Evaluating technology options to mitigate greenhouse gas emissions

monitoringnetworkand modellingnetwork - combinedmeeting

5th - 7th August 2014

Erickson Alumni Center, West Virginia University
One Alumni Drive, Morgantown WV 26504 USA

An IEAGHG meeting, hosted by the National Research Center for Coal and Energy, West Virginia University

IEA GREENHOUSE GAS R&D PROGRAMME

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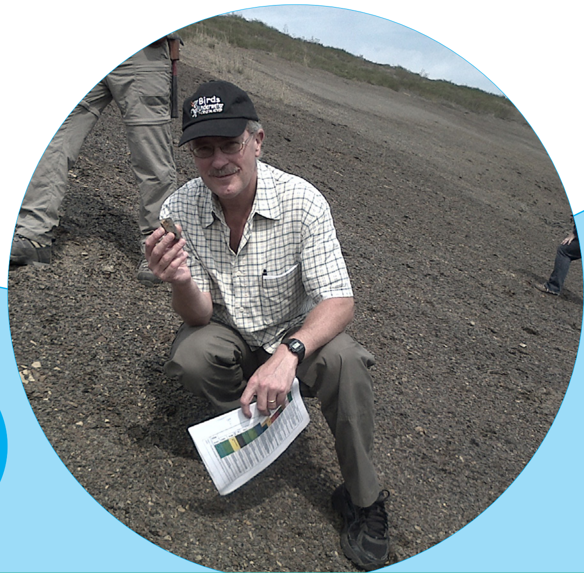

Attendees of the Meeting giving the Jenkins Salute / Tim Dixon of IEAGHG

Session 1: Welcome

Welcome from National Research Center for Coal and Energy, West Virginia University, Richard Bajura, Director NRCCE & Tim Dixon, IEAGHG

A combined Modelling and Monitoring network meeting, organised jointly between IEAGHG and the National Research Center for Coal and Energy (NRCCE), was held between 5th and 7th August 2014. The meeting was held in the Erickson Alumni Center of the West Virginia University in the town of Morgantown about 80 miles south of Pittsburgh. The meeting brought over 60 delegates from eight countries including Australia, Canada, France, Germany, Japan as well as the UK and USA. The three day meeting focussed on the theme of "Reducing uncertainty - the application and effectiveness of monitoring and modelling".

The meeting was opened by Richard Bajura the Director of the NRCCE. Richard highlighted the importance of energy related research at the centre especially its connection with coal. He acknowledged the support from the sponsors West Virginia Division of Energy, Battelle and the Southern States Energy Board as well as NRCCE. Richard also thank Trina Wafle, the NRCCE Communications Director for West Virginia University, for the excellent organisation of the venue and events.

Session 2: Detection and Monitoring of Migration and Leakage – Chair: Curt Oldenburg

Near surface gas monitoring at the CO_2 Field Lab, Norway, Dave Jones, BGS

The objective of this project is to test near surface monitoring of CO_2 during a controlled release experiment. By monitoring released CO_2 the sensitivity of monitoring systems could be determined. Data could then be used to test and calibrate migration models under controlled conditions enabling results to be up-scaled to full-scale storage sites. The results can also be used to develop a monitoring protocol. Although this is a near-surface (<20m controlled release) deeper (100m – 300m) releases are planned.

The selected location is a thick sequence of fluvio-glacial deposits at a sand and gravel extraction site in Southern Norway. These sediments are highly heterogeneous, poorly sorted and characterised by a complex bedding structure although they are permeable. During the early stages of monitoring it became evident that high concentrations of CO_2 had reached the surface but in an area offset laterally from the expected area above the release point. Leakage then developed further still from the release point and this continued after injection had ceased. Flux chamber measurements showed pulses of seepage with flow temporarily impeded by heavy rain. By analysing all the monitoring data it was evident that the released CO_2 followed complex migration paths from the injection point to the surface that also varied with time. This pattern of migration is similar to natural seepage sites. A significant proportion of CO_2 was also dissolved in ground water.

The monitoring methods were highly successful in detecting the CO_2 but somewhat less successful in quantifying the leakage. One of the main implications that can be drawn from this release experiment is that even under controlled conditions, uncertainty about migration pathways is large. Monitoring approaches that can deal with this uncertainty are needed. Obtaining a longer period of baseline measurements and longer post injection monitoring would have been beneficial.

The Use of Tracers to Validate CO_2 Migration Paths and Rates, Linda Stalker, National Geosequestration Laboratory (via WebEx)

Tracers are widely used in different geological environments to track fluid migration. There are three complementary approaches which are all necessary to understand the mobility of tracers in natural systems. Laboratory experiments can be used to evaluate the suitability of a tracer for a particular system. Field trials can reveal how tracers interact with natural systems. Finally modelling can be an effective method for interpreting tracers but it is reliant on accurate data.

The type of tracer can vary quite widely. For example at Otway CD4, SF6, Kr, and R-134a (SF6 substitute) have been used.

Perfluorocarbons (PFCs) and noble gases were used at the Frio Brine Pilot. Other organic and inorganic compounds have also been tested. The quantity of tracer used is governed by the percentage detection rate that is required. Both field and laboratory methods are used to analyse tracers depending on the composition of the tracer. Some tracer compounds can linger or have memory effects (i.e. retained within the analytical equipment). Other considerations such as the composition of formation fluid and the concentration also need to be taken into account. Tracers in combination with other measurements (e.g., CO_2 content) can give long term information on the behaviour of the storage interval.

Perfluorocarbons dominate in CO_2 storage site assessments and are proposed for measurement of leakage rates. There is potential for development of improved chemical tracers, for example esters. Esters are added to the system where they hydrolyse to form an acid and an alcohol. The detection of three compounds (that includes residual ester) can then be used as tracers. It is possible to determine the extent of CO_2 retention using this technique. By measuring the daughter products that have been produced from the hydrolysis reaction, and the timing of the breakthrough, the degree of residual saturation of CO_2 can be deduced.

The use of Isotopes to Track Migration and Retention: a Long-Term Perspective, Mark Wilkinson, University of Edinburgh (via WebEx)

The St John's Dome area of the Colorado Plateau in eastern Utah has a number of CO_2 rich natural springs sourced from natural CO_2 reservoirs. The presence of carbonate travertine deposits across this area shows that natural CO_2 leakage has occurred over the last 500,000 years. There are other gases in these systems which can be used as tracers providing evidence of natural migration over timescales of 10,000s to 100,000s of years. Isotopes ratios have been used to determine the origin of CO_2 in this region and how the fluids migrated to the surface.

The δ18O isotope and the δD isotope ratios reveal compositions of water that originate from two different aquifers connected to the surface by a fault. There is genuine variation between different springs making it is possible to differentiate and measure the contribution from each aquifer. However δ13C ratios are too similar to be able to distinguish the C source in this instance.

The presence of Noble gases can help to distinguish where CO_2 might originate from. 3He is derived predominantly from the mantle. The ratio of CO_2 / δ3He can be used to distinguish the origin of CO_2. The ratio data from the Crystal Geyser suggests it is derived from the upper aquifer and is not of mantle origin. Only 5% of the He sampled from this source is of mantle origin, but the origin of CO_2 is harder to identify partly because of the degree of natural variability (84 – 99% is of crustal origin). There is clear evidence from surface water samples that there has been mixing between the deeper aquifers and ground water.

Carbon isotopes can also be used to demonstrate retention on a geological timescale. The δ13C ratio was measured from calcite precipitated in a caprock and a reservoir beneath it. There are two distinct sample populations, one representative of the caprock and one from the reservoir. One interpretation of the observed pattern is slow migration from the reservoir into the caprock to a depth of ~10m over a period of 50 – 60 M years.

Discussion – Session 2

In natural settings data availability can be a challenge. Firstly, there needs to be a good understanding of the geological environment and the migration paths into and within aquifers. Even if there is a combination of groundwater chemistry and isotope analyses available it is unlikely that a commercial operator would find collection and interpretation of the significant amounts of data needed to interpret the complex natural system and response to leakage cost-effective. Another perspective is to improve the interpretation from limited data.

In cases where artificial tracers are used there is a question of whether they will reach the surface and whether the CO_2 flux at the surface can be quantified. Firstly using stable compounds such as SF6 and PFCs at least to show if tracers work. The choice of tracer should depend on the objective, for instance can they provide high value information about CO_2 retention and residual saturation. It is also advisable to use tracer detection and analysis in combination with modelling. The bigger challenge will be to up-scale monitoring and modelled scenarios to larger systems.

δ14C has been proposed as a 'silver bullet' tracer. This isotope is concentrated in the atmosphere, from which it is absorbed during photosynthesis and therefore its presence indicates carbon of relatively recent origin given that it has a half-life of 5,700 years. It is absent in almost all fossil fuel carbon and so there is a clear distinction between geologically stored and near surface biogenic CO_2. δ14C has been advocated by some researchers for example at Decatur.

In the Norwegian controlled release experiment, there was an initial expectation that there would be a relatively simple migration path. The model had to be modified to account for the high degree of heterogeneity within the sediments. In retrospect it might have been better to have completed a more detailed site characterisation before injection to gain a more comprehensive picture of the site. However, pre-injection disturbance might have compromised the experimental release. The CO_2 field lab experience has highlighted the merits of different monitoring techniques available for use at an industrial scale site. Survey methods that can accurately cover a wide area but can also detect seepage from small areas probably do not exist. A limitation of any mobile technique is the height above ground that a detector is mounted. The greater the height above ground the greater the atmospheric dispersion of CO_2 and therefore the lower likelihood of detecting seepage. One possible solution that was discussed was to begin with a reconnaissance technique that can pick up emissions across a wide area. Once an anomaly is suspected more conventional static measurement techniques could be employed to confirm this and obtain more accurate emission rates over a longer period.

Session 3: Detection and Quantification of Leakage – Chair: Katherine Romanak

What Monitoring Techniques are Appropriate and Effective for Detecting CO_2 Migration in Groundwater: Isotope-Based Monitoring, Philippe Négrel, BRGM

Isotopes can be effective for monitoring CO_2 migration, but the approach and selection of the isotope needs to consider a number of factors including the capacity of the isotope detection tools to track CO_2 leakage and how modelling can be integrated with isotope tracking.

Geochemical tracers using the δ13C, δ18O and δD of the water molecule are potentially capable of recording the changes in water quality as a result of the presence of CO_2. Stable isotope studies have been used to investigate the effects of CO_2 on formation water. For example the relationship between the concentration of CO_2 and the impact on δ18O in water and linking carbonate dissolution to δ13C. A CO_2-water-glauconite interaction has showed how the presence of CO_2 can be linked to the dissolution of glauconite. Boron isotopes (δ11B) were used as a tracer in a laboratory experiment to discriminate between surface reaction and dissolution mechanisms. Dissolution affects the mineral composition which can be traced by comparing glauconite samples that have been subjected to CO_2 - water leaching and CO_2 free water. As the experiment is progressed the δ11B becomes more negative with time as the boron isotopes become more fractionated.

Sr and Li isotope systematics have confirmed the role of glauconite in the interaction with fluids under CO_2 pressure. The key question is the efficiency of these isotope tools in a less constrained system and whether they would be robust tracers at larger scale. To address this question the same set of isotope systematics in the CO_2 field lab experience (Norwegian controlled release experiment) were explored. The multi-isotopic approach (O–, H–, S-, B-, Sr and Li-isotope ratios) converges toward a complex superposition of geochemical processes, and each isotope systematic deciphers different processes, i.e. the mixing of different salinities, interaction between saline- or fresh water and rock, and the interaction between CO_2, water and rock. According to laboratory experiments and site experience to date, further improvements in detection methods and understanding of geochemical modelling for early detection of CO_2 leakage are needed for complex cases. Improved understanding is also required of the system dynamics at large-scale. The adaptation and testing of isotope tools for site-specific conditions, and defining their capability to track CO_2 migration at greater distances from the CO_2 injection sites, is also required.

Methods for detecting and quantifying leakage emissions of carbon dioxide and methane using atmospheric measurements at fixed locations, David Etheridge, CSIRO/CO2CRC

Monitoring the atmosphere near CO_2 storage sites is essential for regulatory, carbon accounting and public assurance purposes. Accurate verification of CO_2 storage is needed. Atmospheric techniques can be continuous, automated, non-invasive and economic. However it is essential to be able to differentiate between any real emissions and background especially because there can be large natural variations. Previous studies have estimated that the maximum tolerable leakage from a CO_2 storage site should be 0.01% per year equivalent to 1,000 tonnes CO_2 per 10 Mt CO_2 stored. This can lead to a relatively small signal in the atmosphere compared to natural variations unless the detection point is very close to the emissions source.

The CSIRO/CO2CRC team have been monitoring atmospheric CO_2 and CH_4 at the Otway test site which included a controlled release. Emissions from coal mines near Emerald in Queensland have also been monitored by the Arcturus monitoring site (originally established for CCS). The Otway site is in an agricultural area dominated by pasture which is characterised by strong diurnal variations in the natural background CO_2 and CH_4. Differences in CO_2 concentrations and fluxes over a period of four years are attributed to climatic conditions. The team have attempted different techniques to distinguish between natural fluxes and released samples. All these techniques can only provide approximations. By selecting specific conditions of the wind direction, dispersion, ecosystem flux (often using simple parameters such as shortwave (solar) radiation) the background variations can be significantly reduced and leakage signals can be more clearly distinguished.

Ideally a multi point network is needed around the site. However a technique of pseudo upwind monitoring at the Otway site, with a single monitoring point, is another technique that has been used to remove the impact of natural variations. Comparison of (wind speed and direction) in two flanking sectors either side of the sample point, downwind of the release point, can reveal an anomaly that corresponds to small leakage rates. Once detected, follow up monitoring from a number of points and with additional measurements such as isotopes and tracers can confirm, attribute and quantify emissions.

FutureGen 2.0: An Overview of the Monitoring Approach and Leak Detection Capabilities, Alain Bonneville, PNNL

This is the first Class VI Underground Injection Control (UIC) draft permit issued by the US Environmental Protection Agency (EPA). The monitoring programme is designed to verify that CO_2 has been effectively stored and that the total CO_2 mass has been accounted for in the evaluation. The programme includes both direct and indirect methods and will concentrate on the first permeable interval, the Ironton Sandstone, above the primary reservoir, the Mt Simon Sandstone. The lower most aquifer that supplies an Underground Source of Drinking Water (USDW) will also be continuously monitored. Direct pressure measurements in monitoring wells and indirect geophysical techniques (passive seismic; time-lapse gravity surveys as well as integrated deformation monitoring using GPS and InSAR) will be used to monitor CO_2 plume and pressure-front migrations.

Assuming a scenario with a breach of the caprock, the model is designed to simulate 1% leakage of the total CO_2 injected (22 M tonnes) over three different time periods: 20, 100 and 500 years. Both CO_2 and brine simulated leakage cases are considered. Modelling results show that the CO_2 would be confined to the Ironton sandstone formation. What this modelling reveals is that the CO_2 pressure increases the total pressure slightly above the fluid pressure within some areas of the formation. Moreover the pressure response is detectable up to 1,000 ft (305 m) from the CO_2 plume. The most permeable section within the Ironton formation, where CO_2 is most likely to spread laterally, would be the optimum place to detect changes within the formation. Detailed characterization of the Ironton Formation at the FutureGen2 storage site will be performed to determine the best vertical location and screen length for the early detection monitoring wells. The monitoring plan could be adapted to track the CO_2 if monitoring revealed a change in the anticipated movement of the CO_2.

What Could Controlled Releases do Better? Lee Spangler, Energy Research Institute, Big Sky Carbon Sequestration Partnership (BSCSP), Zero Emission Research & Technology Collaborative (ZERT), Montana State University

There are several controlled release sites around the world including ASGARD (Nottingham, UK), ZERT (Montana State), Ginninderra (Australia), Norway (CO_2 Lab), Ressacada (Brazil). There are also several natural analogues where CO_2 emissions into the biosphere have been studied. While a great deal has been learned from both controlled releases and natural analogs, there are some gaps.

There are, however, a number of features of controlled releases which need to be scrutinised. These include:

- In a controlled release experiment the detection limits can be established and the location and flux of the source is known, but there is typically very little overburden.
- Natural analogues typically involve more overburden, but the fluxes, energies and source properties and leakage pathways may not necessarily be similar to a leak in an engineered storage system.
- An understanding of the behavoir and the ability to detect a CO_2 flow pattern through the overburden is a gap.

To put release rates into perspective a 0.001% leakage rate from a 4 M tonne / year point source (equivalent to a 500 MWe power plant) is approximately six tonnes CO_2 per day.

Some of the challenges that controlled release experiments can posed are exemplified by the Montana State University field trial. This is a controlled release from a horizontal tube with six release zones installed below the level of top soil. Stress induced changes to the vegetation are evident from monitoring changes caused by CO_2 concentrations above background levels. The effects of CO_2 are clearly evident in this instance because of suppressed plant growth along the line of the release site. At this site modelling showed that the released CO_2 spread laterally when it encountered a low permeability zone beneath ground level. Some plants in this area have deep tap routes of over 1 m that penetrate the low permeable zone and act as channels for the released CO_2. This example shows that the ecosystem, transport properties and heterogeneity of soils and unconsolidated sediments need to be taken into account.

The experience at the ZERT site, and experience elsewhere, has shown that controlled release experiments need to take account of diurnal, seasonal, and annual variations in ecosystem background flux as they all affect detection limits. Natural analogues also seem to have "patchy" or irregular surface patterns. Measurable changes in aqueous geochemistry can occur quickly depending on soil type and affect CO_2 concentrations.

While most technologies deployed could detect CO_2, what should be deployed at storage sites will be dependent on site properties and the purpose of monitoring. If it is primarily health, safety and environmental or resource protection, monitoring the resource to be protected is obvious. Public assurance may require a different deployment. Verification and accounting can present a challenge for near surface techniques because of the lack of information about transport processes in the overburden and how those processes affect flux and horizontal displacement.

In the future more lessons can be drawn from controlled release experiments. Deeper releases to understand CO_2 behaviour in the overburden, and the development of detection technologies that could be effective in this region, is perhaps the most important target.

CO_2 Leakage Detection: A Comparison of Groundwater Sampling and Pressure Monitoring, Elizabeth Keating, LANL

Leakage pathways in the overburden may be complex and hard to predict. It is also unclear how extensive groundwater plumes could be and whether sampling-based monitoring would be able to detect a plume. It is possible that pressure monitoring could be more effective. It is also possible that False Negative situations could occur whereby monitoring simply fails to detect any change or False Positive conditions where changes are detected but are unrelated to a CO_2 or brine leak. A probabilistic approach to this risk assessment has been applied which uses a large number of multi-phase reactive transport simulations. The model simulation revealed that the probability of detecting a leak was low. Moreover, the change in pressure was even smaller than the CO_2 footprint, but it may be easier to detect.

Modelling can provide a probability of leak detection depending on the distance from injection. One simulation revealed that there could be a 50% chance that leak detection could be missed 400 m from the leak and only a 10% chance of detection for a given density of wells in the example tested.

Pressure monitoring could offer a more effective alternative. Although pressure monitoring is unlikely to be effective in a shallow aquifer, it could indicate changes within a storage reservoir. Modelling development is continuing and will lead to the generation of leakage detectability maps in reservoirs and overlying aquifers. Further refinement will include discriminant analysis to determine which scenarios could result in fault rupture.

Discussion – Session 3

It is clear from environmental monitoring at different sites that different approaches are required for detection at the surface and in reservoirs. Although a pressure response might be an indication of a leak a rupture along a fault might be gradual so a pressure response may not be that obvious. The reliance on this technique may not necessarily work at every location but it would be useful to know under what conditions it could work. It could be tested at existing demonstration sites, for example Cranfield.

The distribution and spacing of different monitoring points needs to be selective especially if large-scale storage was developed at several sites. Experience at Otway showed that with refinement it is possible to adapt monitoring so that genuine changes can be detected and distinguished from background variations. Detection limits need to be appropriate for the area and the sensitivity of the technology. Natural fluxes at some sites, for example Otway, are very large irrespective of other influences. Consequently, there is a need to take account of different site activities to quantify all CO_2 sources. However, surface monitoring, and the development of more sophisticated techniques, is necessary to satisfy public assurance and puts land owners at ease.

To date there has been a focus on surface monitoring, but there are also plans for holding deeper detection trials, for example at a Canadian site in Alberta which has planned releases at depths of 200m and 700m. BGS and the University of Nottingham are also looking at a deeper injection test in the UK.

Session 4: Offshore – Chair: Tim Dixon

QICS – A Controlled Sub-Seafloor CO_2 Release Experiment – An Overview of the Scientific Results, Ian Wright, National Oceanography Centre, UK

QICS is a controlled release experiment to gain an understanding of the environmental disturbance, parameter sensitivity and the persistence of low-flux leakage. The release site was in a bay just north of Oban on the west coast of Scotland. The CO_2 was delivered via a pipe drilled through bed rock to a release point below the unconsolidated sediments above the bed rock. By Day 2 (D2) there was seismic evidence that a gas chimney began to develop. The chimney had extended by D12 through the fine grain mud sediments but not the sand layer. As time progressed the plume migrated laterally at the sand / mud interface. By D34 the gas had formed a chimney in the overlying sand. Bubbles were detected using acoustic sensors at a distance of up to 100 m and diver observation. Most of the released CO_2 remained in the sediments and dissolved in the pore water. The changes to the pore water chemistry proved to be the most sensitive indicator of the presence of CO_2.

There are several features of CO_2 plumes in sea water which need to be considered. The plumes are initially buoyant, but following rapid dissolution the plume becomes denser than the surrounding sea water and sinks. Currents and tidal mixing also rapidly disperse the plume. Stratification and sea floor topography can also retain CO_2.

The Monitoring Programme in Tomakomai CCS Demonstration Project, Daiji Tanase, Japan CCS Co

A monitoring programme is being developed for the Tomakomai demonstration project, off the Japanese island of Hokkaido. The project, under the direction of the Japan CCS company, will target two different formations by drilling two separate deviated wells from the shore. The highest reservoir is in the Moebetsu Sandstone Formation between a depth of 1,100 and 1,200m. The second reservoir is in the T1 Member of the Takinoue Formation which is a volcanic lithology between 2,400 and 3,000m. There is a possibility that mineralisation could occur when CO_2 is injected. There is a substantial section of mudstone caprock above this formation extending to the base of the Moebetsu Formation which is also sealed by caprock. Three onshore observation wells will also be installed onshore. A single vertical well will be drilled for the Moebetsu Formation and a deviated well, plus a vertical well, will be drilled for the Takinoue Formation. In addition an ocean bottom cable (OBC) and four Ocean Bottom Seismometers (OBSs) will be deployed on the sea floor above the test site. The OBC, OBSs, three observation wells and one other onshore sensor, will monitor microseismicity and natural earthquake activity. The baseline monitoring is planned for 2015.

The marine environmental monitoring will include physical, chemical and biological parameters. Seawater chemistry, micro biota will be sampled as well as sea floor sediments. Benthos will be collected and observed by divers or an ROV. Tidal currents and direction will also be measured. The baseline monitoring including a seabed side-scan sonar and a sub-bottom profiler survey was completed by 2014.

Differentiation Between Natural Processes and Induced Leakage in an Offshore Environment. Bio-Oceanographic Approach to CO_2 Leakage Detection, Jun Kita, Research Institute of Innovative Technology for the Earth (RITE)

The background to this study is the necessity to monitor CO_2 offshore in case there is a CO_2 leak into seawater. The Japanese Prevention of Marine Pollution and Maritime Disaster Act stipulates that the operator must monitor and test seawater quality and report results to the regulatory authority. It is also important to be able to differentiate between any exogenous signal and natural background variability.

Photosynthesis by marine algae naturally oxygenates the water column and reduces the CO_2 content, but degradation, particularly within seabed sediments, causes O_2 consumption, a reduction in pH and an increase in CO_2. There are both annual and diurnal fluctuations in the CO_2 concentration. RITE have conducted a case study using published data collected by a profiling system in Ise Bay off the east coast of Honshu. A suite of water quality parameters were analysed including temperature, salinity, dissolved oxygen (DO) and pH from the surface to the sea floor. The Total CO_2 (TCO_2) and the Partial Pressure of CO_2 (pCO_2) can be calculated if the relationship between salinity and total alkalinity are known. There is a strong negative correlation between TCO_2 and DO. TCO_2 values that exceed the 95% predicted confidence interval are statistically above natural background variability and leakage is suspected.

Overburden Imaging using High-Resolution 3D seismic: Perspectives from 3 Surveys in the Gulf of Mexico using P-Cable Technology, Tip Meckel, BEG, the University of Texas at Austin

The objective for this study was to refine the capacity estimates for CO_2 storage in Miocene age sediments off the coast of Texas. The project set out to evaluate regional containment potential with capacities up to 30 M tonnes. Seal integrity and the presence of structural compartmentalisation formed part of this evaluation. A 10 mile wide inshore swath under the Texas state regulatory control was characterized using available integrated conventional seismic, well logs, paleontological 'picks', focusing on the most prospective sand-prone intervals of the Miocene age stratigraphy. Additional high-resolution 3D seismic data were acquired using P-Cable technology above prospective storage sites to investigate fault extent and fluid flow processes in the overburden.

Information about the active hydrocarbon system was used to inform understanding of capacity and seal quality for CCS. Natural gas accumulations with equivalent CO_2 replacement of ~30 M tonne capacities are comparatively rare, suggesting that there may be geological limitations to trap integrity. Alternatively, field sizes may be limited by naturally charged hydrocarbon volumes (under-filled structures). An area of particular interest was adjacent to a shallow salt dome, close to the shore, that has a number of dry wells associated with it. This condition indicated that hydrocarbons either did not accumulate, or could have leaked out. Such a site might still be a suitable CO_2 storage site at a shallower depth.

Conventional seismic at lower frequency is not good for imaging shallower sediments (shallowest hundreds of meters of stratigraphy). P-cable seismic surveys utilize closely spaced short streamers that allow processing at small spatial resolution (6.25 m bins) and have high frequency content (150 Hz) at shallow depths. Fluid migration can be detected utilizing such high-resolution systems, often exceeding the ability to make similar determinations from conventional seismic data. Using higher frequency (150 hz), as compared with conventional seismic at (25 hz), it is possible to enhance vertical resolution down to 2.5 m. This new survey has revealed complex geological structures around a salt dome and it has been possible to detect thin fluvial channels plus faults which extend to the sea floor which would be missed at lower resolution. The evidence from this detailed survey has revealed that the seal has been offset and possibly breached. Chimney structures can also be detected which could mean a compromised storage prospect. The migration processes that have given rise to this phenomenon now need to be understood. The documentation of complex stratigraphy and structures in the overburden is important for appreciating the complexity that may accompany vertically migrating fluids, but the imaging of a gas chimney provides a sense that such technologies could be used in a time-lapse mode (similar to Sleipner) for monitoring for leakage at CCS sites.

Snøhvit CO_2 Storage and Monitoring: Update and Latest Monitoring Results, Bård Osdal and Philip Ringrose, Statoil

Under Norwegian carbon emissions legislation CO_2 from a natural gas field needs to be re-injected. The Snøhvit field is the world's first subsea CO_2 injection project. Produced gas is piped to an island close to the Norwegian mainland where there is a separation plant. The purified CO_2 stream is then piped back to the field and re-injected. Initially CO_2 was injected into the Tubåen Formation, but the pressure build up led to a decision to switch to the stratigraphically higher Stø Formation. Seismic interpretation of the Tubåen Formation revealed that its reservoir properties were governed by a fluvial deltaic system that preferentially channelled the CO_2 in a sandstone unit limited by shale barriers causing a pressure build up. Faulting may have also contributed to confining the CO_2 and increasing pressure. In contrast the Stø Formation is a shallow marine formation with good lateral and vertical reservoir properties. By using a reservoir simulation, and continuous history matching using 4D seismic, it has been possible to check the progress of the plume. The exercise has shown that seismic can be used as an effective pressure monitoring tool. Interpretation of seismic enabled the pressure regime to be accurately predicted which was confirmed by later down-hole tests. Pressure and temperature is continuously monitored and shut-in tests are also conducted to check reservoir pressure. Pressure monitoring has subsequently shown that there has been a stable pressure profile, but with a gradual decline possibly due to hydraulic communication with an adjacent fault block. In the very long-term the CO_2 accumulation could eventually migrate across or around the faults into the next structural block and into a producing gas field leading to its contamination with CO_2. A new injection well is planned for 2015 to minimise the risk of contamination.

Discussion – Session 4

The benefits of being able to conduct seismic surveys to improve the resolution of geological features over a broad depth range is now possible as well as the potential for the greater use of microseismic monitoring.

The cost of P-cable for a survey area of 30 – 40 km^2 costs approximately US$700,000, however this is cheaper than an onshore seismic survey covering a comparable area. Onshore seismic might also be useful for providing data on reservoir pressure conditions. The P-cable survey has demonstrated the ability to investigate comparatively shallower formations which are of interest for CO_2 storage. Broadband seismic can enable seismic surveys to be conducted over shallow and deep formations. Improvements in seismic will help to distinguish features such as heterogeneity and faults and aid in the interpretation of changes that have occurred in geological systems through time. Offshore microseismic monitoring is currently too expensive but its application could emerge especially for detecting changes in the proximity of faults. Advances in technology, for example fibre optic cable, might enable microseismic to be deployed offshore. Direct pressure monitoring is another technique of key importance for determining reservoir conditions.

Monitoring: Conclusions and Recommendations – Chair: Sue Hovorka and Tim Dixon

The monitoring topics covered a variety of different techniques both on and offshore. Controlled releases could be tested faster over shorter time periods to observe the main effects. However, more gas is likely to escape. In contrast, a slow leak might lead to complete dissolution. The depth of an aquifer will also influence the degree of dissolution. QICS could give the impression that CO_2 migration through unconsolidated sediments is very rapid, but this may not necessarily reflect what would happen if CO_2 migrated through a thick column (~km+) of unconsolidated sediment such as in the Gulf of Mexico. Natural seeps suggest much slower rates of migration. There is also the question of how much CO_2 is trapped in the pore fluid. Hydrate formation is possible in shallow sediments below 9°C. The lithology will ultimately determine the rate of migration (which could take up to 10 million years).

Research of natural CO_2 seeps can provide comparative analogues. Analysis of noble gas isotopes that are associated with CO_2 has been used to distinguish its origin (for example from two different sources). Recent research is also highlighting the use of a variety of different isotopes to investigate water-rock and dissolved CO_2- rock interaction. Measurement of different isotopes, in formation fluids and within mineral lattices, can potentially show whether CO_2 migration has occurred.

Monitoring methods are implemented for a variety of reasons, for example, operational and assurance aspects. The benefits of monitoring include developing experience and expertise, improvements in risk based approaches and cost effectiveness.

General Conclusions

- Observation of in-zone reservoir pressure could be an effective technique for the detection of induced fault leakage
- Offshore seismic monitoring may be more cost effective for characterisation and monitoring than onshore for similar survey sizes
- Tracers are most useful in combination (i.e. a cocktail) and have shown good results for residual saturation (containment).
- The first two Class VI permits have been issued in the USA by the EPA for FutureGen 2 and Decatur
- Storage monitoring of CO_2-EOR is different from saline storage
- Microseismic monitoring is generating benefits - data from current projects is identifying and reducing uncertainty
- Monitoring to modelling iteration is essential and proving effective.

The gaps identified from the meeting drew attention to the following issues:

- Surface monitoring for leak detection – what are the requirements for monitoring large areas at high sensitivity?
- Will injected tracers make it to the surface?
- How can fracture zones and related migration mechanisms and processes be effectively monitored?
- Can secondary accumulations at shallower depths be adequately detected and monitored?
- Baselines for CO_2-EOR projects are difficult to define
- There is a need for (shallow) monitoring techniques which are continuous, real time, accurate, and cost effective. There are problems with accuracy of available sensors and effective benchmarking of available sensors.
- Monitoring for commercial-scale deployment: what will be the right balance between cost and accuracy to meet regulatory requirements.

The meeting proposed the following recommendations

- More work on faults and fractures – attract people working in this area
- Leakage detection out of reservoirs
- Quantification and mass balance of stored CO_2.

Session 5: Long-Term Predictability – Chair: Rajesh Pawar

Review of Different Regulatory Frameworks and How they Have Dealt with Long-Term Predictability, Anna Korre, Imperial College, London

There are a plethora of international, EU, USA, Australian and Canadian regulations that deal with long-term predictability.

There is considerable variation in the degree of prescription stipulated by these regulations. The requirements vary between two main themes: (a) whether the monitored CO_2 plume is behaving as expected compared to model predictions to; (b) the absence of detected leakage. Some regulations state that the CO_2 plume must be stable or evolving towards stability. Other regulations state that there must be no environmental impacts, integrity of injection wells and integrity of wells within the area of impact.

To meet these requirements a combination of monitoring, modelling and risk assessment activities need to be implemented. All regulations have a requirement for a plan that needs to be submitted for approval before a project can proceed. Particular modelling or monitoring techniques are not necessary but specifying the outcomes of risk assessments is a requirement. The 'OSPAR FRAM' provides an excellent basis for modelling and risk assessment.

Liability referred to in regulations is not clear. The term 'responsibility' is also used to refer to 'liability' in regulations. After liability has been transferred, the state/competent authority may continue to monitor the site. The 'IEA model regulatory framework' contains a clause that the operator should also provide suggestions for monitoring the site after liability transfer.

Some regulations also contain a mechanism which enables operators to contribute to a collective fund to cover costs after liability has been transferred. The 'EU directive 2009/31/EC' requires further monitoring after liability transfer as a backup measure, while other regulations (e.g. 'EPA UIC') do not. Despite this difference both require safety to be shown before liability transfer.

Why do Long-Term Processes Matter? – An Introduction Based on the ULTIMATE-CO_2 Project, Jeremy Rohmer, BRGM

Public perception of long-term processes over scales of 1,000s of years is usually negative. Improving the certainty of long-term processes is therefore important. The life of a CO_2 storage project is long term, but there are several issues which fall under this designation: the end of injection; the end of monitoring; and closure of the site. The long-term physical aspects include the disappearance of free CO_2 and the establishment of a steady state regime. This needs to cover hydrological, chemical and mechanical stability process which could extend over 100s, 1,000s or even 10,000s of years. The classic concept of CO_2 entrapment is a combination of stratigraphic and structural trapping, residual trapping, solubility trapping and mineral trapping. The relative timing of each of these processes, and the dominance of each of them, is subject to uncertainty. Numerical modelling can help to predict long-term conditions, but models require calibration from field data which is not necessarily available. Model realisations are also a simplification of reality. The approach of different models might be valid but they can have widely divergent solutions.

Wellbore sealing integrity in the Opalinus clay is being tested at the Mont-Terri facility in Switzerland. CO_2 fluid is being circulated between the cemented wellbore and the formation to observe changes in permeability. Provisional evidence shows that permeability is decreasing possibly due to carbonation reactions.

Natural analogous are often proposed as examples of potential long-term conditions that might apply to CO_2 storage sites. They can show how CO_2 reacts with different formations over timescales of 1,000s of years. However, the degree of relevance is open to question. The burial history, hydrology and the role of CO_2 in diagenesis might be quite different. CO_2 migration in a natural system might take place over millions of years.

The Role of Glaciation and its Implications for Monitoring and Modelling of CO_2 Emissions: the Case of the North Sea Basin, Tom Bradwell, BGS

Glaciation affects CO_2 storage beneath the North Sea and has a strong influence on seal integrity. Glacigenic deposits have significant discontinuities and heterogeneities and can reach thicknesses of up to 1 km in the North Sea Basin. Successive glaciations have had a significant geomechanical impact due to loading and unloading cycles, and hydraulic pressurisation. Glacial sediments are very diverse and tend to be highly heterogeneous. Glacio-tectonic processes have created widespread, often highly pervasive, discontinuities plus folding and faulting from micro (~mm) to macro (~km) scale. Across the North Sea Basin, glaciation has also created tunnel valleys and channels, on a large scale, as well as 'chimneys' and other vertical porous bodies on a smaller scale. The interconnected, branching morphology of these channels as well as their highly variable sediment composition, makes it difficult to model consistent fluid flow properties. These features can be buried or exposed and can contain over-pressurised pore fluids, due to glacial loading. Pockmarks are also evident. These features are associated with underlying fluid migration routes or 'chimneys' created by shallow gas. All these structures potentially provide fluid migration pathways from underlying formations.

Ice sheets on the magnitude of the northern European Quaternary glaciations have exerted massive loading forces on the underlying formations in the North Sea Basin during the last 2 million years. During ice sheet loading and unloading, stress can propagate to depths of >50 km directly affecting the porosity and permeability properties of the subsurface. Experimental work shows that horizontal stresses remain elevated even 10,000 years after ice retreat. The dynamic changes to the stress regime could disrupt faults and fractures long after the ice sheets have melted. There is growing evidence of post-glacial neo-tectonic activity in Scandinavia which could be related to ice sheet retreat.

Modelling has been applied to the North Sea Basin to estimate the impact of ice sheet loading. This modelling shows that it can take 15,000 years after glaciation for the underlying formations to return to a 100,000 year old former stress regime. Reverse hysteresis shows that stress field paths are not exactly reversed during glaciation-deglaciation (loading-unloading) cycles. The modelling also indicates permanently increased horizontal stress loading. The stress regime around the edges of the ice sheet is likely to experience the greatest change and will, therefore, be more susceptible to subsurface disruption and potential fluid migration.

Long-Term Monitoring Strategy and Modelling Assessment for Underground Radioactive Waste Repository, Guillaume Hermand, ANDRA

ANDRA, the French Radioactive Waste Management Agency, is developing a long-term repository for intermediate long lived and high level radioactive wastes. The facility must have an operational safety limit of 120 years and long-term safety in terms of containment of 1 million years. The agency is currently characterising a suitable site within the Meuse/Haute-Marne region of eastern France. The host formation is a Callovo-Oxfordian clay between two low permeable carbonate formations. In addition to low permeability, the region is tectonically stable, with a very shallow dip of 1.5° and few faults with limited displacement. Physical processes including thermal, hydric, mechanical (THM) and radionuclide diffusion, as well as the coupling of these processes, are being simulated to evaluate long term safety. Simulations of these physical processes (with and without coupling) are integrated with geological data, gained by in situ measurements and geophysical modelling of the strata, enable long term safety to be evaluated. An underground laboratory has been has been built to evaluate construction methods and overall design.

Modelling needs to simulate changes that may occur over a 1 million year period. For instance, due to the exothermic packages there will be a thermal transient over the first 120 years which will diminish with time. The models need to simulate how the primary containment changes and then the conditions and containment properties of the host clay formation over thousands of years.

A monitoring programme has been designed to ensure that the repository will remain safe during waste package installation as well as after disposal. Surveillance is also necessary for operational security and nuclear safety. Monitoring is also designed to meet the requirement for retrieval and long term safety. Because of the demanding conditions imposed by temperature, pressure, chemistry and irradiation, the sensors' hardening needs to be developed and tested. High levels of redundancy need to be built into the instrumentation. The probability of an unplanned occurrence, the seriousness of an anomaly, and the ability to detect an event before it happens, all need to be taken into account. Research and development currently includes the development of fibre optic sensors, sensor metrology, sensor hardening, wireless transmission systems, data mining and decision making.

Discussion – Session 5

The effects of glaciation, and the requirements for radioactive waste repositories, bring a different perspective to long-term processes. The permeability of shale formations is of interest to any form of long-term storage where containment is a primary requisite. Estimates of permeability (for gas in a dissolved phase) are of the order of 10-18m2 (10-3 mD).

The question of whether monitoring techniques have sufficient resolution to meet the requirements of carbon cap and trade schemes was raised. Monitoring techniques are designed for detecting changes and history matching comparisons with models. It is not clear whether they would be suitable for cap and trade verification.

The nature and timing of glaciation across the North Sea Basin has yet to be resolved. The pattern of glacial episodes, their duration, the thickness of ice and the resultant loading in the central North Sea Basin all need considerable further refinement.

The discovery of a seabed fracture (the Hugin Fracture) has been erroneously linked to the Sleipner field. The feature is related to a glacial tunnel valley 200m deep which has created flow paths for biogenic CH_4. There are also pock marks in several areas which are associated with natural fluxes and seeps of biogenic origin. It is clear that glacial processes contribute to the complexity of the overburden across parts of the North Sea. The impact of glaciation on the stress fields of potential storage reservoirs was raised. The Goldeneye area, as an example, has been subjected to several glaciations, however, production of gas is testimony to the field's 55M year containment. Shell have undertaken extensive testing of Goldeneye (at a depth of 2.5 km) to measure its stress field. As a depleted gas field the reservoir has undergone depressurization. Once it begins to be repressurised it will be important to understand how the pre-existing stress fields acting on faults and other structures might change. The experience from Sleipner has demonstrated how important it is to characterise the whole overburden to avoid any confusion between processes within the reservoir and unrelated processes at shallower depths.

Natural seeps from oil and gas reservoirs are evident but on geological timescales and generally much longer than the ~10,000 year time span for CO2 storage integrity. Stress fields acting on reservoirs are important but Quaternary deposits also act as seals. Long term storage integrity for potential storage sites north of latitude 30°N need to consider the impact of glaciation on hydrological and tectonic processes.

Session 6: Heterogeneity and Up-Scaling Capacity Models – Chair: Philip Ringrose

Defining Model Complexity: What Level of Model Sophistication is Required and When? Rajesh Pawar, LANL

One way to simulate an entire system from reservoir to shallow aquifers is the application of reduced-order models (ROMs). Development of ROMs requires a series of multiple simulations of detailed component models for reservoirs, wellbores, faults and aquifers. Validity has to be tested by applying sensitivity analyses of key variables based on field or lab data. ROMs can then be linked via integrated assessment models (IAMs) to predict system performance and risk. ROMs can capture complex processes but remain computationally efficient.

The ROM approach can, for example, be used to predict the time-dependent leakage rate of CO_2 and brine through a cemented wellbore. In this case the ROM has to take account of CO_2 saturation and pressure at the reservoir/wellbore intersection as well as multi-phase flow, phase-change, buoyancy-driven flow, capillary and residual effects. Allowance has to be made of variability in wellbore completions, cement permeability and depth. Similar ROMs have been applied to reservoir simulations and CO_2 leakage into shallow aquifers through time. All these ROMs can be run together to build a picture of how CO_2 migration might occur throughout an entire system, expressed as changes in pH in shallow aquifers. The rate of change relative to variables such as the numbers of wellbores and wellbore condition can be predicted by adapting this approach. The integration of ROMs can produce a prediction of leakage paths and rates and therefore where monitoring should be targeted. Computational efficiency can be achieved by ROMs coupled together to represent an entire system. Probabilistic simulations help to optimise the selection and deployment of monitoring technologies.

Capturing Heterogeneity and its Effects: What are Models Capable of and What are their Limitations – the Upscaling Issue, Emmanuel Mouche, CEA / LSCE

One of the challenges of reservoir models is the ability to capture hydrodynamic complexities created by heterogeneity. This is evident when homogenous effective transport equations are applied to fluid migration in a heterogeneous reservoir. An equation that describes small-scale fluid transport for example advective transport in Darcy velocity fluctuations may not adequately predict larger scale processes such as dispersion i.e. upscaling.

There are three key forces that control CO_2 migration: injection; capillary forces; and buoyancy. Two phase models include mathematical expressions for these three mechanisms. Model simulations also need to incorporate functions for differences in permeability between layers. Gravitational flow and capillary pressure will vary between two layers with contrasting permeability. CO_2 saturation pressure will increase at the interface between the two layers until critical saturation has been reached and then the CO_2 will migrate across the interface into the less permeable layer.

During injection and near the injection well gravity is likely to be a second order process. Stratification is negligible and gravity can be treated as a perturbation. Inversely fluid movement either some distance from the well, or after injection has ceased, becomes dominated by gravity. These conditions lead to local stratification under low permeability layers. Gravity solutions may, therefore, provide a better solution but only for areas with low fluxes. When capillary forces become more dominant transport processes become more complex. Models used to predict plume front to and across an interface with different capillary pressures can have errors of up to 30%. Consequently there is a strong requirement for numerical validation of theoretical approaches.

Effects of Heterogeneity on CO_2 Storage in a Saline Reservoir: A Case Study from Nagaoka Pilot-Scale CCS site in Japan, Takahiro Nakajima, RITE

A small CO_2 storage pilot site at Nagaoka in Niigata Prefecture, Japan has been monitored to test a geological model of the reservoir characterised by heterogeneity. This feature of some sedimentary facies has a strong effect on CO_2 migration which was observed at this site.

At the Nagaoka site, the pressure response was monitored at the injection well and a monitoring well located 60m from the injection well. Between 20 and 40 tonnes of CO_2 were injected per day over a 17 month period between July 2003 and January 2005. A total of 10,400 tonnes of CO_2 was injected over this period. A combination of pressure measurements, CO_2 saturation and cross-well tomography were made between three observation wells drilled between 40m and 120m from the injection point.

Previous 3D seismic imaging was used to reconstruct a profile of the reservoir. Porosity and permeability measurements were deduced from four well logs. These data were then used to build a petrophysical model by applying a Random Function Gaussian Simulation (RFGS). The derived model showed highly heterogeneous distributions of the petrophysical properties. Good matches were achieved when observed pressure and CO_2 saturation were compared with the simulated CO_2 behaviour in the geological model. Monitoring and simulation results suggested that CO_2 continued to migrate up-dip post injection. Further refinements to the model are planned.

Discussion – Session 6

Model development and refinement remains an ongoing challenge. Examples from this session have highlighted the complexities of models which need to incorporate several different parameters.

The validity of models is tested by history matching with observed data. A good example comes from the pilot site at Nagaoka. Conformance match with cross-well tomography between two observation wells (OB2 and OB3) was considered reasonable but not exceptional. In Sleipner shale layers within the reservoir were not thought to be important until seismic showed that these layers did influence CO_2 migration. Another example within the Mt Simon sandstone formation showed that CO_2 migration and pressure transmission was not initially captured in modelling until injection began. In the absence of sufficient detail it may be necessary to upscale to gain an initial understanding of a reservoir before more data can be acquired.

Experience from petroleum reservoir engineering tends to indicate that predicting break through is extraordinary difficult and therefore is it reasonable to expect models to provide accurate predictions. Consequently it is always worthwhile to revisit observed data. Near well observations are considered to be very important for highlighting variability in reservoirs.

The work on theoretical fluid flow properties within formations shows that reservoir simulations neglect capillary forces models built around viscous forces. Current mathematical expressions for capillary and gravity forces do not adequately simulate fluid flow. It is thought that viscous forces within the Sleipner reservoir decay within metres of the injection point. Transitional behaviour from viscous to capillary and gravity are there importance to understand.

The methodology for calibrating reduced order models (ROM) was raised. It should be possible to calibrate simulations of underlying processes for each stage or the entire ROM. As CO_2 leakage from storage sites has not happen there is a lack of evidence available for calibration.

The Sensitivity of Storage Simulations to Pressure Artifacts: Indications from the Sleipner Benchmark, Andrew Cavanagh, Statoil

Pressure artefacts appear to influence CO_2 distribution within Sleipner, but their effects are difficult to simulate. Observations of the Sleipner benchmark have aided model development and improved predictability. The reservoir model has been designed to simulate the CO_2 plume immediately beneath the caprock. The model was based on Darcy flow which applies viscous forces and assumes vertical equilibrium (VE) reservoir simulation. But this approach resulted in a poor match with the seismic response. A percolating flow approach was then attempted based on capillary forces at basin scale. This model allows gravity separation to occur. This too produced a poor match.

The simulated pressure field for the plume is very shallow; there is a pressure difference of only 250 kPa (35 psi) over 3 km. However, the impression of the shape of the plume, and the estimated pressure field, was inaccurate. Pressure was then allowed to dissipate in the VE reservoir simulation. In this case the plume redistributed to its buoyant equilibrium position and a much better match with seismic observation was achieved. However, this match was based on dissipation over a 100 years which contrasts with the 25 years it has taken for the plume to reach its current distribution and thickness.

A simulation of CO_2 injection shows that 75% of the total CO_2 that is injected is rapidly dissolved but once injection stops, in this case after ~12 years, the rate of dissolution is suppressed. A further 10% dissolves within eight years but it takes a further 50 years before another 10% dissolves and approximately 30 years for the remaining 5% to go into solution.

Some important conclusions can be drawn from this work. Pressure dissipation allows a better match. The Sleipner plume is close to dynamic equilibrium at each stage of its development and is gravity dominated. The projected plume shape, and estimated pressure field, can be attained provided simulations are run over ~100 years. This strongly suggests reservoir simulations for CO_2 storage may be susceptible to significant pressure artefacts that distort model predictions.

The Search for Pathways to Integrate Monitoring in Risk Assessment Based Modelling, Tom Daley, LBNL

Monitoring programmes are designed to aid the development of risk assessments at different stages of projects. Techniques which quantify data can be used for comparative purposes and to ensure regulatory consistency. Standardised methodologies and accepted models are therefore required, but does this approach reduce risk and uncertainty?

Quantitative seismic monitoring is difficult, for example at Ketzin the mass values estimated differ within 5 – 7% from the actual quantity of injected CO_2. In Sleipner an upper layer CO_2 mass of 50 – 70 kt is considerably less than the estimated 110 kt. These disparities are attributed to the temperature profile, layer thickness and gas saturation.

Monitoring of a small volume of released CO_2 at Frio has provided an example that is analogous to a leak. The release was monitored by time lapse VSP. Two small scale injections: one of 1,600 tonnes; and a later 300 tonne injection proved hard to trace. A measure of time-lapse noise, Normalized Root Mean Squared (NRMS), was used to refine and quantify data quality but the data resolution was too poor. Modelling was seen as a solution to confirm the quantity of injected CO_2. More continuous monitoring is need so that observations can be history matched with reservoir models. This would improve quantification and risk assessment.

The US-DOE National Risk Assessment Program (NRAP) work highlights a need to improve the cost/benefit ratio of monitoring to achieve good quality data that can be integrated with models. A good example is fibre optic seismic sensing which can provide a low-cost option for long term monitoring. The application of multiple tools enhances data quality and interpretation. Continuous data processing can, however, be challenging, because it needs frequent modelling for integration into an overall subsurface model so that different techniques can be compared at variable time and spatial scales.

CO_2 Storage Uncertainty and Risk Assessment for the Post-Injection Period at the Ketzin Site, Anna Korre, Imperial College

Ketzin is the first European onshore pilot site for CO_2 storage in a deep saline formation. ~67,300 tonnes of CO_2 was injected between June 2008 and August 2013. The reservoir is situated in the Upper Triassic Stuttgart formation within an anticlinal structure. The reservoir formation is composed of highly heterogeneous fluvial sandy channel facies that alternates with muddy floodplain facies. The 3D distribution of the fluvial channels in the far-field region determines the migration pathways and plume footprint. There are uncertainties in the far-field channel distribution and therefore the pattern of the long-term plume behaviour. Consequently there are implications for monitoring, verification and risk management.

A binary facies model representing the two different deposition environments was used for the petrophysical model. An E300 model of reservoir parameters (salinity, permeability, pressure) was set up and history matched with well pressure data. The E300 simulation shows plume migration towards the apex of the anticline and settlement against the faults that transect the formation. To predict the pattern of plume migration in the far-field, 25 realisations of channel distributions were generated based on the petrophysical properties of the near-field. Porosity and permeability estimates in the far-field were generated using Sequential Gaussian Simulations. The uncertainties of plume behaviour were quantified by estimating the arrival time, residence time and the maximum amount of free CO_2. Probability maps for free, dissolved and trapped (residual) CO_2 distributions in the top reservoir layer were also produced. The modelling suggest that there could be significant uncertainty in the arrival time of CO_2 and as much as 10,000 tonnes (15% of the total mass injected) could be present as free CO_2.

Discussion – Session 6

The need for large numbers of different realisations, and the frequency of monitoring to validate models or changes in predicted forecasts, were the key points for discussion.

Some projects have generated up to 100 realisations but is this excessive? Experience from site developers shows that there will always be uncertainties and therefore multiple realisations may be necessary to predict the range and pattern of CO_2 plumes. Site developers need to be able to communication key features of storage sites to regulators to justify the adopted approach and explain the variation in site characteristics. It is possible that there is no single answer. Goldeneye is designed so that if the site behaves differently from forecasts changes to the monitoring plan can be made. Similarly the models can provide high and low case scenarios and can be modified in the light of monitored parameters. This approach should ensure that projected forecasts are correct.

A permit requirement can dictate the frequency and granularity of pressure measurements. At Cranfield pressure monitoring was continuous generating large volumes of data. There was a consensus that at least with continuous data, or regular observations, there is a record which can be analysed especially if there are anomalies that need to be explained. Computer data acquisition and filtration can be used to process data and help with interpretation.

Session 7: Leakage Pathways and Fault Transmissivity – Chair: Jeremy Rohmer

Analysis of Risks and Key Factors Controlling Potential Leakage from Carbon Storage Reservoirs, Christopher Zahasky, Stanford University

Models can provide a semi-analytical assessment and contribute to the risk assessment of storage sites including leakage pathways posed by faults. There are sub-seismic faults, with displacements of <10m, which are not detectable from seismic surveys. Fault characterisation needs to include its width, length, displacement and profile. In this example the base case model assumed a reservoir composed of an Arqov sandstone with a permeability of 28 mD. An injection rate of 7.9 kg/sec equating to 250,000 tonnes per year was assumed. The model included an aquifer with the same permeability immediately above the caprock. The injection point was 500m from the fault. In the base case leakage scenario two driving forces dominate: pressure build up in the reservoir; and buoyancy due to the contrast in density between the CO_2 and formation brine. A sensitivity analysis of different parameters was then applied. Of the nine parameters tested, three were clearly more dominant in terms of inducing leakage: reservoir permeability; fault permeability; and aquifer permeability. This model revealed that the lower the reservoir permeability the higher the leakage rate. In contrast, higher aquifer permeability above the reservoir led to a higher leakage rate.

The evidence from this research suggests reservoir and aquifer transmissivity are as important as fault transmissivity in determining potential CO_2 leakage. Low permeability injection reservoirs pose the highest risk of leakage based on this model.

Modelling Fault Reactivation, Induced Seismicity and Leakage During Underground CO_2 Injection, Jonny Rutqvist, LBNL

Fluid injection into formations were faults and fractures are present can induce seismicity. For example, overpressures due to large-scale fluid injection induced seismic events at the Enhanced Geothermal System in Basel. It is important to determine the potential for structural damage and human perception. The effect of potential fault reactivation caused by CO_2 brine also needs to be understood as part of any risk assessment. Fault reactivation may change the permeability in faults and possibly compromise the sealing properties of a storage site although this needs to be determined. The size of the caprock/storage aquifer may have a role. Minor faults in close proximity to storage sites need to be carefully evaluated and may not be initially detected.

Two different scenarios have been modelled. Scenario 1 (S1) is a minor fault and Scenario 2 (S2) is representative of a fault with a larger offset. Both faults are dipping 80° and the horizontal stress (normal to the strike of the fault) was assumed to be a factor 0.7 of the vertical stress. Both have the same initial permeability. S1 fault permeability changes by 1 – 2 orders of magnitude as injection progresses up to 100 kg/s. Seismicity of magnitude 2 – 3.5 occurs above a flow rate of > 30 kg/s. The higher the permeability the greater the length of time before an event is triggered and the larger it will be. Leakage does not occur at an injection rate of 20 kg/s, but the model shows that leakage as high as 30% of the flow rate can occur when the injection rate rises to 100 kg/s. In S2 there is higher overpressure compared with S1 but induced seismicity occurs when the fluid flow rate into the reservoir is lower. However, no leakage would occur even under worst case conditions (magnitude ~3.6). A dynamic analysis of S2 shows that fault reactivation would occur at 10 MPa overpressure. There would be a 4 cm slip over 290 m along the length of the fault equivalent to a 2.53 magnitude event.

This model has shown that there is a poor correlation between seismic events and leakage. A single event is not enough to substantially change permeability along the entire fault length. It is clear that site characterization is essential to determine, for example, whether there are multiple caprocks and multiple storage aquifers both of which can reduce the leakage amount and the magnitude of seismic events. The model outputs suggest low potential for structural damage. Shallow-induced events and frequency analysis are well within the proposed limits, although they could be unsettling for the local population.

Discussion – Session 7

The main points made were as follows:

- Modelling fault behaviour could be based on a threshold pressure. In the model developed by Lawrence Berkley reactivation was caused by an increase in fluid flow over a five year period equivalent to an overpressure of 10 MPa. The model calculated a rupture length of 200m along the fault. Fluid flow along or across the fault, or leakage, does not necessarily occur during seismic events. Under some conditions flow and leakage can occur.
- Conservative assumptions were made in the Lawrence Berkley model to reactivate faults. Deliberately high pressure was assumed and fluid flow was allowed over a 5 year period. The damage zone was treated as solid medium with anisotropic properties including fractures. If induced seismicity occurs there is no substantial change in fault permeability along the entire length of the fault. Maximum events may be estimated (bounded) provided site-specific characteristics are adequately accounted for.
- In Decatur micro-seismic events line up along lineaments but not necessarily faults. Data on faults in argillaceous formations shows that there is a correlation between the clay content and low permeability. Some conductive faults do occur in carbonate reservoirs with Darcy level permeablities but they are not extensive.
- Fault permeability in civil engineering is of key importance especially in dam construction. There could be some useful experience in this industry of relevance to CO_2 storage.

The permeability of faults and the behaviour of fluid movement either across or along fault zones needs to be better understood. The experience of the civil engineering sector especially in dam construction should be investigated to assess its relevance to CO_2 storage.

Session 8: CO_2-EOR and Long-Term Storage – Chair: Tip Meckel

Modelling and Monitoring Associated with CO_2 Storage at the Bell Creek Field (PCOR), Charlie Gorecki, EERC

Bell Creek is a U.S. Department of Energy Regional Carbon Sequestration Partnership (RCSP) project lead by the Plains CO_2 Reduction Partnership (PCOR) studying CO_2 storage associated with a commercial Enhanced Oil Recovery (EOR) project operated by Denbury Onshore LLC. The Bell Creek project utilizes an adaptive management approach combining site characterization, modelling, simulation, risk assessment, and monitoring to demonstrating the technical and economic viability of safe long-term CO_2 storage associated with commercial CO_2 Enhanced Oil Recovery. Injection began in May 2013 and 997,392 tonnes was injected by June 2014. The planned storage capacity is 14 M tonnes. 40 – 50 M barrels of oil will be recovered from the commercial EOR operation.

A numerical simulation model has been created to determine breakthrough times and saturations to update risk assessments and guide the timing and location of effective monitoring strategies. The model is also used to predict storage capacity, sweep efficiency, recovery factor and utilization factor. Good history matches have been achieved for pressure, gas and water production rates. The model predicted first breakthrough at production wells after 3 months of production and 5 months at a dedicated monitoring well. Monitoring revealed CO_2 breakthrough occurred after about 3 – 4 months. Injected and retained (stored) CO_2 roughly matches predictions after 1 year of injection. Simulation results indicate that by September 2017 at least 1.5 M tons will have been stored in the Bell Creek Field. The amount of CO_2 retained in the Bell Creek field is similar to other EOR operations reported in the literature.

Reservoir Modelling for EOR Associated Storage in Closed Carbonate Reef Oilfields (MRCSP), Neeraj Gupta and Priya Ravi Ganesh, Battelle

Closed carbonate pinnacle reefs across the Michigan Basin form a series of depleted oil fields which are candidates for EOR and CO_2 storage. The Midwestern Regional Carbon Sequestration Partnership (MRCSP) has been actively conducting characterization, modelling, and monitoring of injection activities in multiple fields for CO_2 storage potential in conjunction with EOR. There has been a progressive increase in the amount of CO_2 injected since 1996 when EOR operations started. By 2014 almost 1.4 M tonnes of CO_2 was in-place. Instrumented wells and pipelines in active fields are used to track CO_2 injection and CO_2, brine, and oil production.

One of the highly depleted late-stage EOR fields has been used for more detailed assessment by MRCSP, including injection of more than 240,000 tonnes since 2013. Extensive monitoring has been performed, including pulse neutron logs, pressure, temperature, borehole gravity, vertical seismic profiling, INSAR, and fluid analysis. Reservoir simulations are being used to model the CO_2 injection, pressure response, and plume behavior in the reef across complex phase and compressibility changes. Simulations are run from initial pressure prior to the supercritical phase to supercritical and eventually to a point when reservoir capacity has been reached. There has been successful history matching with oil and gas production as well as reservoir pressure for the primary production. However, the Black-oil model under predicts reservoir pressure during CO_2 injection. There are two possible reasons: the reservoir boundaries are not accurately modelled; or the CO_2 solubility affects pressure. Refinements have improved predictability. Complex CO_2 phase behavior influences reservoir response and needs to be integrated into the reservoir models. The lessons learned can then be applied for MVA in newly targeted fields for evaluation of EOR and associated incidental CO_2 storage.

Discussion – Session 8

The fate of CH_4 in these storage sites was questioned. CO_2 is the dominant gas phase typically 94 – 96% of the injected gas stream. However, CH_4 is reinjected at both sites (Bell Creek and MRCSP Michigan site). Monitoring complications can arise in these oil and gas fields especially pressure. Pulsed Neutron (PNC) logs are run to determine CO_2 saturation but it can be difficult to differentiate phases (CO_2, CH_4, H_2O). CO_2 monitoring in these fields is also helping to validate the monitoring tools' applicability in different settings. The monitoring programme needs to be adapted as the risk profile changes through the life of the storage site. The first phase could last 10-20 years depending on the rate of recovery and EOR economics. The

Weyburn EOR field monitoring was difficult because the EOR function and the presence of different phases.

Both Bell Creek and Michigan Basin site are covered by Class II regulations. Class VI, which is specifically for CO_2 storage, does not apply.

The impact of cyclical pressure on faults is not relevant to the Michigan site as there is no known faulting in the reef. No microseismicity has been observed. The original reservoir pressure declined as the field's oil and gas was depleted. It then increased with CO_2 injection and is currently slightly above discovery pressure. This does not appear to have caused any integrity issues. CO_2-EOR in multiple reefs is possible if they have not been subjected to water flooding.

Modelling: Conclusions and Recommendations – Chair: Philip Ringrose, Andrew Cavanagh and James Craig

A series of conclusions, gaps in knowledge and experience and recommendations were proposed from the modelling topics. The general conclusions that could be drawn included:

Model Complexities, Heterogeneity and Up-scaling

- The definition of long-term is unclear but should it be given a number. The public perception of long-term is usually negative.
- There is a new appreciation of glacial processes on storage integrity. Successive glacial advances and retreats have induced cyclical loading on the underlying formations. Fluvio-glacial processes have created tunnels and other features which act as conduits for escaping fluids.
- CO_2 storage development can learn from radioactive waste experience especially in terms of designing robust and reliable sensor technology.
- The NRAP reduced order model (ROM) concept can be used to assess and link risks associated with storage sites from reservoirs to potential leakage pathways in the overburden, to groundwater contamination and atmospheric emissions. The link to monitoring data and detailed models needs to be validated by applying sensitivity analyses of key variables based on field or lab data. ROMs can capture complex processes but remain computationally efficient.
- History matching is an essential technique for checking the validity of models and refining them so that they provide better predictions. But some phenomena, for example the predicted time for plume migration, can still be difficult to accurately determine. This suggests that some fundamental physics is not clearly understood. The integration of gravity / capillary forces and pressure need further investigation.
- Models are site-specific and need to be tuned to site-specific monitoring data. The modelling and monitoring loop is gradually improving accuracy. The number of realisations that are actually required needs to be called into question. Moreover large volumes of data need to be efficiently processed to produce meaningful results.
- Real site experience from Japan, Norway, Germany and the USA has produced good matches with models but the broader applicability of these matches needs to be assessed.

Fault related issues

- Induced fault leakage may not be as bad as had been previously thought but the question remains on whether fault leakage, or potential leakage, be managed and controlled? Microseismicity may also be minor.
- There is a database of fault properties for oil and gas reservoirs in the literature which has been pulled together and used by operators.
- Some civil engineering aspects, especially related to dam construction, may have relevance to CO_2 storage sites. Fault permeability and risk assessment are of particular interest.
- Slip events are often not large enough to have an impact on whole fault permeability.
- Some experiments show fault slip in clay rich shale lowers fault permeability (range of applicability?)

Long-term Issues

- There are more similarities than differences amongst countries' regulatory requirements. Modelling is an essential requirement. In most countries regulations attempt to be prescriptive about what information is needed from models but not what models to select.

- Monitoring needs to be sufficiently accurate to confirm storage security.
- There is still some uncertainty and variability about long-term issues (e.g., liability transfer).
- Glaciation should be accounted for in some environments (Northern Lattitudes).

CO_2- EOR

- One of the key issues for CO_2- EOR projects is the effect of multiple phases (gas) in the reservoir and the ability to monitor CO_2.
- Experience from the USA shows that CO_2-EOR projects start with good reservoir data and history matched models because of previous oil and gas production.
- Is EOR-CO_2 storage monitoring significantly different from saline storage?
- There could be a need for different CO_2 storage options. At what point does CO_2- EOR switch from oil recovery to CO_2 storage and how is CO_2 storage efficiency (recycle rate) measured?

The following topics were identified as gaps:

- There needs to be a better definition for long term.
- Monitoring of CO_2- EOR for storage is a future topic for more detailed discussion.
- The baseline for CO_2- EOR projects is difficult to define.
- Further work to understand fault related leakage.
- Geological modelling of glacial stress changes.
- Improved simulators for gravity- and capillary-dominated flow would improve the understanding of reservoir physics.
- The level of detail in models could be further improved so that heterogeneity is better represented.
- Improvements in solubility / dissolution modelling.

Recommendations:

- Joint network meetings add more value.
- Learning from other industries (mining, dams) would give another perspective.
- Close the loop between monitoring and modelling.

Session 9: Microseismicity: Implications for Storage Security – Chair: Don White

Critical Geomechanical Processes in the Overburden, Josh White, LLNL

Geomechanical processes can be challenging to model because the underlying uncertainties are large. Stress uncertainty is one area that is receiving more detailed investigation and the In Salah case is a good example. The storage reservoir is covered by two cap rocks: a 740m main caprock and a lower 210 m unit that overlies the sandstone reservoir. A 4D seismic survey revealed a seismic anomaly that extends ~150m above the reservoir formation. Monitoring indicates that fluids have migrated into part of the lower caprock but there is no indication that the main caprock has been affected. A variety of migration mechanisms have been studied: fault leakage; movement through pre-existing fractures; and hydraulic fracturing. Despite the specific mechanism, the state of stress is a critical control. The measurement of stress therefore needs careful consideration.

In an example of stress measurements around the Snøhvit field, there is a general north-west maximum stress trend but the stress orientation is variable around the field. In this case regional stress data measured around a field provides a better understanding of uncertainty but it also shows the extent of variability. Taking point samples in a large, 3D volume means that the stress field may not be fully understood.

Understanding the Microseismic Response to CO_2 Injection at CCS sites – Examples from In Salah, Anna Stork, University of Bristol

Microseismic monitoring of the In Salah CCS site was conducted between 2009 and 2011 using a vertical array in an observation well. Recordings of >9,000 microseismic events from the In Salah field were analysed, revealing two distinct clusters. These are mainly thought to originate from a fracture zone extending NE from the injection point. In this particular case it is difficult to pin point the event locations because data from only one correctly functioning three-component geophone was available. The difference between P and S wave arrival times can be used to estimate the distance to the event. However, errors in the site velocity model could mean events are mislocated. P to S arrivals showed that a very small number of events may be located at a shallower depth than the injection interval but these are not thought indicate CO_2 migration at such shallow depths. Instead, these events are thought to be caused by stress transfer into the overburden. Shear wave splitting, i.e. where a wave is split by an anisotropic medium into fast and slow waves, can be used to determine the fracture orientation and the degree of anisotropy. The dominant orientation of the fracture aligns with the present day maximum stress direction. Detailed scrutiny of the event data has concluded that CO_2 injection induced pressure opening of fractures then close as the pressure falls.

Microseismicity induced by fluid pressure can be used to delineate faults and fractures within storage complexes. Monitoring microseismicity can provide useful real-time information to identify event locations, fracture characteristics and focal mechanisms to understand the seismic and geomechanical response, contributing to the verification of geomechnical models.

Real-time processing is essential for early detection of storage security problems. Microseismicity may be indicative of larger events in future. The technique has demonstrated that it can be a useful tool for monitoring CO_2 and its effects during pressure build.

Connecting Subsurface Seismic Activity to Pumping During Hydraulic Fracturing, William Harbet, University of Pittsburgh, NETL-RUA

The advent of shale gas and shale oil across the United States has led to the widespread use of microseismicity to build a comprehensive understanding of subsurface stress fields. Research applied to hydraulic fracturing of low permeability formations is of relevance to CO_2 storage where it is also important to understand, and predict, the interaction of hydraulic flow with features such as faults and fractures.

Microseismic monitoring from observation wells is being used to determine the position of artificially induced microfractures during shale gas development. The difference in the P and S wave arrival times can be used to identify the origin of microfractures. Data analysis and interpretation of microseismic signals with hydraulic stimulation episode, magnitude, spatial and temporal location, in combination with statistical analysis, can be used to delineate subsurface features. Microseismic monitoring is also an essential tool to characterise the efficiency of stimulation.

Analysis of microseismic data, specifically the frequency-magnitude distribution, can be used to determine the nature of the stress regime and overall failure mechanism. This type of analysis can be used to identify different mechanisms (shear and tensile failure). Shear failure could mean that existing faults are reactivated.

There is another dimension to the study of subsurface microseismicity and fluid injection namely Hydraulic Diffusivity (D). D is defined as the ratio of transmissivity (or hydraulic conductivity) to storativity (or specific storage) of a medium. In terms of hydraulic fracturing it is a comparison of the distance of an event from the injection source to the time of the event since the initiation of injection. Long distances with short time intervals mean high hydraulic diffusivity and visa versa. This approach can be used to identify pressure fronts induced by hydraulic flow which can then be compared with surface pumping pressure, seismic energy and time-distance cross-plots. Collectively these data can provide a detailed image of subsurface fault and fractures and their response to fluid injection.

Advance data processing that can extract trends from noisy or indistinguishable data, referred to as Ant Tracking, can be used to identify faults and their properties.

History and Interpretation of Microseismic Activity at the Illinois Basin - Decatur Project, Marcia Couëslan, Schlumberger Carbon Services

One of the objectives of the seismic programme is to characterise this formation and the over lying seal the Eau Claire shale. Seismicity is also being used to image the plume development over a three year period. Microseismic events are also being monitored. This extensive seismic programme includes 2D and 3D surface seismic surveys, time-lapse 3D VSPs, and microseismic monitoring arrays. Data has been recorded from May 2010 to November 2011.

Pre-injection microseismic monitoring recorded 68,575 trigger events from multiple sources, but after filtering out noise and industrial activity 7,894 were attributed to storage development operations. Since injection began events of magnitudes from -2.14 to 1.14 have been recorded and form distinct clusters distributed between the Lower Mt. Simon Sandstone, Pre-Mt. Simon Unit and the Precambrian basement.

In 2012, early investigations into the relationship between the microseismic activity and other operational parameters showed that there were often bursts of microseismic activity when the injection well was shut-in. Analysis of the amplitude of the P- and S-wave arrivals was used to try and determine the source mechanisms behind the microseismic events that occurred up to December 2012. A dominant north-east trend was detected and associated with a number of parallel planes with the same orientation. A conjugate plane with a N10W orientation is also evident. These planes roughly align with the dominant horizontal stress directions in the basin. Spatial orientation of observed microseismic events appears to be consistent with the local in-situ stress regime. It is not clear what geological features are associated with the clusters possibly faults or fractures.

Discussion – Session 9

Detailed seismic monitoring is capable of providing an image of the geomechanical properties of different formations (mechanical stratigraphy). There is a general question related to this concept: what would be the ideal conditions for containment that would ensure caprock integrity. Ideally sealing formations need to be stiff and have an inherent stress field that does not favour vertical fracture propagation.

One of the challenges of interpreting microseismic signals is to pin down event locations especially with only limited geophone coverage. Multiple arrays, preferably in down-hole configurations, help to reduce uncertainty and allow seismic events to be tied more accurately to a location. Data needs to be carefully scrutinised. The accuracy of velocity models is particularly important to obtain good event locations. Uncertainty can be reduced by comparing microseismic monitoring results with other data. To understand seismicity and how it links to geomechanical properties of formations, faults and fractures depends on a minimum level of monitoring to detect if and where events occur and how they are related to geological structures.

Session 10: How Can Modelling Improve Monitoring Efficiency or Limit Monitoring Costs without Reducing Effectiveness – Chair: Grant Bromhal

Model-based Monitoring Design for Determining Plume Stabilization: a Proposed Plan for the Citronelle Geometry, Sue Hovorka, BEG, University of Texas

To demonstrate permanent storage, the rate and geometry of stabilization of CO_2 plumes will need to be understood once injection stops. Some jurisdictions require post-closure planning as a condition of the permit. Consequently, the properties that lead to the most uncertainty during post-injection CO_2 migration need to be understood. After closure, the flow physics will be dominated by buoyancy and capillary forces. Viscous forces are no longer dominant because of a decrease in differential pressure and a decrease in flow velocity. Once injection ceases, the significance of vertical anisotropy could increase. Monitoring approaches that are designed to validate closure models are needed. One of the conditions that will need to be avoided is the extension of the plume beyond a specified limit (the wrong imbibition curve).

Models of post-injection conditions will need to be calibrated and validated by geophysical measurements. There may be a regulatory component to modelling and monitoring. Under Class VI rules the owner or operator will need to monitor the site following the cessation of injection to show the position of the CO_2 plume and elevated pressure to demonstrate that USDWs are not being endangered. The rule requires that monitoring will need to be conducted for 50 years but that an approved alternative schedule can be proposed.

Experience from those projects where injection has ceased can provide some indication of plume stability. At Frio stabilisation was attained and there was no CO_2 produced from an injection well. Monitoring of reservoir fluids over time shows that CO_2 has clearly been retained in the reservoir and has not migrated away from the injection well.

A new method for testing the plume stabilization using the injection well itself as a monitoring point was proposed, and the potential for augmenting the sensitivity using tracers emplaced at the end of injection considered.

Probabilistic Geomechanical Analysis of Compartmentalization at the Snøhvit, Josh White, LLNL

The application of modelling to assess uncertainty is evident from a case study of the stress measurements around the Snøhvit field off the coast of northern Norway. The field is fault bounded and has a consistent north-south stress field but there is some rotation from this general trend. An increase in fluid pressure could reactivate faults and create leakage pathways. Sensitivity analyses revealed that the most significant critical uncertainty is SHmax orientation, but that the overall leakage risk is low.

Snøhvit downhole measurements need to be carefully analysed. It can take up to two 2 days to allow time for detection equipment to stabilise due to thermal effects. Corrections also need to be made for temperature before accurate values can be obtained. Several down-hole gauges are necessary to resolve the effects of natural formation parameters (pressure and temperature).

The next stage was the selection of the most appropriate monitoring programme to reduce this uncertainty. Well test analysis and continuous inversion of pressure gauge data was indicative of a partly compartmentalized system which tied in with impressions from 4D seismic images. Well tests, such as falloff tests, are commonly used to look for flow barriers, such as faults, and other reservoir characteristics. However, such tests require shutting wells in for long periods. Multi-rate injections are also difficult to analyse. One solution to this challenge is a superposition model to characterize reservoirs from calibrated gauge data and standard well test analysis that can then be compared with typical flow conditions observed from other reservoirs. Alternatively gauge data can be used to forecast future pressure conditions and different injection strategies. If overpressure is predicted brine production could be initiated ahead of CO_2 injection to minimize overpressurisation.

Discussion – Session 10

Fluctuations in pressure measurements and the use of data inversion to make forecasts was questioned. In some cases, for example at In Salah, pressure versus flow rate are an indication of fractures within the reservoir. Making forecasts based on data inversion may not necessarily give accurate projections. There are limitations with this approach and the projections should be treated with caution. Experience shows that data acquisition can be substantial so there is a benefit form analytical tools that can provide quick real time responses and therefore input to reservoir management.

The quantification of CO_2 in reservoirs for cap and trade implications, and the value of CO_2 storage, was raised. At Citronelle there has been insufficient injection to image CO_2 in the reservoir but retention has occurred. Cross well logs between the injector and observation wells will be used to image CO_2 at Citronelle, but at a depth 9,400 ft (~2,866m) it is difficult to image the CO_2 in the reservoir from seismic. This situation is one of the motivations for developing monitoring programmes that can validate post-injection stabilization models quickly and effectively.

Session 11: Cost-Effectiveness – Chair: Jun Kita

Technical Advances and Cost-Effective Monitoring: Results from a Recent Case Study, Katherine Romanak, BEG, University of Texas

All the components of CCS need to become cost-effective, including the shallow monitoring of storage sites. As CCS and the transition from research and demonstration sites to industrial-scale operations progresses monitoring will need to adapt. A less intense, minimalist approach is likely to become the norm. There will need to be a balance between regulatory and technical goals; and a balance between cost effectiveness and accurate data collection.

Process based monitoring has a number of advantages. The approach uses simple gas ratios (CO_2, CH_4, N_2, O_2) to identify the processes affecting CO_2 in the vadose zone. This means that a leakage signal over background noise can be promptly identified without substantial background measurements. Moreover, the method is not dependent on geologic variability. There are, however, drawbacks. Firstly it is time and labour intensive. Secondly a manned gas chromatograph is required; and thirdly it cannot provide continuous real-time data. The advantage of continuous real-time monitoring is that it can provide a higher degree of assurance especially if a leakage anomaly occurs. This should ensure stakeholders have greater confidence in site integrity and risk management.

Existing industrial sensors have been tested in two field trials. Results indicate that compared with gas chromatograph analyses gas sensors lack sufficient sensitivity. This research clearly highlights the need for new technology capable of reliable and accurate real time detection.

Addressing Cost Uncertainties when Planning and Implementing a Monitoring Programme for a Carbon Storage Site, Claudia Vivalda, Nidia Scientific Services

The use of a probabilistic cost model for a system at its feasibility stage should improve the confidence in the cost estimates and the uncertainty in cost estimations. Probabilistic cost estimates also provide a sound basis for comparisons of alternative monitoring programmes. The approach includes evaluation of costs based on sensitivity analyses.

The development of a cost model begins with probabilistically distributed values for uncertain costs using Monte Carlo simulations. The cost data is then subject to statistical evaluation to provide more reliable and realistic estimates. The results are then analysed to aid decisions. The estimated costs are balanced against other relevant parameters such as safety, performance and maintenance.

A cost model for a specific reference monitoring plan has been tested. Monitoring techniques from this example were grouped into categories. The monitoring plan was based on selected techniques designed for the entire life-cycle of the site. Uncertainties of different categories are factored into the model. Costs are separated between internal (e.g. injection phase) and external categories (e.g. regulatory requirements). The level of uncertainty is incorporated into the model by varying the length of time for different stages, for example, the injection phase. The results from one probabilistic model scenario showed that the reference total monitoring cost has a certainty of about 60%, and the closure phase cost increase counts for 54.9% of the total monitoring cost.

Discussion – Session 11

The limitations of field sensors, and the discrepancies between measurements made at test sites and in laboratories, is a key theme. The response from instrument manufacturers to the limitations of their products is to apply correction factors. This does not always improve instrument performance in the field. The reason for inconsistency remains unresolved. Moreover, other organisations including the BGS have experienced similar differences between field and laboratory measurements. Even if this was possible retrospective adjustment is not practical if long-term continuous field monitoring is required.

Monitoring has shown the importance of instrument site-selection. Remote sensing to record CO_2 fluxes needs careful consideration and the development of new technology. Achieving consistent and reliable records will also contribute to cost-effectiveness. New techniques that can cover large areas are under development, for example differential adsorption LIDAR and drone mounted sensors. Challenges still remain. Different flux chambers are known to produce differences in measurements by a factor of two. In commercial deployment not only will instrumentation need to be accurate and consistently reliable but there will need to be sufficient expertise to deploy and operate sensory instrumentation.

The lack of instrument consistency and accuracy has also be experienced in marine systems. The measurement of CO_2 and pH do not meet consistent standards. Sensors are required that can compensate for pressure and temperature conditions. Deployment over long time spans of up to three years without correction are under development. Automation, for example Autonomous Underwater Vehicles (AUVs), are a route to wide spread monitoring in marine environments.

Recalibration is an essential practice because instrument drift will always need to be checked. Duplication using different techniques to measure the same parameter should also be practiced to ensure consistency. This approach can be used to cross calibrate instruments. Further development of borehole monitoring using a package of instruments will be summarised in a publication later in 2014.

Session 12: External Perspective and Examples from Other Industries – Chair: Sue Hovorka

A View from a Legal Perspective, Bob van Voorhees, Bryan Cave

The regulatory framework for CO_2 storage sites in the USA involves two interactive sets of requirements, important parts of which were promulgated in December 2010. The underground injection control (UIC) regulations cover the siting, design, construction, operation, monitoring, testing, reporting and plugging and abandonment requirements for injection wells used to inject CO_2 for geological storage. The new 2010 regulations created a new Class VI for wells used to inject CO_2 for storage not occurring in association with oil and gas production. Injection of CO_2 for enhanced oil recovery (EOR) was already covered by the Class II UIC regulations. The other new regulations were developed under the provisions for reporting greenhouse gas emissions and provided, in addition, a system for quantifying the amounts of CO_2 stored geologically with and without being associated with oil and gas production. As established, the regulatory framework uses primarily a performance standard approach rather than a prescriptive approach and should allow for consideration of significant variations from one site and project to another. This adaptability of the requirements is accomplished primarily through the use of a set of plans tailored to each project. These plans delineate the three dimensional scope of a storage project, or Area of Review (AoR) as defined through computational modelling, the testing and monitoring strategies, the post-injection site care and closure strategies, the plugging and abandonment steps for wells, and the emergency and remedial response strategies, as well as the approach for providing required financial assurance.

The flexibility and adaptability provided for the CO_2 storage quantification process is particularly important for addressing fundamental differences in the approaches taken to storage with and without oil and gas production. The basic approach to storage monitoring under the UIC program and GHG reporting is premised on controlling pollutant emissions and CO_2 storage as an analogue to waste disposal. This diverges sharply from EOR operations, which are premised on the optimal management of valuable resources and commodities to recover resources and avoid waste. Only time will tell whether the regulatory frameworks already created can be adapted to these differing value systems while also accommodating the established sets of rights and contractual obligations associated with oil and gas production projects.

The challenge will be to develop and apply monitoring and modelling approaches that preserve the adaptability of these regulatory frameworks while accomplishing the objectives of protecting the environment and human health, including particularly drinking water sources, and providing requisite assurance of the permanence of containment for geologically stored CO_2. The current frameworks place strong reliance on monitoring and modelling working together through an iterative process of site characterization with appropriately designed data collection and modelling, well construction followed by logging and testing, including formation testing, and then implementing testing and monitoring strategies that are designed to fit the site-specific needs to provide data useful for improving the understanding of site and project performance through the iterative process of data collection and modelling to confirm or modify projections of performance.

The flexibility is there within the regulatory framework to initially match models with available data, recognizing that data availability varies from site to site, and to develop and implement site-specific data collection strategies, recognizing that data availability will increase over time. In addition, these testing, monitoring and modelling strategies should use phased fit for purpose approaches that rely on a normal expected iterative evolution to modify modelling and monitoring during plume development while providing alternative steps to respond to monitoring anomalies.

Session 13 Communicating to Regulators
– Chair: Tim Dixon

Modelling and Monitoring in Class VI Permitting, Mary Rose (Molly) Bayer, U.S. EPA and Inci Demirkanli, The Cadmus Group

The Class VI rule was established to counter the potential impacts caused by CO_2 injection. The Underground Injection Control (UIC) programme elements include site characterisation, AoR, well construction, well operation, site monitoring, post-injection site care, public participation and site closure. Permit requirements are design to ensure the protection of USDW based on a clear, science-based and defensive decision making process. Owners or operators need to communicate their decisions to the EPA and the public.

A key area that forms part of any submission is the delineation of the AoR. The AoR is defined by the maximum extent of the CO_2 plume and / or the pressure front where the injection activity may endanger the USDWs. Operators need to be able to counter dangers to USDWs. Delineation can be determined by modelling but needs to be based on site-specific information. Site characterisation needs to be supported by modelling and tie in with proposed development plans. Challenges that are encountered at any stage, such as lack of permeability data, must be communicated to the EPA. After five years of operation there will be an opportunity to review the AoR in the light of operational experience and monitoring data.

EPA's experience of applications has shown that consistency, specificity and certainty in submissions and communication are the key to successful permit applications. Documenting early experiences in sufficient detail is also essential. Finally AoR re-evaluation and a phased approach to monitoring can provide flexibility to allow projects to adapt to changing conditions. The regulatory aspects to CO_2 storage raised some important points. Firstly the rationale behind plume tracking. There is a view that it is less important to know exactly where the plume is but it is important to know that it is contained within a reservoir and does not extend beyond the target formation. The plume and pressure front should be within the defined AoR. Therefore it is important to know if over pressurisation will occur.

Discussion – Sessions 12 and 13 Communicating with Regulators theme
Panel Session Discussion Sue Hovorka, Lee Spangler, Owain Tucker and Molly Bayer

Owain Tucker from Shell outlined the procedure for a UK project (Goldeneye) which is also subject to EU regulations. Approval for an offshore permit is required from three organisations as well as the European Commission (EC). The storage permit is issued by Crown Estate (CE). (The CE has jurisdiction for the foreshore and the sea bed for the sea area apportioned to the UK for energy production). The other two organisations are the Scottish Environment Protection Agency (SEPA) and the Department for Energy and Climate Change (DECC). The DECC energy development unit also issue a permit under the EU storage directive.

Once the submission is agreed with UK regulators it is forwarded to EC for comment. Experience from the ROAD project shows that communication with the EC is limited and can be delayed.

Lee Spangler from the Big Sky Regional Carbon Sequestration Partnership presented an outline of the implications for potential Class VI submission. The project will extract CO_2 from the Duperow Formation near Kevin dome in north central Montana and re-injecting it into the water leg of the same formation. The first two characterisation wells have just been drilled. Geological information from them will be incorporated into the Class VI permit prior to submission.

For Class VI permits there are no exemptions for USDWs. In this area there are some oil producing zones within the overlying Madison Formation which has total dissolved solids (TDS) below the USDW threshold of 10,000 ppm TDS. This situation may have implications for Class VI regulations and the Big Sky application. The existence of an aquifer which could be classified as an USDW means that the Madison Formation is a protected resource with respect to the Class VI permit. However, waste water injection is permitted into Madison Formation and EOR has also been approved in the area. These factors need to be discussed with the EPA.

Under Class VI the pressure based plume criterion could mean the AoR is much larger than the CO_2 plume. Under the default post-injection site care (PISC) there would need to be 50 years of monitoring but adjustments can be made for the scale of injection especially for research projects with relatively limited quantities of injected CO_2 post-injection site care.

Sue Hovorka gave a Texan perspective. Experience in the state shows that there is a good relationship with regulators. There has been CO_2 injection for EOR since 1972. There is no record of lawsuits for damages to water or other resources under Class II for CO_2-EOR. The implications of previous successful operations for changes set out in Class VI regulations should be considered.

Another issue that is currently widely discussed is how to distinguish between CO_2-EOR (subject to Class II) and CO_2 storage (subject to Class VI). The regulations need to be read carefully to understand the intent and purpose of the regulation. Class II has the same limit on pressure elevation and the same intent of avoidance of transmissive conduits to protect USDWs as Class VI. However, under Class II the AoR is small, typically quarter of a mile (402 m). The area and magnitude of pressure elevation and the areas accessed by the CO_2 plume is controlled by production wells that ring injection wells in patterns, justifying the small AoR. Class VI is fundamentally different because the area of elevated pressure and area of CO_2 are not controlled by production, and therefore the AoR can be large and uncertain.

Molly Bayer stressed that the EPA has regular formal and informal discussions with Big Sky. The EPA is also available to discuss permitting applications with other CO_2 storage applicants. As a regulator the EPA is looking for decision making based on a conservative approach given the comparatively early stage of development of large-scale CO_2 storage projects. An AoR based solely on the extent of the plume may not necessarily reveal CO_2 leakage into thief zones hence the rationale for including pressure fronts.

Class VI appears to be focussed on onshore but not offshore, especially Gulf of Mexico. This was clarified, Class VI does apply in US territorial waters which extend 10 miles (~16 km) in the Gulf of Mexico.

One view expressed is that CO_2-EOR Class II transition to Class VI is prohibitive so the transition will not happen.

Public acceptability has become an issue. At Quest model outputs were subject to external review by experts who produced formal reviews. Shell recognise the importance of liaison with the public following the company's experience in the Netherlands where there was a lack of consultation. Public engagement is now regarded has essential.

Good news stories are emerging and an excellent pool of knowledge and expertise is now developing from different research and demonstration storage projects.

Combined Topics: Conclusions & Recommendations – Chair: Tim Dixon, Sue Hovorka, Philip Ringrose

During the final session of the meeting a series of conclusions, gaps in knowledge and recommendations were discussed and presented.

- Microseismic data from current projects making progress in identifying risks and reducing uncertainty.
- Monitoring to modelling iteration is proving effective but some uncertainty still remains.
- We are getting more out of pressure gauge data – Snøhvit is a good example
- Microseismics – has clear benefits, even if there are no results. The technique may give insights into induced seismic risks.
- Improved real time data analysis is needed to make reservoir management decisions from fall-off tests and/or multi-rate injection
- At In Salah, despite minimal microseismic deployment, integrated interpretation has provided useful information from the technology
- At Decatur microseismic deployment has been successful and there is a unique baseline. Although baseline can be useful it may not necessarily be essential
- Commercial application of hydrofrac' operation optimization is bringing new insights – high quality data and analytical tools can be applied for shale gas extraction.
- Need for characterisation of seismic risk during site selection. Identification of event origin is important. Ambient seismicity can be very low at some sites. Some sites have very low (not measured) seismic response to injection, and investment in seismic monitoring has low value for the project.
- Modelling can be used to design effective monitoring programmes for example by targeting specific areas that are of interest for geomechanical stability.
- Cost effective planning needs further refinement especially the benefits of deploying different tools and the use of dedicated monitoring wells.

Gaps:

- Need more tools to analyze continuous data
- Monitoring for commercial-scale deployment: what will be the right balance between cost and sensitivity to meet regulatory requirements? Includes costs of monitoring wells.
- Need (shallow) monitoring techniques which are continuous, real time, accurate, and cost effective. There are problems with the accuracy of available sensors and benchmarking of available sensors is required.
- Shallow monitoring techniques that are capable of wide area coverage and detection of small seepage features are required.
- Need to focus measurement on the reduction of stress uncertainty
- Need to reduce uncertainty in velocity models.
- Data to determine long term plume containment and temporal, technical and economic considerations.
- Characterisation of fault zones especially hydraulic and geomechanical properties. Experts in fault properties who have access to large data sets on fault properties should be invited to future meetings.

Recommendations:

- Address gaps identified from this meeting.
- Development of new sensor technology that can produce continuous, reliable and accurate data from field deployment.
- On-going need for joint monitoring and modelling meetings.

Field Trip, August 8th 2014: Carbon Dioxide Storage Potential in the Central Appalachians

This field excursion visited the Devonian Helderberg Group exposed along a large roadcut on Highway 48 in West Virginia. There are several stratigraphic intervals that have CO_2 storage potential including the Devonian Oriskany Sandstone and a seal the Silurian-Devonian Helderberg Limestone. The Hampshire Formation was also visited.

The Devonian Helderberg Group - sites of the Monitoring Network and Modelling Network - Combined Meeting field visit

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Trina Wafle, West Virginia University National Research Center for Coal and Energy

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Jeremy Rohmer, BRGM

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Don White, NRCan

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