Evaluating technology options to mitigate greenhouse gas emissions

combinedmeetingof the ieaghg monitoringandmodellingnetworks

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Front cover images: The North Berwickshire cost near Siccar Point / Hutton's Unconformity at Siccar Point looking out across the North Sea / Delegates explore Hutton's Unconformity at Siccar Point / Bob Gatliff and Andy Chadwick from the BGS guiding the field trip to Siccar Point, the site of the 'Hutton' unconformity

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The North Berwickshire cost near Siccar Point

Summary

The 11th meeting of the IEAGHG's Monitoring Network and the 6th meeting of the Modelling Network took place as a combined meeting in the ECCI building, Edinburgh. These meetings bring together leading experts from research and industry to discuss the latest work and developments, with around 60 participants from 11 countries participating.

The theme for this meeting was 'using the modelling-monitoring loop to demonstrate storage performance more effectively'. Sessions on monitoring included induced seismicity, novel monitoring techniques, monitoring costs, near-surface natural variability, monitoring CO_2-EOR, wellbore integrity issues, modelling environmental conditions, updates from ongoing and closed projects, lessons from other industries, modelling reservoirs and overburden, pressure measurements and conformance in the monitoring modelling loop.

Key findings from advances in monitoring included the benefits, and some limitations, of the use of fibre-optic distributed acoustic sensors (DAS) at projects, including helical configured cables to overcome the limitations of directional signals. A topic of much discussion at previous meetings has been how to reduce the level (and cost) of monitoring for commercial-scale projects compared with the initial research-orientated projects. This is now happening at Shell's QUEST project in Alberta where the research team are able to streamline their initial modelling, monitoring and verification (MMV) strategy without losing monitoring effectiveness, including the use of a new laser-based low-cost leakage detection technique over the well area. This principle was also studied in the monitoring, reporting and verification (MRV) plan for Occidental's CO_2-EOR project. In terms of leakage detection, much discussion centred around the temporal and spatial complexity of near-surface baselines and the implications for near-surface monitoring, its purpose, optimization and value to stakeholders, and hence the need for attribution methodologies to identify genuine leakage, with an example from Japan on a new technique for doing this for offshore leakage.

The modelling portion of the meeting discussed the complexities and challenges of upscaling from pore to core to reservoir, highlighting the importance of the influence of heterogeneity in the reservoir. Modelling flow in wellbores was discussed with several examples showing that it can require a different modelling approach. The US DOE's (Department of Energy) NRAP programme has produced 10 'tools' for reduced-order modelling of CO_2 storage, these have been beta-tested and useful feedback was given in a dedicated session.

Recommendations for further work were made, including the development of techniques and experience of CO_2 well control, and modelling of wellbore and near-wellbore events. Proposals were made for more case studies on the demonstration of conformance in practice, and more work on models of dissolution processes. Overall good progress is being made with the experience gained in both monitoring and modelling from demonstration and pilot projects. There is real progress in streamlining MMV at projects and reducing the costs of monitoring. Several sites have now demonstrated conformance of a modelling-monitoring loop, leading to an improvement in the understanding of this principle.

Session Overviews

Session 1: Welcome

Welcome from Bob Gatliff the Director of Energy and Marine Geoscience at BGS and Tim Dixon from IEAGHG

This 2nd Combined Modelling and Monitoring Network Meeting was opened by an introduction from BGS Director of Energy and Marine Geoscience Bob Gatliff who highlighted that despite the DECC withdrawing funding last year the UK and BGS remain committed to making significant process with CCS.

Davey Fitch from the Scottish Carbon Capture and Storage (SCCS) research group introduced the sustainability and design aspect of the ECCI building and highlighted that the SCCS team aims to bring together strong Scottish academic resources. Scotland has the expertise to develop offshore CO_2 storage and needs to demonstrate storage security. Meetings such as this will help to provide confidence and evidence to support this aim.

Tim Dixon from IEAGHG outlined the meeting theme of using modelling-monitoring loop to demonstrate storage performance more effectively. Subordinate themes of the meeting include:

- Has monitoring and modelling integration reduced uncertainty and improved accuracy?
- When is deviation from a model significant?
- What recent technological developments have allowed monitoring data to be analysed more robustly?

Session 2: Induced Seismicity — Chair: Tom Daley

Micro-Seismic Monitoring and Induced Micro-seismicity - Sylvain Thibeau, Total

The Lacq-Rousse project in south-west France, close to the Pyrennes, captured CO_2 at a boiler of the Lacq gas plant before transportation to the Rousse storage site to the south-east. The RSE-1 injection well injected CO_2 at pressures much lower than pre-production levels into a low porosity and permeability reservoir. 51,000 tonnes of CO_2 have been injected over 3 years. A seismic monitoring system was installed, consisting of deep seismic detectors in the injection well and seismic monitoring network was established around a 2km radius from the well. The objectives were to detect any seismicity and to reassure the local population. The network also provided data for evaluating integrity risks and understanding reservoir behaviour.

Regional seismicity (up to Magnitude 4.0) comes both from the Pyrénées mountains and the Lacq depleted gas field. This phenomenon adds complexity to seismic monitoring as the source of any detected seismic events may not be due to CO_2 storage. The monitoring between 2009 and 2015 detected 2,528 events in total in the injection area with a magnitude between -2.2 and 0.4. Some of these events are clustered to the south-west relating to the gas-producer RSE-3. Post-injection, the seismic trend slightly decreased however there were limited pre-injection recordings to make comprehensive comparisons. Another area of clustered seismic events were detected in the Meillon Saint Faust gas field located 2km north of the site where 68 localised events occurred (ranging from M-0.8 to 1.1). Historical records show also seismic activity during the production of this gas field.

The site has completed 3 years post-injection monitoring as required by the French regulatory authorities. The site is now ready for decommissioning. Publications were issued on induced-seismicity and no adverse effects have been reported.

Seismic Monitoring at the Tomakomai Project - Hideo Saito, Japan CCS Company Ltd

CO_2 injection began at the Tomakomai site in Japan in April 2016. The storage site is located just offshore, near a densely populated area (175,000 are located in the city, and the site is only 3.6km from the City Hall). The CO_2 is sourced from a nearby oil refinery. Two land-based deviated injection wells transport the CO_2 to the Mobetsu Formation at a depth of

1,000m and a second reservoir in the Takinoue Formation at 2,400m. A monitoring well is located closer to land at 1,200m. The upper reservoir has had 7,000 tonnes injected since April and a fall-off test is currently being conducted. The aim was to start full-scale injection in August 2016.

The seismic observation network is focused around a narrow scope, for micro-seismic imaging, plus a wider scope for monitoring for low magnitude natural earthquakes. The site is located in a naturally seismically active area associated with the subducting Pacific plate, where earthquake foci are often at 100km or deeper. Alongside the monitoring network, designed by Japan CCS Company Ltd, data was sourced from local seismometer stations where regional data is publically available.

The results of the baseline observation detected low levels of micro-seismicity around the depth range of the reservoirs. The seismicity rate seems to be non-regular and likely to be related to natural events. Data was made available for monthly public disclosure and there were no significant protests over the site. The seismic monitoring data was made publically available with the aim of improving community awareness of the project and increasing public confidence.

Using Transient Stresses to Monitor Poroelastic and Stress Conditions in CO_2 Reservoirs - Andrew Delorey, Los Alamos Geophysics Group

The evolution of stress conditions during natural seismicity provides an insight into the conditions which may also induce seismicity during CO_2 storage. Induced seismicity occurs when normal stresses acting on the rock matrix are reduced which is directly linked to the coupling between pore fluid pressure and stress. Links between natural and induced events are reviewed in the study, for example, an increase in seismicity occurs at injected waste water sites following natural seismic events.

Earth-tides are a predictable gravitational force which produce regular transient stresses to regional geology. Studies have been conducted at the Parkfield area of California to study the effects of these tidal stresses on the San Andreas Fault. If these stresses are transferred to rock masses the dynamic stresses may cause the onset of earthquakes. Looking at the phases of the stress wave gives an indication of the driving mechanisms. The phase of correlation may infer the nucleation time of earthquakes and poroelastic conditions. At Parkfield the poroelastic system showed that stress-induced perturbations to seismicity are correlated with tidal normal stress where earthquakes preferentially occur during the unclamping phase. This is similar to the mechanism that produces induced earthquakes except the unclamping is caused by increased pore-pressure in the latter case. The period of time prior to the M5.6 Prague, Oklahoma earthquake was analyzed. Due to the unknown orientation of faults, seismicity was correlated with volumetric stresses produced by Earth-tides. Preliminary results suggest that earthquakes preferentially occur during periods of volumetric increase in strain in which most faults would experience an unclamping.

In conclusion, tidal stresses may be used to infer poroelastic behaviour and stress conditions but further historical data is required to be able to make a full comparison. The longer-term aim is to develop a more predictive capability to know when faults become critically stressed and induced seismicity may be initiated.

Session 2: Discussion

The discussion focussed on the potential impact caused by induced seismicity and how to differentiate it from natural seismicity. Should monitoring be designed to detect regional background natural seismicity rather than site-specific injection sites. This approach could give a better insight into the frequency and magnitude of natural seismicity so that it can be distinguished from events induced by CO2 injection. Natural seismicity is monitored particularly in regions of the world which are seismically active but it may be necessary to improve detection elsewhere by trusted authorities who can communicate its significance to the wider public.

The impact of seismicity depends on how it effects receptors. If it causes structural damage then seismicity has an adverse effect unless the population is used to seismicity induced by artificial causes such as mining. The offshore Goldeneye project could not justify additional investment in offshore seismic monitoring because effects caused by induced seismicity in the

North Sea central graben are not powerful enough to be detected by the public onshore. If large natural events did occur they would be detected by the existing BGS seismic network and therefore attributable to a natural origin.

Session 3: Novel/ Distributed Monitoring Techniques — *Chair: Philip Ringrose*

Advanced Monitoring Technology: DAS at Otway and Aquistore - Tom Daley, LBNL

Distributed acoustic sensing (DAS) using fibre optic cables is a promising technology being used within the CCS community to help improve long-term repeatable monitoring with permanent sensor installation. Currently, the extent to which long-term monitoring is required for CO_2 has not been constrained, but is expected to be required. Other monitoring technologies have constraints which may be reduced by use of permanent DAS, for example the cost of marine seismic and the surface variabilities and access issues associated with land seismic. DAS is currently focused on borehole seismic with fibre cables deployed in boreholes. At the Otway Project an R&D approach to DAS was adopted which allowed 3-D surface seismic acquisition with buried fibre optic cables along with use of a remote controlled source.

The Stage 2C Otway Project stored 15,000 tonnes of CO_2 at 1.5km depth in a saline aquifer. Over 30km of standard fibre cable were installed and buried with approximately 1km of novel helical wound fibre cable. The first round of data to be collected initially appears to be of good quality although the helical cable was found to be particularly sensitive to the saturation of the ground. Otway has currently installed two permanent surface seismic sources that are used for daily monitoring. The array is designed to detect small quantities ie < 15,000 tonnes of CO_2.

The Aquistore Project (capturing CO_2 from SaskPower's Boundary Dam power station) has stored CO_2 since 2015 which is injected into the Deadwood and Winnipeg formations which are the basal units of the Williston basin. Baseline 3-D surface seismic and vertical seismic profile (VSP) surveys were undertaken in 2013, 2014 and 2015. There is a dedicated monitoring well with fibre cable cemented behind the well casing. Injection first began in 2015 and modelling indicated greater than 30,000 tonnes of CO_2 storage should be detectable. The first post-injection DAS surveys using the cemented in place fibre cable were collected in February 2016 after 35,000 tonnes had been stored. 20 days of continuous recording were also recorded using the permanent 'JOGMEC ACROSS' source into a fibre-optic array. Use of both DAS and a geophone VSP array allows a comparison to be made. A good agreement between DAS and geophones has been achieved in the first rounds of data acquisition. The trenched DAS data is not yet available and detailed analysis of results is currently being undertaken.

Optimizing PNC Logging and Modelling Techniques in Low Porosity and Active CO_2-EOR Fields. Amber Conner – Battelle

The Midwest Regional Carbon Sequestration Partnership (MRCSP) used pulsed neutron capture (PNC) to conduct a large-scale basin test on the Northern Niagaran Reef Trend, of the Michigan southern peninsula. PNC techniques have the potential for estimating CO_2 saturations and allow monitoring of multiple reefs. Approximately 550,000 metric tons of CO_2 have been injected with the aim of injecting 1 million tons in total. The target reservoirs are primary oil and gas fields with reservoir lithology ranging from dolomite to limestone. PNC logging is an effective method for verifying containment in the near wellbore environment and provides saturation levels of oil, gas and water. Traditional PNC logging is thought to be limited to reservoirs with smaller than 10% porosity and less than 50,000ppm salinity. These limitations are exceeded at the Niagaran Reef carbonate fields with porosities up to 20% anticipated and salinity values above 50,000ppm.

The baseline study conducted by the MRCSP was limited to gas and water sample analysis. Saturation analysis did not show any CH_4 and CO_2 differentiation. Gas sampling is therefore vital to show any variation in gas composition. RIN13, RATO13 and Sigma models were run and using a new triangulation technique allowed a new PNC model to be developed.

This study concluded that PNC logging could be deployed successfully in low porosity fields. The method could also be evolved to allow for 3 phase analysis (oil, water and gas). PNC logging has the potential to be used to interpret salt plugged carbonates and improve capacity estimations. The MRCSP program has afforded the opportunity to optimize PNC logging and the development of a "best practice" plan to implement PNC monitoring in low porosity and EOR production fields

Feasibility Study Results from DAS, VSP and Microseismic for Peterhead and Quest; and insights from Tracer Feasibility Study Completed at Peterhead - Marcella Dean, Shell

DAS systems can be used for time-lapse vertical VSP Surveying and microseismic hydraulic fracture monitoring. The motivation for using DAS technology is that it is non-intrusive, continuous, low-cost, efficient and has full vertical coverage although the noise floor is higher than for geophones and incident angles influence the quality of signal. Shell is using DAS for well acoustic monitoring at QUEST during storage operations.

The initial field trial for QUEST involved a comparison between conventional VSPs with geophones and a DAS-VSP. The results shower good repeatability and similar results could be generated. The first repeat DAS-VSP survey after injection commenced has confirmed this.

For the former Peterhead CCS project, a feasibility study was completed for the Goldeneye storage site with a modelling approach involving ray tracing, geometry and diagnostics. The modelling concluded that sufficient rays arrive at required angles for containment monitoring along injectors. A 12km^2 area was modelled which can be achieved in a one day operation (50x50m, 5,000 shots). A multi-well DAS-VSP is likely to identify CO_2 migrating vertically near injectors or along abandoned wells and generally provides a lower cost conformance monitoring alternative to costly surface seismic. The imaging area is still limited and depends on well geometry and a future generation of interrogators would need to deliver a lower noise floor in order to improve the signal to noise ratio. For Goldeneye, incorporating DAS-VSP surveying could reduce monitoring costs significantly. DAS microseismic techniques are not yet fully developed but have been recommended as an R&D activity.

The feasibility of using tracers at Goldeneye was also studied. The recommendation was to identify all natural tracers in injected CO_2 (noble gases and $\delta^{13}C$) and injected artificial Xe isotope tracer ($^{129}Xe/^{134}Xe$ or $^{129}Xe/^{136}Xe$) as it has a low background concentration in subsea gases. It was estimated that a $5x10^{-10}$ cc/cc $^{129}Xe/^{136}Xe$ spike would require a 250L per annum tracer volume.

Testing a Laser Bead Method for Detecting, Locating and Quantifying Atmospheric CO_2 Emissions at the Quest CCS Project - Simon O'Brien, Shell

QUEST is the first full-scale CCS project for oil sands with a planned captured rate of 25million tonnes of CO_2 over 25 years using syngas capture technology. A light source system was developed for detecting leakage to atmosphere by monitoring the above surface area between a laser and retro-reflector. A major challenge to developing this technique is the high natural background and variability of CO_2 levels, as levels are not homogenous and can change quickly. The ultimate objective is to collect CO_2 concentration measurements to allow a computer analysis to calculate where source is.

Reflectors are cheap and the gas sensor is more expensive but only one is needed on each site. Air movement and measurement are also recorded. A model has been created to simulate what each potential leakage source scenario would look like over various wind conditions (a Monte Carlo approach for many possible leak sources was used). In June 2015 a controlled release was conducted to assess the reliability of the laser based method. There were 27 releases in total at 300kg/hr for 30 minutes. The system successfully detected start and end times of each release and the observed leakage could be predicted by the model.

Currently only one wind sensor is being used but trees in the local area may be causing eddies and hence more sensors may be needed to fully characterise the more complex wind patterns. Even though some difficulties were encountered with the model all releases were still detected. During these trials the sensors were placed 100m away from one another (source and reflector) but they could be up to 1km apart. More sensors would not necessarily increase the accuracy of detecting the source location. Once a leak has been detected the next stage would be to locate the source in the field, it would not be inferred by modelling. At QUEST the biggest risk of leakage is from wells as a caprock leak is considered highly unlikely. Snow was the biggest concern for false responses from the sensors but Shell are hoping to collect enough data to improve this aspect of the technology. The overall conclusion was that an estimated release rate of approximately 50 kg/hr can be detected on the well pads using this light-source method.

Model Based Costs for Monitoring - Sue Hovorka, BEG

The monitoring aspect of a CCS project is often considered a minor element of the total costs but given the site specific nature of the monitoring needs, costs can vary greatly. To date any monitoring cost estimates are based on general scenarios but the assumptions made may be unreasonable given site specific elements. A focus needs to be made not only of the costs of the techniques themselves but also the value of the information produced to help optimize costs. The potential costs incurred due to liability if a leak were to occur also needs to be taken into account.

This project looked at pressure and chemical monitoring techniques (PBM and GVM) based at above-zone monitoring intervals (AZMI). The work aimed to develop a model to allow costs to be estimated for generalised plugged and abandoned wells. Equations were developed for calculating the number of wells required for monitoring design needs which relates the pressure to the number of wells required. The AZMI coverage depends on the number of wells and the time taken to detect a pressure change (i.e. less wells increases the time taken to detect a leak).

The work concluded that geochemical monitoring requires more wells (to get the full coverage needed) compared with the number required for pressure monitoring to detect the same leakage rate within the same time. Consequently there would be an increase in costs for geochemistry based monitoring compared with pressure based monitoring. Capital and operational expenses per well were 61% higher for geochemical monitoring compared with the costs for pressure monitoring. Future work is required to verify the cost-variability of monitoring based on site-specific elements and the variability associated within human specifications e.g. leakage threshold, time to detection.

Monitoring and Expected Costs with Secondary Trapping - Jeffrey Bielicki, Ohio State University

The study develops and implements a model to monetize leakage risk from geologic CO_2 storage reservoirs. The Leakage Risk Monetization Model (LRiMM) combines 3-D geospatial data, injection and leakage simulations, and economic costs to estimate the monetized leakage risk, which includes the reduction in expected associated costs due to secondary trapping in the subsurface. The Michigan sedimentary basin was used as a case study, where there are 15,000 active wells and an additional 30,000 plugged and abandoned wells—all of which could serve as leakage pathways. The Monte-Carlo and Bounding Analyses for critical uncertainties establishes the probability distributions for leakage and its extents in three dimensions, which are combined with cost estimates from the Leakage Impact Valuation (LIV) method that arise from four drivers: technical, legal, regulatory and infrastructure. These cost drivers were broken down into seven sub-divisions covering all four categories (legal costs, labour burden to others, technical remedies for damages, business disruption to others, injection interruption, fixing a leak and environmental remediation). The estimated costs of leakage from LIV for the case study show that costs due to injection interruption varied between 3-98% of the total costs, finding and fixing a leak 1-36% of total, and environmental remediation 0-10% of total costs.

Generally, the monetized leakage model (MLR) for an individual storage site will vary over time but it is likely to remain orders of magnitude lower than storage costs. The MLR varies depending on primary or secondary leakage and varies by depth dependant on stratigraphic unit, and the degree of secondary trapping that limits the amount of leaked fluids that encounter cost-incurring receptors. Storage operators are likely to have the monetary resources required to deal with leakage but further substantial economic costs may arise from other stakeholders. Intervention and remediation was shown to substantially reduce MLRs.

The Implications of CCS Economics for Monitoring and Modelling of CO_2 Storage - Professor Dianne Wiley, University of Sydney

The costs of modelling and monitoring verification plans (MMVs) are rarely reported to the public and hence it is difficult to compare conventional or prospective technologies for different projects. The economics of the whole CCS system have been studied but the MMV aspect is reported here.

Pre-operational costs are dominated by seismic surveys and operations are dominated by the seismic survey and injection monitoring (70% of total operational costs). The total project costs are increased by 60% by enhanced MMV during operation and closure period. An 'Australian Power Generation Technology Report' was published by CO2CRC and EPRI which includes information on the costs for CCS. This covered pipelines, booster pumps, wells, platforms and MMV for specific Australian case studies.

The study concluded that MMV (in $ per ton injected) accounts for, on average, 0.6% of total cost, 4% of transport and storage cost and 20% of storage cost. The MMV cost increases when the areal extent of the reservoir increases (as the Area of Review (AoR) is larger) or a small amount of gas is injected over a large area. Generally there is still limited cost data available from CCS case studies. New MMV technologies need to be focused on being cheap, reliable and easily deployed within regular project phases.

Session 4: Discussion

Public availability of data is key to further understand the details of MMV cost implications. The British government have recently provided all CCS cost data but more public sharing is required. (**https://www.gov.uk/government/collections/carbon-capture-and-storage-knowledge-sharing**)

Cost analysis also becomes increasingly difficult as different methods include different MMV elements e.g. interpretation of data was included in the monetized leakage model but not the AZMI plan presented in this session (Model Based Costs for Monitoring). The time factor can be significant for interpretation and data acquisition is labour-intensive. Some of the assumptions made drive the costs and can be underspecified in the MMV plans. For example the inclusion of seismic surveys will be significant as it will be the largest cost item. Also the requirements for specific monitoring can be complicated by site-specific issues. The sensitivity of sites needs to be taken into account for first of a kind projects for example Sleipner and Goldeneye, as site-specific factors (such as access) can have a dramatic impact on costs. Investment in the early stage development of MMV applications will benefit the next generation of storage projects which should reduce the cost of monitoring by developing technology and operator experience.

Session 5: Near-Surface Monitoring – Long-term Natural Variability — *Chair: Katherine Romanak, BEG*

Long-term Seawater Monitoring in Coastal Japanese Waters - Jun Kita, RITE

The Japanese Act on the Prevention of Marine Pollution and Maritime Disaster states that the operator of a CO_2 storage site under the seabed must monitor seawater quality to verify that no leakage above the storage site has occurred and report the monitoring results to a regulatory authority. The main monitoring focus is to distinguish between a CO_2 leakage signal and natural benthic CO_2 and O_2 variations which can fluctuate and occur relatively rapidly.

The study looked at Osaka Bay, 500km west of Tokyo Bay where temperature, salinity, dissolved oxygen and pH have been monitored from the surface to the seabed between 2002 and 2012. Total alkalinity was also calculated using a linear relationship with salinity. The partial pressure of CO_2 and DIC (dissolved inorganic carbon) or TCO_2 were calculated using CO2SYS.

The dissolved O_2 and CO_2 relationship can be used to distinguish CO_2 leakage from natural processes. A quadratic relationship was detected between $\log[pCO_2(\mu atm)]$ and DO% and leakage can be suspected if an anomaly is noted outside the 95% confidence limits of the trend line. Photosynthesis and respiration activity cause CO_2 fluctuations that can occur rapidly in benthic coastal waters. Continuous monitoring is therefore recommended rather than water sampling. Site-specific baseline monitoring is essential for leakage monitoring and the inclusion of accurate pH measurements is also recommended. A systematic increase in dissolved CO_2 has also been seen in the data gradually over the past 11 years of monitoring. This long-term monitoring has revealed CO_2 acidification of the sea. Osaka Bay has many man made factors affecting water quality so it is important to distinguish between background CO_2 levels and any influx from CO_2 storage. This method can be used to identify leakage from storage.

Continuous Monitoring of Weak Natural CO_2 Leakage near Rome - Dave Jones, BGS

European Union regulations require monitoring to detect leakage and for any emission to be quantified. Deep-focused monitoring may indicate a leak but detection and quantification of emissions, should a leak occur, will require near-surface measurements. The lack of CCS sites with leakage occurring led to the study of a natural CO_2 leakage site near Rome, Italy. Temporal CO_2 variations were studied to analyse the release mechanisms in detail and study more subtle seepage features than previously.

The natural CO_2 leak was initially discovered when a geotechnical borehole drilled through a clay layer at 40m depth. The gas was found to be from a deep geogenic source with up to 86% CO_2 in soil gas. The location studied was selected on the basis of logistical as well as scientific criteria. Isotope sampling was undertaken in February 2014, which showed significant differences in gas composition above and below a near-surface clay layer. The deeper samples had a δ13C value representative of seepage from a geogenic gas source. Shallow CO_2 samples were predominantly from biogenic sources with 0-24% from deeper geogenic sources. Below the clay layer as much of 90% of the gas sampled was from a geogenic source.

A strong positive correlation was found between soil temperature and CO_2 concentration which showed a seasonal trend. The CO_2 concentration peaked around 3-4 hours after soil temperatures rose with the signal more subdued in winter.

The study concluded that the clear mix of biogenic and geogenic CO_2 at the site could be diagnosed from C isotopes and gas ratios. Temperature, rainfall (soil moisture content), pressure and wind speed all had an effect on CO_2 content and flux. Geogenic CO_2 concentrations are temporally variable a condition that would need to be considered when monitoring CO_2 storage sites. Further statistical analysis is currently being undertaken to see if biogenic and deeper seepage components can be separated.

Development and Proof of Monitoring Techniques for Sub-seabed CCS - Kiminori Shitashima, Tokyo University of Marine Science and Technology

This study looked at the development of new cost-effective monitoring techniques to study seafloor CO_2 leakage and detection. The development of new techniques are necessary to detect CO_2, measure pH, map leakages from the seafloor and monitor the diffusion behaviour of leaked CO_2.

Initially, the direct leakage of CO_2 at the seafloor was studied with the objective of detecting a leak, identifying the leakage point and then monitoring the leak. Acoustic tomography technology was studied to see if density turbulence and/or acoustic dispersion between two transponders caused by a leakage could be detected by a change in acoustic propagation velocity. This was tested at a natural hot spring site using a prototype transducer. The results showed that the response time was too slow to give a satisfactory signal. This system successfully detected the submarine hot spring water erupting from the seafloor, and obtained information about its behaviour. The results showed that it is possible for this system to detect density turbulence (water temperature perturbation) and/or acoustic dispersion (leakage).

A second experiment was conducted to detect leakages using high precision in-situ measurements of pH and pCO_2. A pH electrode was developed, ISFET (Ion Sensitive Field Effect Transistor) alongside a reference electrode CI-ISE (Chloride Ion Selective Electrode). Using these in-situ sensors gave a much quicker response time and improved precision. At 3,000m depth and 1.8°C the pH response time was less than a second and 60 seconds for pCO_2 detection. The tools were attached to an ocean observing platform (an autonomous underwater vehicle) and an automatic elevator that can monitor the entire water column and conduct continuous measurements.

Short-term diffusion of CO_2 into seafloor sediment pore waters was also studied (QICS – Quantifying and Monitoring Potential Ecosystem Impacts of Geological Carbon Storage). In-situ measurements of pH and pCO_2 in the water column, pH in the sediment and CO_2 in the atmosphere were conducted. Measurements of acoustic reflection from the sea-floor sediment by a sub-bottom profiler were also carried out alongside core sampling. An in-situ measurement of electrical resistivity of sediment was also used.

Session 5: Discussion Panel — *Chair: Katherine Romanak, BEG*

The discussion panel was asked to address the following four key points:

- Detecting changes in natural variability over longer time periods
- Attribution of a signal and differentiation from background noise
- Preparation and response to claims of leakage ahead of project implementation
- Managing the public's reaction to these issues

A reference site away from a potential storage site might be helpful to distinguished natural background from a potential leak. However, reliance on a reference site may not be a suitable approach especially when dealing with public perception. The reference site might not be suitable or be sufficiently representative for comparison purposes. One alternative approach is to conduct test releases periodically to demonstrate that a CO_2 anomaly can be detected.

Extensive baseline monitoring could be valuable. Temporal variability and long-term trends may become evident and offer a more reliable baseline for future comparisons. If sub-surface leakage does occur then it will not affect the entire site equally and therefore leakage would become evident. Coverage becomes important to detect an anomaly. A slow leak in the subsurface may become even harder to detect as the fluid migrates towards the surface and possibly becomes more dissipated. Abnormalities that can be attributed to a leak may become difficult to detect over prolonged periods. Therefore how much surface monitoring is necessary for ALARP (As Low as Reasonably Practicable) given storage at depths of 3km with multiple impermeable layers acting as natural barriers to any upward migration. Caprock layers are very well characterised prior to storage site selection and CO_2 injection. Surface monitoring is much more about stake-holder assurance. It should also be stressed that leakage is most likely to occur near a well.

Japanese coastal fisheries are a good example of stake-holder engagement and reassurance. This community is unfamiliar with CCS and needs to be reassured that the technology does not adversely affect their livelihoods. Consequently marine surveys are essential to maintain confidence that CO_2 storage is secure.

Long-term temporal variation becomes more evident with monitoring but relies on continuous monitoring over long time periods for no significant gain. Offshore spatial variation over a large area can be measured using AUVs. If an anomaly is detected a more detailed investigation can be focussed on the area of interest.

Session 6: EOR-MRV Discussion - What Does It Teach Us? — *Chair: Tim Dixon, IEAGHG*

EOR-MRV Plan from Occidental - Sue Hovorka, BEG

The first Environmental Protection Agency (EPA) approved MRV plan for the Oxy Denver unit has been published. It provides an industry plan for monitoring CO_2-EOR operations for greenhouse gas reporting in the USA. The MRV plan should be celebrated as a successful collaboration between regulators and operators that will lead the way forward for future CCS projects. A brief summary of the plan was presented and followed by discussion.

The Wasson Field has a complex operational history with water-flooding having occurred at the site from 1983. The reservoir is known to have been characterised in great depth although a limited amount of this information was included in the final MRV plan. There are a total of 885 wells penetrating the Denver Unit, 498 of which are active. All wells have been permitted. The field already contains 128.8 Mt of CO_2 and the new plan for the Denver Unit is to supply 13.5 Mt of CO_2 from gas processing plant in Val Verde Basin.

A timeframe of 2016-2026 has been given as the 'specified period' for their MRV plan. Monitoring and modelling after this specified period is planned for 2-3 years to demonstrate that surface leakage is not expected and reporting can cease. However as an EOR site, injection will continue for 50 years after the end of the specified period. One approach for detecting CO_2 releases to the atmosphere was to assure that there will be regular weekly visual monitoring to check for signs of white ice formation. Leakage outside the production wells was not considered a major risk because of reduced pressure in the casing. Personal H_2S meters can detect leakage around production wells and act as a proxy for CO_2 monitoring.

Overall the MRV plan shows a pragmatic approach to monitoring and a highly experienced team collaboration to produce such a plan is a great step forward for future CCS regulation. Some recommendations have been outlined and future improvements would be beneficial.

Session 7: Upscaling from Core to Reservoir — Chair: Jonathan Ennis-King, CSIRO

Upscaling from Core to Reservoir the Statoil Experience - Philip Ringrose, Statoil

A pore to field workflow has been developed for oilfields, illustrated by a Statfjord oilfield case study, showing how multi-scale simulation can be done using upscaling methods. The first step was to identify pore types and laminae then calculate multiphase flow functions, apply functions in lithofacies models and finally upscale the lithofacies model and compile the data in a full field flow simulation. The objective of the study was to significantly improve history matches of simulations to observed data.

The Representative Elementary Volume (REV) concept can also be used at multiple scales to form a lithofacies REV at the metre scale, and then continue through system to have a stratigraphic REV at the 10-100 metre scale. This study looked at different associated flow processes with different scales and applied them to the multiscale REV concept. The balance of forces concept merged with REV was found to be useful to indicate which scales most effect flow. For example, capillary trapping is dominant at laminar REV scale and sequence scale REVs are dominated by gravity flow or viscous channelling.

Steady-state solutions are a faster way to solve multi-phase (CO_2-brine) flow problems. They represent end-member cases for gravity, viscous and capillary dominated flow. The reality for CCS fields lies between these end members and the gravity-viscous ratio is very important for establishing storage capacity factors.

The study concluded that CO_2 storage is dominated by gravity and capillary forces and multi-scale approaches should be used to improve models of these processes. This approach helps provide an upscaling that does not involve thousands of different rock functions or just one simple length scale.

The use of Digital Rock Cores in Flow Modelling. Catriona Reynolds - Imperial College

Digital rock cores are being constructed from experimentally derived data to help analyse how heterogeneities impact fluid flow and scale these processes ton reservoir dimensions. Research at the Qatar Carbonates and Carbon Research Storage Centre has shown in previous studies that neither the wetting state nor relative permeability govern fluid flow as significantly as heterogeneities within the rock core. Large scatters in flow properties can be seen in core samples considered homogeneous (e.g. the Bentheimer sandstone) during fluid flow experiments.

Initial experiments showed rock heterogeneity to become increasingly significant at low CO_2 viscosities. Small heterogeneities can lead to large variations in saturation and thus control relative permeability. This is because larger flow potential can support larger capillary pressure gradients. This heterogeneity hypothesis was tested using nitrogen core flooding experiments where flow rates increased rather than using varying viscosities. Saturation maps were used to estimate capillary heterogeneity and showed impacts of rock heterogeneity were the 'rule' rather than exception.

The objective was to parametrise a digital model for flow modelling and perform numerical core floods. Firstly, the saturation density data at steady state flow is coarsened to improve precision. Then individual capillary pressure curves are extracted and scaled using the average measured curve. This methodology is used to build the simulation.

It was concluded that laboratory experiments show that a low potential gradient in multiphase flow implies that centimetre scale heterogeneity will control flow properties. Accurate flow properties must be derived as the basis for larger scale simulation. Experimental work is constrained by certain elements (e.g. flow rate, rock orientation) and numerical modelling can be used to overcome these and obtain properties more representative of the reservoir conditions. A key to constructing these models is the parameterisation of capillary heterogeneity from core flood observations.

Upscaling Sub-core Scale Heterogeneity - Dave Cameron, Stanford University

Lots of measurements have currently been made at core-scale to establish the physical process linking porosity to saturation. 3-D saturation maps taken in 2010 using X-ray Computed Tomography (CT) scans to look at the core showed nonhomogeneous saturation even in homogenous rocks. Simulations looking at porosity, permeability and capillary pressure show that non-homogenous saturation can only be accomplished by changing the capillary pressure curve. Therefore various curves are needed to create the spatial variation seen within core analysis.

An assessment of the accuracy of permeability maps was conducted using Positron Emission Tomography (PET) 4-D scan. PET is a passive scanning technique that measures radio-active tracer radiation to build a 4-D image of fluid migration through the core. Capillary pressures and heterogeneity were measured directly. The simulation reveals that the trapping behavior is similar to that which would be described by a typical hysteresis model.

This overview of a number of studies showed that upscaling flow processes without taking into account capillary pressure heterogeneities will lead to an overestimation of plume volume which becomes increasingly problematic at field scale.

Session 7: Discussion

Storage when applied in real-world situations is a pressure driven problem rather than CO_2 flooding conducted in experiments. A common assumption at reservoir scale is that the process is a viscous dominated system but in the field as a whole, just a few meters from the wellbore, this condition may not be evident. There is further need to understand and integrate experimental fluid physics of CO_2 with large scale characteristics observed in reservoir studies. Although injection rates will be different for CO_2 storage compared with oil and gas production the main factor that will make a difference is the mobility ratio of CO_2 and brine as heterogeneities will have a much larger impact than previously seen in hydrocarbon fields. Experimental analysis and prediction is likely to improve in the near future given the advances seen in CT-scanning technology. More work will also be required to study CH_4 as a phase. The mobility, density and response of this hydrocarbon to rock mechanics will vary compared to CO_2.

The was a recommendation to acquire more data on the petro-physical properties of low permeability tight zones and high permeability thief zones as these reservoir conditions represent two extremes that influence CO_2 migration within reservoirs. The properties of these 'odd-balls' would be helpful to aid future simulations.

Session 8: Wellbores – Legacy & Future — *Chair: Rajesh Pawar, LANL*

Well Integrity - Andrew Duguid, Battelle

Well leakage is considered a significant risk for CO_2 storage and hence integrity monitoring is important to provide data to constrain any potential flow paths. There is a need for time-lapse integrity monitoring to identify changes in cement, the casing and the bond between the two with time. Tools to monitor integrity include ultrasonic imaging, cement bond logging, corrosion monitoring and saturation tools (e.g. pulsed neutron).

SECARBS's Phase II project at the Cranfield site in Mississippi studied three monitoring wells (one 68 years old and two newer seven year old wells) in an EOR setting. Samples were taken in and above the production zone. All three wells showed a variety of good cement (where no changes were seen) alongside potential integrity issues. Potential pathways were identified using the ultrasonic imaging tool which highlighted poor cement bonding with the casing. Cement material was removed during a cased-hole flow test in 2013 where an analysis from the lab showed it to be of poor quality and an annulus of 0.2-0.4m was predicted. Log images also showed successful cement squeezing in some cases.

Changes in well integrity were identified over a short five to six year period in and above the CO_2 zone which require further research to fully understand their importance. Potential pathways were identified in all three wells and all wells maintained overall integrity throughout injection.

Modelling Leakage of CO_2 in Wellbores using the Drift-flux Model - Curt Oldenburg, LBNL

A review of leakage conceptualisations and modelling of upward fluid leakage was presented, focusing on the capability to simulate coupled processes (e.g. phase change). Degraded cement can be modelled as porous media until connected annular gaps form at which point non-Darcy approaches are needed. The T2Well code was developed that implements the drift-flux model in wells within the TOUGH2 framework. T2Well has been used extensively to simulate two phase flow of CO_2 or CH_4 in water or oil. The code provides a coupling of wellbore and reservoir flow and transport.

T2Well was applied to the Macondo oil well blowout to make an estimation of leakage rate assuming pipe flow up the well. Results showed the oil flow rate is sensitive to the size of the opening to the well (in the reservoir) and is also sensitive to pressure at the bottom of the blowout preventer (BOP), but this sensitivity is tempered by increased degassing for low BOP pressures.

For CO_2 flow up wells from deep storage sites, long vertical upward flow was shown to lead to a phase change including the possibility of formation of liquid CO_2 depending on the thermal connectivity between the well and formation.

In conclusion different well leakage scenarios will require different conceptualisations (e.g. porous media or open pipe flow). Regardless of the conceptualisation a rigorous coupling to the reservoir is needed; bottom-hole pressure cannot be assumed to be fixed and phases must be allowed to flow towards the well. T2Well can be used to simulate non-isothermal, multicomponent, two-phase flow in open pipes or annular gaps coupled to a porous media reservoir.

Two key conclusions were drawn from this modelling:

- Capabilities to model CO_2 leakage from wells are needed.
- CO_2 blow outs are not well understood and therefore there is a need to develop expertise in processes related to multiphase CO_2 behaviour in wellbores. Standard oil industry practice is not adequate.

Modelling Storage Failure (Potential Leakage/Fluid Migration behind Cementations) as an Element of a Risk Assessment. - Sylvain Thibeau, Total

The risk assessment strategy for the Rousse Storage project focused on the RSE-1 injection well (2km deep and constructed in 1967) as the greatest potential for leakage. It assessed the likelihood of a hypothetical pathway between the storage Mano reservoir and the above Lasseube limestone reservoir. Analytical and numerical models were used to evaluate potential flow and review cementations and the above aquifer.

Initially the cement was evaluated and cement bond logs (CBL) showed that the bond index had improved between 1967 and 2009. This is likely due to a contaminant in the cement preventing it fully setting at the time of the first CBL in 1967. A continuous micro-annulus along the cement sheaths with a 50 micrometre thickness was then modelled as a hypothetical migration pathway. A model was produced to look at flow with an assumption that the pathway was open from January 2017 and ran for 200 years. A minimum Lasseube aquifer volume was assumed. The model was designed to represent a worst case scenario.

The model results showed the aquifer formation waters flow into the reservoir as a result of low pressures. At 4.2km depth the lower pressure of approximately 10MPa leads to 1,100m3 of water having flowed into the reservoir by 2200. The flow rate stabilised at 0.01 m3/day. No gas is seen to flow into the Lasseube aquifer. The time taken to reach pressure equilibrium is approximately 1 million years.

Post-injection monitoring has been performed for three years at Rousse in accordance with French regulatory requirements.

Session 8: Discussion

Longer-term wellbore integrity should form part of risk assessments conducted at the start of pre-injection site characterization. Wellbore integrity depends on the type of formations penetrated and at what depth. Abandoned oil and gas fields in the North Sea are known to have shale and salt formations that pack off wellbores due to the movement of these rock types around the wellbore. This phenomenon can form a better seal than cement.

The concept of CO_2 storage based on multiple barriers will ensure long term security. If the capillary pressure ΔP is small then CO_2 flow will be very slow unless the system is pressurised. Migration through multiple barriers means that should CO_2

migrate through one barrier it will be trapped by the next layer but on geological time-scales of hundreds of thousands of years.

The consistency of time-lapse logging as a post monitoring methodology was questioned. Provided similar logging tools are run at different time intervals over 5 – 10 years then it should be possible to detect changes but at long-term times of 50 – 100 years there might be a need to consider what needs to be monitored. The poor quality of some historic logs also needs to be taken into consideration.

Session 9: Modelling Environmental Conditions in the near surface and atmosphere *Chair: David Vega-Maza*

Modelling Marine Impact - Jun Kita, RITE

The objective of this study was to assess the potential impact of CO_2 leaking to the surface and impacting the marine environment. This process considered leakage scenarios and potential CO_2 dispersion. A base-line survey was also conducted for a marine environmental impact assessment. Leakage through a fault was modelled with the assumption that a leak would be undetectable from a seismic survey. Using TOUGH2 and ECO2M models the simulation produced CO_2 flux at the seafloor. An extreme event two phase MEC-CO2 model was required to simulate CO_2 dispersion in the water column. The results showed that the estimated area of environmental impacted was negligible even given the large scale of the leakage scenario.

The study looked at the determination of a threshold for an ecological impact which was estimated from a biological impact database. The effects on organism physiological when exposed to high CO_2 concentrations were examined including the Sillago japonica and Japanese flounder fish. Generally the results showed that any changes in morphology were minimal (some growth suppression due to lower metabolic rates) only affecting approximately 10% of organisms tested and the recovery was rapid (3-24 hours for the flounder fish). The recommendations for monitoring methodologies were to adopt a staged approach including diver surveys, in-situ sensors and ship-board measurements.

The study highlighted the importance of public acceptance and necessitates a wider dialogue between scientists, policy makers and the public. International collaboration was highlighted as being highly derisible. It can be concluded from the organisms tested that 200µatm of CO_2 can be considered a safe threshold for CO_2 concentration.

Modelling Near-Surface Processes - Katherine Romanak, BEG

The spatial and temporal complexity of the near-surface makes the source attribution of anomalies difficult. BEG have used a "process-based" approach that uses soil gas geochemical ratios for attribution. Such assessments are currently standard procedure in groundwater monitoring but under-utilized in soil gas studies. The gas ratio technique is beneficial as no background is required and can be applied to a variety of environments regardless of variability.

Gas ratios were used to identify processes such as biological respiration, methane oxidation, dissolution and leakage. The O_2:CO_2 relationship distinguishes between respiration, CH_4 oxidation and dissolution to give an initial assessment of leakage as any increase in CO_2 will change the ratio. The ratio of N_2:CO_2 identifies whether a gas has migrated from depth, and hence identifies whether CO_2 originates from a deeper source or from surface dissolution.

The variability observed in ratios from various environments was modelled and the outcome showed that the soil's water saturation had a large impact on the gas ratios due to the differences in the solubilities of each gas. Ratios provide a "use-friendly" environmental monitoring technique that is easy to communicate to stakeholders and provides a clear and universal threshold for knowing when additional action may be required. This is a conservative method that reduces the risk of false positives. In conclusion, these ratios are sensitive even when dissolution occurs. Work is currently being developed in using the ratio data to quantify surface emissions and make flux calculations.

Overview of Modelling of CO_2 Flow and Dispersion in the Shallow Subsurface and Above Ground - Curt Oldenburg, LBNL

Darcy flow methods were run using EOS7CA under the TOUGH2 framework to study H_2O, brine, tracer and air in a vadose zone simulation. CO_2 migration through a 30m thick vadose (unsaturated) zone with an infiltration rate of 10cm/yr. The results showed greater lateral spreading occurred where the flow rate was higher (i.e. at the water table).

The ZERT shallow release facility was used to compare simulations and monitoring results. Tests in 2007 showed a close match between the two and this field-scale testing allowed a validation of the modelling approach. Wind is a highly effective means of dispersion and dilution of CO_2, that overcomes the higher density character of the gas. Calm conditions and topographic influence could therefore have a large effect and requires further research.

Releases from pipelines were also modelled using CFD modelling (Computational Fluid Dynamics). The model showed that CO_2 dispersion was greater at higher wind velocity and at a greater energy of release. Buildings and obstacles on site also had an influence on atmospheric plume migration. Very high concentrations did not persist around the leaking pipeline for long due to the small dimension of the pipe (and therefore its low volume capacity).

Session 9: Discussion

Pipeline failure has also been studied by the UK's National Grid to validate catastrophic pipeline failure of CO_2 to improve experience in the area. Controlled failure experiments have also been used to validate models of rapid releases. Automatic pipeline shut-off is not yet well regulated although it is a standard procedure for controlling emergency conditions. Pipelines are shut down automatically if there is a large pressure drop.

The smaller scale of the CO_2 migration studied, for example in shallow sediments, the more likely heterogeneities such as channelling and preferential flow paths are to become influential. Evidence from macro-scale field experiments have corroborated models.

Monitoring methods can also be carried over to study CH_4 emissions, but this gas is rapidly oxidised in the atmosphere. CO_2 absorption into soil should be the next research topic on the agenda.

Session 10: Ongoing Projects — *Chair: James Craig, IEAGHG*

Current Norway Strategy Update - Philip Ringrose, Statoil

In May 2015 Gassnova delivered a pre-feasibility study on potential full-scale CCS projects in Norway and recommended continuing studies for capture at the Norcem cement plant and Yara ammonia facilities. In July 2016 the Norwegian Ministry of Petroleum and Engineering announced results of the full-scale feasibility report for CCS. The Norwegian Ministry emphasised they intend to share all knowledge gained, improve the market situation for CCS and demonstrate CCS is safe and effective. The cost for planning full-value chain CCS is estimated between 7.2 and 12.6 million NOK and operational costs are estimated between 350-890 million NOK per year. All costs have an uncertainty of +/-40%.

Three storage sites are currently being evaluated, Smeaheia area, Heimdal platform and Utisra South area. All three associated capture sites are industrial. Transport is to be handled by the Norwegian entity Gassco with the main focus on shipping solutions. Of the three sites Smeaheia is currently preferred as it is located close to the 'Troll' field, 50km due west of the coastal city of Bergen. It has the lowest associated risk, largest storage capacity and best potential for scale-up. Government budget evaluations and hence the future of CCS investment will be announced in September 2016. Should the process begin then injection could start in 2022.

The Quest CCS Project – the First Year of Commercial Operation - Simon O'Brien, Shell

The QUEST project in Canada has been operation for a year. The CO_2 source is an oil sand facility (upgrading bitumen to synthetic crude) where 1 million tonnes of CO_2 per year is captured (1/3 of the emissions). A 65km pipeline is in use with 6 block valves (with maximum 14km spacing). The compressor includes a dehydration unit to minimise water within the pipeline and pressure is maintained above 10MPa to ensure dense phase CO_2 throughout.

The storage is into basal Cambrian sands with 17% porosity and 1,000mD permeability at 2,000m depth. Shale and salts form the seals. The storage facility consists of three well pads with an injection and deep monitoring well on each pad. Conventional drilling techniques are used with multiple steel casings for the injection wells all cemented to the surface. A comprehensive MMV program is in place from atmosphere to geosphere with baseline data collected before start-up plus an independent review. Remote sensing was removed from the MMV plan given poor correlation results and lack of spatial and spectral resolution. Surface deformation models and InSAR data have been collected and are currently being analysed. A Light Source system has been deployed for atmospheric monitoring and release tests have confirmed the detection of CO_2. Comprehensive baseline data of groundwater analysis has been undertaken and Shell are currently working with regulators to optimise a sampling methodology with the focus likely to be shifted to monitoring close to injection wells. A tracer assessment is currently being tested with laboratory work hoping to show the injection gas has a distinct background CO_2 source.

Seismic VSP modelling and acquisition have been conducted with wave equation synthetics used to predict seismic. The initial VSP design was to incorporate 3-D imaging but proved to be too expensive. Data collected so far have shown a good correlation between the expected and measured plume size. A microseismic array has been continuously collected at one of wells since November 2014. Surface noise has been detected alongside minor natural seismicity.

The pressure data collected from deep monitoring wells shows no indication of any problems or leakage paths. A pressure fluctuation greater than 200kPa is the threshold indication for a leak. The current pressure build up in the reservoir is less than expected and reservoir properties are better than expected. Total pressure build up is expected to be less than 2MPa by the end of project life.

To date $CAD1 million has been reduced from the project budget in streamlining the MMV process, removing RIA and MIA, revising the groundwater strategy and changing the VSP survey design.

Aquistore - One Year of Injection - Kyle Worth, PTRC

One year of injection into the deep saline CO_2 storage project at Aquistore was reached in April 2016. A total of 71,000 tonnes of CO_2 have been injected and sorted at a maximum injection rate of 2,100 tonnes/day. No induced seismic events have occurred and 30 new monitoring technologies have been developed as a result of the extensive MMV plan. The first monitoring results from well logging and 3-D monitoring seismic surveys have been focused on but a much wider variety of techniques were used.

A reservoir simulation model was produced by EERC and is being updated daily with pressure and injection data. This data is providing an updated breakthrough prediction and providing a guide for the repeat logging programme. A non-isothermal model reservoir geochemical simulation is also currently under development to take into account the 60°C temp differences between the reservoir and injected CO_2.

A 3-D surface seismic and 3-D VSP were acquired in February 2016, the forth seismic survey acquired but the first post-injection. The same seismic parameters have been used for all the seismic surveys (260 shots, 600 receivers and a 72m receiver spacing). The reservoir is deep (3,200m) and relatively small quantities of CO_2 have been injected to date. The baseline and first monitoring seismic surveys are seen to be almost identical showing excellent repeatability. The mean nRMS (normalized RMS amplitude, a repeatability measure) value was 12% for the baseline compared to first monitoring result. A value less than 40% is considered excellent. A clear anomaly within the reservoir relating to CO_2 injection has been detected in the first monitoring survey conducted but CO_2 had not intersected the monitoring well by July 2016.

Aquistore is expecting an increase in injection volumes to 800-1,000 tonnes a day following the October 2016 outage. In general CO_2 capture volumes have been increased and stabilised since November 2015.

Progress of the Tomakomai CCS Demonstration Project. Hideo Saito - Japan CCS Co. Ltd.

Test injections began in April 2016 at the Tomakomai project and the first fall off test is currently underway. The start of full-scale injection was planned for August. Public outreach events have been important throughout the project with a website, live camera, panel exhibitions, site visits and disclosure of monitoring results of injection to residents.

A baseline 3-D seismic survey was conducted in 2009, and a 2-D baseline was completed in 2013. Monitoring surveys will be undertaken in 2-D at the end of 2016 and 3-D in mid-2017. A trial of passive seismic imaging with seismic interferometry was also conducted using continuous data recording by permanent type OBC (Ocean Bottom Cable). A total of 158 natural seismic events were extracted and processed with seismic interferometry. Although reflectors at the depth of the reservoir were clearly imaged, time lapse application remains a future task. A modelling-monitoring loop is due to start at the end of 2017.

Otway - Jonathan Ennis-King, CSIRO

The Otway project located in south-eastern Australia has completed stages 1 and 2B (initial injection and dissolution testing). Stage 2C is currently in progress, the seismic detection test, and began in December 2015. This involves in the injection of 15,000 tonnes of CO_2 rich gas into a saline aquifer detected using a buried geophone array. The Stage 2C project goals are to ascertain a minimum seismic detection limit for CO_2 injection. The gas plume development is to be observed using time-lapse seismic and to verify the stabilisation of the plume within the saline aquifer.

The monitoring methodology involves a 4-D seismic array with a buried receiver array acquired concurrently with 4-D VSP. A baseline survey was carried out in March 2015 with monitoring sur-veys at 5kt, 10kt and 15kt. Surveys at one and two years post-injection are also planned. A 4-D seismic survey with buried DAS array, 4-D VSP in CRC-2 and continuous seismic sources is also planned. Multiple downhole pressure and temperature gauges both in and above reservoir zone will also be used. The monitoring design has been based around the predicted plume extent pro-duced by models in 2009. The next stage for the project is to history match the observed geophys-ics with the initial models.

The buried geophysical array has been successfully deployed and the seismic data acquired shows a good signal to noise ratio. Above-zone pressure monitoring shows a detectable response to the injection in the three reservoirs.

Midwestern Regional Carbon Sequestration Partnership (MRCSP), Phase III – Neeraj Gupta, Battelle

More than 600,000 tonnes of CO_2 rich gas have already been injected at the MRCSP Phase III Site with the goal of injecting 1 million tonnes after 5 years. A gas processing plant is located towards the south of the injection site where CO_2 is captured and transported. There are 10 fields at the site currently used for EOR. The MRCSP site includes 10 reefs at different stages of the oil production cycle.

Pressure monitoring in the late-stage reef started at 700psi (4.83 MPa) below critical CO_2 injection pressure levels. Within a few months the reservoir reached its injection capacity and pressure quickly increased. A two year fall-off period was then started and studied, and a 200 to 300 psi (1.4 – 2.1 MPa) drop in pressure per day was noted.

Based on two years of InSAR data no perceptible change was noted. Simple geomechanical modelling was conducted using log based data from a nearby reef to compare the predicted surface displacement with any observed data. This model also indicated that if any displacement occurs it will be below the detection threshold of the InSAR resolution.

A baseline microseismic monitoring survey was also conducted using high detail fibre optic arrays. Only a few true microseismic events were noted and these were not large enough to be conclusively distinguished from background noise.

Heletz (Israel) Pilot Project - Auli Niemi, Uppsala University

Heletz CO_2 injection site in Israel is a scientifically motivated, mainly EU funded, R&D site with CO_2 injection at 1,600m depth. The main objectives of this experimental programme are: to develop understanding of residual and dissolution trapping mechanisms at field-scale and to evaluate the impact of heterogeneity on them; secondly to estimate how to enhance trapping with different modes of injection; and the effect of gas impurities on the CO_2 stream.

There are two specific experimental wells on site, for injection and monitoring purposes, with well instrumentation including pressure and temperature sensors, U-tube fluid sampling and optical fibre monitoring. Old oil well records gave a good indication of geological properties in the area and were locally refined based on data from new wells to provide an initial site characterization. This structural model was enhanced by an extensive laboratory testing programme on rock properties and their changes when exposed to CO_2/brine under in-situ conditions, as well as field-scale testing of hydraulic and thermal characteristics. It can be noted that laboratory tested permeability measurements were notably higher compared with old oil field records and the field-scale permeability exceeded all the previous records.

The CO_2 injection test program is broken down into four parts. The first test in the programme determined in-situ residual trapping parameters from a push-pull experiment. The second test is on impurity gases using SO_2 and N_2. The third test addresses residual and dissolution trapping parameters by means of a dipole experiment and the final experiment addresses enhanced trapping mechanisms using different modes of injection of CO_2. The first test was started in November 2015 but the U-tube sampling system could not maintain formation pressure and leakage occurred in the tubing. Replacement U-tubes were provided and single-well experiments resumed in late summer 2016, with the residual trapping experiment now being completed and the second experiment in the series now underway. The entire programme is planned to be completed during 2017.

Monitoring and Modelling CO_2 Injection at K12-B - Vincent Vandeweijer, TNO

K12-B in the Netherlands in the first site to inject CO_2 into the reservoir it originated from. Injection started in 2004 and serves also as a field laboratory on a fully operational gas platform. Currently, twelve years of successful re-injection of CO_2 have been undertaken without any major incidents.

The initial project was performed by Gaz de France and TNO with the aims of studying regulatory and social aspects, necessary equipment, economics, behaviour of the gas field, and safety / environmental aspects. The CO_2 is separated from the natural gas via an adsorption process after which it is re-injected into the mainly fluvial and some aeolian sediments of the Upper Rotliegend reservoir at 3,900m depth. The primary top seal of the reservoir is hundreds of meters of salt deposited during the Zechstein.

History matched cellular models for pressure flow were created and CO_2 concentrations in production wells were also modelled. Various simulators were used and regular updates have been performed. Currently these models are being applied in two projects. The results of back-production tests are being investigated in the EU MiReCOL project, where simulations have predicted higher CO_2 concentrations than measured samples. The migration and retardation effects of CO_2 and CH_4 in reservoir via chemical tracers is also being investigated under a nationally funded project.

Two rounds of chemical tracer injections have been conducted to study migration and retardation effects of CO_2 and CH_4 in reservoir. The latest testing (June 2016) has been designed together with CSIRO. The tracers are expected to migrate at different velocities through the reservoir with the objective of detecting their presence at production wells. A future experiment to restore the original natural salt seal by removing part of the casing is being planned. Part of the casing will be removed to let natural salt creep close the well.

Adaptive Approach to Modelling and Monitoring 3 Million Tonnes of CO_2 Stored at the Bell Creek Oil Field - John Hamling, EERC

Bell Creek, operated by Denbury Onshore LLC, is an oil field in Montana where the EERC is studying CO_2 storage associated with commercial EOR. The CO_2 is sourced from ConocoPhillip's Lost Cabin natural gas-processing plant and Exxon's Shute Creek gas processing plant. CO_2 injection started in May 2013 with over 3 million tonnes having been stored to date.

An adaptive management approach has been taken to site characterization, reservoir simulation and monitoring. Three major geo-model and simulation model revisions have been undertaken (time-lapse seismic data showed pressure and fluid communication across a permeability barrier separating two portions of the reservoir). A strategic MVA plan is in place driven by performance forecasts. Extensive geologic characterization and MVA programmes have been developed since 2009. The research-monitoring program used over 16 techniques with 1.5years monitoring pre-injection and 3+ years of operational monitoring planned.

SASSA (scalable, automated, semi-permanent seismic array) is a new seismic method used at Bell Creek to track CO_2 saturation changes. A remote-controlled seismic source is used with autonomous node recording instruments to make regular time-lapse recordings. The concept is that a small percentage of CO_2 in the reservoir may change the reflection character in a detectable way as it moves past a monitored point.

Session 10: Discussion

Now that good quality monitoring results are being obtained from a series of demonstration sites history matching can improve model forecasts. In addition to predicting the pattern of CO_2 distribution within a reservoir monitoring can also reveal details about the reservoir geology which were not necessarily known prior to injection. A better understanding of a reservoir enhances the ability to forecast CO_2 behaviour and the ability to manage CO_2 storage.

Reservoir engineers' perspective is that a history matched reservoir model is only as good as the properties that were under investigation. CO_2 has low viscosity and is a good tracer because of its response to seismic under most circumstances. Dynamic flow models used in K12-B did produce a good history match but the model predictions for pressure and the timing of CO_2 migration were poor. This was attributed partly due to reservoir heterogeneity but there were also external factors including a leaking well from another reservoir below the storage unit that was at a higher pressure. This set of circumstances only became evident through actual operation.

3-D seismic decomposition images are generated from signal processing and detailed analysis by experienced geophysists which requires considerable time and skill. Consequently a high quality trained work force is necessary in geophysics, reservoir engineering, geochemistry and geology to deduce and predict how CO_2 behaves in reservoirs.

The evidence from the demonstration projects shows the effectiveness of the monitoring-modelling loop. There also needs to be a good understanding of the underlying physics particularly in relation to wave propagation. The next step is to improve the understanding of CO_2 saturation within a reservoir especially with different hydrocarbons present. Interpretation and understanding is an iterative process which requires confidence in reservoir models to predict where CO_2 migrates and the limits of the plume so that a final case can be made to regulatory agencies. This criterion distinguishes CO_2 storage sites from CO_2-EOR operations. Storage site operators need to be aware of this distinction and plan for eventual site closure.

There is a general perception that CCS is expensive, but the evidence from demonstration sites shows that storage can be successfully achieved. The ZEP (Zero Emissions Platform) has estimated reasonable costs of $8-$20/tonne for transport and storage of CO_2. The aim is to shift to these projections towards $5/tonne. Experience indicates factors such as heterogeneity has a notable influence on storage costs. Pressure management and the related pre-treatment of formation water is another cost factor that has been taken into consideration. Costs for treatment can equate to $4/tonne of CO_2 stored up to $80/tonne for highly saline formation water. The water quality of onshore reservoirs is a key factor in site selection. Offshore controlled discharges can be used to alleviate costs. The selection of site-suitability on costs is a key factor in the prioritisation of sites.

Session 11: Closed and Post Injection Projects — *Chair: Jonathan Ennis-King, CSIRO*

Experience from the Ketzin site - Stefan Lueth, GFZ

The Ketzin site in the north-east German basin is a sandstone saline aquifer with a mudstone caprock in part of an anticline structure. CO_2 injection started in June 2008 and last for 5 years until August 2013. The project is now in the 'post-closure' phase. The reservoir model is in its fifth phase and has been progressively updated with successive phases of monitoring data. History matched observations of the pressure evolution at the injection well have been incorporated. Geophysical monitoring was performed intensively during the injection phase which now continues in part during the post-injection phase. Other monitoring techniques included neutron-gamma logging and cross-hole and surface-downhole geoelectrics.

Repeat 4-D seismic surveys were undertaken, two during the injection phase and one two years post-injection. Seismic amplitude difference at the top of the reservoir indicates that stabilization has occurred. For three months at the end of 2015, 3,000 tonnes of brine were injected into the storage formation. The first purpose of this activity is to enhance the imbibition process to enable studies for quantifying residual trapping and also to test brine injection as a remediation measure in case of a leaking well. The brine injection experiment was accompanied by a dense sequence of crosshole and surface-downhole ERT surveys. Images generated from these surveys revealed decreasing resistivity related to brine propagation and saturation changes in the reservoir.

Well Ktzi 202 has now been backfilled and surface installations removed down to a depth of 2m with surface soil restored. The remaining wells are planned to be filled in Q2-Q3 of 2017. Side-core drilling is planned for Ktzi 203 prior to closure. No further seismic is currently planned due to budget restraints.

Rousse CO_2 Storage: Geomechanical and Geochemical Modelling - Sylvain Thibeau, Total

Historical hydrocarbon production of the Rousse reservoir led to the area adjacent to the well (being used for CO_2 injection) RSE-1 being dehydrated. Flow modelling predicted CO_2 flow would be driven by its density and flow away from the caprock. Geochemical stability was assumed to be straightforward in the modelling process as injection was into a gas reservoir at low pressure. Extensive investigation incorporated initial stress scenarios, 1-D and 3-D mechanical earth models, seal rupture analysis and fault stability studies. However, geomechanical stability was challenged by third parties. Proof of geomechanical stability in a pressurised store would have been even more challenging. Modelling of pH changes with time was also undertaken and showed a pH increase over time in depleted areas. This shift in pH is attributed to CO_2 degassing due to depletion. These effects are the same as a natural depletion associated with oil or gas production which would not normally be studied.

Overall it is difficult to use 3-D coupled models to perform a safety diagnosis as any parameter can be challenged and even if no risk is identified or predicted by 1-D models, 3-D models add complexity and uncertainty that can be counterproductive.

Session 11: Discussion - Meeting Project Goals via Modelling-Monitoring Loop

The concept of the 'Assessment of Low Probability Material Impacts' (ALPMI) was introduced by Sue Hovorka to assess whether projects met their objective goals and whether the monitoring-modelling loop was able to address issues when the original goals were not met. Emphasise was also placed on a need to specify what needs to be achieved to define a 'successful project'. A list of material impacts would help define this. The definition of what constitutes a failure also needs to be clarified. Experience from demonstration sites has shown positive progress:

- The Nagaoka projects are currently considered to have been 'successful' as they have met the initial goals with solubility, capillary and mineral trapping having taken place.
- At Otway, during Stage 1, evidence has been produced that CO_2 migrated to the top of the structure without any sign of leakage.
- The Decatur Project in Illinois set out to show that it is a good site for injection into a deep saline formation demonstrating the suitability of this reservoir. Storage had been shown to be secure even though detailed reservoir characterization did not take place due to its location. With limited characterisation pressure matching with reservoir models has now taken place and stabilization criteria are now being analysed.
- The K12-B site has demonstrated containment. Risks were analysed and quantified so that unacceptable thresholds could be define and if exceeded the project could be stopped immediately.
- Rousse was considered a very safe site due to its history as a gas field with good quality wells. Modelling was not necessarily helpful. Because key elements of the site are safe the site's closure could be accepted.
- At Ketzin, the CO_2 migration within reservoir was not initially known during the most critical period (which created some unease with local stakeholders) even though a repeat of the first 3-D seismic survey showed that nothing unexpected was happening. The presence of reservoir heterogeneities caused deviations from the model.

To establish conformance, direction has to come from the regulator and stakeholder to constrain what has to be achieved. Knowing exactly where the CO_2 will migrate to and by when in order to predict future arrival times may not always be possible or necessary. There is a need to design a modelling-monitoring programme to address stakeholder concerns, i.e. risk based. For example setting a threshold level of no leakage hypothetically guarantees zero impact but proving that no impact has occurred may not be possible especially if very minor change has been induced by CO_2 injection. Expectations need to be set at the start of a project based on the limitations of modelling techniques. Heterogeneities invariably occur and experience shows that these features will effect predictions.

Overview of NRAP Tools - Bob Dilmore, NETL; Rajesh Pawar, LANL; Tom Daley, LBNL

To begin this session, Robert Dilmore, NETL Laboratory Lead for the National Risk Assessment Partnership presented an overview of the National Risk Assessment Partnership (NRAP) and the set of ten quantitative risk assessment tools that have been developed by NRAP research team and released to the international CCUS research, development, and deployment community for download and beta testing (presentation entitled: NRAP Tools for Assessment of Carbon Storage Risk Performance: Supporting Decision Making Amidst Uncertainty). Other members of the NRAP research team (Rajesh Pawar – LANL, Tom Daley – LBNL, Curt Oldenburg – LBNL) augmented that presentation with additional details on specific NRAP tools and assessment approaches. Following that overview, prepared feedback was presented by NRAP tool beta testers from organizations outside of the NRAP team – both to provide the NRAP team with valuable information to revise the NRAP tools, and to spur discussion (in the subsequent session) on broader development needs going forward for integrated assessment in CO_2 storage.

Seyyed Hosseini from BEG and Neeraj Gupta from Battelle presented individual feedback at the network meeting. Four additional NRAP tool beta testers were not in attendance, but provided written comment; a summary from those four beta testers was presented by Lydia Rycroft of IEAGHG. Each beta tester was asked two specific questions:

- Can NRAP tools be applied to a specific problem that you are working on now? To a problem that you have worked on in the past? To one that you are planning/hoping/expecting to work on in the future?
- What idealized/generalized questions do you imagine NRAP tools would be useful to probe?

The following NRAP Tools were discussed:

- Integrated Assessment Model – Carbon Storage (NRAP-IAM-CS) previously called CO_2-PENS. Simulates long-term full system behaviour to identify key drivers of risk (amidst system uncertainty). It estimates storage permanence quantitatively and incorporates reservoir, wellbore, shallow aquifer and intermediate reservoir/ atmosphere components. The tool provides Monte-Carlo simulations, with a variation of 10s to 100,000s of realisations.
- RROM-GEN Prepares reservoir simulation data for use in NRAP-IAM-CS (tool described previously), and writes output files in the format specified by the IAM. The outputs are pressure and saturation data in a time series of 2-D grid data. It is a utility function designed to take reservoir simulation results and extract the data needed for IAM, convert into a 2-D grid and write output files in format specified.
- Reservoir Evaluation and Visualization (REV) Tool. This reservoir visualisation tool generates images of CO_2 plumes over time and is suitable for Area of Review (AoR) determination.
- Short Term Seismic Forecasting (STSF). Estimates seismic event frequency over short-term periods associated with injection. The tool uses injection and seismic data inputs to provide a quick analysis on the type of seismic risks (i.e. are observations normal or unusual).
- Natural Seal ROM (NSealR). This tool estimates CO_2 flow through a fractured or perforated seal. It also assesses the impact of system parameters and uncertainties on potential flow to be determined. It evaluates the impact on groundwater aquifers based on threshold values. The program produces time history plots for 200-1,000 years and a 3-D cell flux plot.
- Wellbore Leakage Analysis Tool (WLAT). This tool evaluates the leakage potential for existing wells and records leakage response as a function of well disposition.
- Aquifer Impact Model (AIM). The tool allows a rapid estimation of volume of a reservoir that will be impacted by an abandoned leaking wellbore, distinguishing between CO_2 and brine impacts. The tool can be used to determine the threshold of impact criteria.
- Design for Risk Evaluation and Monitoring (DREAM). This tool can be used to estimate the time taken for an event to exceed monitoring detection limits. This then allows an evaluation of selection process to be undertaken of optimum monitoring designs.

Session 12: NRAP Tools (Part 2) – Evaluation, Discussion and Moving Forward

Chairs: Tom Daley and Lydia Rycroft

Following presentation on NRAP, the NRAP toolset, and feedback on those, Tom Daley (NRAP Monitoring Group technical lead) and Lydia Rycroft of IEAGHG facilitated discussion on the NRAP tools, and the capability needs of the GCS research, development and deployment community on topics. Generally, discussion showed feedback received on the NRAP tools has been largely positive, however, in most cases, there has been only limited use of data to trial these tools which would enable them to be compared with real field data. This will be addressed, going forward, by the NRAP team by pursuing demonstration and validation of the NRAP tools through collaboration with established large scale field sites.

Session 13: Lessons from Other Industries

Chair: Jun Kita, RITE

Detection of Shallow Gas from Gas-Field Projects Offshore Norway - Prof. Martin Landrø, NTNU (to be presented by Philip Ringrose, Statoil)

In 1989 exploration well 2/4-14 (in the Southern North Sea, operated by Saga Petroleum) developed a gas blowout which lasted for 326 days. The blowout consisted of natural gas from the exploration target zone but also mixed with natural gas which had migrated over geological time periods. The blowout was finally stopped using high density drilling mud. Shallow seismic studies were used to monitor the blowout with 10 surveys conducted during and after the blowout. This case study gives a valuable insight into the migration of shallow gas to the surface.

Seismic surveys showed clear chimneys around the well and in the vicinity with a range of sand layers incorporating gas (492m, 565m and 605m depth). Seismic images of the upper layer sands during the blowout show a circular plume which was dominated by pressure rather than structure at 490m depth. Initial operator analysis of the scale of the blowout was smaller than measured via monitoring techniques. 4-D refraction time analysis shows a gas accumulation which may be associated with tunnel valleys. It is currently thought that more gas migrated into the 840m depth sands than originally predicted.

Both natural gas and gas from the blowout are now present in shallow sediments. These shallow sand layers acted as a buffer against leakage to the surface with geological ice scours creating small traps for shallow gas. Geological tunnel valleys might also have acted as storage volumes and transport routes. Overall, this case study shows that the concept of a leak immediately migrating to the surface has to be re-evaluated and overburden characterisation needs to be undertaken.

Controlling Well Blowouts: Lessons Learned from Modelling the 2015-2016 Aliso Canyon Natural Gas Leak - Curt Oldenburg, LBNL

The Aliso Canyon gas storage leak occurred between Oct 2015 and Feb 2016 from the Sesnon-25 well adjacent to the Porter Ranch neighbourhood, California. Approximately 100,000 tonnes of methane were released to the atmosphere. Seven kill attempts failed until a new relief well was drilled (drilling started after a third failed attempt) to a depth of 8,400ft (2,561 m) finally killing the leak. DOE lab (Lawrence Berkeley National Laboratory) team assistance was required to review the failed well attempts using numerical modelling techniques.

Hydrates plugged the tubing of the SS-25 well at about 500ft (~152m) depth and well kill methods were not effective with the tubing plugged. Low-temperature mud was injected to clear the hydrate and kill the well but instead led to an increase in flow rate and return of the kill fluid to the surface. The well began to oscillate during kill attempts so a bridge was constructed over the well to help with support and prevent any further damage.

The failed kill attempts are thought to be due to the creation of a complex flow path for the gases and kill fluid within the well. Two-phase flow models were developed to simulate flow conditions that could kill the well. Simulated and measured pressures roughly matched giving confidence to the model. Simulations showed the actual amount of kill fluid used were insufficient to kill the well and they failed because the liquid fraction of the mixture in the annulus was never high enough to stop the gas flow.

Natural gas storage has some notable differences to CO2 storage which should be taken into consideration (flammable gas, corrosion, use of odorant, etc.). This case study highlights the importance of maintaining wellbore integrity for effective storage. Injection should be through tubing with casing providing secondary containment (unlike the well design at Aliso Canyon). At the Sesnon-25 well site, production and injection through the casing provided no back-up when well failure occurred. Overall, complex well geometries should be avoided and the use of downhole safety valves should be considered. A full quantification of the amount of methane released is currently underway.

Session 13: Discussion

For multi-layered systems AZMI could be considered simplistic whereas geological successions are often multi-layered and complex. Therefore it might be better to look at pressure response in multiple layers. It is possible that there are several cases where geology is simpler and AZMI monitoring could be beneficial and possibly low-cost if the storage used a former gas well but AZMI might not be beneficial in all situations. The technique might be helpful to plan how many wells might need to be used (either legacy or drilled) for monitoring purposes.

Session 14: Modelling Storage Reservoirs and the Overburden — *Chair: Rajesh Pawar, LANL*

CaMI Field Research Station: Shallow Release Monitoring. Don Lawton - CMCRI & University of Calgary

The CaMI (Containment and Monitoring Institute) field research station in Alberta is a 480 acre site (~194 hectares) on a 10 year lease from Cenovus Energy. A controlled release of CO_2 is being undertaken at 300m and 500m depth up to 1,000 tonnes a year. The aim is to constrain the CO_2 detection threshold for different monitoring technologies. Modelling has indicated that the injected gas should be detectable after approximately 800 tonnes. Given the remote location stakeholder engagement was not problematic but wildlife and livestock provided some constraints (i.e. cables had to be buried and protected).

The Phase 1 monitoring covers a surface area of 1km^2 with the injector well in a central location. Injection is into basal Belly River Sandstone which is overlain by coals and shales. A vertical flow is expected and the objective is to monitor its development. A baseline seismic survey is currently underway (with the aim of completion by August 2016) and the first groundwater monitoring well was installed to a depth of 70m in June 2015. Observation well 1 (geochemical monitoring) is located 30m north-east of the injector well to a depth of 350m. It was constructed with 120m steel surface casing and 4.5" (11.43 cm) steel production casing. It also has integrated fibre optic cable capable of distributed temperature sensing (DTS) and distributed acoustic sensing (DAS). Stainless steel U-sampling will be undertaken and an above zone pressure monitor is present above the coal zone. The second observation well (geophysical monitoring) is 20m southwest of the injection well with 56m steel surface casing and the same design as well 1. There is an integrated fibre optic cable for distributed heat pulse testing as well as DTS and DAS. Sixteen-level electrical resistivity cable with electrodes was mounted on the outside of the casing. A 24-level geophone array with nodes at 5m spacing for vertical seismic profile (VSP) acquisition and micro-seismic monitoring during injection was also included.

Injection was planned for the end of September 2016 and the monitoring methods to be evaluated are: high resolution GPS; INSar; surface tilt-meter array; borehole based muon tomography; optical fibre based sensors; continuous seismic sources and trenched surface DAS.

The geochemistry monitoring will include: atmospheric monitoring; groundwater sampling from domestic wells and from multi-level wells; soil gas (CO_2 and CH_4) monitoring with up to 24 soil gas probes and soil gas using 12 moveable soil gas flux measurements. Surface casing vent flow monitoring, plus observation well fluid sampling and analysis and tracer studies including 'doped' CO_2 with a trace of thermogenic methane. A collaborative study with Edinburgh University using noble gases is also planned.

Multi-level Pressure Measurements, AZMI and Earth-tide Monitoring at Otway - Jonathan Ennis-King, CO2CRC

Stage 2C at Otway is currently underway with 15,000 tonnes of CO_2-rich gas injected between December 2015 and April 2016. The primary objective is to detect the plume using geophysical techniques with a secondary opportunity to examine above and in-zone pressure response to injection rate changes. Multiple gauges were utilised to protect against failure or poor quality data. The pressure difference between two gauges was measured and related to average fluid density and calibrated when only brine was present in the formation. The in-zone water-gas interface at the wellbore is then tracked using computed fluid densities. At periods when injection rate reduced or ceased the interface is seen to rise sharply, giving an insight into how the vertical distribution of CO_2 during injection depends on the rate.

For analysis of the above-zone pressure, corrections had to be made for natural variations such as barometric pressure and tidal effects. The three phases of injection of 5, 000 tonnes in-zone led to an above-zone response of at least 30 kPa for each phase. A variety of physical mechanisms that might cause this response were investigated, to determine the 'signature' of each mechanism. Wellbore leakage has a much shorter characteristic time set by reservoir permeability, and could not explain the time lags in the above-zone response. Single-phase theory and simulation of pressure diffusion gives good predictions for the above-zone response. Smaller harmonic variations in the injection were trialled as a means of probing the pressure communication mechanism, but the effects of this in the above zone pressure data are currently inconclusive due to a very small signal.

In conclusion above-zone pressure monitoring is sensitive to small-scale injection and is able to detect large variations in the injection rate. Pressure diffusion through the low permeability baffles is the most likely mechanism. The analysis is complicated by multiple signals (barometric, tidal, pressure diffusion etc.).

Diffusivity Tomography with Harmonically Modulated Pressure Signals to Detect CO_2 Leakage in Above Zone Monitoring Interval - Seyyed Hosseini, BEG

The study investigated the applicability of pressure pulse testing for above-zone monitoring and leakage detection. Tests were used to detect if leaked fluid identification (brine or CO_2) was achievable by analysis of pressure data in a frequency domain. The objective was also to characterize CO_2 leakage geometry using a diffusivity tomography map.

A benefit to using pressure based monitoring is that a large area can be covered and can be deployed at any depth. Pressure gauges are a well-developed technology and are relatively cheap compared to other monitoring methods. They are also able to detect very small changes in pressure. Noise and data resolution/ frequency can present challenges for this method. Data management is also important to prevent a storage memory shortage. Pressure pulse testing requires at least a pulser well and observation well. There is a distinct pressure response due to periodic behaviour generated from the pulser well. The technique is also sensitive to hydraulic diffusivity changes but the ability to quantify the amount of CO_2 leaked given a diffusivity change is not yet possible.

In summary a pulse test response is sensitive to hydraulic diffusivity coefficient and can detect gaseous phase leaks. Frequency domain was applied to analyse the pulse test pressure data and derived diffusivity maps predicted the leakage geometry with reasonable accuracy.

The Requirements and Limitations for using Above-Zone Pressure Monitoring to Locate Leaks - Dave Cameron, Stanford University

This study took a computational approach to investigate how much monitoring data is required to detect and locate a leak. A model was designed with a 25x25x13 grid simulating injection of 5Mt/year for 30 years with a 470 year equilibration period. The simulation was conducted using Eclipse CO2Store.

The study concluded that multilevel AZMI pressure testing was unnecessary in the cases modelled and the shape of the leak and local grid effects were inconsequential (given the same leakage rate). The leaks modelled were detected long before breakthrough and located within 0.5km accuracy. It is assumed that a homogenous AZMI model loses approximately 200m in accuracy which increases when true geology is channelized. The models were insensitive to AZMI size.

Six to twelve months of data collection was sufficient to detect and locate single sources of leakage. Background noise in the pressure data initially serves to reduce accuracy, but eventually serves to improve location estimates by improving the conditioning the inverse problem. Leakage location detection was available using approximately 3-4 wells although a reasonable leakage volume estimate could be made from only 1 well. The model has some limitations which require further test evaluation. These challenges are an increase in the AZMI geological complexity, simulation of multiple leaks and comparisons of geo-mechanic versus leakage response.

Session 15: Discussion

There are differences in approach between North America where there are often hundreds of legacy wells to contend with, and Europe where storage complexes are envisaged with relatively few wells. Here pressure measurements might be confined to the caprock, reservoir and adjacent formations to test whether the pressure regime can be adequately characterised.

Pressure measurement techniques or modelling might be able to provide an alert to potential changes in the near-surface. AZMI or reservoir pressure measurements need to be able to give some indication of changes in the overburden. Near-surface monitoring can then be planned to anticipate potential changes. However, a small pressure difference at depth will translate into a very minor disturbance higher in the overburden. Another challenge with near-surface detection is noise created by groundwater conditions or other processes. Consequently, some caution needs to be applied with the interpretation of pressure changes. Integration of deep sub-surface monitoring in the AZMI and reservoir and near-surface would be a logical step. False positive signals might also occur if for instance pressure is increased in a reservoir that then induces upward movement and an increase in pressure in the overburden. This does not mean leakage out of the reservoir has occurred because caprock integrity is likely to be maintained especially if it is hundreds of meters thick.

If a leak does occur from a reservoir a pathway analysis can be conducted to anticipate the likely migration route. This exercise could then be used to decide where additional monitoring might be necessary.

Session 16: Conformance in the Monitoring and Modelling Loop — *Chair: Andy Chadwick, BGS*

Integrating Monitoring and Modelling at Sleipner: History Matching a Growing CO_2 Plume - Gareth Williams, BGS

A key element in the EU directive for CO_2 storage operation closure is that the 'actual behaviour of injected CO_2 conforms to the modelled behaviour'. This study looked at whether the modelling-monitoring loop could enhance the understanding of CO_2 migration and storage at the Sleipner CO_2 injection operation. Baseline laboratory measurements of flow properties, seismic monitoring and repeat gravimetric surveys were analysed. 4-D time-lapse seismic surveys have revealed the CO_2 distribution. CO_2 density contrasts derived from gravity data, reservoir pressure, temperature and permeability have also been used to constrain flow properties. Current unknowns include reservoir-scale permeability at the injection site, the detailed temperature distribution within the plume and the detailed geology of the reservoir.

Modelling has shown that the central part of the plume is at a higher temperature than the surrounding reservoir. Steady-state temperature profiles were established in the core of the plume by the time of the 2004 seismic monitoring survey. CO_2 is at 48°C at the injection point and 36°C at top of the reservoir which will reduce CO_2 density and viscosity and increase mobility of the plume. The average CO_2 density predicted by modelling was found to be consistent with observations from gravity data.

It was concluded that integrating monitoring data with flow simulations can enhance understanding of the reservoir and plume dynamics. Modelling can help constrain upper and lower bound parameters of geological characteristics. New high resolution seismic data acquired at Sleipner has greatly improved imaging and plume migration analysis which highlights the importance of a high quality baseline dataset to draw predictions from.

Stochastic Inversion of Time-lapse Seismic with Flow Simulations for the Weyburn CO_2-EOR Project - Vincent Vandeweijer, TNO

History matching of multiple dynamic flow models to seismic data at Weyburn showed that time-lapse seismic can be used to improve CO_2 migration simulation models. This in turn can be used to optimize CO_2-EOR strategies and reduce uncertainty. A new parameterization-based approach to model-data evaluation was used.

Baseline and repeat seismic surveys were conducted in 1999, 2001, 2002, 2004 and 2007 at the Weyburn field. A reference model was provided and permeability and porosity realisations were generated. Combined production and seismic data mismatch could be effectively reduced by up to 80%. Seismic data quality and interpretation is not 'perfect' and models will contain biases related to neglected model uncertainty.

Overall a new efficient workflow based on CO_2 flood front positions was developed for conditioning multiple models to time-lapse seismic data. This workflow was used to incorporate plume front information into a sector model. Updates of grid-cell permeability and porosity lead to an 80% reduction of the total seismic and production data mismatch at a cost of only 500 simulations. Further work will be carried out look at the Statoil Norne field.

Monitoring-Modelling Loop and Experience from the Ketzin Site - Stefan Lüth, GFZ

The first reservoir simulation models at Ketzin were based on 3-D baseline seismic data and predicted relatively fast CO_2 migration from the injector towards the north. As more geophysical observations became available during injection the model was updated and arrival times were accurately predicted. A reasonably good match was observed between measured data and calibrated model simulations at the injection and monitoring well. The reservoir model therefore describes the effective hydrological properties between the wells but does not necessarily prove that the CO2 behaviour in the reservoir is under control.

Differences were noted between time-lapse seismic and modelled plume extent and an attempt was made to quantitatively describe these. Effective reservoir properties were used as performance parameters e.g. plume footprint area (permeability), maximum lateral migration (anisotropy) and plume volume (permeability, pressure and temperature). One key difference between the simulated plume and the observed CO_2 distribution was a larger modelled footprint compared with the seismic plume which decreased in size. Therefore, either the simulation underestimated the effects of dissolution or the seismic observation encountered a detection issue. The technique of using effective performance criteria was found to be useful to compare the extent of a match between observed and simulated plumes. The next step forward in this research is to conduct coupled inversion of geophysics and reservoir simulations by including performance criteria into objective function.

Session 16: Discussion

Conformance does not necessarily improve with more data acquisition over time and plume movement can still vary when dissolution/ dissipation starts to occur. For example, the plume shape at Sleipner was not predicted and although the plume has now been accurately imaged if the seismic resolution was lower the difference between predicted and actual plume shape may not have been detected. A difference between modelled predictions and detected limits of plumes is not necessarily a problem if the CO_2 remains secure. Scenarios need to be analysed to determine what outcomes are sufficiently acceptable. On the other hand, the less accurate and reliable the modelling the higher the potential costs for monitoring unknowns might be.

Experience from Sleipner has demonstrated that a clear image of a CO_2 plume, ~1m thick at edge, can be generated partly because of advances in seismic acquisition and processing. High resolution is improving seismic images but the original baseline will always be of lower quality because seismic processing is invariably less advance at the time of the original survey. Plume resolution also depends on the shape of the trap. In instances where a structural trap is well defined, especially in depleted oil and gas fields, then injected CO_2 will fill the trap and be readily identified by monitoring. Seismic images cannot be treated as an absolute reality as there could be a variety of parameters that have changed including equipment or natural variations.

A more robust definition of the term 'conformance' from the EU directive for site closure would be beneficial. Quantitative thresholds and approaches may be too specific and a qualitative based on a number of parameters is a safer approach and is more appropriate.

Session 17: Conclusions, Further Research Areas and Recommendations

Chairs: Andy Chadwick, Philip Ringrose, Tim Dixon, Sarah Hannis

Monitoring Conclusions and Key Messages

Conclusions and Key Messages

- DAS can offer a new paradigm potential with permanent installation and continuous moni-toring in space and time. Comparison of DAS data quality with conventional geophones is demonstrating improvements with technology advancements. Helical cable is being tested to measure strain in all directions, not just longitudinally along the well. Helical cable also improves signal:noise responses for both vertical and horizontal orientations. DAS de-ployment is feasible for application at full-scale (i.e. at wellbore depths of 1,000s of me-tres).
- DAS could enable significant cost reduction for remote geophysical monitoring by eliminat-ing the need for geophone deployments in the well(s). DAS can be installed in existing wells by attaching the cable to tubing, but signal:noise challenges may exist due to a lack of direct coupling with the geological formation.
- A lightsource leakage detection system, tested at Quest, is a low-cost large-area surface monitoring technique that has been successful at the site with a detection resolution of ~50 kg/hr. There are currently spatial limits. The system was tested over ~100m, but it can be extended to 1 km. Atmospheric conditions including dust, rain and particularly snow can interfere with the signal, but continuous monitoring can build a comprehensive baseline of CO_2 variation. The technology is still under development.
- Pressure-based down-hole measurements are more effective (detection and cost) than geochemical analyses from wellbore samples for leakage detection.
- For offshore attribution monitoring the relationship between pCO_2 and dissolved oxygen (DO) can be used for attribution monitoring to establish the source of CO_2.
- Baseline complexity needs to be investigated and understood. There is a continuing dis-cussion on the purpose of near-surface monitoring and its optimization. Temporal and spa-tial variability may reveal long-term trends. If leakage does occur then it may not neces-sarily affect a specific site in a uniform pattern. Comparison with background trends will be important to detect any anomalies and reassure stakeholders. However baselines are shifting due to climate change and using baseline comparisons to attribute potential leak-age signals may risk false positives for leakage and project shutdowns.
- Microseismic monitoring that incorporates the use of Earth-tides can be used to identify changes in geomechanical conditions. Microseismic monitoring includes good examples of data comparisons between induced and natural events from two more projects (Rousse and Tomakomai).
- The risk of Induced Seismicity at large scale storage sites needs to be anticipated. The management of events large enough to be felt will play a larger role for onshore sites in populated vicinities. The risk management of these sites will need to include pressure monitoring.
- The use of new technologies can reduce MMV costs on future projects and bring cost/detection requirement thresholds down. Even projects starting in the next decade could be considered first of kind until the public becomes familiar with CCS. Monitoring costs can be a function of specific decisions including: the detection thresholds required; tolerable leakage rates; and the time within which a leak has to be detected, in addition to the "more obvious" site-specific geological parameters. Monitoring cost data is essential for economic-based model analysis perspectives. Cost data feeds into improved under-standing of monitoring cost-benefits. The value of monitoring can be a function of the ability to detect early indications of leakage compared with delayed detection and associ-ated remediation measures. MMV

costs averaged 20% of the storage costs, with storage costs being only 1% of total full-chain project costs (in a study of Australian projects for a relatively short transport distance). Limited publically available data on monitoring costs constrains economic-based modelling conclusions.

Future work needed

- DAS – further technical development is recommended to improve limitations due to geometry and noise.
- In-well microseismic monitoring is a possibility as signal:noise response improves.
- More work on mechanisms that cause induced seismicity is recommended.
- Tap into earthquake research expertise especially monitoring stress conditions near major faults.
- Explore the use of Earth-tides for seismic event prediction. Review existing research work in this area.
- Re-visit the use of wire-line logs for monitoring.
- Baseline complexity, including the issue of changing baselines due to climate change, needs to be better understood and taken into account.

Modelling Conclusions and Key Messages

Upscaling from Core to Reservoir

- Heterogeneity within reservoirs matters. It has a large influence on fluid flow and it effects trapping processes. If heterogeneity is ignored CO_2 migration can be overestimated.
- Capillary Pressure heterogeneity is key to simulating saturations observed in cores.
- Novel pore-scale experimental and modelling techniques have great potential application for understanding and improving upscaling projections.
- Multi-scale modelling work flow is ready to use
- Upscaling is a highly complex problem. The multi-scale REV concept should be applied at length-scales (5-10 rock functions).
- CO_2 storage is dominated by gravity and capillary forces away from the well.
- Two phase CO_2-brine flow modelling requires careful assessment of the gravity, viscous, and capillary forces used by numerical reservoir simulators.

Wellbores – Legacy & Future

- More confidence is needed to understand and characterise wellbore integrity.
- The timing and frequency of integrity log requirements needs to be further resolved.
- Improvements need to be made to understand cement flow pathways.
- The use of more advanced downhole instrumentation has great potential, but installation of downhole instruments could add risks (that outweigh the benefits).
- Modelling flow in an open wellbore is non-darcy and requires a different modelling approach.
- The coupling of reservoir to wellbore is important. Depressurization and associated effects can lead to phase changes during upward flow.

Generic Advances in Modelling

- Several pilot projects have now started to demonstrate closure conditions (e.g., Ketzin).
- Several projects are demonstrating the value of the Modelling – Monitoring feedback loop.
- Modelling based on characterization informs the design of monitoring plans.
- Monitoring results can be used to inform modelling requirements.
- Monitoring data can provide important information about reservoir geology and flow processes.

- Progress has been made on defining values for acceptability thresholds for environmental impacts in marine and onshore environments.
- Pilot projects have demonstrated the safety and integrity of CO_2 storage.
- Stakeholders should be consulted on what is important (ie what are the low probability material impacts (risks) of importance). Consultation necessitates a wider dialogue between scientists, policymakers and civil society groups.

Modelling Environmental Conditions

- CO_2 concentration variations in shallow soil can be large.
- Field-scale testing has allowed validation of models that simulate CO_2 migration in the near-surface.
- Careful analysis of monitored data can reveal subtle evidence of leakage signals.

Gaps / Future work needed

- More work on cement wellbore integrity is required.
- CO_2 well experience and operation would benefit from practice of well-control to prepare for low probability, high impact failures and to validate models.
- More focus on the investigation of the petro-physics of high and low permeability facies within reservoirs to gain a better perspective on less favourable storage conditions within reservoirs.
- Develop quantitative and probabilistic project success and closure criteria.
- Build more expertise from oil-field experience to improve CO_2 storage projects.
- Learn which monitoring methods can be dropped from MMV plans (for cost reduction). Modelling the value of information (aka data worth in terms of risk management, potential environmental impact and safety) is a key approach to minimizing monitoring costs.

Combined Modelling and Monitoring Conclusions and Key Messages

- Operator experience of leakage from wellbores at CO_2 storage sites would benefit from the valuable lessons from hydrocarbon exploration and gas storage blowouts.
- The realisation of complex interactions between wellbores and formations is essential for effective fluid flow control in wellbores.
- Observations have shown that gas leakage can penetrate to shallow depths and migrate laterally.
- To gain a better understanding of CO_2 leakage also requires a better understanding of natural gas accumulations and migration.
- The advent of projects that are now looking at CO_2 migration and detection in shallow overburden (CaMI) is a significant advance.
- CO_2 well design can benefit from recent gas-storage well incidents. In particular wells should avoid complex flow geometries that make a well hard to kill during blowout situations.
- It is important to simulate well blowout and kill scenarios as part of well design so that efficient well kills can be carried out if necessary.
- Use of legacy 2-D seismic to examine historic overburden leakage can provide useful background information.
- Recent advances in emissions quantification could be useful for CO_2 storage projects.
- There is increasing technological maturity in understanding pressure gauge data in above zone intervals, including physical mechanisms for pressure transfer.
- There are now several sites demonstrating conformance in the modelling-monitoring loop. Understanding conformance is becoming more mature with the experience of several years' of monitoring CO_2 in the subsurface and with an increasing number of demonstra-tion sites reaching a completion stage.

Gaps/ Future Work Needed

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

High-Level Messages

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

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