Evaluating technology options to mitigate greenhouse gas emissions

12th IEAGHG Monitoring Network Meeting

13th – 15th June, 2017

Hotel Indigo, 263 West Grandview Parkway, Traverse City, Michigan 49684, USA

An IEAGHG meeting, hosted by Battelle and Core Energy

IEA GREENHOUSE GAS R&D PROGRAMME

SPONSORS

BATTELLE
It can be done™

CORE ENERGY, LLC

MRCSP
MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP

ADVANTAGE ELECTRIC

BIGARD HUGGARD DRILLING INC.

BAKER HUGHES

SIWECKI CONSTRUCTION, INC.
1801 Milbocker Road Gaylord, MI 49735-7420
Phone (989) 732-2244 Fax (989) 731-0327

SAGE RIDER

Northern A-1
ENVIRONMENTAL SERVICES

OILFIELD TOOLS INC.

SIGMA³

Schlumberger
Carbon Services

TAPLIN
GROUP, LLC
Environmental Services

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. The IEA fosters co-operation amongst its 29 member countries and the European Commission, and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under 39 Technology Collaboration Programmes. These agreements cover more than 200 individual items of research, development and demonstration. IEAGHG is one of these Technology Collaboration Programmes.

Disclaimer

IEAGHG supports and operates a number of international research networks. This report presents the results of a workshop held by one of these international research networks. The report was prepared by IEAGHG as a record of the events of that workshop.

Copyright And Citations

The report should be cited in literature as follows:

'IEAGHG, "12th IEAGHG Monitoring Network Meeting", 2017/10, November, 2017'

Further information or copies of the report can be obtained by contacting IEAGHG at:

IEAGHG, Pure Offices, Cheltenham Office Park, Hatherley Lane, Cheltenham, GLOS., GL51 6SH, UK

Tel: +44(0) 1242 802911

E-mail: mail@ieaghg.org

Website: www.ieaghg.org

Date Published: November 2017, Review compiled by Lydia Rycroft, James Craig and Tim Dixon; design and layout by Becky Kemp.

Front & Back Cover Images: Sleeping Bear Dunes National Lakeshore looking west toward Lake Michigan / CO_2 - oil separation and recycling plant, northern Michigan / Winery located on the Old Mission Peninsula north of Traverse City / Delegates enjoying field trip lunch / Compressor plant for injecting CO_2 for enhanced oil recovery

IEAGHG Research Networks

www.ieaghg.org

Contents

Sleeping Bear Dunes National Lakeshore looking west toward Lake Michigan

Summary

The 12th meeting of the IEAGHG's Monitoring Network, hosted by Battelle and Core Energy, took place in Traverse City, Michigan between 13th and 15th June 2017. These meetings bring together leading experts from research and industry to discuss the latest work and developments, with around 60 participants from 7 countries participating.

The theme for this meeting was 'The Cost and Value-Effectiveness of Monitoring: What Key Drivers are Required to Deliver an Optimum Outcome'. Sessions included project updates, the application of oil and gas production experience, innovative monitoring techniques, offshore monitoring developments, overburden research including controlled release experiments, wellbore integrity and micro-seismicity. Delegates also took part in a group exercise on how to respond to a hypothetical leak scenario.

Key findings from advances in monitoring included the benefits, and some limitations, of the use of fibre-optic distributed acoustic sensors (DAS) at projects, including helical configured cables to overcome the limitations of directional signals. A topic of much discussion at previous meetings has been how to reduce the level (and cost) of monitoring for commercial-scale projects compared with the initial research-orientated projects. It was clear how monitoring is evolving to application now at commercial-scale projects. The learning and experiences from the early projects has enabled more refined, optimised and reduced level of monitoring at larger projects, resulting in more cost-effective monitoring overall. This was seen from the SECARB Cranfield project to Petra Nova, from IBDP to ICCS Project at Decatur, and at Quest which has learnt from across the USA's RSCP projects. Advances in the use of autonomous underwater vehicles (AUVs), equipped with multiple sensors, can be deployed for up to 20 days. AUVs are now capable of large-scale offshore monitoring. Other topics included well bore integrity and microseismicity.

A number of recommendations were made including improvements in DAS optic fibre technology and related data utilisation, better marine baseline methods for global use plus further AUV sea trials and CO_2 release tests to verify instrument sensitivity. Further investigation into chimney structures to improve the understanding of their formation and fluid content were also proposed. Other recommendations included the production of a standardised suite of leakage cases, geomechanical site characterisation, more data on abandoned well leakage including gas migration issues along the outer well casing, and the effectiveness of tracers.

Session Overviews

Session 1: Welcome

Welcome and Introduction – Neeraj Gupta - Battelle, Bob Mannes, Core Energy & Tim Dixon, IEAGHG

This 12th Monitoring Network Meeting was opened by an introduction from Neeraj Gupta from Battelle who heads the Midwest Regional Carbon Sequestration Partnership (MRCSP). Neeraj stressed the importance of field work especially the development of CO_2 enhanced oil recovery (CO_2-EOR) in northern Michigan. He emphasised the generous sponsorship from Core Energy, the operator in the region, and several other companies directly engaged in the MRCSP research programme. Bob Mannes from Core Energy stressed the beneficial relationship with Battelle and the mutual respect for each organisation's technical skills and the opportunity for joint learning.

Tim Dixon from IEAGHG outlined the meeting theme of the Cost and Value-effectiveness of Monitoring with a subordinate theme of leveraging oil and gas industry experience for CO_2 storage.

Session 2: Project Updates – What Fresh Insights are New and Recent Monitoring Data Providing   Chair: Tom Daley

Petra Nova - Sue Hovorka, BEG

Petra Nova is the most recent integrated Carbon Capture Utilisation and Storage (CCUS) project to go on-line. Up to 1.6 M tonnes of CO_2 can be captured from the NRG WA Parish coal-fired power plant. CO_2 is then transferred via pipeline to the West Ranch oilfield. This major new CO_2-EOR project has benefited from the experience gained from two previous smaller-scale SECARB projects of Cranfield and Citronelle. The monitoring programme that was developed at Cranfield was used to define and refine the monitoring requirements for Petra Nova. The suite of monitoring techniques is designed to check the effectiveness of isolation and of containment of CO_2 as well as accounting for its use.

Above Zone Monitoring Interval (AZMI) pressure surveillance has been implemented to check for signs of significant out-of-zone migration. Water curtains are used to constrain injected CO_2. The operations are monitored as part of the EOR. CO_2 is also subject to accounting procedures. Groundwater and soil gas monitoring are deployed as precautionary measures to detect signs of possible incidents and to guard against potential allegations.

Otway – Results from Fibre Optic Array - Barry Freifeld, LBNL

There are three Stage 2C project goals at the Otway site: to ascertain the minimum seismic detection limit of a signal caused by injected gas; observation of the gas plume development using time-lapse seismic and; verification of plume stabilisation using the same technique. This collaborative project involves Curtin University and Lawrence Berkeley National Laboratory (LBNL). Previous experience from the Frio CO_2 storage project in the US has helped with the Otway seismic monitoring. A full 4-D finite-difference time domain (FDTD) synthetic dataset was generated prior to commencement of the first monitor survey and then used to pre-define and validate processing flows. The 4-D seismic was acquired with a buried receiver array acquired concurrently with a 4-D VSP survey. The LBNL group led with a trial using 4-D seismic with a buried DAS array and a 4-D VSP using optical fibre on the tubing and continuous seismic sources. The monitoring array included 3,000 source points with 900 geophones perpendicular to them spaced over ~1km. In total there are 35km of fibre optic cables. Good relations with local land owners were essential to ensure access to the site could be maintained. The electrical transmission unit was affected by high rainfall after 2 years. The high wind and rainfall at the site can cause considerable noise.

LBNL trialed multiple designs with varying physical properties. One length of helical wound cable was deployed for comparison with straight fibre. DAS fibre optic pulse back scatter causes acoustic signal changes in the helical cable. As a result of this latest research the signal : noise ratio and repeatability has been improved. Overall a higher resolution was achieved with a combination of a better source and a greater geophone sensitivity compared with the 2009/2010 surveys.

VSP data is in-line with the surface seismic data and iDAS (in trenches) can be used to image subhorizontal reflectors. The difference in geophysical surveys pre and post-CO_2 injection revealed that CO_2 is detectable at this site even if only 15,000 tonnes was injected. The next steps for DAS are to improving its sensitivity.

Aquistore – Kyle Worth, PTRC

CO_2 injected into the deepest stratigraphic formation, the Lower Deadwood, has been detected. The plume is moving down dip which was not expected. As most CO_2 has been sold for EOR less has been injected since the fall of October 2016. A channel in the basement structure may influence CO_2 movement direction. DAS and 3D seismic has detected CO_2 (36,000 tonnes) at a depth of ~3km. Both monitoring techniques appear to be working successfully and consequently the team has more confidence that the CO_2 plume can be imaged despite the small quantities injected.

New iterations with reservoir models and monitored observations are taking place. The geomechanical properties of the site have been compared to the dynamic reservoir simulations but are not fully understood yet so more work is required. Future research will also include an evaluation of the impacts caused by a 24°C (75°F) drop in downhole temperature. Non-isothermal parameters will be incorporated into future reservoir simulations. Other planned activities will cover an evaluation of how variable rates of injected CO_2 may have an impact on injection well casing, tubing, packer and cement integrity. The impact on near-wellbore and long-term injectivity due to salt precipitation phenomena will also be investigated.

Heletz – Update since 2016 - Auli Niemi

Heletz is a deep CO_2 injection experimental site that is utilising a depleted oil field 1.6km deep. The CO_2 injection experiments are carried out in the saline portion of the formation, to reflect properties of saline formations. Good site characterisation has been achieved from the field's previous oil production history and the more detailed CO_2 specific characterisation experiments in the area are dedicated to the CO_2 injection experiments. Small-scale CO_2 injection experiments to understand the trapping mechanisms, especially residual trapping, have been planned and/or conducted. A hydraulic withdrawal test was conducted by extracting formation fluid from the reservoir to induce a pressure response prior to creating a residual CO_2 zone. A tracer is injected followed by 100 tonnes of CO_2. The fluids are then withdrawn until residual saturation is reached. Another hydraulic withdrawal test was then conducted after the residual CO_2 zone was created. Pressure and temperature were continuously monitored. The CO_2 mass flowrate, temperature, pressure and density were also recorded. Distributed temperature sensing (DTS) was recorded during the entire sequence plus downhole fluid sampling and measurement of high pressure, pH, and low pressure alkalinity and gas composition, as well as measurement of the partial pressure of CO_2 during the production phase. The analysis of the results so far indicate low residual trapping, both based on the simple analytical model and 'full-physics' TOUGH simulation with hysteresis. Further work is still being conducted by accounting for the heterogeneity and flow in the well in more detail. The laboratory results on a 100mD core indicate 0.2 Sgr (residual gas saturation) when hysteresis is taken into account.

A pore network model to analyse the residual trapping in the cores has also been developed. The model has now been successfully fitted to the Stanford University experimental data for a 100mD core. The next step is to model the higher permeability (>400mD) cores tested by Göttingen University. The next step will be a more detailed analysis of dissolution and a bubble flow test in the well to gain a more detailed understanding of the CO_2 released when the well is opened plus further analysis of tracer data to gain a better insight into reservoir heterogeneity. For comparison purposes, a second residual trapping test using fluid injection rather than with-drawal along with gas-partitioning tracers will be carried out.

Quest – Update since 2016 - Simon O'Brien, Shell

Quest is an integrated CCS project that captures CO_2 from the Scotford upgrader unit north of Edmonton, Alberta. The CO_2 is then delivered by a 65km pipeline to the injection site. CO_2 has been injected into a basal sandstone formation since August 2015. The measurement, monitoring and verification (MMV) plan has been implemented to very high technical specifications. Casing has also been cemented to the surface. Lower cost monitoring techniques have been used to determine the timing of more expensive monitoring techniques. Tier 1 down-hole instruments are continuously monitored. Tier 2 and 3 techniques focus on potential air and water impacts and are used if more detailed analyses are required.

The CO_2 plume is smaller than expected probably because good permeability properties in the reservoir have enabled the CO_2 to push reservoir water away. Very low amplitude seismicity has been detected in the basement but no impact has been observed at the surface. Pulse Neutron Log (PNL) runs have revealed good horizontal permeability (kH) consequently CO_2 stays in a high permeability zone. kH is much greater than vertical permeability (kV) by a factor of 100. Reservoir modelling predicts that pressure build up within the reservoir formation is likely to be less the 2MPa. The maximum size of plume is unlikely to exceed 2-4km over the 25 years. 2Mt has now been captured and ~1.2Mt stored. Overall cost are 30% lower than expected.

Southwest Carbon Partnership Farnsworth Unit – MVA Summary - Rich Esser, University of Utah

The Farnsworth Unit is a CO_2-EOR field situated in the northern Texas pan-handle. The objective of this partnership project is to optimise CO_2 storage, and an associated monitoring programme, that ensures CO_2 is retained within a designated reservoir or detected if it leaks into the overburden. CO_2 injection began in 2011, 56 years after initial field discovery. CO_2 from two anthropogenic sources (a bioethanol plant in Liberal, Kansas and a fertilizer plant in Borger, Texas) supply 500,000 – 600,000 tonnes per year. Groundwater chemistry (USDW), soil CO_2 flux, CO_2 and CH_4 eddy covariance, aqueous and vapor-phase tracers and spontaneous-potential have been emplaced to check for the presence of CO_2 or brine outside the reservoir. Microseismicity is also monitored. A variety of monitoring techniques including in situ pressure and temperature, 2-D/3-D seismic surveys, VSP, cross-well seismic, passive seismic, reservoir fluid chemistry, tracers, gravity surveys and magneto-telluric have been deployed to track CO_2 migration and retention.

Results to date indicate no apparent increase in surface levels of CO_2 although there is poor temporal resolution. CO_2 eddy towers have undergone successful field trials, prior to deployment, to test their sensitivity to point sources of CO_2. The High Plains regional aquifer, the Ogallala Formation, is monitored to pick up signs of any anomaly. Water quality has not changed since monitoring began. Geophysical monitoring has highlighted the presence of CO_2 near injectors but further seismic will be necessary to track the progress of the plume.

Session 2: Discussion

The integrity of casing at CO_2 storage sites was raised. Pressure monitoring to test casing integrity is undertaken. At Aquistore multiple calliper, magnetic flux and vertical logs have been used to check casing.

Detecting the presence of a leak is a challenge particularly in ground water. The quantity of CO_2 or brine that would need to migrate out of a reservoir or a designated formation before a leak could be detected remains uncertain, however, in marine environments anomalies can be picked up especially with advances with monitoring technology. Monitoring ground water near onshore sites does offer reassurance to local stakeholders and provides background data should anomalies be suspected or if claims are made against an operator.

Existing wellbores, especially in CO_2-EOR fields do present a risk, however industry operator experience has highlighted the economic penalty of allowing CO_2 losses. A 10% loss of injected CO_2 means that a CO_2-EOR operation would be uneconomic. Operators check well integrity and then decide if intervention is necessary. With continuous recycling 99 – 100% of CO_2 is stored over the lifetime of EOR operations.

The potential for microseismicity to occur raised the question of what intervention might be necessary. If a magnitude 2 event occurs in the Canadian province of Alberta in needs to be reported. If a magnitude 4 event occurs the project would be stopped. Unusual activity would be checked with pressure data to ascertain the cause.

DAS is a technology gaining momentum. Experience from different sites shows that current DAS cable is less sensitive than geophones. However fibre and seismic used in combination work well when either is vertical or horizontal but the configuration is less effective when one is vertical and other is horizontal.

Session 3: The Application of Oil & Gas Production Experience Including CO_2-EOR to Storage in Deep Saline Formations

Chair: Sue Hovorka

Monitoring Storage Efficiency During CO_2 Injection for Enhanced Oil Recovery in Depleted Oilfields - Ashwin Pasumarti, Battelle

Continuous CO_2 injection into deep saline formations (DSFs) creates a pressure plume as all of the injected CO_2 is stored. In contrast, only a portion of the injected CO_2 is permanently stored during EOR operations, and the rest is continuously recycled through pipelines for re-injection. The retention factor can be quantified and expressed as an Injection Efficiency Ratio, which is a metric that quantifies the amount of CO_2 injection required to store each unit of CO_2. The difference between CO_2 injected and CO_2 produced equates to the CO_2 stored in the reservoir. Monitoring of pinnacle reef reservoirs in northern Michigan has enabled a series of such performance metrics to be devised. Material balance techniques for instance, can be applied to quantify the CO_2 storage capacity of a reef. Estimates of storage capacity in depleted oil fields where EOR takes place, are obtained by calculating the amount of pore space that can be occupied by CO_2 at the end of EOR operations, at a pre-defined pressure. An excel-based dashboard tool that incorporates multiple metrics has been developed that enables rapid comparison and ranking of reef storage performance.

Quest – Simon O'Brien, Shell

Quest is a leading integrated CO_2 capture, transport and storage project that has benefited from Shell's expertise as an oil field developer, operator and refinery company. Building experience from full-scale projects like Quest is an important first step to longer term commercial development of CCS. The annualised capital cost is CAN$38/tonne with initial operating costs of CAN$41/tonne. Potential future savings from capital and operating costs are expected to reduce costs by as much as 30%. Operational experience is being used to identify which monitoring costs are most cost effective. Risk and uncertainty management is needed to identify barriers and then identification of mitigation measures that may be required as well as the cost implications of the consequences of non-intervention.

There are distinct differences between oil field operation and CO_2 storage. CO_2 wells differ from oil and gas wells especially if water enters the well. This situation can give rise to hydrates that can increase the time for running logs. Injection into a reservoir cannot be regarded as a remote storage facility. The injectivity rate may need to be varied or temporarily suspended if logs need to be run. Downtime at a refinery, or other large point source of CO_2, needs to be co-ordinated with the storage team to optimise performance and minimise operational costs.

With growing experience regulators and other stakeholders can be briefed so that they have a better understanding of how a CCS project works. Previous experience shows developing good communications with local stakeholders delivers real dividends especially if a specific liaison contact is established that is trusted by local communities.

Session 3: Discussion

The extent of a pressure plume for a project like Quest needs to be accommodated so that it avoids interference with other storage projects injecting into the same formation. In the case of Quest the lease area is 3,600km^2 which is large enough to accommodate the pressure plume over the project's life of 25 years.

Precautionary measures for this key project included cementing completed wells to the surface. The MMV and closure plans will be renewed after three years after more monitoring data becomes available. There is some ongoing research at the site to explore temperature dependence on injectivity.

The maximum predicted uplift at Quest detected by InSAR is 3mm at the centre of the plume which has an approximate diameter or 2km. Originally 10mm was thought to be the extent of uplift. A rate of 4 or 5 times predicted rates would necessitate intervention. 10mm is not considered to be a problem at Quest but at In Sahal the pattern of uplift, and associated deformation, was significant even though it was only 10 mm because it revealed a problem. Elsewhere uplift is not necessarily a problem depending on the nature of deformation. At Bell Creek an uplift of 30mm is expected and is considered to be manageable. The significance of deformation detected by InSAR is the pattern of uplift over an injected area not necessarily the increase in elevation.

Impacts such as induced seismicity also depend on proximity to physical impacts. For example a magnitude 4 -5 in the central North Sea would not be a problem because receptors onshore would not be able to detect it. An event of this magnitude onshore would be felt.

Communication is important when explaining or discussing CCS especially when talking about CO_2-EOR. As a closed loop system CO_2 is not lost to atmosphere and is eventually completely stored but this concept needs to be carefully explained to avoid misinterpretation.

Session 4: Innovation in Monitoring Techniques and Advances in the Understanding of Rock-Physics

Chair: Caitlin McNeil

Sparse Seismic Array and K-Wave – Shaughn Burnison, EERC

Two different seismic techniques have been trialled at the Bell Creek oilfield in southeast Montana: a Semi-permanent Automated Scalable Seismic Array (SASSA); and a monitoring method that uses guided waves and a type of wave called the K-wave. SASSA is a seismic method to track CO_2 movement in the reservoir using a sparse array of 96 nodal geophone sensors and a single stationary, remotely operated source. Future evolutions of the method could increase either the number of receivers or sources. Discrete locations in the reservoir were monitored by individual array sensors. A series of source shots were recorded at weekly intervals over the course of a year while injection was occurring in the field, creating multiple time-lapse datasets for each monitored point. Changes to the reservoir reflection character over time may indicate the movement of CO_2 past monitored points. To increase the signal to noise ratio, traces acquired each week were processed to remove noise and stacked. The weekly stacked traces for individual nodes were displayed side by side to present an incremental time-lapse display to see when consistent character changes thought to be due to the passing of the CO_2 saturation front occurred because of injection timing and proximity. To validate and corroborate, CO_2 saturation plume images were generated from dynamic reservoir simulations and compared to monitored locations that showed changes. Differences on time-lapse 2-D seismic lines that were shot pre and post-injection indicate the presence of CO_2 where changes are also seen on one or more monitored locations.

The Krauklis wave or K-wave is a slow dispersive wave mode that propagates in a fluid layer bounded by elastic media. The guided properties of this wave, and several other guided waves, such as Stoneley and Scholte waves that are normally discarded as noise, are to be exploited in this project which has just started. It is designed to monitor the movement of the CO_2 saturation front away from injection wells in a CO_2-EOR application. Tube waves (Scholte waves) generated in a well at the surface by a special high pressure displacement source, induce wave energy through the perforations into the reservoir which for some wave types acts as a waveguide. When the induced guided wave energy from Lamb, Stoneley, or K-waves encounters perforations at nearby wells, tube waves are induced that are detected with special pressure sensors on the wellhead at the surface. Shots numbering in the hundreds are stacked to increase signal strength. For a CO_2-EOR application, the high density of wells allows for a network mesh of areal coverage. A pre-injection baseline survey establishes the arrival times of the guided waves at each well. Arrival times are delayed on monitor surveys conducted after injection has progressed due to the lower propagation velocity through CO_2 saturated rocks, allowing the dimensions of the CO_2 saturation plume to be deduced between different source-receiver well pairs. To validate the method, two conventional 3-D surface surveys are planned over the study area: a pre-injection survey coinciding with the timing of the K-wave baseline survey this year; and a second at the conclusion of the field effort about one year later and coinciding with the third planned K-wave monitor survey. Difference displays from the 3-D surveys that show the location of CO_2 saturation will be compared to the saturation geometries inferred from the K-wave monitor data. This new monitoring technique is scalable and has the advantage of using only wellhead mounted equipment.

Baseline DAS VSP of the Chester 16 Field (Reef), Michigan – Mark Kelley, Battelle

The objective of this research was to conduct a pre-CO_2 injection DAS VSP that can serve as a baseline for future VSPs during the CO_2 injection period into a pinnacle reef. The secondary objective was to determine the quality of DAS VSP that is possible in a Niagaran reef/carbonate rock in the light of potential issues (thick glacial till, well construction). The wells are deviated and therefore not ideal for DAS VSP. Vibroseis and dynamite were used for sources. The match between DAS and geophone seismic is now a standard approach.

The results from this comparison shows that the DAS VSP images match with previous 3-D seismic, indicating the DAS VSP processing methods are sound. Uncemented multi-string completions are less than ideal for borehole seismic. Vibrator recordings look better than dynamite. Two vibrator trucks may be sufficient. When compared side-by-side both dynamite and vibroseis sources look good enough for imaging after the full sequence of processing steps. The Battelle team are in a strong position to plan cost-effective repeat surveys as a part of a 4-D programme that might or might not include 4-D surface acquisition.

PNC Logging to Detect Effects of Fluid Saturations on Monitoring - Amber Connor, Battelle

The effectiveness of Pulse Neutron Capture (PNC) logging in pinnacle carbonate reefs has been tested. The Northern Niagaran Reef trend has well-developed intercrystalline and vuggy porosity which is important to understand when applying PNC to determine CO_2 saturation. PNC is a near well-borehole technology suited to multi well logging and time-lapse comparisons. A triangulation method is used to differentiate between oil-gas-water fields. At any depth CO_2 saturation can be deduced using PNC logging. Preliminary saturation analysis needs to be checked for outliers. Control data is collected from three wells in a single reef structure. PNC logging is repeated at different stages of CO_2-EOR and the differences in saturation change analysed.

The draw back with PNC logging is that it is limited to near wellbore investigation and the technique cannot differentiate between CH_4 and CO_2. PNC does not discriminate between gas/liquid CO_2 and is not suited to low porosity fields with low formation fluid salinities. Its positive attributes include sensitivity to pressure and production changes. The technique provides a quick look at saturation changes in formations within the vicinity of wellbores and it operates effectively in high salinities.

The next step is to perform control and repeat logging in new CO_2-EOR fields that have not been previously injected with CO_2. PNC monitoring data needs to be combined with other monitoring data to build saturation models. By using sigma analysis and salt plugging analysis capacity estimates will be investigated. PNC logs will also be used to analyse potential oil density and CO_2 phase changes.

Integrating Monitoring Data: Understanding Reservoir Behavior and CO_2 Movement at the Bell Creek Commercial CO_2-EOR Project - John Hamling, EERC

The Bell Creek research-monitoring programme has adopted a multiphysics approach which incorporates 16 techniques over a 1.5 year pre-injection monitoring period and 3+ years of operational monitoring. The objective is to demonstrate and validate monitoring techniques and their associated economics to inform viable monitoring, verification, and accounting (MVA) strategies. The programme builds from the backbone of commercial operations data. CO_2 injection began in May 2013. Since that time 3.7Mt of CO_2 has been injected resulting in 3.7Mbbls of tertiary oil production.

The multiphysics approach enables comparison and integration of different monitoring techniques including seismic, InSAR and PNC. A 3-D 104km baseline seismic survey was conducted prior to CO_2 injection in August 2012. Seismic time-lapse difference displays have imaged the presence CO_2. Results from lower cost monitoring techniques such as 2-D seismic and PNC logging combined with simulation forecasts were used to inform the acquisition of time-lapse 3-D seismic monitoring and validate time-lapse seismic as a method for imaging CO_2 at the site. This validation provided justification for proceeding with the acquisition of more expensive but higher value time-lapse 3-D seismic. The 4-D differencing revealed a pattern of CO_2 distribution and migration pathways governed by geological features within the reservoir. These features provided insight into the location and extent of fluid and pressure communication between reservoir compartments. The 4-D analysis results, along with other coupled operational and monitoring data, are being used as a diagnostic tool to update the static model of the reservoir and to inform and improve history matching and predictive simulations. Monitoring results are also being used to validate and interpret other monitoring techniques.

Regional InSAR datasets have been shown to have sufficient sensitivity to identify regional natural ground deformation trends. Work is being performed to attempt to correlate in-field time-lapse ground deformation patterns with injection and production pattern performance and in an attempt to identify well performance that is influenced by geological features.

In conclusion low impact, low cost monitoring technologies have been successful as part of a monitoring strategy for de-risking and optimising the utility and application of higher value monitoring techniques.

Aquistore, Seismic Monitoring - Tom Daley, LBNL

CO_2 storage requires long-term repeat monitoring. Active source seismic is widely used for this purpose but it can be expensive, land access can be a hindrance onshore and large numbers of sensors are required adding to the cost. DAS on fibre optic cables offers a promising technology to improve long term repeatable monitoring with permanent sensor installation and large spatial sampling. Fibre optic cables as sensors can also be relatively easily deployed at shallow depth. This cable can also be cemented behind the casing. The technology is being tested at the Aquistore CO_2 storage site. Post-injection monitoring was conducted in February 2016 and repeated in November of the same year. The difference between baseline and post injection of 4-D surface seismic enables the CO_2 plume to be imaged near the injection well in the Upper Deadwood formation. The DAS signal can be converted to a geophone equivalent particle velocity and matched to conventional geophone data. Multimode and single mode fibres have been deployed. Multimode fibres are used for temperature sensing. Noise reduction in DAS has also been improved between 2013 and 2016. Surface seismic produces a better quality image but it is more expensive compared with DAS.

This research has demonstrated that successful seismic monitoring with permanent surface and borehole DAS sensors can be achieved. Both surface 3-D and 3-D VSP techniques have successfully detected small amounts (~15 - 30kT) of CO_2 at a depth of 3.2km. Moreover, DAS VSP appears to be a cost-effective monitoring tool and it has the potential for microseismic monitoring. Cemented borehole fibre is now established as a default VSP tool.

Mont Terri – Rock Physics Experiments - Yves Guglielmi, LBNL

Fault slip can be triggered by fluid injection and lead to an increase in fault zone permeability. The Mont Terri Swiss rock laboratory is an experimental facility in a very low permeability clay formation which also includes a fault. The fault zone can be monitored to detect potential displacement and to estimate the associated fault leakage. There are two monitoring points one on the main fault slipping surface and one injection point 3 meters away in the fault fracture damage zone. Displacement is measured relative to the structure's orientation and changes in effective stresses. Its plasticity through time (elastic modulus) can also be measured. A comparison of different tests allows the difference outside fault and within the fault to be measured. Inside the fault shear-slip occurs. Outside the fault zone normal opening occurs. Pressure and flow rate are used to measure transmissivity. Slip motion is captured before there is a pressure increase. A slight shear then increases (accelerates) before there is a pressure drop.

The inference drawn from this experiment is that large fault permeability variations are associated with infra-millimetre dilatant slip pulses. The aseismic component induced by fluid pressure drives low level seismicity within the pressurised zone. However, passive seismic monitoring may give an incomplete picture of a fault's status. Implementation of complex permeability monitoring in comparison with a critical shear relationship could help refine the analyses. Complementary monitoring of pressure difference transients and active seismic imaging will help to advance this research.

Geological CO_2 Storage at the Laboratory Scale: Novel Response on Core Variable Pore Pressure and Partial CO_2 Saturation - Ismael Falcon Suarez, NOC

Distinguishing between pore pressure and pore fluid distribution effects is key to effective CO_2 storage monitoring. A novel multidisciplinary experimental approach has been developed to relate geophysical signatures of rock samples to their hydromechanical and geochemical properties during CO_2-brine flow-through tests in the laboratory. The tests procedure consists of forcing the flow of increasing CO_2-to-brine fractional flows through the rock at variable (realistic) pore pressure and constant confining stress, while simultaneously monitoring ultrasonic P- and S-wave velocities and attenuations, electrical resistivity (transformed into CO_2 saturation), strains and (relative and absolute) permeability. Synthetic samples were initially used to replicate physical, chemical and petrological properties of siliciclastic reservoir formations, simulating Sleipner reservoir conditions. An actual Utsira Sand (the main reservoir formation in Sleipner) core sample was also tested. Comprehensive datasets have been obtained. This valuable information has the potential for calibrating field monitoring techniques and improving coupled geophysical-hydro-mechanical models. Better predictions of the onset of geomechanical instability of reservoirs during and after CO_2 injection should now be possible.

Session 4: Discussion

DAS VSP is a promising monitoring technology but it still exhibits a lower resolution compared with 3-D VSP seismic. The quality of the signal from the geophones can be partly attributed to their depth of burial (20m) which suppresses surface noise. More work is necessary to produce a good seismic image. At Aquistore it takes one month to process surface seismic whereas DAS VSP takes 4-5 months to get results. However, most of the effort is required when a baseline is set up for later comparison. Most of the work goes into developing the velocity model. Faster processing in a velocity model would be beneficial.

Cemented fibre outside the casing produced the best results but fibre cable can get stretched or damaged. DAS fibre strapped to tubing works well on the MARS platform. The durability of DAS was also questioned especially given potential monitoring requirements of ~20 year periods and the high temperature conditions experienced in wells. The level of robustness depends on the brine chemistry, temperature and well depth. Eventual geophone obsolescence might occur but the technology still has an important role. In conclusion, good signal processing from DAS has proved to be beneficial. It was suggested that work flows related to DAS and conventional seismic processing should be standardised for CO_2 storage and consolidated in a best practice manual.

Session 5: Monitoring – Selecting a Cost- and Value-Effective Approach that Aids Policy and Outreach Objectives – Discussion led by Neeraj Gupta

Technology is being developed for the measurement and surveillance of injected CO_2 to assure safe storage. Monitoring is used to assess the integrity of the storage complex, detect any loss of containment and determine the displacement and fate of injected CO_2, pressure fields and reservoir fluid displacement. Whether current technologies and monitoring programmes can answer questions that stakeholders and regulators might ask is less certain.

The minimum Class VI requirements specify analysis of the CO_2 stream, continuous recording of injection, corrosion monitoring, groundwater monitoring above the confining zone, mechanical integrity, reservoir pressure, containment assurance and monitoring to support modelling. No specific methodologies are prescribed, but periodic review and revisions are required. Revisions must be approved as permit amendments.

There are broader questions to be addressed. For example, can the entire plume be tracked and is pressure monitoring alone effective for plume monitoring? How are difficult sites going to be treated? Sleipner is a good example of a site where plume progression has been relatively easy to track but in difficult sites which are harder to monitor, and difficult to model, plume tracking would be more challenging. Under these conditions simulating worst case scenarios and the conditions that led to them might be the only way to gain acceptance for the site from stakeholders. Models are being developed for this purpose.

The ROAD project only has pressure monitoring in one well in a highly depleted field. A fault separates the field from an adjacent field that might need to be investigated to satisfy EU regulators.

Detailed CO_2 saturation distribution may not be necessary but it will be necessary to know where plume is supposed to be.

Natural gas storage is becoming more highly regulated. API 1171 the regulation for natural gas storage is not as prescriptive compared Class VI requirements.

The material balance between injectors and producer wells is the main means for checking CO_2 retention. High quality data sets are important to verify models but the affordability of high resolution monitoring in a commercial environment is open to question. For example the amount of high value monitoring required to track a very thin plume will depend on the associated risks and the complexity of the reservoir conditions.

Tomakomai – Re-Injection has Started with Regulatory Approval – What Really Happened? – Daiji Tanase, Japan CCS

Tomakomai is an industrial city on Hokkaido 800km north-east of Tokyo. CO_2 is injected from deviated wells on the shoreline in close proximity to an oil refinery hydrogen unit which is the source of the gas. CO_2 at 99% purity is captured at a rate of 100,000 tonnes per year or more. It is injected into a sandstone reservoir at a depth of 1.0 to 1.2km. The CO_2 injection was launched on 6th April 2016. In Japan, marine site disposal of CO_2 is governed by the Act for the prevention of Marine Pollution and Maritime Disaster under the jurisdiction of Ministry of the Environment (MOE), which reflects the London 1996 protocol. A marine baseline survey has been conducted off the coast. Seasonal surveys are to be repeated during and after injection. There are three phases of the marine environmental survey namely: a regular survey; a precautionary survey; and a contingency survey, which are prescribed by the pCO_2 / DO threshold based on the baseline seawater survey data. If the threshold is exceeded in a regular survey, a precautionary environmental survey then has to be conducted after injection is stopped to ensure that there are no potential detrimental effects on the marine environment. Results from fresh surveys must be reported to the MOE.

On 24th May 2016 injection was suspended for a scheduled annual maintenance shut-down of the capture facility and the refinery. Between 1st to 8th June 2016 a regular marine survey revealed that the pCO_2 / DO (dissolved Oxygen) threshold had been exceed. The planned restart was subsequently postponed and precautionary and contingency surveys were conducted later in the year. The results were reported to the MOE. Finally the MOE judged that no CO_2 leakage had occurred. A supplementary permit application with a revised marine environmental survey plan was accepted by the MOE in 1st February 2017 and the CO_2 injection recommenced on 5th February 2017. A regular marine environmental survey was conducted between the 17th and 24th May 2017 without exceedance of the threshold. In the revised marine environmental survey plan, side-scan sonar surveillance for bubble detection and pH towed senor surveys are now planned in case the revised threshold is exceeded.

The CarbonNet Project: Plans for Commercial CO_2 Storage and Monitoring in the Nearshore Marine Environment - Nick Hoffman, CarbonNet

The CarbonNet project is designed to be a commercial venture with a 5Mt/year capacity. This storage project benefits from good data from the offshore oil and gas industry in the Gippsland Basin which extends off the coast of Victoria. Onshore lignite produces CO_2 from coal-fired power plants. A gated approached will be applied to appraise the commercial viability of the project as more detailed assessments are progressed. The commercial viability of any CCS project depends on the industrial source of the CO_2 and the associated capture cost. Several offshore storage sites are under review but there are some near-shore locations with high thickness and permeability properties. There is a formation that has good structural closure, permeability and a caprock seal with sufficient capacity for at least 125 million tonnes of storage. The aquifer extends 140km east-west and 100km north-south with a capacity of a peta-litre of water. 56 simulations have been generated to produce probability contours of the aerial extent of the plume to give a range of plume predictions. A 3-D marine seismic survey of 166km^2 is planned in Bass Strait during the summer of 2017-18. Stakeholder engagement and marine environmental surveys are also planned. The project is now entering the project development stage. Industrial collaboration is being progressed with the ultimate aim of a transition to the private sector by 2020.

STEMM-CCS Project – Horizon 2020 - Doug Connelly, NOC

The STEMM-CCS project has a series of objectives which include the development of a baseline assessment methodology under real conditions. It will include methods to assess the permeability of CO_2 in marine sediments and a suite of tools to identify, detect and quantify CO_2 leakage from a controlled release point. The project will also assess the applicability of artificial and natural tracers for detection, quantification and attribution of leakage of CO_2 in a marine environment. Modelling to assess different leakage scenarios will also form part of the project.

An experimental release site 2-3m below sea bed above the Goldeneye site has been selected. The immediate area will be heavily monitored to detect CO_2 as it is released. AUV acquired automated image processing will be deployed to conduct marine surveys. By comparing observed images with a bank of recognisable forms the AUV mounted system will automatically only select and retain images of interest. This function is especially useful for conducting biological surveys over large areas or over extended periods of time. Optodes (optical sensor) mounted in the AUV will monitor pCO_2 to an accuracy of ±1 µatm, pH to an accuracy of ±0.001 pH and O_2 to an accuracy of <3µmol/l. The UK's National Oceanographic Centre has developed a lab-on-a-chip chemical sensor platform. The system can be deployed on an AUV and has low power demand for extend year-long deployment. A lander system will also be deployed as part of the baseline assessment and to check on seasonal variability. Observed background physical conditions will provide information for models that can simulate submarine conditions. There is currently very limited data on the North Sea. Once set up CO_2 will be released under carefully controlled conditions to avoid a potential blow out.

Other aspects of the project will be used to conduct seismic surveys of chimneys in the North Sea. These structures could act as natural conduits for CO_2.

Energy Technologies Institute – Autonomous Underwater Vehicle (AUV) - Graham Brown, Sonardyne

The underwater technology company Sonardyne is currently developing a sophisticated AUV capable of conducting large-scale multiple parameter surveys of key environmental indicators. The AUV, affectionately named "Boaty McBoatface" has received 50% of the development cost from the UK's Energy Technologies Institute. The purpose of the AUV, and its on-board instrumentation, is to: detect and locate the source of leaks from a CO_2 storage site in the form they are expected to emanate from the sea bed; provide a capability to detect CO_2 leaks which have the potential to damage the marine environment; jeopardise the financial success of the store; or represent no more than 0.01% loss store-wide per annum of the planned inventory at the end of the injection phase. The AUV has an operational window in marine environments of water depths of between 20 - 200m and can cover an area of 10 - 3,000km^2, at distances of 25 - 150miles (40 – 240km) from land within sea temperatures between 5 - 17°C. The system provides data analysis and has an interpretation capability that can distinguish between leaks from CO_2 storage sites and other seabed emissions. This AUV is equipped with an array of chemical sensors, a sonar system and can operate autonomously for 20 days which avoids the cost of using an expensive survey ship. Its on-board computer has an image comparison capability that can distinguish between a CO_2 plume and other features such as a shoal of fish or a ship's wake. Sea trials began on 17th July 2017.

One of the challenges presented by the North Sea is the paucity of data on natural conditions and the highly variable conditions. The shallow waters of the southern North Sea induce mixing whereas the deeper waters of the northern North Sea lead to stratification. Experience of terrestrial sensors have shown that in some cases they have under delivered. Multiple sensors in the marine environment do have a track record of exposure to known parameters and they have a high reliability track record because of extensive offshore oil and gas experience. Sensors are rigorously tested for specific applications as part of pre-deployment assessment to ensure reliability. There is an AUV working group with a remit on interference from other sea users for example trawlers.

Session 6: Discussion

Offshore developments are now showing real promise both in terms of technology development for example STEMM AUV, at a planning stage, GipNet (CarbonNet) at pre-project testing stage, and actual experience at Tomakomai.

The importance of monitoring to counter allegations from regulators or other stakeholders remains paramount. A vehicle that could provide background environmental parameters capable of surveying several sites is now in prospect. Other suggestions proposed included a containerised response system equipped with such an AUV and a compact portable laboratory which could be deployed at short notice. One example of similar marine response and surveillance was the plume from the Macondo well which was tracked by an AUV. Rapid deployment is already planned. Oil companies have collaborated and have such monitoring systems for rapid deployment to respond to incidents. Monitoring protocols could trigger future response as has occurred at Tomakomai. More background baseline data is still required for the project. Carbon isotope analysis is now being carried out at Tomakomai. Sr isotopes can be done but not in-situ. Demonstrating that a leak has not occurred is still important for re-assurance and necessary to comply with regulatory requirements.

Session 7: Overburden - Project Updates – What Fresh Insights are New and Recent Monitoring Data Providing

Chair: Frederick Gal

CaMI Field Research Station Update – Amin Saeedfar, CMC Research Institutes

The objective of the CaMI Research Station is to track CO_2 from a controlled release point at a depth of 300m using multiple physical monitoring techniques. The site is located in southern Alberta south-east of Calgary. The injection point is 300m below the surface. A 3-D seismic array within a one km^2 has been established around the injection well. There are two monitoring wells 20m and 30m away from injection well. Fibreglass casing with an integrated fibre optic cable DAS DTS has also been installed. The CO_2 will be injected in gas phase and then detect in gas phase.

The monitoring will consist of continuous passive seismic acquisition with seven stations using broadband regional seismicity and solar powered sensor array. 100 surface geophones have been installed 1m below surface and complemented by a fibre optic system in a 1.1km trench with helical fibre optic cable. Other monitoring techniques deployed include electrical resistivity tomography (ERT) which can only give 2-D images. A portable ERT survey borehole-to-surface portable system is capable of generating 3-D images. The objective is to combine responses from different physical monitoring techniques to determine which is most suitable and to integrate responses.

ENOS (Enabling Onshore CO_2 Storage in Europe). CO2GeoNet initiative - Dave Jones, BGS (British Geological Survey)

Near surface monitoring forms part of the ENOS Horizon 2020 project co-ordinated by BRGM (Bureau de Recherches Géologiques et Minières) and involving partners largely from CO2GeoNet. The GeoEnergy Test Bed in the UK and Sulcis field site will be shallow experimental injection sites within the project. Natural release sites in Italy will also be studied. A variety of continuous monitoring stations, rapid survey systems, ground based and airborne systems (UAV gas monitoring, thermal imaging) will be deployed. The objective is to assess leakage associated with faults and abandoned wells, controls on leakage, and to attribute the source of CO_2.

The GasPro CO_2 system continuously monitors CO_2 in soil gas and uses wireless transmission of data. Up to 50 of these systems are planned to be deployed at the Sulicis site in Sardinia. The BGR's (Bundesanstalt für Geowis-senschaften und Rohstoffe) near surface gas monitoring system will be deployed in a cross comparison with other eddy covariance and chamber flux monitoring. Probes will be set above the water table at different depths to see how the concentration of CO_2 varies relative to the water level and how the water level influences flux levels. Vertical profiles of CO_2 concentrations close to the ground will also be monitored. CO_2 concentration and wind speed will be co-monitored. Three permanent soil monitoring probes were installed in March 2017 at the Hontomin site in Spain.

Different mobile gas monitoring systems will be tested and compared with existing open-path lasers. They include the GasPro ground mapper and an airborne (UAV) system capable of measuring CO_2 concentration, humidity, pressure and temperature. Monitoring campaigns will be conducted before and after the injection. Data integration from horizontal and vertical profiles using the UAV will be used for comparison or with the other monitoring techniques/tools tested at the sites.

The determination of C-O isotopologues "clumped isotopes" has the potential to differentiate higher-temperature deep source CO_2 from that of lower temperature shallow origin. Isotopologue data from natural seeps will be assessed against other methods such as standard stable isotope data, and gas ratios. A leakage simulation alliance has now been established (GTB, Sulcis, Field Research Station, Otway shallow injection, South Korea (e.g. K-COSEM sites), Brazil field site, CO_2 Field Lab).

GeoEnergy Test Bed - Ceri Vincent BGS

The GeoEnergy Test Bed (GTB) will be a national facility in the UK to advance geoscientific research to support the global need for secure, sustainable and safe energy. The GTB will be used to test innovation monitoring techniques and will provide a platform for international collaboration. The GTB was founded by the University of Nottingham and The British Geological Survey. The GTB was initiated with funding from the founding partners and has received capital investment from the UK Government's Treasury as part of the Energy Research Accelerator (ERA) project. Characterisation of the GTB project is still ongoing. Permissions for injection of CO_2 are being sought at an early stage. This onshore site will target a Sherwood Sandstone Group reservoir which has a Mercia Mudstone Group caprock as well as a thin sandstone layer within the Mercia Mudstone Group to examine CO_2 migration through natural pathways in the shallow subsurface. The Sherwood Sandstone Group is a candidate for CO_2 storage and containment in the southern North Sea basin. Some shallow geophysical ERT characterisation, geochemical, microbiological soil samples and soil gas flux surveys have already been conducted. Drilling has been completed followed by logging and hydrogeological testing. Baseline geophysical surveys should be completed in 2017. A ground water monitoring programme will also be instigated to satisfy the Environment Agency (EA) that the aquifer is not being compromised. Experience from the site will also aid the EA's understanding of CO_2 storage. A draft science plan will be drawn up for the site but will be subject to modification when site models have been validated against recorded observations. Additional research collaborations to enhance the value of the site are welcome.

Constraining Fluid Flow Processes and the Physical Properties of Sediments Relevant to CCS - Jon Bull, University of Southampton

Chimneys, pipes and pock marks are ubiquitous in sedimentary basins and indicate that there is widespread natural vertical fluid migration. The formation of these structures and their permeability is not fully understood. The objective of current research is to investigate the mechanisms that cause vertical flow of fluids in sedimentary basins and how these structures form. Observations from the QICS experiment showed that the original chimney structure disappeared after two years but the presence of bright spots in shallow sand layers is still evident. The inference form QICS is that capillary pressure is responsible for gas migration in sand whereas fracture pressure is responsible for gas migration in mud rich sediments.

It is clear from seismic profile observations that chimneys and pipes can form penetrative vertical features of up to 2km through sedimentary strata including clay rich layers that could form seals. These features could form natural conduits for fluids from deep sediments. There is currently very poor control on permeability either vertically or horizontally particularly associated with chimneys. Onshore analogues offer some insights into these phenomena but further research is needed. STEMM-CCS is underway and will be complemented by new seismic acquisition and coring to improve the understanding of chimneys and their formation.

Session 7: Discussion

There are a series of detailed projects now underway to characterise overburden and CO_2 migration through sediments, for example STEMM. Collectively this research should give a much better understanding of fluid movement in the overburden and improve future storage site characterisation. Many experimental sites also have the potential to quantify fluid migration. It may also be possible to quantify CO_2 that shows deviation from natural background levels. There have been no discernible trends in flux measurements at sites with low concentrations of CO_2 that can be attributed to specific sources.

Session 8: Near-Surface / Surface Baseline Monitoring – Commonalities / Site-Specific Subtleties and Leakage Monitoring

Chairs: Charles Jenkins and Katherine Romanak

Three Key Questions were put to each research team:

1. Given the near surface baseline data that you have collected how will you use these data to attribute a signal?
2. Have you done a sensitivity analysis or any quantitative analysis on what a leakage signal would look like given your data set?
3. What are your protocols for deciding that there is nothing in the monitoring data that justifies any action?

SECARB / ANLEC - Katherine Romanak, BEG

A process-based approach was adopted at SECARB (USA) and ANLEC (Australia) sites. The method used O_2 : CO_2 gas ratios to differentiate between CO_2 that could be attributed to leakage and CO_2 attributed to natural biological respiration. The percentage of co-existing N_2 was also used to indicate whether the CO_2 was formed in-situ or added to the system from depth. When using a process-based method, the respiration line provides a sort of global trigger point that is simple and will be the same at every site. Varying degrees of CO_2 dissolution into ground water at the SECARB site has shifted gas concentrations to the left of the respiration line, slightly decreasing the sensitivity of the system to leakage. The ANLEC site (Australia) showed no dissolution of gases and therefore was slightly more sensitive to a leakage signal. The ability for real-time continuous measurement capabilities for all four gases of interest for the process-based method would be a significant advance. A sensor with this capability is currently in development.

Tomakomai - Jun Kita, Marine Ecology Research Institute (MERI)

Near-surface baseline data CO_2 : O_2 ratio at the Tomakomai project is used to determine potential leakage based on four (seasonal) measurements per year. However measurements above the original threshold line gave the impression that leakage was suspected. This was a false positive indication which reflected natural fluctuation. A sensitivity analysis was conducted by comparing Tomakomai measurements with a dataset from Osaka Bay recorded over 10 years. This comparison showed that long-term baseline data is needed to avoid false positive indications. If measurements rise above a specific threshold corroborative evidence of leakage, specifically the presence of bubbles is required.

The reason the initial baseline was only based on four measurements was because the regulatory authority decided that only four measurements were adequate but this quantity is clearly insufficient. A stoichiometric relationship could be used as an alternative to baseline measurements. Water mixing, daily and seasonal fluctuations in biological activity all influence variations.

Bell Creek - John Hamling, EERC

The first step taken was to establish baseline conditions and natural variability in surface water, soil gas, and shallow groundwater chemistries in the vicinity of CO_2 injection. This can provide a defensible source of data to show that near-surface environments are not adversely impacted by CO_2 injection and/or to identify anomalies that could be indicative of an out-of-zone migration event should they occur. A variety of natural seasonal and environmental factors were shown to result in large variations in background soil gas and water chemistry compositional changes (e.g. CO_2 concentration, etc.). The research monitoring programme evolved into a more commercially viable approach where signal attribution (i.e. identifying the cause or phenomenon leading to a change in chemistry) was de-emphasised compared to anomaly detection (i.e. identifying if a significant change in chemistry had occurred). Focus was placed on understand and distinguishing the anatomy of an out-of-zone migration signal compared to naturally occurring variability.

Modelling and laboratory exposure testing were used to predict, measure, and model hydrogeochemical changes based on exposure to CO_2 in order to identify key indicators. A key indicator is a chemical change in the system that is:

- accurately measured using field techniques.
- results in a significant shift upon exposure to low concentrations of CO_2.
- generally not significantly affected by natural variability occurring within the system.

Of particular value are combinations of key indicators that when observed together provide improved confidence regarding the ability to determine if a particular signal could be the result of an out-of-zone migration. Key indicators identified for water chemistry were a significant and rapid drop in pH with a corresponding increase in alkalinity and specific conductance. In soil gas the biological respiration line in combination with carbon isotopes were used to differentiate the origin of a CO_2 signal. Combined with baseline data trends these indicators were used to define action levels which signalled the need for further investigation to determine if an anomaly could be indicative of out-of-zone migration. No indications of out-of-zone migration were detected at the Bell Creek field.

Farnsworth Unit - Trevor Irons, University of Utah

Monitoring protocols in the Permian Basin of the Texas Panhandle need to take account of the risk to the High Plains Aquifer. Monitoring includes soil flux measurements and eddy covariance sampling which shows CO_2 influx from roads plus potential sources from oil fields in close proximity. Rapid changes in ground water chemistry are complicated by ground water extraction. The most valuable indicators are aqueous and vapour phase tracers in the reservoir that show no indication of migration into the ground water. This is supported by sensitivity and quantitative analysis to identify sources of CO_2 and CH_4. Sensitivity tests of tracers are planned to test how effective they are as leakage indicators. TOUGH 2 modelling has also been used.

IBDP and IL-ICCS Project - Randy Locke, University of Illinois

The Illinois Basin-Decatur Project injected 1MT into the Mount Simon Sandstone and is a first of a kind saline storage demonstration from a biofuels source. The project has commercial, regulatory and research drivers that influenced its rigorous monitoring requirements. The monitoring programme has involved over 20 monitoring technologies. Up to 11 years of monitoring will be conducted; 2 years pre-injection, 3 years during injection, and up to 6 years post-injection. Shallow groundwater quality evaluations are based on intra-well trends and statistical assessments for sentinel parameters responsive to CO_2 (pH, alkalinity, Ca, TIC for the presence of CO_2) or brine components (Br, Cl, Na, conductivity). Four different soil gas ratios/relationships including: O_2 vs. CO_2; CO_2 vs. N_2; and CO_2 vs. N_2/O_2; and the isotopic differentiation of $\delta^{13}C_{CO2}$ are used to attribute the source of the CO_2. Laboratory experimentation has been used to evaluate potential geochemical signals from local geological materials as a response to CO_2 interaction. The NRAP aquifer impact model was used to predict the impact of CO_2 or brine leakage were it to occur at the IBDP and those results were tested against groundwater data from the site. In general, the IBDP employs logical and statistical testing of environmental monitoring data to characterize natural variability and monitor for anomalies. If anomalies are identified, they are investigated to determine the source of the variability. No anomalies from CO_2 injection have been identified.

For the larger-scale Illinois Industrial CCS (IL-ICCS) Project that plans to inject a total of 3 to 5 MT, a more stream-lined monitoring programme has been developed, drawing upon the experience at the first project in Decatur. For example, monitoring density and frequency is decreased and only pre-injection baseline data were collected for soil flux and soil gas. Monitoring is planned for up to 17 years; 2 years pre-injection, 3 to 5 years during injection; and 10 years post-injection. Injection started in April 2017, and 137,000 tonnes were injected as of June 2017.

Quest - Simon O'Brien, Shell

At Quest near-surface monitoring and soil analysis have been sampled to build a long-term data set of the site. Ground water wells within 1km of the injection site have also been sampled. Spatial and temporal variation is used for baseline and discussion with the regulator. The distinctive $\delta^{13}C$ signature of CO_2 has been used to identify its source. CH_4 from shallower coal seams is also evident. A light source system has been deployed to detect leaks that may have reached the atmosphere. Three separate light sources beams are statistically compared with each other temporally and spatially to identify an anomaly that might be a leak. The system has been calibrated to predict and quantify leaks. Ground water anomalies are regularly checked and include sensors that detect 18 different ground water parameters at each sampling point. Extra checks are preformed if anomalies are picked up.

Aquistore - Kyle Worth, PTRC

Aquistore produces CO_2 from a coal field. Sampling is evaluated on an annual basis to reduce the frequency of monitoring. A comprehensive background data set is still being compiled. The isotope signature of the CO_2 that is injected into Aquistore is difficult to distinguish from CO_2 from the coal field.

InSAR, plus tilt meters have been used to see if there is any uplift but measurements have also been acquired to help support model and conformance predictions. Non isothermal geomechanical models of the site show that it is subsiding 3mm due to glacial rebound but this is not helpful in the context of public reassurance. Triggers of leakage include DAS seismic and pressure / temperature gauges down-hole. Shallow seismic surveys are also conducted for public reassurance. Improvements in subsurface imaging mean that smaller quantities of CO_2 (10 – 15kt) can be detected and tracked, that is ~1% of a 1Mt/year project.

Lacq pilot project, post-closure monitoring – Frederick Gal, BRGM

The Lacq site is now closed. There has been nearly three years of post-closure monitoring which is required by the regulator. Threshold levels were agreed between Total and the regulator at the start of the project and redefined by a third expert at the end of the injection period. One of the conditions stipulated that if threshold levels of CO_2 are exceeded then measurements have to be repeated. Post-closure measurements were taken once a year during the period of low biological activity in soils. Soil gas measurements have higher variability compared to the CO_2 flux. CO_2 isotope data needed to be interpreted along with soil gas data which pointed towards a near-surface origin. The threshold level definition can be debated as it may not adequately account for the annual variation of the CO_2 flux at this site or its concentration.

Seasonal and annual variations were evident form this site and the duration of the baseline acquisition was insufficient to account for all the natural variation. Isotope data were essential to conclude that there was no leakage. The local community was influential in setting up the monitoring programme at the Lacq.

Mountaineer Project, 5 Years of Data and Site Closure – Caitlin McNeil, Battelle

As this was a first of a kind CCS project, four ground water wells needed to be monitored. They were sampled quarterly pre-injection. Sensitivity analyses were used to try and pick up anomalies following injection. Hydrogen and Oxygen isotopes were used to characterise the groundwater and were compared with deep brine samples prior to injection. Cation and anion tracking alone can lead to false positive deductions.

The highest priority for the monitoring regime was meeting the permit conditions of non-endangerment requirements that included verification of the CO_2 plume's stabilization and protection of underground sources of drinking water (USDWs). Although the UIC (Underground Injection Control) permit included monitoring for groundwater no specific indicators were included in the UIC permit as formal reporting requirements for alerts. The secondary priority for this project was to determine potential causes and impacts. It was recognized that analytical results may be affected by surrounding environmental conditions which could be difficult to identify or isolate. An analytical programme was developed to establish baseline conditions but specific and quantitative analytical ranges to trigger investigation were not defined.

STEMM - Doug Connelly, NOC

In a marine environment it will be important to look for precursors and indicator tracers that indicate change caused by CO_2 or brine leakage. Shifts in chemical and physical conditions such as pock marks might be indicative of such changes but baseline conditions are not well understood especially in deeper parts of the North Sea. Pock marks may need to be characterised. Advances in AUV (Autonomous Underwater Vehicle) technology mean that Eh can be monitored and sophisticated image processing over time has the capability to detect changes such as the appearance or growth of bacterial mats that might indicate environmental change. Biological modelling is another tool which can be used to simulate leaks of variable dimensions. Spatial and temporal anomalies need to be identified but more background data is required. There is a need to proceed with some caution because of the lack of baseline understanding.

Session 8: Discussion

An operator needs to explain to a regulator the monitoring approach that will be taken and provide sufficient information about the site and monitoring programmes for the regulator to agree that the designated storage site is safe and what intervention protocols would be used if needed. There is an opportunity to educate regulators on the necessity to build more reliable threshold criteria that take account of natural environmental variability. Subtle changes could indicate that a leak is occurring but it may not be clear what a leakage signal might actually look like. Moreover, can this type of background detection be done within a regulatory framework. A community wide case history of leakage patterns would be helpful. Another approach is to use models to simulate different leakage scenarios. Natural phenomena can be difficult to understand especially with climate-change induced influences that are more gradual than indicative leakage patterns. There is some disagreement with regard to the effectiveness of control sites for showing long-term natural or climate-change induced change. Good site characterisation will help build confidence in risk assessment and develop strategies to identify anomalies that could be leaks. Outliers will still need further investigation. More consideration needs to be given to the development of protocols that define trigger points of when to take further action.

Another key question that needs to be addressed is the selection of the most appropriate technique to pick up an anomaly in terms of technically suitability, reliability and cost. Commercial decisions will lead ultimately to the formulation of the most cost-effective and reliable suite of monitoring techniques.

Session 9: "Portrait of an Anomaly" Group Exercise – Sue Hovorka / Katherine Romanak

This was a team exercise based on hypothetical scenarios to discuss and define monitoring strategies that could be deployed to attribute near-surface / deep leaks from a CO_2 reservoir.

Session 9: Discussion

This exercise involved all the delegates who were split into four separate groups, each was given a variation of a leakage scenario. Each group evaluated the potential for leakage to occur based on information which was supplied to them in increments. They were also asked to select the most appropriate monitoring techniques, taking account of their specific costs, to elucidate whether a leak was occurring and its origin. The following conclusions were drawn:

- Attribution of an anomaly (incident or allegation) is hard, prepare for it.
- Smarter monitoring design would help. For example, attention to groundwater system dynamics, discharge points; well in top of depleted gas field structure, details of reservoir heterogeneity.
- Smarter monitoring design does not mean more monitoring. Cost and effort should be optimised without sacrificing accuracy.
- Models of expected and unexpected material impact events (Assessment of Low Probability Material Impacts (ALPMI)) would be helpful, it is very hard to interpret data without a model.
- We think the leakage events shown are not really realistic - leakage to surface would be retarded more. Give more monitoring rounds to detect it.

The groups appreciated the complexities that can occur at storage sites, and enjoyed and learned from the group exercise.

Session 10: Monitoring - Modelling Loop: New Advances – NRAP *Discussion led by Rajesh Pawar (LANL)*

Modelling is used to predict what may happen in future based on the current state of knowledge. Models can be used to help design projects, make operational decisions, understand the impact of uncertainties and predict risks and help to minimize them. Monitoring is implemented to understand what is happening in the present. It can build on the current state of knowledge and is used to characterize and improve the knowledge of a site. Data acquisition helps to design projects, assess the impact of operational decisions and reduce uncertainties.

In oil and gas operations monitoring only needs to be conducted for the limited operational life of a field. For CO_2 storage long-term predictions are required and therefore confidence in long-term model projections are necessary. Consequently monitoring is required to improve the confidence in models. Strategic monitoring is also required to build models and therefore risk assessment ahead of injection. The monitoring – model loop has been successfully applied at Sleipner, Weyburn and Ketzin. However, experience shows that uncertainty still remains. The definition of a good match is when conformance is demonstrated. Adjustments need to be made to reservoir models post injection, and based on observed plume migration, because models do not adequately predict geological heterogeneities. CO_2 has low viscosity and preferentially migrates into high permeability areas and very thin layers.

Experience of monitoring at the Decatur project showed that there were limitations but the Stage II monitoring programme benefited from the experience gained in Stage I. At Ketzin seismic monitoring was not a good predictor of the permeability distribution. Predictions need to assume that storage capacity is based on P90 estimates to guarantee capacity and how extensive the plume will become as well as its limits. Good predictions are essential to avoid high risk areas and to ensure plumes stay in designated areas. Models are useful for forward projections but the monitoring – modelling loop highlights the influence of anisotropy. This could mean that monitoring regimes need to be modified to improve predictably. The edge of plumes can be thin and not detected by seismic. In oil fields it is not possible to measure the level of saturation. Seismic is only a qualitative technique. The approach adopted at Ketzin is regarded as good practice because the monitoring regime met the regulatory conformance and stability conditions.

Dealing with Legacy Wells, Subsea Leakage from Abandoned North Sea Gas Eells – Lisa Vielstaedte, Stanford University

Industry and government reported data on well integrity issues provide an uncertain estimate of 2-75% of all wells that could be compromised and potentially at risk of leakage. However, the focus of attention is mostly on active wells. GEOMAR has conducted the first CH_4 emission measurements at abandoned offshore wells in the Central North Sea and found that considerable amounts of biogenic CH_4 (i.e. δ13C < -70 ‰ VPDB and $C_1/\Sigma C_2+ > 2{,}300$) originates from shallow gas accumulations (<1,000 m sediment depth) in the overburden above deep reservoirs and is then released at boreholes. This type of leakage is neither considered by operators nor regulators, but could be just as important as leakage through damaged wells. In the North Sea, analysis of 3-D seismic data showed that one-third of the wells penetrate through shallow gas pockets and could possibly emit CH_4. GEOMAR hypothesise that extrapolation of these findings to a North Sea scale could equate to a large number of drilled wells (> 11,000) that could release between 3,000 - 17,000 tonnes of CH_4 per year into the North Sea. This could pose a significant contribution to the North Sea CH_4 budget. A substantial fraction of this gas (~40 %) may reach the atmosphere because most of the North Sea wells are located in shallow water depths.

GEOMAR'S findings have important implications for CCS as it implies that leakage from a CO_2 storage site in a depleted oil and gas reservoir could potentially occur along any type of legacy well if there is a poor seal above a CO_2 reservoir and if there is no remedial action. A CO_2 release experiment in the vicinity of the Sleipner CO_2 storage site has demonstrated that dissolved CO_2 is rapidly dispersed in the water column by tidal currents. GEOMAR has recommended that long-term monitoring, with high spatial resolution, is implemented in order to positively identify point-source CO_2 leaks through and along wells. The team have concluded that monitoring of well integrity by conventional testing of sustained casing pressure may be insufficient and remediation of gas migration along the outside of cased wells may prove difficult.

Is Your Well Flat or Carbonated? What Sustained Casing Pressure Testing and Beer have in Common for Monitoring Wellbore Integrity for CO_2 Storage Applications - Joel Sminchak, Battelle

Over one million wellbores have been drilled across the mid-west since the 1860s. With this number of legacy wells there are implications for CO_2 storage because of the potential for gas migration outside the casing. The objective of this study was to evaluate CO_2 wells for defects based on well records and sustained casing pressure testing. By adopting an integrated approach that combines analysis of well information with field monitoring and pressure testing it is possible to identify where remedial action is required.

In conclusion, Sustained Casing Pressure (SCP) Analysis has proven to be an effective low cost method to detect a variety of wellbore defects. A limited number of CO_2 wells tested for well defects did not appear to be in any worse condition than typical oil and gas wells. SCP testing/monitoring is an effective option for CO_2 storage sites with many legacy wells compared with more expensive well plugging or indirect monitoring.

Analysis of CO_2 Exposed Wells and Potential for Long Term Leakage - Andrew Duguid, Battelle

A monitoring well at the Cranfield SECARB Phase II Gulf Coast stacked storage site has been the subject of well integrity testing. This is an EOR field but the experiment focused on the down dip water leg. Heavily instrumented monitoring wells with intervals of fibre-glass casing were constructed in 2009 for the experiment. Control lines were installed outside the casing to transmit data on pressure and temperature and for Electrical Resistance Tomography (ERT). Class H cement containing silica flour was used for completion. This material can be affected by carbonation reactions if exposed to CO_2 that can lead to $CaCO_3$ leaching followed by precipitation. Although this can decrease the cement's permeability it can also reduce its structural strength. There was evidence from cement bond logs of a possible annulus in the cement around the control lines.

During the plug-and-abandonment procedure at the end of the experiment (7 years after well construction), well integrity testing was conducted for research purposes. Side-wall cores of the casing and cement above the reservoir zone at Cranfield showed evidence of carbonation. There was a slight decrease in solid material within the annulus cement. Reaction fronts observed in the side-wall cores showed that carbonation occurred at the interface of the cement and casing or formation. Tests also revealed that there was progressively less degradation above the CO_2 reservoir zone. This may suggest that CO_2 had migrated up the outside of the casing. During the discussion it was pointed out that other extensive isolation measures (e.g. time laps Reservoir Saturation Tool (RST) logging, cross well seismic, thermal surveillance, above-zone pressure monitoring, ground water and soil gas monitoring and extensive natural and introduced tracer programmes) did not detect vertical migration of CO_2 or brine at these wells, suggesting that migration was limited.

Key Points from Wellbore Integrity Workshop – Barry, Freifeld, LBNL

The objective of this workshop was to review the wellbore integrity of natural gas storage facilities in the light of the Aliso Canyon disaster. A leak began on October 23rd 2015. Eight top kill attempts caused erosion and expansion of the vent. Eventually the well was killed in February 2016 by using a relief well. A well integrity team was formed in April 2016 which included NETL. The team analysed the Aliso incident, evaluated broader well integrity risks and provided recommendations.

There are ~415 underground gas storage sites across the US which equates to ~17,500 wells. In addition to the Aliso Canyon failure there have been two other major incidents in the past 15 years: Yaggy, Hutcginson, Kansas, in 2001; and Moss Bluff in Liberty County, Texas in 2004. Record keeping for minor incidents do not appear to be collected or maintained. ~80% of wells are older than 1980 and ~15% of wells are older than 1921. It is not uncommon to see gas produced through casing without tubing or through both casing and tubing. Moreover, maintenance practices vary significantly from site to site. Following the workshop a series of recommendations were made. On well integrity:

- Operators should phase out wells with single-point-of-failure designs.
- Operators should undertake rigorous well evaluation programs.
- Well testing must be a top priority for lowering well integrity risk.
- Well integrity testing should use a tiered approach.
- Well integrity testing should use multiple methods.
- Storage operators should deploy continuous monitoring systems.

In addition the team, recommended that operators should institute a standardised records systems, risk management transition plans and account for a broad range of risk factors. Research and data gathering should also be implemented to evaluate the effectiveness of casing tools, wellbore simulations, and the proximity of gas wells to centres of population. Monitoring activities should include continuous pressure monitoring, infrared thermal imaging for leak detection and enhanced training.

Session 11: Discussion

Carbonation mostly occurred above the reservoir at Cranfield, however the rate and volume of alteration to the cement within the annulus is unknown. Other measurements at Cranfield, for example pressure measurements, did not indicate movement of CO_2 out of the reservoir. Geomechanical stress on the casing will also affect its integrity. The evidence of stress on the casing at this site needs to be considered because it could have influenced its durability.

The ability to constrain CO_2, and its potential to migrate through the annulus of wells, needs to be ascertained. There is no evidence here of measurable quantities of CO_2 reaching the surface. It should also be stressed that the risk of installing a control line at this site was taken because this is an experimental field site. This action has benefited from the acquisition of large quantities of useful down-hole data. Control line installation would not necessarily apply elsewhere. Industry experience shows that over 40 years of casing log inspection suggests the extent of cementation will prevent significant fluid migration up an annulus.

Session 12: Induced Seismicity / Microseismic Monitoring — Chair: Neeraj Gupta

Microseismicity Signals in Northern Michigan Reef Reservoirs – Mark Kelley, Battelle

The objective of this research was to monitor microseismic activity while injecting CO_2 into a closed carbonate reef reservoir that is close to discovery pressure. The results were then compared to a baseline microseismic study that was conducted at a low reservoir pressure of 800 psi. Finally the research set out to determine if there was an increased likelihood of microseismic activity at end of the planned injection when pressures would be higher.

During a 21 day injection period, with a 200 – 300 t/day injection rate, three different types of event were manually picked. Type 1 were well work events; Type 2 were near well events; and Type 3 were long duration events. P waves arrive first but have less intensity compared with S waves. With sensitive geophones the origin of events can be detected. Analysis of the microseismicty, and wave forms, has led to the conclusion that Type 3 events may be related to fluid movement or noise. There appear to be no microseismic events from CO_2 injection induced fracturing or fault activation. More work is needed to understand Type 3 events.

Tomakomai Experience - Hideo Saito, Japan CCS

CO_2 injection began at the Tomakomai site in Japan in April 2016. Seismic monitoring was started 14 months before the beginning of the injection phase and is ongoing at present. The seismic observation network is focused around a narrow scope, for microseismic imaging, plus a wider scope for monitoring for low magnitude natural earthquakes. The site is located in a naturally seismically active area associated with the subducting Pacific plate, where earthquake foci are often at 100km or deeper. In addition to the monitoring network, designed by Japan CCS Company Ltd, data was sourced from local seismometer stations where regional data is publically available. Monitoring results are open to the public.

The results of the baseline survey showed very low rates of microseismicity in the vicinity of injection points. To date, no significant induced micro-earthquakes have been detected in the area of interest. Interpretation of induced seismicity, if it occurs, will be a future task.

Time-Dependent Monitoring of CO_2 Plume Expansion by Combining Active and Passive Seismic Data – Volker Oye, NORSAR

At In Sahal and Decatur microseismicity has been observed during injection. 5,000 events related to injection were observed at In Sahal. The pattern of microseismicty is valuable if combined with pressure and injection rate data. As the flow rate and pressure increased microseismicty could be linked to a fracture opening. With an improved network better results could have been achieved.

Observations at IBDP in Decatur indicated that microseismicity occurred naturally before any injection occurred. Events related to large-scale CO_2 injection occur in clusters along pre-existing fractures. Analysis of shear wave splitting revealed different amounts of anisotropy. The anisotropy is associated with sedimentary stratification and basement rock foliations. High relative depth resolution using waveform cross-correlation has been achieved, which reveals seismicity migration patterns from sediment into the basement. Shear-wave splitting analysis might reveal the state of stress and change of stress due to injection.

Session 12: Discussion

Decatur could be critically stressed pre CO_2 injection. The amount of CO_2 that can be injected into the basal sandstone might be constrained because of the stress induced on the basement and the associated microseismicity. If the basement is difficult to image this does not necessarily mean that the amount of CO_2 that can be injected into a basal sandstone is limited. Evidence from shallower injections during the next phase at Decatur may show that the basement is not perturbed. There is a mudstone layer beneath the second injection zone which may act as a buffer shielding the effects of the injected CO_2 from the basement. Experience from other sites shows that in general with increasing volumes of injected CO_2 there is a tendency to detect larger events although this trend is not always observed. The pattern of events associated with the second phase of injection at Decatur could provide some interesting new data. In Ohio regulations restrict injection into the basal sandstone which could limit the amount of CO_2 that can be injected.

There is a need to have a good understanding of microseiemicity. Public engagement is important to reassure communities and therefore seismicity has to be monitored. Events with magnitudes of greater than 2 should be avoided. It is also important to recognise that microseismicty does not necessarily occur everywhere. In Oklahoma modifications to waste water disposal practices has reduced induced seismicity. The identification of faults and their stress condition is necessary for site characterisation for onshore sites. It is therefore recommended that regional stress maps in areas of interest should be improved.

Conclusions and Recommendations — *Chairs: Neeraj Gupta, Charles Jenkins, Tim Dixon*

Conclusions and Key Messages

- Commercial-scale projects are now able to evaluate and implement reductions in complexity of monitoring.
- The monitoring strategy applied at recent commercial scale projects (Petra Nova, IL-ICCS, Quest) has built on knowledge transfer and expertise gained from early projects (SECARD, IBDP) especially the selective deployment of different monitoring techniques.
- There is a trend towards right-sizing the number, type, and timing of technologies deployed at commercial-scale projects. For example, the 'tiered and phased monitoring, measurement and verification (MMV) strategy' approach at Quest, that has been approved by the regulator. This approach reduces monitoring and its associated costs. Technology maturation and a more simplified monitoring programme has not had a negative impact on project success.
- DAS technology and permanent seismic sources, plus other permanent receivers, have led to several beneficial advances including lower cost, decreased surface impact, and increased subsurface resolution. Surface seismic gives better quality images but is more expensive compared with DAS.
- Stakeholders may have an input into MMV technology choice (does this relate to regulatory requirements and in what context?)
- There is clear progress towards the adoption of more derived, quantitative and targeted environmental monitoring both onshore and offshore.
- Environmental monitoring is useful for characterisation and to determine well defined performance metrics instead of simple baseline thresholds.
- There is a convergence towards more nuanced evaluation of methods, detection performance and probabilistic leakage detection plus the identification of false positives.
- The use of lower cost monitoring can be effective to define where and when more expensive monitoring is required to verify the presence of CO_2, for example, conducting 2-D seismic before 3-D.
- DAS VSP can be a more cost-effective monitoring technique under certain scenarios compared with surface seismic even with lower resolution images. DAS helps facilitate permanent monitoring.
- Some improvements in DAS can be achieved with pre-installed optical fibre (cemented in well or placed in trenches). The overall DAS technology is improving at a fast pace, for example, DAS – helical wound cable improvements are moving DAS into surface horizontal seismic configurations.
- Determining the exact position of a plume edge is not necessarily crucial. The level of monitoring required depends on risk and the complexity of reservoir conditions. A series of several simulations can be used to generate probability contours of a plume's aerial extent and boundary.
- There has been substantial progress in monitoring technologies over the last decade. For example advances in microseismic monitoring have provided greater insights into geomechanical processes during and post-injection.

Offshore

- There has been a rapid development of sensors and commercial delivery platforms. The technology readiness level (TRL) is higher than expected on many sensors (6-8).
- Sensor calibration and comparisons are now possible.
- Data processing advancements (data hub, data pods, automated image filtering) can now be applied minimizing multiple image acquisition and enabling the selection of the most relevant observations.
- Cost-reduction can now be achieved using shore-to-shore AUVs without the need for ships.
- AUV subsurface development has benefited from leveraging oil and gas industry and defense experience.
- Experience from the Tomakomai project has demonstrated that care is needed when applied to thresholds derived from baseline data.
- Marine environmental transport mechanisms differ to onshore processes (diffusion is far faster in the atmosphere than in a water column).
- Some progress has been made with chimney characterisation with implications for fluid migration in the subsurface down to depths of 1-2km.
- Technology advancement in compact AUV design, and related mobile sensor systems, could lead to a global response system and portable laboratory facilities.
- Microseismic monitoring is important for regulatory requirements and for stakeholder assurance but it can increase characterisation costs.
- Well integrity continues to be very important with the potential for low level leakage.
- Properly designed, monitored and operated wells can reduce risk.
- Monitoring at CO_2 storage sites has demonstrated that small amounts of CO_2 can be detected at depth with seismic, for example Otway, Aquistore, Frio.

Future Work Recommended

- Deployability and durability of DAS optic fibre needs to be further evaluated.
- Improvements in utilisation of DAS data.
- Improved cementation of fibre cable within an annulus and lower-risk ways of running fibre.
- Better marine baseline methods for global use are required. A stoichiometric approach may lead to improvements.
- AUV sea trials and CO_2 release tests to verify instrument sensitivity under different conditions is necessary.
- Continuous monitoring ability would be advantageous.
- Chimney investigations to improve the understanding of their formation and fluid content.
- Improve environmental understanding and the reasons for natural variability.
- Learn more on use and effectiveness of tracers.
- Produce a standardised suite of leakage cases.
- Improve reconciliation between models with monitoring data (conformance). The approach needs to be risk based.
- Geomechanical site characterisation is required to improve the ability to predict stress conditions across faults and fractures.
- Selective data acquisition and retention for later processing.
- Review and gather more data on abandoned well leakage and gas migration issues along wells.

Future Work Recommended

- CO_2 well-control technology and procedures, along with modelling of well blowouts and well-kill approaches, needs to be improved. The existing knowledge and experience gained from CO_2 injection wells needs to be expanded. Training and demonstration of well incident management is required.
- More case studies on what conformance looks like in practice would be beneficial.
- More effort to reduce uncertainly about how to handle ALPMIs (Assessment of Low Probability Material Impacts).
- More work on models of dissolution processes.
- Conformance parameters need to be established in advance of a project. Evidence from demonstration projects that have ceased injection, or are in a post-injection monitoring phase, can help define practical metrics.

High-Level Messages

- Good progress is being made with learning from industrial demonstration and research pilots.
- Progress in reducing costs and streamlining MMV programmes at large-scale projects.
- Further progress is needed to develop well interventions for CO_2 wells, which includes modelling well blowout conditions and well-kill procedures.

Steering Committee

Tim Dixon, IEAGHG (Chair)

James Craig, IEAGHG (Co-chair)

Neeraj Gupta, Battelle (Host)

Caitlin McNeil, Battelle (Host)

Bob Mannes, Core Energy

Rick Pardini, Core Energy

Andy Chadwick, BGS

Charles Jenkins, CSIRO

Katherine Romanak, BEG at the University of Texas at Austin

Tom Daley, LBNL

Tracy Rodosta, NETL US DOE

Sue Hovorka, BEG at the University of Texas at Austin

Jun Kita, MERI

Frederick Gal, BRGM

Lydia Rycroft, IEAGHG

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

Pure Offices, Cheltenham Office Park, Hatherley Lane,
Cheltenham, Glos. GL51 6SH, UK

Tel: +44 1242 802911

mail@ieaghg.org
www.ieaghg.org