ieaghgmonitoring networkmeeting

10th - 12th June 2015

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Front & back cover images: The University of California Botanical Gardens / Attendees of the meeting / LBNL's Advanced Light Source / View over the city of Berkeley looking toward San Francisco

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Attendees of the Meeting / Lively discussion on CO_2 storage during filed trip break

Introduction to the IEAGHG Monitoring Network Meeting 2015

We were very pleased to hold our 10th Monitoring Network meeting at Lawrence Berkeley National Laboratory in California on 10th - 12th June. The venue provided great views over San Francisco bay area, which complemented the technical programme of presentations and discussions inside.

The 45 presentations and 17 posters covered a range of topics, with sessions on cost-effective monitoring of large projects, permit requirements, induced seismicity, shallow monitoring, geophysical monitoring and CO_2 relationships, pressure monitoring applications, monitoring tools for shallow, surface and deep monitoring, update on projects, and post-closure monitoring. As well as the new results and developments, new at this meeting was a group-work exercise created by Sue Hovorka of the University of Texas. This involved the groups designing monitoring plans for fictional but realistic storage sites, and then these being actually tested with leakage scenarios. The groups were able to apply what they had learnt in the meeting as well as their own expertise, and I'm pleased to say that all the monitoring plans 'caught' the various leakage scenarios!

Also of particular note were the international research collaborations being created around the Aquistore storage site in Saskatchewan and around the CMC controlled release in overburden being developed in Alberta. The Aquistore project has just started injecting CO_2 captured from the Boundary Dam coal power station into a deep saline formation, some 7,000 tonnes injected so far. PTRC has monitoring research collaborations with 26 organisations from 7 countries at this 'field laboratory', and the first monitoring data was shared at this meeting from downhole pressure, seismic, and pulsed-neutron logging measurements.

The overall conclusions of the meeting included identifying the value of pressure based monitoring for assessing reservoir behaviour and in the overburden for leak detection, the potential in fibre-optic distributed acoustic sensing (DAS) and permanent sources, the benefits of good engagement with regulators, the importance of geomechanical analysis using the monitoring data, and the feasibility of offshore monitoring for leak detection and quantification.

Overall, a meeting packed with new developments in all aspects of monitoring CO_2 storage, shared and discussed by this group of leading international experts. Monitoring continues to make great advances.

Session 1: Welcome

Welcome from LBNL Associate Laboratory Director Horst Simon, Tom Daley and Tim Dixon, IEAGHG

This 10th Monitoring Network meeting was opened by an introduction from Associate Laboratory Director Horst Simon who emphasised the importance of Lawrence Berkeley National Laboratory's (LBNL) research into fundamental problems including Green House Gas (GHG) control. The facility is engaged in the development of a number of low carbon technologies including artificial photosynthesis to produce biofuels, energy efficiency programmes and CO_2 storage.

LBNL was founded by Earnest Lawrence in 1931 and moved to the present site, overlooking San Francisco Bay, in 1940. It now has an annual budget of $US820M and has defined core capabilities in subsurface science, climate change science and biological systems science.

Tim Dixon from IEAGHG stressed the importance of CCS in stablising CO_2 emissions. This is evident from the recent IPCC 5th assessment report, published in November 2014, which has concluded that without CCS costs of CO_2 mitigation could increase by 138%. The inclusion of CCS in modelled scenarios will be a key technology required to stablise CO_2 at 450ppm and limit average global temperatures to 2°C.

Session 2: Monitoring for Large-Scale Industrial Projects – How are Large-Scale Projects Monitored Cost-Effectively and How is Sufficient Sensitivity Achieved?

Chair: Curt Oldenburg

Integration of Dynamic Multi-Sensor Surveillance during an injection program at Lost Hills California. Paul Harness – Chevron

The Lost Hills injection programme is a pilot project where an integrated surveillance programme was designed to capture uncertainty and provide a basis for alternative production strategies. The objective of this approach was to reduce uncertainties related to induced treatment, variation in production flow and the range of well production. The surveillance included three microseismic monitoring wells plus one horizontal well with a fibre optic temperature sensor. Other wells had pressure monitors. The sensor configuration was established so that microseismic events could be detected with a resolution of a few feet (~1 meter) via triangulation. InSAR, GPS and tilt meters were also deployed. Observation data from the field was then transmitted to a distant location for interpretation. This combination of parameter monitors provided temporal data flow at frequencies of a few seconds to daily and monthly periods. Integration of different data streams was essential to interpret how the reservoir behaved. Understanding flow patterns, pressure variation and other parameters is important to control production which is also governed by the necessity to inject and produce from specific horizons and maintain wellbore integrity.

Experience of data integration and interpretation has revealed how the Lost Hills reservoir responses can be linked. A good example is the association between microseismicity and injection cycles. Microseismic events can be linked to a single well cluster around fractures in the reservoir. Another example is the use of subsurface pressure monitoring to optimise the production rate. Pump performance can be used to monitor pressure in reservoir. Reservoir pressures can also be inferred from sensitive monitoring using surface deformation with InSAR. The technique revealed a lack of pressure difference across this reservoir which enable operators to alter the pressure regime. Variation in tilt meter data from several monitoring points also allowed operators to visualise variations specifically fluid movement across the reservoir.

The overall conclusion is that subtle monitoring of different reservoir parameters can be integrated to reveal temporal and spatial variations that can be used to modify and optimise production.

Peterhead – Goldeneye Project. Owain Tucker, Shell

The Peterhead – Goldeneye project will capture 90% of the CO_2 from a 300MW gas turbine. The CO_2 will then be injected into the Captain aquifer which is a turbidite sandstone with a darcy level of permeability. The monitoring programme has been designed to show containment and conformance. A Bowtie method of risk assessment has been developed to identify potential migration routes, barriers and mitigation measures for each risk.

Linked bowtie assessments have been developed for different risks. For example releases from wellbores into undesignated formations. A control philosophy can then be applied to identify scenarios of where CO_2 might migrate to. The monitoring programme is then designed to detect the presence of CO_2 and the mitigation measures that might be applied. Monitoring techniques would then be selected on the basis of cost-benefit. For example, seismic is selected to monitor for potential reservoir fluid movement below the original water contact because it provides the best spatial and temporal resolution. There is a mix of residual gas, CO_2 and water, however the use of seismic clearly shows the temporal movement of CO_2. 3D Vertical Seismic Profiles (VSP) might be able to show CO_2 movement in a reservoir but this approach is unproven. New technologies are being investigated, but the application of any technology needs to satisfy regulators and therefore needs to be proven and established technology. Distributed Acoustic Sensing (DAS) fibres have the ability to record 3D VSPs. If the technique works then it could be a more cost-effective method for tracking CO_2 in reservoirs.

The seismic risk from an event 100km offshore is minimal. Sensitive onshore monitors at this distance would only detect an event at Magnitude 4 or above.

In conclusion this monitoring programme is designed around a thorough and integrated bowtie risk assessment methodology that identifies potential risks, barriers to migration out of the designated reservoir and mitigation measures. Seismic provides the most cost-effective measure for tracking CO_2 movement and VSP could be highly effective once fully tested and proven.

Developing Monitoring Programmes for Large-Scale Projects: the Experience from CO_2-EOR, Sue Hovorka – BEG

This is generic summary of three US DOE funded projects to monitor CO_2-EOR operations. At present there is no qualified plan for monitoring storage related to CO_2-EOR. The challenge for these projects is that operators are only interested in the most efficient sweep and do not want any oversite or reporting of CO_2 retention. The potential benefit for CO_2-EOR operators is the increase in the supply of CO_2 from anthropogenic sources. Effective demonstration will also help to convey the positive benefits to the wider public. Existing hydrocarbon reservoirs also have provable seals and have good reservoir characterisation.

EOR floods can be controlled by the operator. Moreover, 40 years of experience in a commercial environment shows that CO_2-EOR is highly effective. Operators claim that they have good knowledge of well status and pressure gauges are an effective means of monitoring conditions. CO_2-EOR can lead to CO_2 moving to wells in an adjacent operation. This condition can be controlled by a water curtain. However, it could be assumed that at the end of the project, ending the water curtain will lead to CO_2 migration forming a stable configuration. More evidence about the technique would help to establish its effectiveness.

There are important issues to consider about the end of the project. The pattern of CO_2 migration is different from hydrocarbon migration and its distribution within a reservoir will also be more rapid because of its miscibility properties and its viscosity. No CO_2-EOR operations have been stopped, so there is no experience with a project end. In US oilfield operations, there is no transfer of liability post-project end. Quaternary[1] recovery might also become an issue.

Commercial CO_2-EOR operations can be a highly effective means of storing CO_2 and developing a supply chain from anthropogenic sources. Commercial operators are understandably reticent to release technical data or report CO_2 retention. Post-closure status is also a potentially contentious issue but CO_2-EOR could offer a route to the expansion of CCS.

Discussion – Session 2

The development of CO_2 storage from commercial CO_2-EOR operations is currently constrained because of commercial confidentiality. Operators guard their expertise in conducting CO_2 floods and dislike releasing detailed information on well status. They are also reluctant to discuss operational difficulties. Reporting could be designed to demonstrate an inventory of retained CO_2.

Monitoring programmes can be rationally planned to be cost-effective. For example, a monitoring plan based on risk assessment should be able to identify where risks are most likely to occur and the most effective remediation. Monitoring every wellbore may not be practical but pressure monitoring may be an effective means of detecting an anomaly. In Salah is a good example where an increase in pressure caused microseismicity which, combined with other factors, led to the cessation of injection. Remedial action has also been effectively demonstrated by seismic and pressure monitoring in the Snøhvit field. Injection has been switched to another stratigraphically higher formation.

The development of monitoring programmes begins with a conceptual model to build risk scenarios. No single monitoring system will provide a complete picture. Multiple systems with integrated data analysis will provide a more detailed appraisal of reservoir behaviour. The monitoring programme can then be designed to address risks. It may also lead to the development of new technology if there is a gap in capability. Distributed Acoustic Sensing (DAS) is a good example.

Microseismic events are related to natural fractures. The technique, in combination with wellbore logs, can detect linearity and the pattern, position and size of fractures. Very low detection levels (-3ms) are now possible from sensors in vertical wells and give a much better resolution compared with surface monitoring. Microseismic monitoring can also provide an indication of a well's production performance.

[1] The term Quaternary Recovery is used to refer to more advanced, speculative, EOR techniques

Session 3: Permit Requirements Under the Three Objectives of Conformance, Containment and Contingency

Chair: Tim Dixon

Act on Prevention of Marine Pollution and Maritime Disaster for offshore CO_2 storage in Japan, Jun Kita – RITE

Tomakomai is one of two Japanese CCS demonstration projects. Injection will begin in 2016 and continue until 2018. 100,000t per year will be injected into a subsea reservoir off the coast of this Japanese city. The regulation of CO_2 storage in Japan is covered by the Act for the Prevention of Marine Pollution and Maritime Disasters which was amended in May 2007 to permit CO_2 storage in offshore formations. The act requires consent from the environment minister and the implementation of an Environmental Impact Assessment (EIA). The EIA must include an assessment of the potential dispersion of CO_2 from a leak. The act also specifies three key compliance criteria conformance, containment and contingency.

The Act stipulates that a three tiered monitoring plan must be implemented depending on the severity of changes that could occur following CO_2 storage:

- Normal time monitoring i.e. no indication of leakage
- Suspicious time monitoring i.e. possible leakage
- Abnormal time monitoring i.e. leakage has taken place. The location of the leakage needs to be determined and its impact.

In conclusion the regulation of CO_2 storage in Japan is covered by the Act for the Prevention of Marine Pollution and Maritime Disasters. The act requires adherence to conformance, containment and contingency criteria. This regulation is already developed. The operator, the Japan CCS Co Ltd, is now in the processes of applying for the permit.

Monitoring Programmes in the ROAD Project, Philippe Steeghs – TNO

The ROAD CCS project was the first to receive a permit under the EU storage directive. The CO_2 will be sourced from a 250MW power plant post-combustion capture unit located on the Maasvlakte near Rotterdam. The scheme will supply a planned 1.1Mt CO_2 / year via a 25km offshore pipeline before injection into a depleted compartment of the P18 gas field.

The monitoring plan has been formulated on the EU storage directive which is focussed on safety and integrity. The project is technically relatively simple in comparison to other CO_2 storage projects, with a single well penetrating the reservoir and minimal equipment installed on the offshore platform. In spite of this thorough approach to monitoring will be adopted. As new techniques and equipment are developed, these will be included whenever judged appropriate provided that these techniques do not add to the complexity or cause significant interference with other operations. Hydrocarbons will continue to be produced from neighbouring compartments throughout much of the project timeline.

The monitoring and contingency plans are part of a set of related plans that are part of the storage permit. A site specific risk assessment is the main input for the corrective measures and closure plans. The development of the monitoring plan is also based on a site specific risk assessment and has strong links with the corrective measures plan. Its status as a demonstration project requires the reporting of operational and technical information. Commercially the project also needs to satisfy ETS. The current monitoring plan will be updated before injection starts.

The monitoring plan is based on a site-specific risk assessment of the storage site. Reservoir integrity is a key consideration. The P18 field is subdivided into four distinct reservoir compartments. The planned storage location is the P18-4 compartment. The sealing capacity of bounding fault (P18-4/P15-9) has been studied extensively but remains an uncertainty to a certain level. There is a storage permit for the two compartments on either side of the fault. One of the permit conditions is an assessment of potential movement across this fault which separates these two compartments. Migration across the fault would be detected by a pressure gauges in the reservoirs.

A traffic light approach has been developed in anticipation of a potential escalation from a predicted condition where data fall within a specified range (green), to irregularity in expected data (yellow), to a condition where observed data are outside the expected range and a scale-up in monitoring intensity and model refinement is required (red).

Across this location the storage reservoir seismic response is not expected to show much detail therefore pressure monitoring is the most important form of monitoring activity. However, it is foreseen that a baseline seismic survey will be conducted for shallow sediments in the overburden, with additional seismic surveys as an option in the contingency monitoring plan. Regular well integrity and monitoring is also planned. A series of corrective measures are planned in case there are indications that there may be movement of CO_2 outside the designated reservoirs.

Throughout the process of developing the documents for the storage permit application, there has been frequent contact with the competent authorities. This has helped the operator and authorities to develop an understanding of the risks associated with storing CO_2 in P18-4. Moreover, frequent meetings have helped both parties to address all the issues covered in the EU Storage Directive and the level of detail required. The application for storing CO_2 in P18-4 was the first to be undertaken in The Netherlands, and the frequent contacts during the permit application preparation period helped shape the process for both operator and authority and provided clarification for elements of the Directive that are left open-ended.

Monitoring of Decatur project, ADM CCS Projects UIC Class VI Permitting Experience, Scott McDonald – ADM / Randy Locke ISGS

The Illinois Basin Decatur Project (IBDP) is a large scale >1MtCO2 /year CO_2 storage project into the Mt Simon Sandstone deep saline aquifer (DSA) in central Illinois. The second stage of this project has a permit to inject 5.5Mt over five years. The CO_2 is sourced from a bioethanol plant at 99% purity. The DSA has a shale cap rock plus secondary and tertiary seals. There is another sandstone formation, the St Peter Sandstone above the primary seal (Eau Claire Shale), which is classified as an underground source of drinking water (USWD), although only shallow aquifers above this formation are used as sources of drinking water. The St Peter Sandstone has to be monitored because of its USWD status.

Injection at Decatur (first stage) was permitted in 2011 under Class I after initial application in 2008. The permit application process for post closure monitoring began in 2011 and final approval was given in December 2014. Concern was raised over the 50 year post-injection site care (PISC). Consequently, the site operator, ADM, proposed a 10 year timeframe based on evidence of a decline in reservoir pressure, plume stabilisation and CO_2 partitioning. The monitoring programme was designed to meet the requirements of a 10 year PISC. After 10 years the site operator must be able to demonstrate non endangerment and conformance of recorded data with predictive models particularly pressure. The model will then become the proxy for demonstrating stabilisation and containment of CO_2. The analysis showed that if the plume did not stabilize and continued to expand 1% per year, it would take ~600 years for the plume to reach a nearest penetration of the seal formation 17 miles (27.4km) from the injection point. Two 3D time-lapse seismic surveys are planned to compare with previous baseline surveys, however reservoir heterogeneity means that pattern of the CO_2 plume does not form a clear image.

Experience from the Class I application shows that proactive engagement with regulators and technical collaboration with them proved beneficial. The US Environment Protection Agency (USEPA) focused on technical, risk-based permit decisions that often required additional information. Discussing models in detail and the use of published examples in support of permit applications helped. Regulations will drive primary monitoring activities but other environmental baseline monitoring may be necessary to reduce risk regardless of regulatory requirements.

Discussion - Session 3

Monitoring requirements for CO_2 storage sites is partially driven by regulation. In the USA and Canada protection of fresh water aquifers is a key priority therefore the area of elevated pressure where brine or other potential contamination could be lifted is highly relevant. Modelling shows that this is unlikely to occur. For offshore storage the CO_2 footprint is still important but brine movement is less significant as there are no fresh water aquifers.

Models are an essential tool for predicting future conditions but they can also be used to project extreme scenarios that show the limits of conditions that might occur.

Pressure monitoring is an effective technique for detecting CO_2 leakage, but it may require other techniques, or several monitoring points, to detect a leakage pathway or a CO_2 accumulation. The monitoring frequency also needs to be decided to determine the detection threshold of CO_2 and its migration path. The EU storage directive says detection must be at any level. In the US regulators base their judgement on whether models are compliant with monitored data.

Regulators could drive the permit process based on existing frameworks but it is also possible that existing frameworks are formulated by the interaction between themselves and operators. Experience in the USA, Europe and Japan is revealing a pattern of regulators relying on interaction with operators. Project planning by operators is meeting generic requirements which in turn is helping to educating regulators.

Session 4: Induced Seismicity: How Can We Devise a Monitoring Strategy for Safe Operation? Chair: Jun Kita

Strategy for Monitoring Large Regions of Fluid Injection Induced Seismicity: Oklahoma's Experience, Austin Holland - Oklahoma Geological Survey

Across the state of Oklahoma there are about 4,000 saline waste disposal wells operated by over 100 companies over an area of 25,000km2 (~9,653 miles^2). Saline disposal is governed by Underground Injection Control (UIC) Class II temporal and spatial waste water disposal regulations. Since 2008 there has been a dramatic rise in Magnitude 3 and Magnitude 4 (M4) earthquakes. Despite the state wide network of seismic stations regional uncertainties mean that quake foci could only be tracked to within ~8km. With a rise in seismicity in certain areas the regional network was augmented with a higher density of stations which led to an improvement in quake foci to within ~1.5km.

Oklahoma Geological Survey implemented a more proactive and responsive surveillance programme by increasing the coverage of stations particularly in areas of concern. This higher density of temporary monitoring stations is mostly within a central belt of the state. This initiative has led to a rapid increase in the detection threshold. Disposal wells with the highest volume of injected saline coincide with highest concentration of quakes. The Arbuckle group of dolomitic limestones, is the predominant recipient of injected saline. This formation directly overlies basement where seismicity occurs.

The rise in seismicity associated with saline disposal has led to a change in requirements for monitoring. Previously there was an eight month lag between injection and reporting of disposal operations represented as monthly averages. In 2014 the new regulations demanded daily records of injection rate, volumes and pressures to improve data granularity. Weekly reporting for Arbuckle group and non-Arbuckle group wells is also required in specified areas of interest. The proximity of two recent M4 earthquakes was within 20km of a seismic station which has improved the data quality associated with them. The increase in the density of monitoring stations has also improved the location accuracy of quakes. Ground acceleration and ground motion data is archived and is publically available.

Induced Seismicity Protocols used in Geothermal Energy Development. Protocol and Best Practice for addressing IS associated with EGS, Ivan Wong – AECOM

Induced seismicity is not a new phenomenon and is associated with several industries including mining, oil and gas, wastewater disposal as well as geothermal. Hydraulic fracturing is used in enhanced geothermal systems (EGS) to open and track fractures patterns and associated fluid flow. Some EGS projects have caused felt events to occur, for example the M3.4 in the Swiss city of Basel. Although there was no structural damage the project was closed. The US Department of Energy (DOE) has developed a protocol to address public concerns and an advisory document which identifies important issues and provides possible mitigation measures.

The Geysers field in northern California is the largest conventional geothermal field in the world. To boost energy output some EGS hydraulic stimulation has been recently applied. Seismicity is commonplace and affects two communities about 5km from the seismic activity. To date, more than 30 M4 and larger events have occurred since 1972 with the largest earthquake being a M4.7. An outreach programme has been implemented to communicate issues related to induced seismicity. Experience has shown that operators should be proactive and need to identify local stakeholders and be aware of the impact of potential induced seismicity. Risk-based mitigation plans also need to be developed. Local conditions at each site will call for different types of action. The protocol developed by DOE is a seven step process beginning with a screening evaluation which includes a preliminary risk assessment of the probability of structural damage or other adverse effects such as landslides. The next step is to develop an outreach and communication programme. Experience of geothermal energy development in the US to date shows that there have been no instances of significant damage. The next step is to set up seismic monitoring and quantify the baseline hazard from natural seismicity. The next stage is to characterize the risks in terms of physical damage to buildings and infrastructure, interference with human activities and socio-economic impacts. The final stage is to develop risk-based mitigation plans.

In summary this is a good example of an initiative to deal with the effects of induced seismicity through the development of a flexible protocol and best practice guidance.

Seismic Monitoring in the Tomakomai Project. Daiji Tanase - Japan CCS Company

The Tomakomai CCS project will capture CO_2 from off gas of a hydrogen production unit of an oil refinery located near the port of Tomakomai on the Japanese island of Hokkaido. Two injection wells have been drilled onshore near the oil refinery and deviated to two different offshore reservoirs. The highest reservoir is a sandstone formation (Moebetsu) at a depth of 1.1 – 1.2km. The lowest is in the volcanic Takinoue Formation at a depth of 2.2 – 2.8km.

A 3.6 km long Ocean Bottom Cable (OBC) with 72 seismometers and four Ocean Bottom Seismometers (OBS) have been deployed above and surrounding the injection site plus three observation wells and one onshore seismometer. The onshore seismometer complements the blank area of the national Hi-net (High Sensitivity Seismograph Network of Japan) stations to provide a record of baseline natural seismicity of the Tomakomai region. Three observation wells have pressure / temperature sensors and seismic sensors. Baseline 2D and 3D seismic surveys have been completed and will also be conducted to track the progress and distribution of CO_2. Injection begins in April 2016.

Japan is prone to natural seismicity consequently understanding the magnitude and location of seismic events is especially important. In the Tomakomai region an earthquake of M4.4, with an epicentre 17km from the injection site, was observed in January 2015 at a depth of 29.9km. A month later a M1.5 event was detected 14km from the injection site at a depth of 24.1km. More recently, in May 2015, a <M-2 event was observed in the project area at a depth of 5.45km, which is an example of frequent natural microseismicity.

Induced Seismicity linked to Fracture Zones in the In Salah Field. Bettina Goertz-Allmann – NORSAR

Induced seismicity has been monitored and interpreted at the In Salah field and used to delineate subsurface fractures. At In Salah 4Mt CO_2 has been injected into a naturally fractured sandstone reservoir. 5,000 microseismic events were recorded between August 2009 and June 2011. Because of a technical fault only the uppermost geophone at 80m depth provided reliable data for detailed analysis. With only 1 geophone it is not possible to accurately locate events. However, several clusters with similar arrival-times can be differentiated. The differential S-P onset times give an estimate of event-to-receiver distance. The event direction can be inferred from the particle motion of P-waves. By combining S-P, azimuth, and inclination, four different clusters can be separated.

The b-value[2] of S and P wave magnitudes allows extrapolation from observed small events to expected larger events. The b-value can also be linked to the in-situ reservoir stress state. There are significant variations in b-values between different clusters. High b-values (1.5 – 2) observed in three clusters suggest opening of new fractures whereas a lower b-value (~1.0) observed at the most distant cluster may be related to pre-existing fractures.

Shear wave splitting has also provided useful information. Three clusters have anisotropy of up to 5%. In contrast one cluster has an anisotropy value of <2%. This analysis has been used to aid a geomechanical appraisal of the reservoir particularly by comparing different event clusters with injection history. The most distant cluster showed no correlation with injection data in contrast to the other three. One cluster in particular showed a high degree of activity but only during the main injection phase.

[2] (slope of the Gutenberg–Richter law describing the relative size distribution)

Detailed analysis of microseismicity and comparison with injection history allows differentiation between two distinct event classes. Class I events are furthest away from the injection point and may be located about 150m above the reservoir formation top in the lower caprock. They are not directly correlated to injection history. Their b-value (~1) indicates seismicity on pre-existing faults. Class II events are highly correlated to the injection history. Higher b-values of 1.5 to 2 are observed, indicating new fracture opening. Strong anisotropy is also observed.

Discussion – Session 4

The theme for this discussion session was how to devise a monitoring strategy for induced seismicity. Each contributor put forward a view based on their experience:

Austin Holland, from the Oklahoma Geological Survey, remarked that data acquisition for seismicity linked to CO_2 storage is greater than for waste water disposal. He also stressed the importance of data acquisition through time especially from the beginning of operations.

Ivan Wong, from AECOM, observed that induced seismicity is used in the development of geothermal energy and monitoring is essential for this purpose. Given the locations where geothermal energy is developed higher magnitude events are more likely (~M4). These events need to be recorded as part of a mitigation strategy.

Daiji Tanase, of the Japan CCS Company, stressed the importance of being able to distinguish natural seismicity, which is prevalent, from induced seismicity. CO_2 storage is a new technology in Japan and therefore it is necessary to avoid felt events. Consequently, CO_2 injection needs to be carefully controlled.

Bettina Goertz-Allmann, from NORSAR, stated that a good depth resolution, plus coverage to improve the resolution of event locations and detailed source analysis, was important. This will require a comprehensive sensor network. Real time data acquisition and interpretation can enable microseismic data to be used to guide injection and other operations. There is a strong relationship with pressure build-up in reservoirs which can be used for geomechanical modelling. One of the differences between waste water disposal and CO_2 storage is injection into thin bounded reservoirs. Fluid rheology properties are also different.

Local attitudes in the vicinity of the Decatur site would strongly suggest felt events should be avoided. Best practice procedures are applied. Induced seismicity that might cause the reactivation of faults should be avoided which might mean shifting the location of injection.

Depth control using surface and shallow observation boreholes is a good monitoring approach because it can provide more detailed information on low magnitude events. Induced seismicity can also be related to geomechanical models to give predictive capability on faults and caprock thresholds.

In Oklahoma and Illinois reactivation of basement structures is the cause of induced seismicity therefore injection at stratigraphic higher intervals is preferable. The basement is heavily faulted which can generate induced seismicity to the extent that injection above basement in Ohio is banned. M3.4 events associated with water injection have been recorded in the Youngstown area of Ohio but the magnitude of events in the Decatur area are much lower. This suggests the geomechanical properties of the basement are different and that the overlying Mt Simon Sandstone CO_2 storage potential should not be discounted. The stress state and the properties of the Mt Simon Sandstone need to be properly characterised. During injection reservoir pressures need to be controlled to avoid inducing slip on fault planes. Experience of microseismicity associated with CO_2-EOR in the Cogdell field, Texas has not stopped operations. The disposal of high volumes of saline could have implications of CO_2 storage capacity but further research is needed.

If thousands of millions of tonnes of CO_2 are to be stored in the Mt Simon formation it means that attention should be given to geomechanics which may limit the amount of CO_2 that can be injected because the basement may have a large number of stressed faults that could be reactivated.

Session 5: Shallow Monitoring: How Much Do We Need and How Can We Do It? Chair: Charles Jenkins

Scene setting – the Detection-Attribution-Quantification Cycle, Katherine Romanak – BEG

The detection-attribution-quantification cycle is a key aspect of potential leakage detection. In this session the experience of four practitioners with expertise in different aspects of surface monitoring presented their views. These researchers were: David Risk, St. Francis Xavier University, (soil gas); Jerry Blackford, PML, (marine); Susan Carroll, LLNL, (ground water); and Sarah Hannis, BGS, (atmospheric monitoring).

Katherine Romanak from BEG outlined some of the challenges related to surface and shallow monitoring which can be directly related to water, air quality, ecosystem quality or landscape changes. The two key components are the detection of an anomaly and attributing its source. A multidisciplinary approach is necessary as well as the education of regulators. She emphasised that there are a number of practicalities with data acquisition from highly variable natural systems and a careful approach is necessary. Monitoring techniques also need to consider the implications implementing CCS on an industrial scale. Although different media may present different challenges the objective of monitoring is to detect anomalies and characterise a baseline that demonstrates a lack of leakage, or if a leak has occurred, it can be quantified. Under these circumstances monitoring would be used to detect the source of the leak and enable operators to respond to potential public claims. There will always need to be a balance between economy and the feasibility of locating a leak as well as the perception that leaks will occur or the extent to the risks that they pose.

Baseline may take one and three years of pre-injection monitoring to understand seasonal variations. Spatial and temporal variations in a baseline could mean leakage has occurred but without complex reasoning and statistical analysis it may not be possible to differentiate between a leak and background variability. However, baselines will be highly dynamic and will fluctuate with climatic and land use influences over the life-time of a project. A sound investigation and analysis at Weyburn using complex statistical analysis of multiple geochemical parameters proved the site was not leaking but this example demonstrates how careful any monitoring programme, and its subsequent interpretation, needs to be. Understanding the process which causes a phenomenon not the absolute concentration is fundamental. The transition from research and demonstration sites to industrial-scale projects will also demand a minimalistic approach. A balance needs to be struck between operator and regulatory goals.

Dave Risk presented the example of monitoring soil gas. Detection and attribution based on 20 – 25 geochemical indicators would give a clear indication of leakage, moreover, background surface monitoring can be minimised. Some caution does need to be applied because leaks can be caused by defective infrastructure from surface sources unrelated to subsurface origins. Following risk assessment logic rather than widespread and unnecessary monitoring is likely to be far more effective. Therefore monitoring for leakage detection should be specific.

The challenge of monitoring in a marine environment was presented by Jerry Blackford. He stressed that no single monitoring technique is sufficient. There are important criteria to consider. The area of survey will be dependent on technology power requirements. The detection sensitivity of the technology will determine its valid range. For example the acoustic effect for bubble detection extends to ~100m. Marine ecosystems such as the North Sea have complex baselines. Therefore the use of biological indicators requires detailed baseline appraisal that incorporates the influence of seasonality. Natural variability adds further complexity.

Targeted sampling in the proximity of wellheads is likely to be the most effective approach. Good baselines are vital to reduce false positive and non-detection of genuine anomalies especially at the initial stages of large scale offshore demonstration projects. The frequency of monitoring can be varied. A few periods of intense high frequency monitoring may be required in some instances whereas less frequent, monthly, yearly or even surveys repeated after a decade could be appropriate.

The case for ground water was presented by Susan Carroll. Changes to ground water can be caused by small amounts of CO2 and brine which can change pH and total dissolved solids (TDS) above thresholds. The ability to detect small leaks is only possible over long periods of time and if the monitoring point is near a wellbore. The simulation of plume volumes can be an effective means of predicting the impact of leaks and therefore where to deploy monitoring sensors. Pressure changes will be best method for detecting leaks but a well density of more than one well per km2 is probably necessary.

Sarah Hannis outlined the issues related to atmospheric monitoring. The detection of anomalies is the greatest challenge based on the studies of natural analogues and test release site evidence which indicates leakage is likely to occur on the scale of meters to 10s of meters. This research also shows that CO_2 rapidly disperses and mixes. It is very difficult to detect anomalies unless there is a large density of eddy-flux towers. Ground laser sensors are a possibility for wider coverage. False positives are always possible with any system.

Attribution is more difficult for CO_2 concentration alone but carbon isotopes and gas ratios, especially with CH_4, have been shown to work. Diagnostic site signatures can be helpful. Continuous monitoring offers the best chance of not only detecting leaks but also quantifying them but this approach will only be effective with frequent surveys.

In response to these views one operator commented that a balance needed to be struck between the level of monitoring and the obligation to meet regulator requirements. Under US federal Class VI requirements 28 parameters now need to be monitored. This condition tends to lead to a blanket approach rather than a more focussed plan. The experience of other practitioners stressed the importance of good site characterisation. At Ketzin intensive site monitoring, including soil flux measurements, was implemented to demonstrate to the local populace that natural processes and natural variability were fully studied and understood.

In marine environments low levels of CO_2 from a seep have negligible impacts but this perception could be contrary to public acceptability. Characterisation of natural variability is very useful for general scientific research not just CCS. However surveys around injection wells need to be able to detect changes that might be linked to injection. The presence of bubble streams would be monitored at the highest areas of risk to gain a better understanding of natural changes not necessarily because of risk.

Session 6: Developing the Link Between Geophysical Monitoring Responses to CO_2 Distribution, Pressure and Saturation in Reservoirs

Chair: Andy Chadwick

New Developments of CSEM (Controlled Source Electro-Magnetic) to Map CO_2 Distribution and Saturation in Reservoirs. , Pierre Wawrzyniak – BRGM

The CSEM method in LEMAM setup uses energised metallic casings as long electrodes to induce currents directly at the depth of the reservoir and then retrieve the electrical resistivity signature of a supercritical CO_2 plume from surface measurements. The resistivity within the reservoir is altered by the injection of CO_2, which creates a resistive body inside the conductive reservoir. Because of the presence of clay in the reservoir, imaged resistivity needs to be corrected in order to obtain a clear CO_2 signature.

At the Hontomìn Spanish pilot injection site, the technique was applied for a baseline campaign in December 2013 using one steel cased borehole and surface electrodes. Later CO_2 was injected but only in small quantities (5-10kT of CO_2). 96 receiver stations were deployed and electric currents were induced for seven different frequencies. By integrating signals from these stations, and fixing their position using GPS, it will be possible to monitor resistivity variation induced by CO_2 injection across the field.

The technique has also been applied for geothermal exploration in Martinique with two steel cased boreholes. Subsurface conductive areas were imaged and are related to temperature anomalies. The conductive area is consistent with high wellbore temperature measurements and models.

At Ketzin two sets of eight electrodes were used in two boreholes at 550m depth. There were 14 surface receiver stations.

A baseline survey was conducted in 2008 followed by three repeat surveys in 2009, 2010 and 2011. Results were then compared with a 3D forward model associated with different plume propagation scenarios.

CSEM can be a useful imaging technique that is complementary to seismic profiles. It can also be used to monitor the progress of the plume. The technique still requires further refinement. A 3D inversion code is being developed to improve resolution.

The Surface Deformation Measurements for Monitoring, Verification and Accounting (MVA) of Injected CO_2, Tim Dixon - University of South Florida

InSAR is a satellite-based technique which can be used to measure very minor changes in surface elevation (~mm). Comparison between baseline data and later surveys can be directly related to changes in underlying reservoirs. The technique is particularly well suited to deserts but recent research shows that it can be effective in more heavily vegetated regions. Reflectors can be used to enhance the response signal to satellites. The SBAS (Short baseline subset) technique can also be applied. It relies on the selection of interferogram pairs based on optimum perpendicular (spatial) baseline and temporal baseline.

A 10cm uplift in the SAROC field, west Texas, has been matched to CO_2 injection. A series of satellite images have been used to work out the rate of uplift and compare it with cumulative CO_2 within the reservoir. Residual differences between observed and modelled images are attributed to reservoir heterogeneity.

In another example GPS observations were used to monitor an EOR field in south Texas. The field was subdivided by faults. In this case GPS data was used because it was available over most of the EOR-injection operation. A regional reference frame signal compiled from a series of other regional GPS stations was used to filter the noise from this site. Several stations rose by amounts up to 1 cm, correlated with an increase in reservoir pressure. Other areas did not show vertical elevation. The elevation change was related to part of the reservoir where pressure increased during CO_2 injection. The subtle difference in elevation across the field showed that injected fluids remained entirely within a delineated fault block, suggesting that the fault has a sealing function. In this case vertical motion can be directly related to a pressure response and can be used to measure it.

Surface deformation techniques can provide a low cost MVA technique that can augment more detailed wellbore and seismic techniques. InSAR can be used in some areas of sparse vegetation without ground reflectors, while high precision GPS can be used in areas with increased vegetation.

Continuous Monitoring of Injected CO_2 using Ambient Noise and Controlled Seismic Source, Takeshi Tsuji - Kyushu University

The objective of this research project is to develop a method of seismic interferometry to monitor injected CO_2. The technique relies on the retrieval of seismic data from ambient noise. Time-lapse seismic surveys using an active-source is a high cost approach. A continuous monitoring system, based on seismic interferometry, has the potential to be a cheaper alternative using ambient noise. The technique relies on the propagation of a wave at depth which is recorded by a seismometer at the surface. The wave is reflected back into the subsurface and is then reflected off subsurface structures before returning to the surface where it is recorded by a second seismometer. By using a second, active source at the surface near the first seismometer another waveform can be created. Cross-correlation and cross-coherence of the waveforms eliminates the path from the source to the first seismometer leaving a signal that is representative of a reflection from the subsurface structure. The technique was tested using a fluid injection experiment in Spitsbergen. In this case the ambient noise was mainly derived from the injection well. The seismic survey enabled the generation of time-lapse reflection profiles to be created before during and after fluid injection. The pattern of fluid migration can then be traced. The technique relies on ambient noise from a stable source.

To generate a continuous frequency-controlled seismic source at the surface, the Kyushu University team developed an active source system "small-sized Accurately Controlled Routinely Operated Signal System (ACROSS)" to produce a consistent, continuous frequency-controlled seismic wave in a CO_2 storage field. The system has the advantage of producing a high quality repeatable source enabling continuous signal acquisition and a higher signal to noise ratio. This allows continuous monitoring during CO_2 injection. A small field test of the system has been conducted at Toyohashi in Aichi prefecture in the central part of Honshu. Because of the short offset of the seismometers it was difficult to analyse the reflection waveform.

Analysis of the surface wave could be used, however, to determine the time variation of S-wave velocity. Comparison with a model of CO_2 migration showed that small changes in P and S-wave velocities (~5%) induced by the presence of CO_2 can be monitored (or detected) using this approach. The research team has been able to show that the techniques using surface waves can detect the presence of CO_2 in shallow formations which has the potential to be used for leak detection.

Seismic Reflections at Sleipner: how have they changed with time and what do they mean. Andy Chadwick – BGS

Sleipner has been the subject of detailed seismic investigation for around two decades. 3D time-lapse seismic surveys have revealed a pattern of CO_2 migration within a plume comprising nine different layers trapped beneath a series of successive thin mudstones in the reservoir. By 2010 improved seismic resolution enables some of the layers to be resolved, with explicit separation of the top and base reflections. The topmost layer of CO_2 has accumulated beneath the topseal by a buoyancy-driven fill-spill process governed by the topography of the caprock. Forensic interpretation focused on the CO_2 accumulation beneath a particularly well-defined ridge in the topseal. This has enabled the key relationships between ridge elevation, temporal layer thickness and velocity pushdown (time-shifts) beneath the ridge crest to be measured. It is clear that strong tuning effects beneath the ridge flanks give way to much weaker tuning beneath the ridge crest where temporal separation of the top and base reflections is observed. The ratio of velocity pushdown to ridge temporal elevation is a key parameter, diagnostic of layer velocity.

A series of synthetic models was built to simulate different thicknesses of the CO_2 layer and different ridge elevations and to take into account the variable interference effects depending on layer temporal thickness. Correlation of the observed time-shifts with synthetically derived time-shifts enables the ridge elevation and layer thickness parameters to be isolated and layer velocity estimated. Very preliminary results suggest layer velocities in line with earlier rock physics calculations, but work is ongoing.

In conclusion improvements in seismic resolution have enabled advances not only in the detection of CO_2 but also in forensic analysis of CO_2 layer properties.

Gravity Surveys over time at Sleipner, Håvard Alnes – Statoil

Gravity as well as seismic surveys have been conducted across the Sleipner field to test the changes induced by CO_2. ~15Mt of CO_2 has been injected to date. The subsurface mass changes caused by this injection induce subtle differences to gravity measurements. However, account also has to be taken of water which moves up into the gas producing zone in the deeper gas field. This phenomenon needs to be corrected by subtracting the effect of this fluid migration. The amplitude depends on the density contrast and the depth. Typical values of gravity shifts are ~-2µGal for Mt CO_2 at 800m depth and ~+1µGal for 1Mt water influx at a depth of 2,400m. To put these values into context the standard gravity measurement is 980,000,000µGa (µGal = 10-8 m/s2).

Gravity measurements are made from instruments deployed by ROVs on to concrete bases across the seafloor. Changes in the gravity field are possible within an accuracy range of 2-3µGal. Changes in sea bed down to 2-3mm are also possible. Inverted gravity data indicates that the CO_2 plume is growing mainly in centre which also ties in evidence from 4D seismic.

Gravity can be used to make quantitative measurements. 9.4Mt CO_2 was injected between the gravity surveys in 2002 and 2013. Inversion of gravity data estimates that 8 ±2Mt CO_2 is stored in the Utsira Formation, if no CO_2 is absorbed in brine. The data shows that CO_2 absorption into brine is happening with a rate of less than 2.7% per year. However, the accuracy is limited by uncertainty in the subtracted signal from water influx to the Ty Formation and the lack of gravity stations over the northern part of the plume in the base survey.

Seismic Discrimination and Mapping of Saturation and Pressure Changes at Snøhvit. Andy Chadwick – BGS

In this example seismic has been used to discriminate between CO_2 saturation and pressure changes within the Snøhvit field. The CO_2 is separated and reinjected into non-producing formations. Originally CO_2 was injected into the Tubåen Formation at a depth of ~2.5km but injection was then switched to the Stø Formation as the pressure increased.

The Tubåen Formation is a faulted reservoir. Initial downhole pressure gauge measurements indicated a pressure difference between injection and fall-off within the reservoir of ~80bars. The initial reservoir pressure was 29MPa at 95°C when injection began. Flow simulations were developed over different distances from the injection point. The model assumed variable porosity / permeability properties and the CO_2 had a tendency to migrate into a lower section with higher permeability.

Pressure simulations conducted over relatively short distances of ~1.6km from the injection point showed the highest increase in pressure. There is a rapid transfer of pressure out to the boundary of the model. This simulation was then compared to simulations with leaky boundaries which show pressure drop off. In this case the model implied a significant flow restriction at a distance of 1.5km. The model simulation closely followed observed pressure data.

Amplitude changes observed from seismic surveys can be tied in with a fault bound compartmentalised reservoir. There is no leakage signal across the east-west trending faults either in amplitude or time-shift indicating a constraint imposed by faults. Fluid migration east or west was still evident. The research team then investigated the frequency spectral composition of the seismic signal which showed higher frequency waveforms closer to the injection point. Lower frequency tuning was dispersed across the fault block. This is consistent with thin layer tuning (related to CO_2 layering close to the injection point) and thicker layer tuning (related to pressure change across the entire reservoir thickness).

InSAR Monitoring of Surface Deformation: Experience and Lessons Learned from CCS Projects Worldwide, Adrian Bohane - TRE Canada

InSAR is a monitoring technique of growing importance for CO_2 storage sites. Operators provide the data from polar orbiting satellites. By recording phase shifts from successive satellite transits it is possible to calculate changes in elevation. Corrections are necessary to remove errors caused by atmospheric interference and other topographic changes such as vegetation growth. Advances in the technology are also becoming evident. It is now possible to repeat satellite records every four days compared with earlier systems that took 24 – 35 days. It is possible to detect changes in elevation at a single point of ≤1mm if there is sufficient data.

Time-lapse history of repeated observations can reveal uplift rates. Examples of >25 inches (63.5cm) have been recorded and correlated with steam injection at a US oil field. At In Salah a more complex pattern of uplift and spreading was detected which indicated movement relative to fault bounded sections of the reservoir. The desert location of this site made it an ideal candidate for InSAR. The technique was applied to Quest which is more heavily vegetated, but with a sufficient number of reference points changes in elevation can be observed in the future. At Decatur a full three year surveillance cycle from original pre-injection, to injection and then post injection has been recorded. In this case 21 artificial reflectors were used. Accuracy improves with time. In contrast the example, of observations recorded over a pinnacle reef reservoir in Michigan revealed virtually no vertical movement. InSAR has also proved to be an effective method for monitoring vertical fluctuation in a gas storage system between summer and winter. This movement is a key parameter for testing the reservoir's caprock integrity. The reliability and resolution of InSAR could make it a good tool for regulators. It also offers a high cost / benefit ratio.

Discussion - Session 6

The theme of this session and related discussion was making the link between CO_2 saturation and a geophysical response. Controlled-source electromagnetic (CSEM) surveys are claimed to be more sensitive at higher saturation levels of CO_2 but this has yet to be demonstrated. It is also unclear if EM methods can always produce reliable data at sufficient resolution. At sites like Ketzin, with closely spaced wells, the method can complement other techniques; but at other sites low well densities and thin plumes can lead to a lower resolution and mean that it is harder to quantify CO_2 in reservoirs.

There is a broader question as to whether it is necessary to accurately quantify CO_2. Tracking the plume and identifying where the edge is could be of greater significance. Ongoing industry-driven advances in seismic techniques are improving our ability to detect and characterise migration of CO_2. The ability to detect pressure changes within the subsurface is becoming more significant and again seismic techniques are proving very useful in this respect. Quantification of CO_2 saturation especially in thin layers still remains a challenge. The extent of CO_2 saturation can also provide an indication of reservoir capacity as injection continues over several years. EM techniques have been used to detect pre-existing leakage paths in an US oil field. In this example EM forms part of the risk assessment, but it can suffer from vertical resolution. One advantage of EM is that it can screen a large area and then identify areas where the use of other techniques can be more effective for more specific investigation.

Another key question is what measurements are needed to history match models and how can they be refined. A second survey at Goldeneye is planned to review where CO_2 might migrate to long-term. Once there is sufficient CO_2 in a reservoir it can be used to check and possibly modify models to improve their ability to provide long term predictions. The procedure could be repeated again after three or four years to fine tune the models. Better long-term prediction is fundamental for conformance and risk assessment.

Containment monitoring is also necessary to ensure that risks, such as not exceeding the fracture pressure of caprocks, or wellbores integrity, are checked. In the event that CO_2 does migrate, and reaches a barrier like a fault, simulations will be necessary to predict the effectiveness of the barrier. Modelling can be used to predict the frequency of monitoring that may be necessary. The cost-effectiveness of monitoring has to be assessed in terms of the relevance and benefit of different techniques and what they can deliver. Pressure monitoring is a good example of a relatively low cost option that can be a highly effective tool.

Technology advances can influence data quality. The original 1994 baseline seismic survey at Sleipner is inferior compared to contemporary surveys and further improvements are very likely over the next 30 years. Time-lapse comparisons with inferior baseline data could mean that contemporary surveys are compromised.

With any geophysical observation it is important to be able to tie back a conceptual model to understand the fluid properties of interest including CO2 movement, for example using seismic observations to test the sensitivity to saturation.

The permeability of sealing layers could have an impact on CO_2 retention. In the case of Sleipner the objective of geophysical investigation was to test the degree of compartmentalisation created by shale layers within the reservoir.

Session 7: Pressure Monitoring and its Application to Reservoir Management / Leakage Detection

Chair: James Craig

Quest Pressure Monitoring. Owain Tucker – Shell

Shell have devised a comprehensive pressure monitoring plan for the Quest project. The reservoir is in the basal Cambrian Mt Simon Sandstone which has multiple seals above the reservoir that act as barriers. Pressure measurements will be made just above the Quest reservoir from an observation well 30m away from the injection well in the Cooking Lake Formation. The comparatively close proximity of this position will allow early warning of any potential leakage around the casing into higher formations.

Simulations were run to test the rate at which any fluid might leak. The injection rate planned for the site is 1Mt / year or 2,700t /day. A single day's leak might only be 600kg/day and take ~4,000 years before it reached 1Mt.

Pressure buildup at a close distance of 30m can potentially detect an anomaly of ~600kg/day, in the order of kPa (Kilo Pascals). Lower leakage rates of ~10kg/day would equate to a pressure differences ~Pa at close distances. The sensitivity will be related to the formation permeability. At low permeabilities the pressure difference will be higher but the response will be later compared with more permeable formations. Heterogeneity can create uncertainty because geological variation could mean permeability barriers such as shales will influence the time and level of pressure detection. Multiple detection points allow the detection of regional affects within the same formation.

Noise sensitivity is in the order of ~10Pa. The effect of earth tides can be removed by spectral filtering.

The risk assessment defined the monitoring plan. The assessment showed that the most likely, although still extremely unlikely, leak path is the injection well annulus hence the use of observation wells. Pressure gauges have been operating successfully for ~20 years.

Pressure Monitoring, Field Observations and Interpretation Challenges. Sue Hovorka / Seyyed Hosseini – BEG

Pressure based monitoring can be a highly effective, mature technique for monitoring CO_2 injection and leakage detection of either CO_2 or brine. Sensors can be deployed at most depths, the technology is well developed, cost-effective and capable of detecting small differences in pressure. Small leaks can be picked up with time. There are challenges. The noise level needs to be determined to distinguish genuine signals and sensors need to be synchronized. Instrument drift needs to be checked and a regular and reliable power supply is necessary to ensure consistent and accurate measurements.

Pressure detectors can be deployed for passive detection above the reservoir in an aquitard and also in an Above Zone Monitoring Interval (AZMI). To investigate reservoir uncertainty a series of model realisations can be created to determine the level of heterogeneity and therefore well density and distribution for an injection programme. For example at Cranfield pressure records were matched with a geomechanical model. Two wells approximately 30m apart revealed quite distinct pressure response patterns. In one case there was an immediate fall followed by a consistent rise in the AZMI; in the other pressure remained at a relatively consistent level. Temperature monitoring did not match the pressure in the AZMI which led to the deduction that brine leakage was occurring in a distant area.

In an active system pressure monitors are installed in wells in a monitoring zone above the seal. Active monitoring involves an induced pressure response followed by signal analysis in an observation well.

Engineering Aspects of Pressure Monitoring – a Review of the State-of-the-Art, Barry Freifeld – LBNL

Pressure gauge technology is well established and reliable. Piezoresistive or quartz technology sensors have been in existence for 50+ years. Quartz is considered the gold standard for deep well deployments and costs in the range of US$20 – 30,000. 96% work effectively after four years at temperatures of 60-80°C. Electronic components tend to be vulnerable at higher temperatures. Failure rates of 50-60% after four years are more typical at higher temperatures ~175°C and at 200°C technical life expectancy is ~two years. There are technical innovations, for example fibre-optic systems are more suitable for high temperature applications. Memory gauges can record over long periods of time before retrieval which can be a useful fall-back for a surface read out gauge. Acoustic transmission systems have the advantage of avoiding cable connections. Pressure gauges can be highly effective tools for optimising production, pinpointing operation problems, and providing necessary reservoir information for effective control. Pressure data is used to confirm model predictions and demonstrate that the reservoir remains within operation limits set by the regulator.

Pressure was a key monitoring parameter at the Otway project. Pressure was used as a diagnostic parameter to measure permeability. Four gauges were used, two on each downhole deployment. The redundancy was justified because of the necessity to record data without returning to the site. The experiment involved water injection, CO_2 injection, and water extraction from the reservoir. Pressure was measured during each stage to test the fluid response to each injection. A residual saturation test programme was able to pick up very small changes in pressure. Pressure change measurements caused by tidal earth-moon tides were also detected.

Experience has shown that quartz gauges tend to drift less over time compared with piezoresistive based detectors. Most gauges tend to drift further over time than manufacturers' claims.

Tubing encapsulation of cable is used to increase the life of a gauge deployment, is now possible especially if monitoring is required over several years. A key supplier of quartz based detectors, Quartzdyne, publish failure rates on their website. 14% get returned over a 10 year period. Analysis of returned detectors has improved reliability.

Discussion - Session 7

The baseline for AZMI at Cranfield has been complicated due to EOR operations.

Corrosive formation waters can make wireline logging impractical over periods of several years. Tubing encapsulation was developed to overcome this problem which has enabling long-term monitoring. Gauge reliability has been enhanced by pre and post testing procedures. Some manufacturers test each quartz gauge at a specified operational temperature range before it is deployed for field applications. Operators return failed gauges which can then be examined to determine the cause of failure.

Session 8: Monitoring Tool Development: Technology R&D for Shallow / Surface Monitoring.

Chair: Katherine Romanak

Quantification of Released CO_2 using Acoustic Methods at QICS, Jerry Blackford on behalf of Paul White at the Institute for Sound and Vibration Research, University of Southampton

Passive acoustic methods can be an effective means for detecting bubbles (and leakage) in a water column but there can be limitations. The background ambient noise level could be a factor from both natural sources such as marine life and anthropogenic sources such as ships. In a shallow sea (<30m) this can be a substantial problem. Detection also depends on a number of factors: the proximity of hydrophones to the source; the bubble size and rate of emission; whether hydrophones are deployed in an array; and the duration of the recording period. For example with one hydrophone a release rate of 10l/minute would be detected at a distance of 1-5m. With an array the range could be extended to 10 – 20m.

Bubble size determines the frequency of the associated noise. Small bubbles have high frequencies and larger bubbles have low frequencies. This relationship could be a means of quantifying the amount of escaping gas. The spectral density of bubble observations can be compared with a model to estimate the quantity of gas. Laboratory based simulations were used to generate a reference condition. Firstly bubbles were generated through a bubble stone and then through an array of needles. The latter configuration produces a consistent pattern of spherical bubbles, whereas the stone produces a variety of shapes.

Bubble observation was an integral part of the QICS release experiment. A bubble model was compared with site observations. Consistent monitoring revealed that the site's 3m tidal range has a big effect on bubble generation. Increased water depth at high tide substantially supressed bubble formation. Bubbles also varied in size (1-2mm – 1-2cm) and shape from spherical to irregular ellipsoid and they can break up and coalesce. Evidence from both experimental and subsea deployment shows that the technique can be used for both observing and possibly quantifying gas emissions from the sea floor[3].

Groundwater Monitoring Network Design for Geologic Carbon Sequestration Sites, Ya-Mei Yang – NETL

A risk based monitoring strategy for ground water and above-zone monitoring has been developed to deduce leakage pathways. In this case the High Plains Aquifer was selected to simulate leakage from a single well over 200 years. Synthetic data was used to test the system. The probability of leakage was based on the location of a known well and another well whose location was unknown.

Three monitoring parameters pH, TDS and Benzene were modelled. The model outputs were used to determine the mean probability of detection and median probability of detection for these three parameters over one, five and ten years for the two scenarios. TDS is more sensitive compared with pH. The same exercise was repeated for an unknown well and then tested against monitoring density grids. For the median case it is hard to detect a leak until at least 4 -5 years. TDS is the most sensitive parameter and the first to be detected followed by benzene and pH. TDS is more associated with a brine leak. The probabilistic design allows a full risk assessment of true leakage events and the simulation of false positives and false negatives. Further modification to the monitoring design, using multiple criteria and background field data to simulate more leakage scenarios, will enhance this methodology.

2D Laser Scanning Absorption Spectroscopy Tool, Jeremy Dobler

GreenLITE is an experimental system to develop a 2D laser scanning absorption spectroscopy tool. The technology relies on two scanning laser spectrometers that can generate a 2D image of CO2 in the atmosphere. The laser is bounced off a reflector and transmitted at two frequencies. One at the wavelength of the target gas (CO_2) and a reference wavelength that is different. The difference between the absorption spectra is used to detect presence of CO_2.

[3] Passive acoustic quantification of gas fluxes during controlled gas release experiments. Benoît J.P. Bergès*, Timothy G. Leighton, Paul R. White. Institute of Sound and Vibration Research, University of Southampton, Highfield Campus, Southampton, Hampshire, UK. International Journal of Greenhouse Gas Control 38 (2015) 64–79.

The transmission and detection system is entirely portable. A 4G network is used to transmit data. Measurements were made over 1km with a precision of over 2ppm. However light snow and rain can attenuate the signal and in some conditions no return signal is possible. 24/7 remote processing is possible.

The system was tested at the Zero Emission Research and Technology (ZERT) site at Montana State University in August 2014. The facility is permitted to release 0.3t of CO_2 per day from a 70m pipe split into six segments. 600 hours of data were recorded over a wide range of conditions. An insitu LiCOR system showed a good agreement with the laser (LiDAR) system. An anomaly was caused by a local manure pile. Some diurnal fluctuation was also observed.

The system was deployed at the Decatur project in February 2015 and ends in September 2015.

Weather conditions can influence results. Line of site observation is essential and may be non-ideal, but the technology is capable of monitoring in real time. The system now being developed has a range of 5km possibly in future it could operate up to 10km and over an area of 100km^2. Increasing the system's range requires more retro-reflectors and could reduce its sensitivity.

Detecting Leak Locations from Pressure Monitoring Data Assimilation, David Cameron – Stanford University

Leaks can be detected from the assimilation of pressure data long before CO_2 is detected. It is also possible to detect where a leak is occurring but this will depend on the location of the monitoring wells, the number of wells, and the duration of monitoring.

A three layer computational model has been created to simulate leakage, the time it would take to detect, and the influence of well density. In this model nine potential monitoring wells were positioned in an aquifer above the caprock. A heterogeneous reservoir and aquifer were incorporated into the model based on a course grid. The model assumed residual trapping as well as solution trapping. Leakage was simplified to occur through a single grid block, representing an up-scaled leaky well or other leakage mechanism. Five realisations of synthetic pressure data were generated in order to history match simulated field pressure data. There was a good match between the pressure data and the five model simulations.

The amount of time required to accurately locate a leak was then tested. The simulations indicated that around six-to-twelve months of data would be required to detect and locate a leak within one grid block of ~400m of its true location using all nine wells. Additional monitoring time provided no additional benefit. The mass of leaked CO_2 can also be predicted to within around 70% of the true value, using six-twelve months of monitoring data.

To determine how many monitoring wells might be needed to detect a leak, twelve months of pressure data were history matched with simulations of one, two, three, four and nine wells. The results were expressed in terms of the relative proximity of a history-matched versus true leak, expressed in grid block widths, relative to the number of wells. With a single well a leak is evident but only within an area of over 10 grid blocks. With four wells there is a much closer match which is almost as good as a simulation with nine wells over a 12 month period.

In conclusion leakage location with this model is possible with three-four monitoring wells. A reasonable guess for the mass of leaked CO_2 could be estimated using only one monitoring well, with additional monitoring wells providing marginal benefit. The promising nature of these results warrants further and meticulous investigation.

Discussion – Session 8

Initial results from simulations are encouraging but they need to be tested with further refinement. The next phase of the Stanford modelling work will increase the level of anisotropy and include channelized simulations in both reservoir and monitoring aquifers above caprock. Characterisation based on an actual realisation could improve the predictability of models. This includes using data from both the storage reservoir and the overlying aquifer. The combined use of pressure data in both formations may indicate where a leak may occur and the direction of fluid flow.

The examples from this session have demonstrated that detection methods can be coupled with quantification. Models can also help with the design of smart data monitoring.

Session 9: Monitoring Tool Development: Technology R&D for Deep Monitoring Chair: Tom Daley

Aquistore Developments, Kyle Worth – PTRC

Aquistore is a buffer storage for a commercial CO_2 capture plant on Saskpower's Boundary Dam coal fired power plant and active oilfield EOR operations. CO_2 that is not used for EOR is sent to the Aquistore reservoir. Injection started on 16th April 2015. The injection well has been drilled to a depth of 3,396m through the entire section of the basal Cambrian Deadwood Sandstone which is very similar to the Mt Simon Sandstone. An observation well was drilled to a depth of 3,400m into the same formation so that pore pressure conditions can be monitored. The two wells are 150m apart. A casing conveyed pressure sensor showed a slight increase in pressure 100psi (685kPa) when injection stopped demonstrating an immediate pressure effect linked to injection.

The Monitoring, Measurement and Verification (MMV) programme is reviewed daily and the recorded parameters are discussed with the Aquistore operators. The CO_2 volume is influenced by plant operations specifically fluctuations in generation output consequently the monitoring programme has to be modified depending on the quantity of CO_2 injected.

The MMV programme includes 150 fluid sample analyses which began at the start of injection in April. A key objective of this frequency of sampling is to detect first arrival of CO_2 at the observation well. By June 2015 no CO_2 had been detected. Repeat Pulsed Neutron Log (PNL) runs will be conducted until the autumn of 2015. Reservoir simulation has provided guidance on the frequency of repeat logging. Distributed Acoustic Sensing (DAS) and Digital Temperature Sensing (DTS) using fibre optic cables have also been installed.

Other forms of monitoring will include ACROSS seismic surveys which generates seismic waves at the surface which are then detected by a permanent 6.25km2 array of 620 buried geophones. Micro-seismic monitoring will also be recorded from an array of 51 vertical component geophones at a depth of 20m plus 25 3-component geophone arrays at a depth of 6m. Background seismicity has been recorded since November 2014. These arrays are complemented by three surface broad band seismometers that have been recording since November 2013. There is an additional 5-level down-hole array above the reservoir which has to be re-orientated when it is redeployed for a specific survey. A 20 day passive seismic survey has also been conducted via DAS. No seismic events have been recorded with the exception of background natural seismicity worldwide. There have been some events linked to a large potash mine with a disposal well 200km to the north-east.

Surface monitoring consists of InSAR, GPS, tilt meters, soil gas and ground water monitors. InSAR and GPS should detect any uplift from CO_2 injection, however there is a regional ~5mm subsidence in southern Saskatchewan.

Reservoir modelling suggests ~30kT of CO_2 could be detected within 90 days.

Comparison of Fibre Optic Monitoring with Conventional Geophone Detection Systems at Aquistore, Tom Daley – LBNL

The DAS, which uses a fibre optic sensing system, has been compared with a conventional down-hole geophone recoding array. Comparison of single-mode and multi-mode fibre data sets has also been performed with two different sources: dynamite and vibroseis. The fibre was deployed behind casing. At ~2,867m there was damaged cable but a good signal was received above this depth.

DAS works by interpreting the impact of acoustic waves on a fibre that continuously interrogates a recorder such as the iDAS, made by Silixa, Ltd. Sampling occurs along each meter of cable at a frequency of ≤10 kHz. The iDAS records fibre strain rate which can be compared to a particle velocity measurement that a geophone would record. This property allows a direct comparison of equivalent units. DAS data has its own noise characteristics. R&D has focussed on noise reduction to improve the signal to noise (S/N) ratio over the entire 2.8km section of the well. Processing enhances signal quality especially for low frequency (<200 Hz) waves. Further work needs to be applied to improve higher frequency signals.

Multi-mode fibre has been deployed for temperature sensing and has shown that good quality data can be recorded for VSPs.

A comparison of DAS and geophone data has shown that a good match can be achieved. However, the noise level is higher in DAS compared to geophone records and therefore more source effort (energy) is required for DAS to get the same S/N ratio recorded by geophones. The advantage of a DAS system is that it can continually record a seismic profile over the entire well as opposed to the limited section covered by geophones. There appears to be little difference between explosive shock wave response and vibroseis records. DAS 3D VSP imaging has also produced good quality results.

DAS appears to be a good cost-benefit match for CO_2 monitoring.

Strain Measurements using Fibre Optics at a Small-Scale Field Experiment. Ziqiu Xue – RITE

Fibre optics can be used for strain measurements. In this example the technology is used to evaluate caprock and wellbore integrity and to monitor fluid injection (CO_2 and water). Properties of two forms of light scattering Rayleigh[4] and Brillouin[5] can be utilised to record and transfer pressure, temperature and strain data. DTS has been installed at Quest.

A DTS / DAS system allows continuous recording which allows data to be recorded throughout injection. This five year R&D programme has included laboratory experiments with sandstone samples contained within a pressure vessel to test the impact of pressure on the fibre system. Different fibres can be used to detect different parameters. The sandstone core was subdivided between coarse grained and fine grained sections. The fibre mounted around the core was then subject to increasing pressure when the core was compacted (confining pressure) and when pore pressure was increased (expanded). The Rayleigh light scattering response was measured under both conditions. By injecting CO_2 into the core and monitoring the Rayleigh frequency shift the CO_2 migration can be tracked.

The concept was then tested in wellbore at a depth of 300m. The cable was installed behind the casing. A small amount of CO_2 was injected to test the response. The fibre optic system can detect where the strain is occurring which can be directly related to fluid pressure (water injection). Strain measurements were also used to test the cement bond with a caprock. The system was used to detect water extraction from a shallow aquifer which verified its sensitivity to pressure changes.

Session 9 – Discussion

CO_2 delivery to Aquistore has been influenced by commissioning, EOR operations and flexible power generation. Intermittent hydro power generation and grid (transmission line) maintenance can lead to one or two day periodic shut downs. A consistent volume and flow rate has been supplied to the Aquistore site when the power plant has been operational.

By installing fibre optic cable at an approximate mid-point between the rock mass and the casing it is possible to record strain measurements from the formation.

DAS tested over a length of 2.7 km had the same S/N ratio. The system can detect the vertical component of a shear wave.

A crosshole electrical resistivity tomography (ERT) monitoring system was deployed at the Cranfield site for tracking migration of CO_2 plumes at a depth of 3,200m. Monitoring over a five year period was used to evaluate the spatial and temporal evolution of CO_2 plumes between two observation wells. Preliminary processing of first 10-months' worth of data showed that ERT tracked CO_2 saturation changes successfully.

[4] Rayleigh scattering - The elastic scattering with materials smaller than the wavelength of the light.
[5] Brillouin scattering - Inelastic scattering which occurs when the incident light interfere with sound wave through material.

Session 10: Updates on Monitoring in Current and Planned Demonstration Projects Chair: Sue Hovorka

CMC Overburden 300m and 500m Depth Release, Don Lawton - University of Calgary

The Containment and Monitoring Institute (CaMI), of CMC Research Institutes, Inc. (CMC), and the University of Calgary are planning two CO_2 release experiments at depths of 300m and 500m at a site in the Canadian province of Alberta. CCS initiatives and related issues are driven by a series of factors. Alberta has the highest carbon emissions of all Canadian provinces that includes daily production of 2-3M barrels from oil sands. There are approximately 450,000 legacy wells within the province and in many of the older wells, only the bottom sections of wells were cemented in addition to surface casing. Evidence from a 2D seismic survey of a former CO_2 EOR operation revealed that even after 60,000t it was not possible to detect the CO_2 partly because 2D seismic data does not recover all scattered energy and a 0.5m thief zone may have dispersed the CO_2 across the top of the reservoir. Thus, the anomaly within the reservoir may have been too thin to detect. Pressure interference of existing hydrocarbon accumulations and other CCS projects also needs to be taken into consideration. Consequently this controlled release experiment will have specific objectives to ensure that secure containment can be demonstrated in future storage sites. The project will include:

- Determination of CO_2 detection thresholds
- Improvement of monitoring technologies and cap rock assessment especially geomechanical properties
- Monitor gas migration at shallow to intermediate depths (~300m) and impacts on groundwater (CO_2 and CH_4)
- Determine the fate of CO_2 (trapping/dissolution)

In addition the project will be used as a field training and research programme. It will also include public outreach.

The test site south-east of Calgary will be monitored over an area of one square kilometre. The lowest release point at 500m is a 23m thick reservoir consisting of three units with a good quality shale cap rock. In contrast, the shallower release point at 300m has a relatively poor seal of mixed coals, sandstones and shales which has been selected to test how CO_2 may migrate out of a target reservoir. There are thin coal seams which could trap CO_2 but then release CH_4. Consequently the CH_4 flux will be monitored as well as CO_2. The experimental release will be used to measure the detection threshold of CO_2.

The project will also test a new monitoring system based on Muon density tomography which can act as a proxy for density changes induced by the presence of CO_2. Fibre-optic monitoring technologies (DAS, DTS, chem) will also be deployed.

A baseline 3D seismic survey was conducted in 2014. Other characterisation has included a cored 40m interval through the injection zones in the first well drilled. A mobile geochemistry monitoring unit will be deployed to analyse soil gas and ground water at a monitoring well drilled to a depth of 70m. A FLUTe hydrology profiling system will be used to measure the transmissivity distribution with shallow aquifers.

The current goal is to begin injection into the deeper target early in the spring of 2016 once all the monitoring wells have also been drilled in the early winter of 2016.

QICS Marine Controlled Release, Jerry Blackford – PML

The QICS project mimicked a leakage event in a shallow marine environment near Oban on the west coast of Scotland. 4.2t of CO_2 was released over 37 days 11m below the sea floor, and was monitored by several different techniques. On the first day gas propagation to the sea floor via pre-existent pathways had been established. By Day 7 clear chimney structures had appeared in the sediment and by Day 13 the area of reflectivity had increased. After 34 days a narrower chimney, from diffuser to surface, and vigorous venting into water column had become evident.

Quantified flow from observation revealed that ~15% of the gas had entered the water column as gas bubbles. The remaining 85% was not directly measured, but modelling suggests that to achieve the observed chemical changes in the water column approximately 35% of the CO_2 probably seeped from the sea floor in the dissolved phase within the bubble plumes. Longer-term monitoring suggests that a significant proportion of the injected CO_2 may be retained in sediments even after three years. The detection of key parameters pH and pCO_2 depends on the proximity of the sensor to the release point. Field observation at the QICS site shows that the CO_2 anomalies were only evident within a 20 – 30m radius of the release point.

This background information has been used to develop models of large-scale environmental impacts that might be caused by released CO_2. A number of different scenarios with different assumptions have been generated. In the case of the North Sea modelling shows that strong tidal mixing ensures rapid dispersion and minimises impact. With neap tides there is less mixing and dispersion compared with spring tides. Seasonal fluctuations are also evident. These simulations also show that rapid recovery of chemical perturbations occurs on a timescale of hours or days after a leak has ceased. Modelling has revealed that between ~38 – 90% of the released CO_2 had reached the atmosphere within 90 days via equilibration of dissolved CO_2 (not by direct bubble transfer). Models can also be developed to produce comprehensive baselines and thresholds beyond which pCO_2 and pH would not normally be exceeded.

Biological impacts were minimal at the site and had fully recovered within three weeks. A more prolonged release could have a more severe impact. QICS has revealed that quantification of leakage will be challenging. Bespoke modelling of baselines and leakage scenarios will aid monitoring strategies and impact assessments.

Ketzin - CO_2 Extraction Experiment, Ben Norden – GFZ

The German experimental CO_2 storage site at Ketzin ceased injection in August 2013. A total of about 67kT of CO_2 were injected over the duration of the storage project. As part of the abandonment phase there has been a CO2 back production which began in October 2014. The operation was a condition of the original permit. The back-production test presented an opportunity to measure the impact on the reservoir formation. One of the main challenges of the back-production test is the behaviour of the CO_2 in the reservoir and wellbore. The composition of the back-produced brine and gas and the spread of CO_2 at the surface was analysed. Atmospheric monitoring was conducted using Eddy covariance and infrared spectroscopy. During the final phase of injection in 2013 two-phase CO_2 was injected at 10°C. A 95%/5% CO_2:N_2 mix was also injected. During these final injection phases Kr and SF6 as well as N_2 were added to the CO_2. A total of 242t of CO_2 and 55m^3 of brine were produced. Daily production was restricted to ~ 800 kg/hr. The tracer gases and N_2 were immediately detected.

The CO_2-related resistivity signature decreased during back-production but increased with brine production. The extraction observations made at the site were within expectation for a pilot scale experiment.

Battelle's CO_2 EOR Storage in a Pinnacle Reef, Neeraj Gupta – Battelle

This CO_2-EOR project is one of a series of Phase III Regional Carbon Sequestration Projects across the USA. This project has reached a large-scale stage to develop the potential for commercial-scale CO_2 storage and EOR. The gas is injection into a pinnacle reef. There are three different types of reef depending on the stage of CO_2 injection and EOR. The pre and post injection monitoring programme includes wireline logging, borehole gravity, fluid sampling, VSP, microseismic and InSAR. The CO_2 flow and pressure / temperature logging is conducted during injection. 600 – 800t CO_2 is injected daily and some is recycled and retained in the reservoir. This project has tracked net retention over time across multiple fields. Since 1996 ~1.5Mt has been retained. Late stage reef pressure response shows slow, long-term decline six months after injection. There have been challenges with matching models with post January 2014 pressure observations. This has been attributed to limited data availability and the heterogeneous reservoir geology. It is not clear whether some pressure equilibration across reef complexes could also be attributed to hydraulic communication beneath these structures. InSAR modelling with reflectors shows no perceptible increase in elevation.

Repeat Pulsed Neutron Capture (PNC) logging is being conducted in multiple monitoring wells. Initial results show an increase in fluid phase constituents and a decrease in gas phase constituents because of the mix of oil and gas. It is possible that the change is due to CH_4 going back into solution and the CO_2 is moving from a gas phase to a super critical liquid. Further logging events may help distinguish phase behavior from fluid saturations. PNC logging is an effective method for verifying containment in the near wellbore environment. It is also inexpensive and easy to deploy.

Gravity surveys are conducted by taking point measurements along the injection wellbore. The data is then converted to density. Repeat surveys indirectly measure the change in CO_2 saturation. Wellbore data is combined with a CO_2 density model to compile density contrasts induced by CO_2 post-injection. Differences in the δ13C for dissolved carbonate suggest the brine chemistry is altered by the injection of CO_2.

PCOR's Bell Creek CO_2 EOR / Storage, John Hamling / Shaughn Burnison – PCOR

The Plains CO_2 Reduction (PCOR) Partnership is one of the seven Regional Carbon Sequestration Partnerships managed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). Lessons learned from monitoring applications were discussed from two years of operational monitoring for the Bell Creek demonstration project, which is studying associated CO_2 storage at a commercial enhanced oil recovery (EOR) project operated by Denbury Onshore LLC. CO_2 injection is ongoing. Since May of 2013, over 1.6Mt of gas has been injected, of which 1.51Mt is retained in the reservoir at current operating conditions after accounting for gas composition and recycle volumes.

This project is employing an integrated approach to site characterization, modelling and simulation, monitoring, and technical risk assessment to guide monitoring strategies and to study CO_2 storage associated with EOR activities. Several challenges exist for understanding associated CO_2 storage compared to traditional storage in deep saline formations (DSFs). These challenges include multiple fluid phases present (CO_2, reservoir gas, water, and oil), operation at near-steady-state pressure, and simultaneous injection and production. The concept of monitoring strategies compared with individual monitoring techniques become key, considering the large geographical area covered by operations. However, considering potential widespread commercial DSF storage, coupled with active reservoir management strategies (i.e., pressure plume control through water production), many of these challenges may not be unique to EOR scenarios.

Near-surface characterization and monitoring present several operational and technical challenges, particularly regarding the high degree of natural annual and inter-annual variability within the environment. Images from near the field illustrated environmental variability, including high rainfall events, blizzards, drought, and wet cycles, all of which add complexity to understanding monitoring data within these environments. In general, biological activity in the soil increases CO_2 concentrations as summer progresses (wet spring and high temperatures). During late summer and autumn when dry weather dominates (minimal precipitation and cooler temperatures), CO_2 concentrations decrease. These conditions also affect the chemistry of surface waters. Therefore, groundwater monitoring, isotope analysis, monitoring key indicator analytes, and biological process analysis provide improved data reliability for monitoring purposes.

Subsurface monitoring strategies have incorporated a large pulsed-neutron logging (PNL) programme because of the ability to provide both characterization and monitoring information. Time-lapse PNLs have demonstrated the ability to monitor changing fluid and gas saturations within the reservoir in very low salinity environments and have demonstrated the ability to identify breakthrough at production wells in high-permeability zones. This monitoring technique has also confirmed that no migration has occurred through low-permeability confining layers.

The integrated approach is exemplified by the combined use of PNL logs and seismic. PNL logs, combined with simulation results, were used to determine when CO_2 saturations in the reservoir were sufficient to image via seismic methods. Then a 2-D seismic line was acquired to validate that the distribution of the CO_2 in the reservoir could be delineated via time-lapse seismic methods in advance of acquisition of a higher-cost time-lapse 3-D seismic survey, which was employed to provide greater detail. The seismic programme has been useful for locating and delineating features that impact fluid movement within the reservoir such as channel features and permeability barriers.

Field Demonstration of CO_2 Geothermal at the Cranfield Site, Cranfield, Mississippi, USA, Barry Freifeld – LBNL

Cranfield is a field demonstration site for CO_2-EOR, but it has also presented an opportunity to test the use of CO_2 as a heat transfer medium for geothermal energy. A key objective of this experiment was to evaluate the effectiveness of CO_2's thermodynamic properties to extract and transfer heat energy. There are three wells at this site drilled to a depth of 3.2km. Geothermally heated fluid is returned to the surface before it is passed through a heat exchanger and reinjected. The Large compressibility, low viscosity and large expansivity properties of CO_2, compared with water, are beneficial for heat transfer. While this demonstration used heat exchanges to cool the produced CO_2 a commercial system would use a turbine system to generate power.

Heat output was compared with a geothermal reservoir simulation. A series of simulations were run at different volumes ranging from 5kg/s to 100kg/s and pressures. The simulations have shown that for rates of between 5 and 25kg/s, and wellbore of between 4 and 7 inches (10.16 – 17.78cm), a pressure difference of between ~7.5 and 8.0MPa can be sustained. The results from these simulations reveal strong theoretical thermosiphon properties.

The monitoring programme included a fibre-optic DTS sensor and quartz pressure / temperature sensors. Temperature, fluid density and flow rate were monitored over a three day period. The operation did highlight some technical problems including the formation of CO_2 hydrates and plugged filters.

At the end of this trial it was clear that the thermosiphon could be set up but it was not self-sustaining. Water production was also higher than predicted. Detailed analysis of the data will be required to gain a better understanding of field observations.

Session 10 – Discussion

Multiphase fluid circulation and water slugs were recirculated at the Cranfield site. The experimental results from the circulation experiment now needs to be compared with the simulations. The water / CO_2 mix was measured and provides data on heat transfer, but the model needs to be run with different water / CO_2 ratios. Different fluid combinations need to examine to see how they influence reservoir dynamics.

During the Ketzin extraction experiment there was some brine recovered. The reservoir's heterogeneity is likely to influence the rate of extraction.

Risk assessments of CO_2 venting always assume the most conservative case, although this is unlikely to occur. In one of the fields, CO_2 co-production with oil continued at a fairly consistent rate, even after several months of no new CO_2 injection. This is an indirect indication that the residual CO2 saturation in the field is relatively low.

Session 11: Post Closure Monitoring: What Should be Required for Closure? Chair: Tim Dixon

This session consisted of a series of short summaries from a number of different demonstration sites followed by a panel discussion.

Ketzin, Ben Norden – GFZ

Post closure monitoring at Ketzin consists of surface monitoring and 3D seismic. There is no requirement to monitor wells and by 2018 there will no further monitoring. The wells will be plugged and abandoned. Casing has to be removed which means that geo-electric downhole measurements cannot be continued. However it is important to ensure that all relevant processes have been fully understood for the potential benefit of future injection projects possible in the same basin.

Post closure monitoring should include pressure monitoring of the aquifer, pressure / temperature and down-hole geoelectric techniques. Fibre optic systems are more cost-effective than other methods due to a multiple usage of the downhole cables (e.g. for pressure, temperature, and acoustic sensing). With wellbore closure only soil gas natural flux measurements and ground water sampling from shallow wells will continue.

Mountaineer, Caitlin McNeil – Battelle

The AEP Mountaineer Power Plant CCS project consisted of a pilot-scale 20MW CO_2 Capture and Storage System. Injection took place from October 2009 - May 2011. There were two injection wells and three reservoir monitoring wells. The 18 month injection programme used two reservoirs, the Rose Run Sandstone and the Copper Ridge Dolomite. One of the key objectives of the monitoring programme was the protection of an Underground Source of Drinking Water (USDW). Differential reservoir pressure monitoring, modelling, and plume assessment were combined with soil gas sampling, groundwater analysis and isotope measurements. Plume stability is based on modelled prediction not monitoring, but pressure measurements have been used to validate the model. Part of the validation for this project, stipulated by the West Virginia Department for Environmental Protection, is adherence to the post-injection site care (PISC), which initially was designed around a 20 year post-injection monitoring and closure plan. The Underground Injection Control (UIC) permit and the PISC plan allowed for revisions to the post-injection monitoring period, which has now been updated to reflect a phased approach of well plugging and abandonment and planned site closure. To date, all regulatory and operational programme requirements and goals under Class V have been met. As part of the revised PISC plan, the site's UIC permit was extended for five years and the two injection wells and one monitoring were plugged in the first phase of site closure.

Cranfield, Sue Hovorka – BEG

The Cranfield CO_2-EOR operation is governed by the Mississippi Oil and Gas Board regulations. The SECARB R&D wells were plugged and abandoned on 5th June 2015 and no further monitoring is required. In an EOR setting, when production ceases no further access is permitted.

If a CO_2 provider/operator had been collecting Green House Gas (GHG) credits what would happen at end of injection? There would be legal questions of access and rights when production had ceased at a commercial EOR site. For instance, monitoring would no longer be permitted for research and verification purposes. There might be a concern over the integrity and access to former production wells in the centre of the structure because of upward migration of CO_2. There is also a question over the impact of future "quaternary" recovery from a field and whether the CO_2 would be retained should more oil be extracted in the future. Oil and gas operators in the USA have no transfer of liability.

Goldeneye, Owain Tucker – Shell

The safest wells post-closure are ones that are properly plugged and abandoned. Experimental evidence shows that CO_2 would take 30,000 years to diffuse completely into a Portland cement plug, and the carbonation process makes it less permeable. Oil and gas fields can have complex fluid compositions including H_2S so why should a CO_2 storage site be any different? However, operators need to be certain that shareholders are not exposed to risk once a site is closed. At Goldeneye the proposal is that there will be post-injection seismic and surface monitoring to check that no problems or impacts have occurred with the storage after injection has ceased and then five years later. The site would then be transferred to a competent authority.

Tomakomai, Jun Kita – RITE

The Tomakomai CCS demonstration project will inject CO_2 from 2016 to 2018. The permit will be renewed every five years. The measures for maintenance and/or closure of the injection wells require monitoring to ensure: conformance of the reservoir pore pressure; containment of CO_2 distribution within the reservoir; and contingency to avoid adverse impacts on the marine environment. There are important considerations that need to be addressed for post-closure stewardship of CCS sites because the post-closure conditions are not covered by legislation. These include:

- The length of time to continue monitoring.
- When should responsibility be transferred to the government or another entity?
- The level of financial compensation for the affected individuals or entities who might have been affected by leakage.

ROAD, Philippe Steeghs – TNO

For the ROAD project the closure plan is based on the risk assessment for the project. Transfer and closure is permitted if all conditions in the plan have been met. The post-injection monitoring period is 20 years but it may be less if the Competent Authority is satisfied. After injection operations have ceased, the monitoring plan recognizes four post-injection phases. First, while the reservoir is still accessible, there will be a (one-year) period of observation to verify that the reservoir is moving towards a stable condition. Then the well will be plugged and monitoring will focus on integrity of the well, and if the quality of the seal is found to be sufficient, the well is sealed and the monitoring is continued in the post-abandonment phase. Finally, after the site is transferred to a Competent Authority any developments in the reservoir will be followed periodically. However, as post-transfer monitoring is the responsibility of the Competent Authority the monitoring program does not address this phase. However, it can be expected that environmental monitoring activities will continue into this phase.

Session 11 – Discussion

The containment of CO_2 needs to be successfully demonstrated but in certain circumstances, for example, the migration of a thin CO_2 plume, detection by seismic might not be possible. Good site characterisation is therefore essential to understand the extent of heterogeneity within a reservoir and the level of CO_2 saturation, so that long-term predictions can be made with confidence. If competent caprock is present, and can be demonstrated to be an effective seal, then the trapping mechanism is less important because the CO_2 is retained. A risk assessment should identify risks, and their magnitude, at a specific site and that approach should determine how risks are addressed.

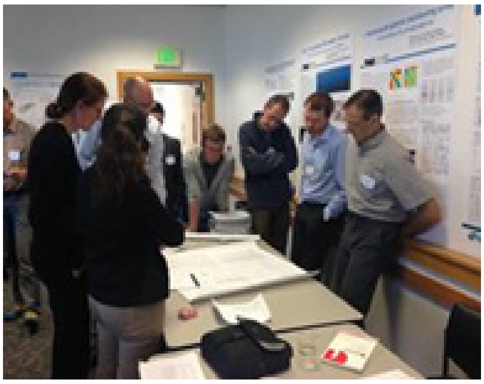
There are stringent demands being placed on CCS such as no change in ground water. This view could be regarded as an acceptable standard or too demanding. As a new industry more demanding regulations and monitoring is inevitable. There is an understandably cautious approach adopted by regulators towards large-scale demonstration projects, particularly if key resources like drinking water need to be protected. Operators have to implement monitoring programmes and risk assessments to detect and avert leakage even if there is a very low probability of leakage occurring.

Research techniques and advances in technology might encourage regulators to demand more monitoring without understanding whether it is necessity. The research community needs to explain the distinction between monitoring for compliance and the use of research and development (R&D) for new techniques that need to be evaluated before eventual deployment. R&D also determines the sensitivity of different techniques and whether they can make a relevant contribution to any monitoring programme. There is a tendency to implement detailed monitoring and characterisation of new projects because they are first of a kind, but future commercial projects will benefit.

Communication between operators and regulators has an important role. Parameters such as the level of exposure that is anticipated compared with an observed baseline needs to be conveyed. The risks also need to be put into perspective especially for the general public.

Session 12: Leakage Failure Scenarios – How to Detect them. Group Exercise. Led by Sue Hovorka and Katherine Romanak

New at this meeting was a group-work exercise created by Sue Hovorka of the University of Texas. This involved the groups each designing a monitoring plan for a storage site assigned to them. These sites were fictional but based on realistic scenarios and data (created by Susan Hovorka). The groups applied what they had learnt in the meeting as well as their own expertise. These monitoring plans were then challenged with leakage scenarios revealed for each site (created by Susan Hovorka). The results revealed that all the groups' monitoring plans succeeded in detecting the various leakage scenarios. This proved to be an interesting and stimulating exercise.



Session 13: Conclusions, Further Research Areas and Recommendations Chairs: Tom Daley, Tim Dixon, Charles Jenkins

Key Messages and Conclusions

- Pressure monitoring is a prime tool for interpretation but there is scope for further refinement. Pressure signals are dependent on geology and good quality signals can be detected if natural conditions allow. There is great potential for pressure based monitoring but noise levels and interpretation remain as challenges.
- Pressure monitoring has the advantage of large area coverage within reservoirs. Above Zone Monitoring Intervals (AZMIs), above storage reservoirs, are the best locations to deploy sensors for leak detection if models show that such leakage creates a sufficient pressure difference. The pressure monitoring in the AZMI can potentially locate leak pathways before CO_2 leakage occurs. Assimilation of pressure data can be used to predict the volume of leakage expected along the pathway. The approach will not be effective in a case like Sleipner because the pressure difference between the reservoir and the AZMI is so low.
- Risk assessment should identify highest areas of risk and therefore guide the design of a monitoring programme. For example in the Goldeneye project leakage via wellbores is the highest risk so monitoring is focussed in this area.
- Pressure monitoring can be an effective means of detecting anomalies such as leaks especially if used in combination with other measurements.
- There is potential in DAS and permanent source seismics as monitoring techniques, but further development is required. Various field deployments will probably be precursors of improvements in seismic imaging.
- There is a requirement for more geomechanical analysis and models to use monitoring data. In some cases InSAR monitoring has revealed surface uplift within reservoirs that is directly related to an increase of pressure within a reservoir as at In Sahal. In other cases, for example Decatur and in Michigan pinnacle reefs, no uplift is observed. Pressure dissipation could be the reason. Variable sensitivity in different regions and surface conditions is also a factor.
- The lesson from CO_2-EOR and upcoming CCS projects (ROAD, Peterhead, Quest) is that monitoring plans can be quite simple but the interpretation and connection with regulatory requirements could be quicker and clearer.
- Passive seismic may be needed more as the understanding of induced seismicity becomes more important, and it can be combined with opportunities presented by ambient noise recording and virtual source seismic.
- Should there always be a concerted effort to detect leaks or should leaks develop until they are detected?
- The effort directed into leakage detection might be more effective if it was initiated once evidence of a leak occurred.
- A key message is that potential leakage to surface is very low with the exception of old wellbores. Consequently, it would be more effective to concentrate on leakage from reservoirs rather than at or near the surface.
- CO_2 extraction from storage has been measured at Ketzin. A preliminary field test to evaluate the potential of CO_2 as a thermal transfer medium for geothermal energy, including a controlled release of CO_2, was conducted at Cranfield.
- Controlled release experiments in a marine environment have demonstrated that leak detection is possible. Initial investigation suggests that the potential quantification of released CO_2, using acoustic monitoring of bubbles, is possible.
- Monitoring at various demonstration sites has shown that Conformance, Containment and Contingency requirements of regulations (London Protocol, EU CCS Directive, US EPA Class VI) has been met.
- Spectral partition can be used to show CO_2 distribution and pressure variation. Seismic Interpretation of the spectral content from the Snøhvit Field is a good example of this approach.
- Time lapse gravity has been used effectively at Sleipner. The technique is highly sensitive, differences of 2-3 µGal can be detected and related directly to the CO_2 plume.
- Injection started at the Aquistore demonstration project on 16th April 2015.

Areas for Further Research

- There is a lack of knowledge of CO_2-EOR operations and CO_2 accounting within the CCS community.
- The link between shallow monitoring and quantitative risk assessment needs to be developed, however the effort required and what should be done needs to be refined.
- The application of pressure tomography to CO_2 storage.
- Accounting of stored CO_2 for regulators is under-developed in some regions.
- Communication of risk could be improved and is not always put into context. For example a minor leak of 600kg/day when 2,600t/day is being injection is only ~0.02%.
- Finding the most cost-effective combination of geophysical monitoring at any given site, and the development of an effective approach beyond the demonstration stage, has yet to be determined.

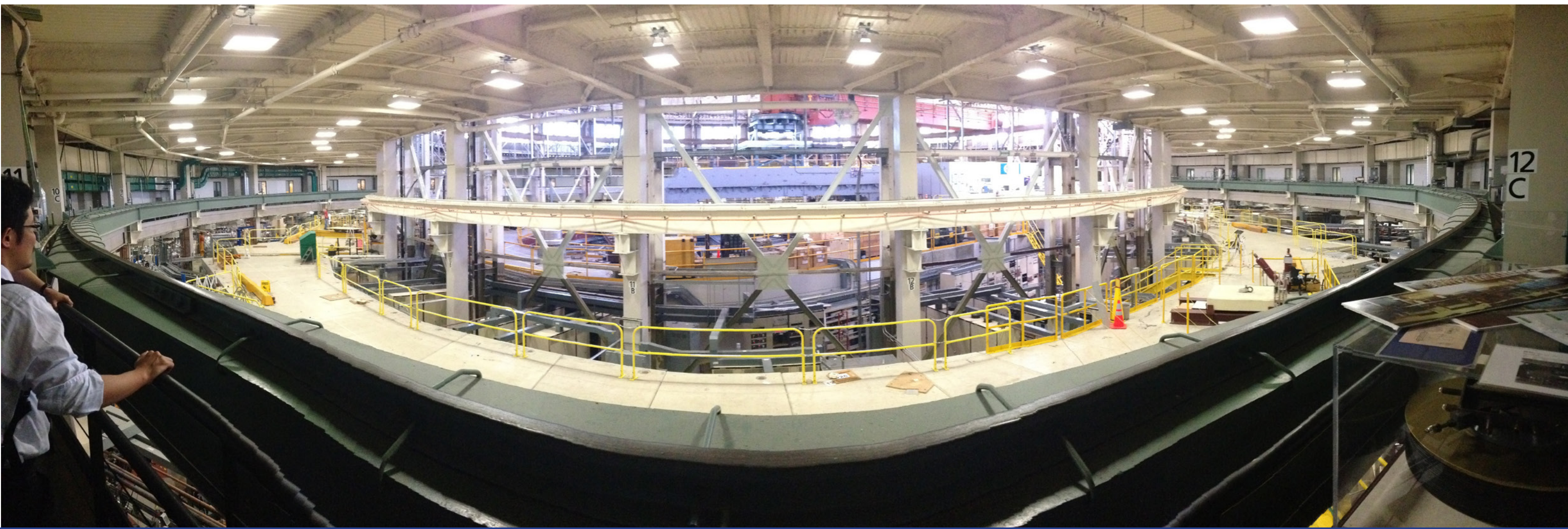
Recommendations

- Share expertise with oil industry groups like SPE and the EOR fraternity especially the management and accounting of CO_2 in the subsurface.
- Spread the experience and understanding of induced seismicity to a wider audience outside the US.
- Improve understanding of near-surface monitoring and what additional advances need to be made in monitoring and modelling.
- Identify R&D to improve the understanding of the link between shallow monitoring and quantitative risk assessment.
- Develop a better understanding of AZMI pressure monitoring and its relationship to geomechanics.
- Develop initiatives with regulators to encourage regular dialogue with them.
- Include a carbon accounting case study in a future network meeting.
- The development of a traffic-light system for managing the impact of induced seismicity, as part of best practice procedures and protocol development for induced seismicity in CO_2 storage.
- Induced seismicity needs to be included in risk assessment.
- Run future meetings with pre-set objectives that are developed throughout the course of the meeting.
- Allow more discussion time and set aside time dedicated to poster sessions.
- The Monitoring tool is useful for novices but a bit out of date. Its continued use was endorsed by the meeting.

Field Trip

Lunch at the University of California Botanical Gardens.

The tour of LBNL's Advanced Light Source was guided by Dr. Jonathan Ajo-Franklin who featured his work on micro-CT imaging of CO_2 storage reservoir and seal rock. The Geoscience Measurement Facility tour was led by Tom Daley and Michelle Robertson. This field testing support facility has built and operated innovative monitoring tools. Among the 'tools' shown were wireline trucks, borehole seismic sources, fibre optic cables, mobile recording containers, and fabrication facilities.



LBNL's Advanced Light Source facility used in micro-CT (computed tomography) imaging of CO_2 storage reservoir and seal rock research

Steering Committee

Tim Dixon (IEAGHG) (CHAIR)

Tom Daley (LBNL)

Andy Chadwick (BGS)

Sue Hovorka (BEG, the University of Texas of Austin)

Charles Jenkins (CSIRO)

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Curt Oldenburg (LBL)

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Valarie Espinoza-Ross (LBNL)

James Craig (IEAGHG) (CO-CHAIR)

Host

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Jeremy Blackford (Plymouth Marine Laboratory)
Adrian Bohane (TRE Canada Inc)
Shaughn Burnison (EERC)
David Cameron (Stanford, Energy Resources Engineering)
Susan Carroll (Lawrence Livermore National Laboratory)
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Bernard Giroux (Institut National de la Recherche Scientifique)
Bettina Goertz-Allmann (NORSAR)
Neeraj Gupta (Battelle)
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Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

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