:15 – 10:30	Motivation and rationale for down-selecting MMV technologies at Quest	Simon O'Brien, Shell
10:30 – 10:45	'Real-time wellbore monitoring for early leakage detection using distributed fibre optic strain sensing'	Dr. Takayuki Miyoshi, RITE
10:45 – 11:00	'Novel Monitoring at the Otway International Test Centre, Australia'	Charles Jenkins, CSIRO
11:00 – 11:15	'Pressure and Temperature Monitoring of CO_2 Storage Operations'	Mehdi Zeidouni, LSU
11:15 – 11:30	'Monitoring in carbonates (MRCSP work)'	Neeraj Gupta, Battelle
11:30 – 12:00	Discussion: 'How to use these techniques in a commercial environment'	
12:00 – 13:00	Lunch	
Session 3: **Offshore Environmental Monitoring**		
13:00 – 13:15	'Field tests of marine monitoring offshore Gippsland, Australia'	Charles Jenkins, CSIRO
13:15 – 13:30	'Marine monitoring – learnings from the North Sea'	Jerry Blackford, PML
13:30 – 13:45	Advancements in the C-seep attribution method	Katherine Romanak, GCCC, BEG at UTexas
13:45 – 14:00	CO_2 Deep Storage Formation vs. Migration, Transport and Cycling	Richard Coffin, TA&MU
14:00 – 14:25	Discussion	
Session 4: **Near-Surface Monitoring**		
14:25 – 15:00	Discussion Session: 'Challenges in assessing surface signals & integration of subsurface data to inform action at the surface'	Led by: Katherine Romanak, GCCC, BEG at UTexas
15:00 – 15:30	Break	
Session 5: **Automation & Integration of MMV**		
15:30 – 15:45	'The SmartAUVs project: Enhanced autonomy for environmental monitoring'	Ivar-Kristian Waarum, NGI
15:45 – 16:00	'Deep learning accelerated monitoring data assimilation: lessons learned from SMART Initiative'	Bailian Chen, LANL
16:00 – 16:15	'How bp is accelerating technology to deliver Sustainable Seismic'	Ted Manning, BP
16:15 – 16:30	Gippsland work with sail drones: capabilities & data analysis	Andreas Marouchos, CSIRO

16:30 – 16:45	Discussion	
	Session 6: **Conclusions & Recommendations**	
16:45 – 17:00	Led by: Tim Dixon, Sue Hovorka, Charles Jenkins	

DAY 2: REGULATORY PERSPECTIVE --- HYBRID MEETING, IN-PERSON & ONLINE ---		
	Session 1: **Framing the Problem**	
09:00 – 09:15	Recap / brief summary of talks from Day 1	Tim Dixon, IEAGHG
09:15 – 09:45	US versus EU versus Australia approach: A Panel Discussion	Ian Havercroft (GCCSI) *[VIRTUAL]* Eva Halland (Norway) *[VIRTUAL]* Laura Sorey (DNR) Tim Dixon (IEAGHG)
09:45 – 10:00	What we've learned from UIC permits	Sue Hovorka & Angela Luciano, GCCC, BEG at UTexas
10:00 – 10:30	Discussion	
10:30 – 11:00	Break	
	Session 2: **Tools**	
11:00 – 11:15	'Pressure and Temperature Monitoring to Address Regulatory Requirements'	Mehdi Zeidouni, LSU
11:15 – 11:30	Review of results of groundwater monitoring comparing different projects	Sue Hovorka, GCCC, BEG at UTexas
11:30 – 11:45	Marine environmental monitoring	Laurence Pinturier, Equinor *[VIRTUAL]*
11:45 – 12:00	'New Directions in Monitoring Onshore and Offshore' + DAS technology 101	Charles Jenkins, CSIRO
12:00 – 12:30	Discussion	
12:30 – 13:30	Lunch	
	Session 3: **Environmental Aspects**	
13:30 – 13:45	'Effective monitoring in a complex environment (onshore)'	Katherine Romanak, GCCC, BEG at UTexas
13:45 – 14:00	'Effective monitoring in a complex environment (offshore)'	Jerry Blackford, PNL
14:00 – 14:15	'Monitoring background seismicity, offshore Norway (HNET)'	Philip Ringrose, Equinor *[VIRTUAL]*

14:15 – 14:45	Discussion	
	Session 4: **Societal Considerations of Monitoring**	
14:45 – 15:00	'Determinants of public perceptions about monitoring, and why perceptions matter'	Darrick Evensen, University of Edinburgh
15:00 – 15:15	Communication of monitoring & risk, and the Gulf Coast communities survey	Katherine Romanak, GCCC, BEG at UTexas
15:15 – 15:30	Quest and Atlas community engagement and monitoring	Simon O'Brien, Shell
15:30 – 15:45	Environmental justice and clean energy infrastructure	Clark Miller, Arizona State University *[VIRTUAL]*
15:45 – 16:15	Discussion	
16:15 – 16:30	Break	
	Session 5: **Panel Discussion: Getting to Closure**	
16:30 – 17:15	Led by: Sue Hovorka, Charles Jenkins, Frederick Gal, Rob Trautz	
	Closing Session: **Unmet Needs** (Conclusions & Recommendations)	
17:15 – 17:45	*This session will draw strongly on the audience in attendance; what are the regulators' needs, what do they need from the monitoring community etc. to conclude the event and provide recommendations.*	Led by: Tim Dixon, Sue Hovorka, Charles Jenkins, Laura Sorey

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

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