Evaluating technology options to mitigate greenhouse gas emissions

summary report of the ieaghg combined meeting of the modelling network and the risk management network

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Front & back cover images: Nidaros Catheral , built on the burial site of Saint Olaf the patron saint of Norway; Delegates visit the Sverresborg Trøndelag Folk Museum, an open air museum with more than 80 historic buildings; Network Delegates" & "Trondheim harbour; Nidaros Catheral; Delegates at conference; Nidaros Catheral central Trondheim; Trondheim waterfront dinner

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Sheraton Noosa Resort / Sheraton Noosa Resort (courtesy of http://2.bp.blogspot.com)

Introduction

At the 2nd IEAGHG Joint Network Meeting, held between 19th and 21st June, 2012 in Santa Fe, it was decided to hold combined meetings of the Networks. . The first such combined network meeting was held in Trondheim between 10th - 13th June 2013. It combined the Modelling Network and the Risk Management Networks and was hosted by Statoil, and sponsored by Statoil, SINTEF and CLIMIT. This combined meeting brought together 60 international experts in the field of modelling and risk assessment and management of CO_2 geological storage. The meeting was chaired by Tim Dixon of the IEAGHG and Philip Ringrose of Statoil RDI.

The three day event consisted of a day dedicated to modelling applications; a second day covering a variety of risk management issues and a final day where topics involving both topics were discussed. The meeting was preceded by visits to the SINTEF research facility in Trondheim and the CO_2 pipeline test facility at the Statoil Rotvoll site. During the visit to SINTEFF delegates were shown lab-scale development of new solvents for CO_2 capture and an oxy-fuel combustion test rig.

During the introduction session Tore Andreas Torp of Statoil received an award in special recognition of his life-time contributions and achievements in progressing greenhouse gas reduction from fossil fuels through carbon dioxide capture and storage. The award was presented to Tore by Tim Dixon on behalf of John Gale, General Manager IEAGHG.

Day 1: Modelling

Session 1: Modelling

How Risk and Modelling are embedded into emerging Regulations: USA EPA and UNFCCC CDM, Tim Dixon, IEAGHG

The IPCC Guidelines for Green House Gas (GHG) Inventories methodology for CCS, shows the importance of monitoring and risk assessment linked with modelling. This concept is reflected in subsequent regulations, such as the US EPA Class VI wells and GHG reporting rules. For Class VI regulated wells there are minimum criteria and risk assessment is core. The criteria are driven by the necessity for the protection of drinking water, which can be potentially affected by the migration of brine and CO_2. Risk assessment is based on site characterisation and modelling which becomes an iterative process as more data becomes available from monitoring. The identification of potential leakage pathways will always be a challenge as sites are selected on the basis of security of storage, therefore modelling is an approximation and should be seen as qualitative.

The networks have contributed to the United Nations Framework Convention on Climate Change (UNFCCC) when information was needed to progress CCS as part of the Clean Development Mechanism (CDM). Modelling and risk assessment are now included in the Modalities and Procedures for the CDM. There is a recent consultation out to clarify some aspects of the modalities and procedures and procedural matters, some of the UNFCCC proposed solutions cause concern, such as a quantitative criteria for history matching, hence IEAGHG proposes to add:

"History-matching will inevitably show some deviations between predicted and actual behaviours. Whether these constitute a 'significant deviation' should be based upon a risk assessment and expert judgement, and will be specific to the project and the site. Therefore it would be wrong to assign a generic quantitative value across projects to define a significant deviation". The delegates specifically commented that a significant deviation does not necessarily mean unsafe if the phenomenon can be understood and its impact known.

[An expanded version of this statement was subsequently submitted by IEAGHG to UNFCCC].

Development of Standards for CCS, Jørg Aarnes, DNV

There are several reasons for developing standards, including the promotion of an industry standard, harmonisation of regulations, the provision of a transparent basis for independent verification, and offering assurance and transparency to stakeholders.

Guidelines already exist but standards make these into a discrete set of requirements which should be easy to follow. The proposed scope includes the establishment of requirements and recommendations for onshore or offshore geological storage of carbon dioxide to promote environmentally safe and long-term containment of carbon dioxide in a way that minimizes risks to the environment and human health. The guidance should cover all phases of a project from initial design through to construction, operation, monitoring and closure. It is also recommended that management documents, risk management procedures and community engagement form part of each project. Guidelines should be primarily applicable to saline aquifers and depleted hydrocarbon reservoirs, but not preclude its application to storage associated with enhanced oil recovery (EOR).

Risk modelling should describe a proposed monitoring plan. The proposed risk management plan should also describe the proposed analysis or data acquisition to achieve risk reduction and mitigation measures

Session 2: Modelling Toolsets

Sleipner Benchmark Dataset and Model Comparison, Sarah Gasda, University of Bergen

The Sleipner Benchmark dataset is taken from the uppermost layer (layer 9) of the Utsira Formation and has been made available to members of the IEAGHG modelling network by Statoil. Injection into the Utsira Formation began in 1996 at ~0.9Mte/year. 14 Mte had been injected up to 2012. Statoil has been monitoring the progress of the CO_2 plume with seismic, CSEM, gravity and seafloor mapping surveys. The plume has now extended over a diameter of 3 km. The reservoir model was calibrated on actual mitigation observed from previous years and then used to predict future migration patterns. When higher temperature and low densities where applied to the model it showed a better match with monitored results. Formation heterogeneity can also greatly affect flow and uncertainty in formation composition and is considered in some models.

38 people have downloaded the data; most have not yet carried out significant work but have found it useful to test simulations. Four research projects have reached a stage whereby their work can be compared. The differences in the models are thought to be related to the flow mechanisms. A number of the models assumed that density changes are the main influence on flow. This is an uncertainty factor related to the temperature changes of injected CO_2. In some cases models can produce a better match to the observed data.

The disparity between modelled and actual migration patterns depends partly on different types of model and reservoir-specific characteristics which can create uncertainties. The model also needs to be calibrated on the right criteria. The subtleties of modelling need to be appreciated by regulators to ensure that modelling criteria are not prescriptive.

SIMSEQ – Model Comparison Study for Geologic CO_2 Storage, Curt Oldenburg, LBNL

The dataset used in this model comparison study is taken from the Cranfield injection site in Mississippi. In this example CO_2 was injected into the Cretaceous Lower Tusculossa Formation at a depth of 3,300m. The site is part of an EOR field which has a strong water divide and CH4 dissolved in formation brine. There is one injection well and two observation wells. Six conceptual models have been applied to the site.

There are 15 participating teams. Modelling by six teams has now been compared. There are a wide range of predictions because of different modelling techniques, coupling methods, approaches for multiphase behaviour and interpretations of site data. Sim-SEQ aims to address model uncertainties and examine what causes the differences in predictions made by different modelling teams. An example of differences in a modelled prediction is the arrival time of CO_2 which differs amongst all the models. The arrival of CO_2 has been observed more rapidly than the predicted migration rate. Model predictability needs to include more site-specific parameters including the influence of CH_4 on CO_2 flow. The far-field production, and injection, has revealed preferential flow paths within the reservoir. This quantitative model comparison illustrates that model conceptualisation plays a significant role in deciding outcomes. To improve the model prediction mode site specific parameters are necessary (e.g. relative permeability, entry pressure, residual saturation etc). Ongoing activities include iterative model refinement using observation data, quantitative model comparison and uncertainty analysis, reactive transport modelling, integration with NRAP and extension to other storage sites. It was concluded that some models are based on homogenous assumptions and do not take account of heterogeneity within the reservoir. Reservoir models are also tailored to maximise oil and gas production whereas the timeframe for CO_2 injection and retention is far longer.

Goldeneye dynamic modelling: key approaches and learning, Owain Tucker, Shell

This project is one of the two in the running for the UK's first proposed commercial scale project. It is a depleted gas field designed to receive 2 Mte/CO_2 year over a 10 year period from Longannet power station, which was cancelled. It will now come from Peterhead gas power station. . Modelling is essential to predict the plume evolution of both mobile and immobile CO_2. It is also important to be able to detect migration patterns within hydraulically connected formations. An analytical approach is important to identify model parameters that can be used to calculate the theoretical CO_2 capacity especially if it is lower than the original reservoir capacity. Full field models allow the extent of geological variability to be incorporated.

A phased approach was used to define and understand physical processes. Each subsequent, and more complex model, was compared to check consistency with simpler models. These included analytical solutions, simulacrum model, full field model, regional model and coupled models.

The key conclusions reached from this study are that a phased approach is useful to understand the physical processes. The validation of physical processes with simple simulation models proved useful. Screening for key sensitivities was followed by the exploration of relevant dynamic variations in full field simulation. It is important that models are built to answer specific questions which needs to be kept in mind throughout the modelling process.

Session 3: Geochemistry and Impurities

Identification of Major Issues related to fluid rock geochemical interaction when modelling CO_2 geological Storage, Joachim Tremosa (on behalf of Pascal Audigane), BRGM

Potential impacts of geochemical reactions are effects on: the sealing integrity of caprocks; clogging or opening of the pore rock structure; chemical effects of leakage through faulted/ fractured systems; impacts on groundwater; and the effects of impurities. These effects have been examined using modelling, lab experiments and observation of natural analogues.

Chemical reactions have been identified as playing an important role in both the efficiency and security aspects of storage. Mineralisation as a trapping mechanism, is relatively minor in sedimentary rock, but becomes significant mechanism in mafic and ultramafic rock containment sites.

Homogeneous shale/clay caprock appears not to be impacted by CO_2 acidification and diffusion. However, heterogeneity matters especially for features such as mircocracks, fractured rock, faulted systems or near wellbore zones. These weak points remain difficult to simulate.

Numerical modelling can be used to simulate processes over long time scales and the evaluation of coupling processes including fluid-rock interactions on fluid flow properties. Modelling can also be used to evaluate mechanical and sealing integrity of caprock, fault stability and wellbore cement stability. Actual numerical codes have limitations. These include redox processes, high salinity formations and high CPU time which are difficult to incorporate into numerical codes highlighting the need for additional improvements. Mobilisation of trace metal elements, organic compounds and brine concentrations will also have an effect on CO_2 behaviour. Data calibration from demonstration and pilot sites, as well as lab experiments, can improve database content.

Modelling of leakage scenarios enables the characterisation of cement, and clay or shale alteration, to be included. The quantification of leakage rates, and the predicted chemical quality of impacted groundwater, should be improved.

Geochemical Modelling of CO_2 Storage in Saline Aquifers: Examples from Ketzin, In Salah and Snøhvit storage sites; Joachim Tremosa, BRGM

Saline aquifers are choice targets for CO_2 storage, but their salinity differences can have a significant impact on the chemical behaviour of a system which is rarely considered in geochemical modelling. The salinity can affect speciation within the brine and interaction between solute species. Different solution activity models (Debye-Huckel, B-dot model and Pitzer formalism) were considered for each of the three case studies. Overall there was better agreement found for Pitzer databases, although there are still limitations with regard to deviations with temperature and brine composition. Pitzer databases are currently incomplete and contain incoherencies for different species and temperature conditions. The uncertainties in the databases can strongly affect the results of geochemical simulations of CO_2 storage in deep saline aquifers.

Simulating Geologic Co-sequestration of Carbon Dioxide and Hydrogen Sulfide in a Basalt Formation; Diana Bacon, PNNL

This study considered the effect of co-sequestration of CO_2 and H_2S which is what would happen if impurities were not removed. The STOMP-COMP simulator used includes the ability to vary the number of components, vary the compositions in each phase, and is applicable to deep as well as near surface saline reservoirs.

Basalt is expected to be very reactive and H_2S is the most reactive component of the stream. In the simulations, most of the mixture reacted within 30 years with the remainder mostly dissolved. On injection the pH decreases from 9 to 5 and after 30 years it returns to near neutral. There are very similar results for pure CO_2 and a 99% CO_2 / 1% H2S mix.

The simulation work indicates that basalt formations are a viable option for long term storage of CO_2. Both CO_2 and H_2S are rapidly mineralised. Porosity changes near the wellbore would be relatively small for a pilot-scale injection. The amount of H_2S (1%) injected does not impact on the proportion of CO_2 mineralised but causes variations in secondary minerals.

SO_2 related mineral reactions in Buntsandstein sandstones during CO_2 storage - a geochemical modelling approach, Susanne Stadler, BGR

The COORAL study looked at the effects of impurities over the whole CCS chain. This presentation focused on the impact of impurities on storage formations. The formation considered in the study is the Bunter sandstone formation in Germany which has a relatively high salinity. Pure CO_2 was compared to a 99% CO_2 / 1% SO_2 mix.

The presence of SO_2 favours the precipitation of ankerite at the expense of hematite; and there is more intense feldspar dissolution and related clay mineral precipitation. Less CO_2 is trapped in carbonates due to anhydrite precipitation; however, in the project scenario no significant differences in porosity and permeability changes can be seen when the CO_2 and CO_2+SO_2 models are compared.

Session 4: Modelling Leakage

Process Modeling of Wellbore Leakage for GCS Risk Assessment, Curt Oldenburg, LBNL

Well integrity is a primary concern for leakage from CO_2 storage sites and models have been developed to understand processes that lead to loss of integrity. Different concepts are used for different well leakage scenarios such as using porous media and open-pipe flow conceptualisations of flow. Drift flux models can be used to simulate non-isothermal, multicomponent, two-phase flow in open pipes or annular gaps coupled to a porous media reservoir.

For each concept coupling reservoir, and wellbore processes, it is necessary to understand the variation in the bottomhole pressure and the use of mobile saturation in the reservoir. There are a number of risks to take account of including: the diffusion of CO_2 into cement; the cathodic reactions induce by carbonic acid; and gas exsolution and decompression cooling caused by the release of CO_2 from a supercritical phase both of which can affect upward leakage.

Modelling Scenarios for Low Probability CO_2 Leakage, Richard Metcalf, Quintessa

A well chosen and operated CO_2 storage site is unlikely to leak, however, cautious and realisitic scenarios and models are necessary to understand and communicate risks. Stakeholders often request 'worst case' scenarios, however this is often not useful in demonstrating, understanding or putting together mitigation plans. What is required is expert judgement which is necessary for assessing the combined significance of quantitative and qualitative uncertainties. The identification of features, events and processes (FEPs) that can be represented in scenarios is also required. The specification, representation and allocation of model parameters needs to be clear to ensure that the significance of modelling results can be communicated.

This study used a 'top-down' approach, whereby the big issues were considered and details added. An example was presented from the RISCS project of one of the 'cautiously realistic' scenarios. In this case there is a localised release to soil as a result of wells/ faults/ fractures, leading to high concentrations of CO_2 in the near surface. In this scenario a realistic flux rate shows relatively low impacts comparable to natural variation which is similar for fluxes ranging over several orders of magnitude.

Modelling CO_2 leakage through faults, Rajesh Pawar for Elizabeth Keating, LANL

Fault-leakage scenarios need to be considered as there is always the chance that faults could be undetected by subsurface characterisation and, even if existing faults are benign flow barriers, CO_2 injection could potentially lead to changes in fault permeability.

Estimating CO_2 fluxes in leakage scenarios can be based on studies of natural systems or multi-phase flow simulations based on measured or assumed fault architecture, reservoir pressures and CO_2 saturations. Risk assessment calculations assumed CO_2 mass flow rates along faults are much greater than natural CO_2 mass flow rates along faults in highly active systems which may not be possible. Many natural CO_2 release sites are emitting approximately as much CO_2 as would be deemed 'acceptable' by IPCC standards. These sites are worthy of further study as analogues. Ongoing work suggests unintended and significant caprock breaches by fault activation would not release the majority of stored CO_2. The presence of faults could add to the risk which highlights the necessity for accurate site characterisation.

Geomechanical and Hydraulic Modelling of Faults for Stage 2C Injection at the Otway Project, Charles Jenkins, CSIRO on behalf of Eric Tenthoray

This study modelled the splay fault near the Otway injection project to investigate the minimum mass of CO_2 that can be detected seismically. Secondly if the plume were to reach the fault would it be reactivated; and thirdly if CO_2 were transmitted through the fault, how far would it be transmitted.

Fault stability modelling considered scenarios for both strong and weak fault conditions. For a weak fault, more than 1MPa is needed to move the fault, which is unlikely as this is a small injection into permeable sandstone. Shale Gouge Ratio Modelling, used in this study, determined the degree of clay smearing on different parts of the fault. The model showed that the fault is sealed to some extent by clay smearing. Leakage up the fault was modelled as there are several permeable formations above the storage horizon. CO_2 migration is more likely to migrate into permeable saline aquifer horizons rather than up the less permeable fault zone. Modelling simulation shows CO_2 transgression across the fault. This opens the question as to how much CO_2 could cross the fault. In conclusion, modelling indicated that fault reactivation is not possible under the Stage 2C injection scenario and upward migration of CO_2 through the splay fault will be very limited. Faults could act as barriers or conduits for CO_2 migration. This is a potential area for future research.

Session 5: Uncertainty in Modelling

Effect of stress field uncertainty on Modelling geomechanics and seal integrity for CO_2 storage sites, Laura Chiaramonte, LLNL

Knowledge of the stress field is necessary to understand and calculate caprock integrity as well as fault and fracture reactivation; which can cause induced seismicity and potential leakage through created pathways in the overburden. Stress field data can be determined from the orientation of wellbore fractures, earthquake foci, shear velocity anisotropy and hydraulic fracture orientation. The stress uncertainty in the Snøhvit storage site is a good example of a site where uncertainty was lower than expected. The stress uncertainty differed by up to 90° compared to the reported SHmax.

The strong stress uncertainties lead to difficult predictions. Faults are fairly stable under "most likely" stress state: SS & NS SHmax. Caprock failure would happen before fault reactivation. Under these conditions it is unlikely that a theoretical sub-seismic fault could act as a flow barrier; and faults are ~ 30% less stable with EW SHmax, where several segments are close to critically stressed levels.

Combining downhole data to reduce modelling uncertainties in the CO2CRC Otway Project, Charles Jenkins CSIRO on behalf of Jonathan Ennis-King

This experiment created a region of residual CO_2 around the well followed by an injection of 150t of pure CO_2, followed by injection of formation water pre-saturated with CO_2. Heating tests and residual saturation and wells tests, with noble gas tracers, were conducted before and throughout the experiment with additional tests using reactive ester tracers and dissolution tests. Different techniques were used to test trapping depending on the distance from the injection well. Site data was used to validate models. The CO_2/H_2O distribution in the wellbore was variable. Temperature readings were also variable due to heat convection.

The experiment successfully injected CO_2 and drove it to residual saturation. Uncertainty in formation characterization is reduced by analysis of baseline tests and matching far-field and near-well properties. Uncertainty in wellbore fluid distribution is reduced by combining data from multiple P-T gauges, DTS and RST logs. Pressure analysis gives Sgr 15-19%, noble gas tracer analysis gives Sgr 11-20%, and RST gives Sgr ~ 20%.

Pressure uncertainty and the Implication for Risk, Karl Bandilla, Princeton University

The probability of leakage will depend on the presence of potential leakage pathways and a sufficient driving force. Potential leakage pathways consist of faults and wells, where there is uncertainty in subsurface leakage pathways. The area of review can be reduced by an order of magnitude by using brine producers to lessen the pressure increase and therefore the area where leakage may potentially take place.

Uncertainty in basic parameters may have large impacts on risk and active pressure management. For example, optimal permeability for injection declines with depth. Saline could be re-injected into other formations but this approach would require a large number of wells to manage displaced saline fluid.

Uncertainty in modelling raised some important issues. A large number of variables need to be taken into consideration. To overcome uncertainty data acquisition is necessary to build high levels of confidence for large-scale CO_2 storage. To reduce uncertainty investment is required, an approach analogous with reservoir appraisal in the oil industry. However, oil and gas have commercial value, which can be quantified relative to production costs, whereas CO_2 is a disposal cost fixed by regulation or other mechanism.

To reduce uncertainty it will be necessary to hone in on critical areas to understand reservoir characteristics and CO_2 migration. Even with multiple data sources, modelling may not be able to adequately predict CO_2 behaviour. Information for risk evaluation may not be adequate or it may be in the wrong format. Models may not be fit for their intended purpose especially as the field becomes more mature. Maintaining essential data will be critical for reservoir management.

Session 6: Modelling Conclusions

The understanding of CO_2 storage is improving but there is still a knowledge gap, for example, the roll of faults in migration. The use of models, especially their predicted outcomes, can provide useful insights. Models can be used to reduce uncertainties and prompt questions about migration, leakage and reservoir management, however, models are not necessarily good for predicting CO_2 migration behaviour.

Modellers need to communicate the validity of the conclusions that can be drawn from their use and not the technical complexities that are associated with this approach. Regulators need to understand why certain approaches are taken and how modelling can be used to predict outcomes. They should be discouraged from becoming too focused on unsophisticated problems that are perceived but unlikely to occur. Regulators could be trained in modelling so that they understand complexities better. This approach could include a comparison of a range of scenarios and comparison with other long-term environmental disposal initiatives such as waste water and radioactive material.

Day 2: Risk Management

Session 7: Projects and their Applications of Methodologies

Quest and Goldeneye risk assessment – focusing the monitoring and additional safeguards on key areas, Owain Tucker, Shell

Quest is a fully integrated saline aquifer CO_2 storage project which included injection into basal Cambrian sands below hydrocarbon potential and faults. This is a multi-barrier site but monitoring helps to ensure containment. Risk management ensures a systematic evaluation of passive safeguards, for example, avoiding seismicity. All potential risks need to be reviewed by checking whether previous events like leakage form previous water injection events have occurred. The monitoring programme is based on a plan to detect injection / leakage from a series of monitoring techniques.

Risk assessment for Quest and Goldeneye was not centralised and the teams independently used the same Bowtie assessment technique, although this approach was slightly differently in each case using different packages, but with the same idea. Each team looked at passive and active safeguards. They used passive safeguards to look at potential migration pathways and then built active safeguards. There was a systematic evaluation of passive safeguards to determine how effective each is and whether a backup active safeguard is necessary. An active safeguard must have detection, decision logic, and a control response in order to be valid. The combination of active and passive safeguards further decreases the potential for leakage.

Monitoring techniques are being evaluated to determine their effectiveness with support from the UK's Energy Technology Institute. There is also a cost-benefit consideration. For example, seismic can effectively cover a large lateral area and different layers within target formations but it is an expensive technique. Monitoring tool responses need to be independent to be effective. As more information becomes available from different tools risk needs to be reassessed such as with InSAR. At the Quest site there is a deep monitoring well close to the injection site to detect factors such as induced seismicity.

A key conclusion from this work is that demonstration is essential. Goldeneye has held gas in a reservoir for 50M years so CO_2 could be held for 50M years, but gas extraction changes the reservoir characteristics. There are subtle changes caused by extraction and reinjection which need to be evaluated, tested and communicated. This is another example where it is essential to outline what is involved with CCS.

Mapping of Norwegian CO_2 storage sites- how risk is approached, Eva Halland, Norwegian Petroleum Directorate (NPD).

Storage atlases for the Norwegian North Sea and the Norwegian Sea have been produced with one on the Barents Sea in progress. The biggest risks that have been identified are economic and political but this project focuses on geological risks. NPD have access to all offshore data and have mapped down to 3,000m, concentrating on deep saline formations, water filled structures, abandoned hydrocarbon fields and producing fields.

21 saline aquifers have been explored. Capacity estimates are based on pressure build but exclude water extraction. The main risks are from potential leakage points, faults, fractures and old wells. Risk assessment for each potential site covers reservoir quality and seal quality. The potential effects on adjacent petroleum provinces were also evaluated. No geochemical data has been included. A characterisation system was created to rank reservoir quality for storage. If all the best sites were selected and there were a series of mass injections they would all become part of a regulation programme.

Risk Management Process for the SECARB Anthropogenic Test, Jørg Aarnes, DNV

This is a full chain project involving capture from a coal fired power plant, transport along a 12 mile pipeline and storage into a deep saline formation. This project involves different companies involved in different sectors of the power generation – storage chain who all have different concepts of risk. For example, a risk assessment for a power plant will be more quantitative, whereas the oil and gas industry needs to be able to deal with greater uncertainty. There needs to be a collective recognition of opportunities and risks that can impact on integrated operations. Coherent plans for effective risk management, plus transparent and traceable documentation, will be required.

Significant and tolerable risks were defined which have been reduced. 70 actions were recorded initially: 53 were closed; 19 are in progress; and 7 are active. The top ranked risks were initially related to permitting, injectivity and containment, modelling and monitoring, reliable operations, pipelines and wells. By May 2013, after the project had been operating for 9 months, these risks had been greatly reduced. The top remaining risks are: possible loss of containment; reliability of operations; post-injection MVA; and closure. Some of the key challenges on the project have been the permitting process, which has been more lengthy than expected, and execution of contracts between organisations. One of the most important lessons learnt was that communication between partners is essential from the start.

Applying the MANAUS Risk Assessment Methodology to Fault leakage scenarios, Yann Le Gallo, GeoGreen

The aim of this project was to develop a common operational methodology and risk management for CO_2 geological storage within the context of French regulations. It considered surface installations, different elements of the geological system, and the well system. A functional analysis according to several criteria in space and time was also performed.

An example of a leakage event along a fault was presented which included the possible causes, consequences and targets. The iterative risk analysis included preliminary risk assessment and analysis, detailed risk analysis, scenario and risk evaluation, risk mitigation actions plus probability and uncertainty assessment. In this case pressure propagation across a fault is difficult to predict and therefore there is a need to know how reservoirs will respond in order to quantify the risk. The influence of key drivers on CO_2 migration and pressure propagation was investigated using commercial modelling tools. AS an example the probability of pressure propagation along and across the fault was computed to enable risk quantification.

Session 8: Mitigation and Remediation

Impacts and input from Environmental Assessment meeting, Tim Dixon, IEAGHG

Understanding potential environmental impacts of CO_2 leakage is particularly important for any risk assessment of a CO_2 storage project. Some of the main outcomes of the last network meeting were that Environmental Impact Assessment (EIA) regulations are not proving a barrier to projects. EIAs are different for offshore compared with onshore and there are a good number of controlled release projects and associated knowledge. There has been significant progress with marine projects including the collation of baselines and monitoring (AUVs).

CO_2 release behaviour is not always as expected. If leakage occurs it is patchy, and in small spots, but not over large areas. Onshore electro-magnetic remote monitoring of brine can be used for 'early' leakage detection. Process-based techniques for monitoring are moving in right direction and less baseline data are needed; however, baselines for leak detection and impacts are still required.

Indicator species are being identified, especially benthic and terrestrial plants. Seasonality and timing can affect leakage impacts. There has been a broader acceptance of near-surface monitoring.

CO_2 emission monitoring from the sea floor has been carried out at shallow depths of ~1m but not at 300m where CO_2 solubility is much higher. Plymouth Marine Laboratory (PML) is able to obtain seafloor samples, including a 1m column of water, at these depths. A CO_2 release at 1,000m has been undertaken by Montreay Lab in the US. Controlled releases of onshore CO_2 have also been tested. Heterogeneity within marine sediments can cause unpredicted dispersal of CO_2 gas releases which can be difficult to detect and could be missed in future monitoring programmes.

Methodologies and Technologies for Mitigation of Undesired CO_2 Migration in the Subsurface, Niels Bo Jensen, IRIS

The aim of this project was to review the state of knowledge of novel and standard mitigation and remediation practices, and associated costs, and to review current mitigation plans in place on past, present and future CO_2 geological projects. Migration pathways considered can be man-made (e.g. wells) as well as natural (e.g. caprock defects, faults/ fractures). Mitigation measures were categorised as: interventions on wells; fluid management techniques; breakthrough and novel technologies; and remediation measures on potential impacts. To select the most suitable action the maturity, efficacy and the cost of the mitigation measures need to be considered. This is highly site specific and situation dependent. When actual projects are considered the mitigation plan needs to be integrated with the risk assessment and monitoring plans. These plans need to be designed by experts and reviewed by stakeholders especially as there are diverse formats which are dependent on regulations.

Brine Extraction and Pressure Management, Charlie Gorecki, EERC

The aim of this project was to develop an understanding of realistic CO_2 storage water extraction rates and volumes. It also identified appropriate treatment technologies, and potential applications for the beneficial use of extracted water; and analysed the economics of water extraction plans implemented at different case study sites. An assessment of the global regulatory environment and the identification of potential obstacles as also performed.

Some of the main observations are dependent on site-specific geology and injection scenarios. Increases of 4% to 1,300% in CO_2 storage capacity have been observed. In most of the scenarios, CO_2 plume movement was observed with water extraction. This resulted in larger plumes in terms of areal extent but also increased storage capacity. Generally, reservoir pressure is reduced by around 10% to 20% with extraction, depending on the site and the scenario. The influence of water extraction on pressure and free-phase CO_2 plumes was observed in each of the storage–extraction systems. However, for the purposes of reservoir pressure and plume management, water extraction is best applied to reservoirs with low structural control.

An injection - extraction combination is required to achieve high CO_2 quantities (150 mt/y). Careful selection is therefore required to optimise CO_2 injection and simultaneous brine extraction. Site-specific conditions are highly influential. This exercise has shown that at some sites, for example, at the Teapot site the water source could be treated and used as coolant water for the power plant. At Ketzin the salinity of the formation water is too high and the only option is re-injection. District heating and Lithium extraction are other possibilities. The modelled extraction flow rate at this site needs to be four times greater than the injection rate for CO_2 to manage the reservoir pressure.

Using the water for beneficial use is highly dependent on the end users and the climate and in most cases it is not likely to be economical. To achieve pressure reduction by a significant amount the quantity of extracted water is usually higher than the quantity of injected CO_2. This phenomenon is attributed to the heterogeneities within the storage formations.

Advanced Risk Mitigation Strategies for Active CCS Projects, Sallie Greenberg, ISGS

The Decatur project is an active CO_2 storage demonstration in the Illinois basin. 1Mt/CO_2 has been injected over three years into the basin's Mount Simon Sandstone which has highly variable porosity and permeability properties. The risk assessment included a large number of variables and refinement of potential risks to cover pre-injection and injection monitoring above and in the reservoir. Heterogeneity within the reservoir affected the CO_2 migration. The shape of the plume was pancake shaped not a predicted pumpkin shape. Modelling had underestimated the rate of plume development. 75,000 te of CO_2 were injected before the plume was detected by seismic. The plume is controlled by the reservoir's pressure boundary and very porous sand channels within the reservoir.

A second project will have two wells about a mile apart. The team responsible for this second phase have developed a compliance plan that includes crisis management and media interaction. Staff have been given training in crisis management linked to the project. Active plume management based on detailed reservoir characterisation is also planned.

Session 9: Risk Communication

Communication of Geological Risk, Svein Eggen, Gassnova

Public understanding of risk is often complex, based on many factors, and often based on misconceptions from media images. Even if a risk assessment is perfect from a technical perspective it does not mean that the public will agree with it.

Communication needs to be simple but not overly simplistic and should be based on facts and evidence. Is it important not to strengthen peoples' misconceptions. Myths need to be replaced with facts and if possible explanations should be presented in a way that aligns with peoples' worldviews. Projects should also be described within the wider context of climate change. An important part of communication is the trust of the communicator, therefore choice of communicator is important.

CCS Risk Communication in the Canadian Prairies: Who Cares? Tim Dixon, IEAGHG on behalf of Neil Wildgust, PTRC

The Aquistore and the Weyburn-Midale projects have been associated with a false allegation of leakage. This experience shows the importance of baseline data in communication. Ensuring clear communication between projects, and the engagement of scientific experts who can address issues quickly is also vital. Key stakeholders need to be identified and contacted about any planned course of action before a projects start. Contacting individuals in the media is essential, especially journalists who understand and write clearly about science, ahead of the release of any results. There also needs to be a thorough understanding of the wider repercussions of potential incidents.

One of the main lessons from both projects is the importance of understanding the views of the local people and communication with them from the start of the project. Consultation with local communities about risk, and what can be controlled, is therefore essential. Local monitoring can help to re-assure the local community, however, the myth of leakage is difficult to shift even when disproved.

The Hugin Fracture, Anne-Kari Furre, Statoil

In the summer of 2011 a 3km long sea-floor fracture feature was discovered in the middle of several producing or post-producing sites 25 km north of the Sleipner CO_2 injection site. This discovery was part of the ECO_2 project and formed part of the work package to 'identify potential pathways and the likelihood of leakage from storage sites through the sedimentary overburden'. Statoil have access to pre 1996 seismic data where the fracture is visible. Channel features can be seen on timeslice data and the fracture is thought to be part of an extensive system of sub-glacial channels and tunnel valleys. The escaped fluids from the fracture are a mix of dissolved methane and glacial water. There is no indication of CO_2 leakage from seismic data which suggests that the feature is not connected to the Sleipner field.

Gas seeps are widely known throughout the North Sea, but this is the first time that they have been observed directly at this level of detail on the sea floor. The discovery of the Hugin fracture will be useful for testing and the development of cutting edge monitoring technology.

Public communication of CO_2 storage site risk, Jens Hetland, the European CCS Demonstration Projects Network

This presentation gave an update of the European Energy Programme for Recovery (EEPR) initiative as well as the lessons learned from it. Within the EEPR project six Front End Engineering Designs (FEEDs) have been completed; although there has been no Final Investment Decision (FID) and two projects have been cancelled.

Perceived risks differ from actual risks. There is a necessity to convince the public of the urgency to progress CO_2 abatement. With renewable energy it is easier to communicate the benefits, but with CCS there are uncertainties. It is not always clear that renewables also have limitations, for example, the large surface area required for wind energy.

Public perception and issues vary between different countries. For example in Italy the link between CO_2 and climate change needed to be explained. The timing of communication is important otherwise misconceptions can be generated.

For example a seismic survey for Compostellia in Spain was commissioned for CCS and not oil and gas exploration.

Engagement with the public must ensure that the audience is understood and listened to. Projects must ensure that stakeholders have a reasonably good understanding so that they will not be surprised about specific developments at a later date.

Projects should help stakeholders to contextualise risks. The project leaders must address stakeholders concerns, for example, why the Rotterdam Capture and Storage Demonstration (ROAD) project went offshore; and why the proposed Don Valley project provides options for stakeholders. The use of experts as messengers for a project may be important, subject to communication training. Communication experts were not trusted in these projects.

Info-graphics can be a good tool, but they should be checked for accuracy and include comparative scales that can be easily understood. The use of terminology is also important and should be consistent, for example the use of CO_2 and carbon dioxide interchangeably should be avoided. The significance of CO_2 should also be explained.

Session 10: Risk Management Conclusions

There needs to be more debate and public discussion about mitigation with examples from other industries. Comparable examples such as gas storage would be helpful although gas is a valuable commodity. Internal communication, particularly planning ahead and simulating a major incident can provide significant dividends for teams directly involved in CCS.

There is genuine benefit from real projects, for example the controlled release of CO_2 which revealed unexpected behaviour. In this instance the pattern of gas emissions has provided a better understanding of gas migration and release in a natural environment. Learning from projects provides valuable information for future planning and it provides a better understanding of the processes the govern gas injection, migration and release. Full-scale industrial demonstration is essential.

There are competing methods of risk assessment. How risk assessment is presented to the public is crucial especially conveying uncertainty and the long-term retention of CO_2 in storage. Risk assessment methodologies need to be fully auditable. Criteria for risk assessments also need to be unambiguous so that monitoring and auditing can be transferred to different organisations and individuals especially given the timespans involved. Regulation is another factor that needs to be considered as it may force different types of risk assessment.

Mitigation measures need to be immediate to contain problems.

Examples of successful CO_2 storage, especially where there has been public engagement, need to be publicised. Public acceptability will be necessary especially for onshore sites. Public ignorance of energy and related environmental issues, such as CO_2 emissions, needs greater explanation. Setting an annual energy budget is as a means of emphasising the importance of energy supply and demand. The risks measured against the benefits of CCS are not always clear.

Session 11: Risk Management Case Studies

In Salah CO_2 Storage Project: Lessons Learned, Phil Ringrose, Statoil (In Salah JIP project team)

The initial plan at In Salah was to inject 1Mt/yr into a depleted gas field in a Carboniferous sandstone reservoir 20m thick. The actual injection was 0.5Mt/yr. 4Mt CO_2 has been injected significantly below design capacity. The CO_2 injectors are around the periphery of the field. Injection began in 2004. The site has been subject to extensive monitoring to ensure that there was a good baseline. The use of shallow observation wells for microseismic monitoring were integral to the project. 3D seismic surveys were conducted in 2004 and 2009. This is expensive but essential to track the CO_2 plume. InSAR surveys (Interferometric Synthetic Aperture Radar) have also been conducted. The technique works very well in dry rocky regions such as this part of the Sahara. The surveys are highly sensitive and can measure uplifts of mm scale at the surface. An uplift of cms has been detected between the reservoir and the caprock. Methods were selected using a cost-benefit analysis. Seismic acquisition, though very expensive, was vital for many operational decisions. It was implemented at the start of the injection programme whereas InSAR was started mid-project.

Velocity pull down features were predicted and hydraulic fracturing caused by CO_2 injection. Microseismic monitoring was able to differentiate between different modes of mechanical deformation. Monitoring was also able to detect events related to CO_2 injection. To fill the reservoir to capacity (with a permeability of 1 – 10 mD) CO_2 would have to be injected at fracture pressure or higher. Project monitoring, particularly from InSAR data, revealed an unexpected rise in pressure and surface deformation. Geomechanical modelling was able to show a fracture at the top of the reservoir which extended into the caprock. In June 2011 the decision was taken to suspend injection when this feature became apparent. The caprock integrity was not jeopardised and the fracture served to increase storage capacity. Even though the technical risks were considered low injection was not resumed. The political risks associated with the perceived risk to a potable aquifer above the storage formation outweighed other considerations.

Important new surface monitoring methods and good baseline data, including that generated from satellite InSAR, has been especially valuable. Monitoring programmes need to be adapted during operational phases and should be part of the Field Development Plan. Risk assessments should be conducted as part of regular operational and monitoring strategies

Injection strategies need to be linked to detailed geomechanical models and related stress fields within the site.

Snøhvit: Injecting and storing 1 Mt CO_2 in the fluvial Tubåen Fm, Olav Hanson and Douglas Gilding, Statoil

The Tubåen Formation was initially identified as the storage reservoir for CO_2 from the Snøhvit field. This is the lowest and most permeable formation closet to the Snøhvit field. The formation consists of three main sands with interbedded shale. This gas field contains ~5% CO_2 which was reinjected at a rate of 80te/hour (equivalent to 2,000 reservoir m3/D). Gas production started in August 2007. Injection commenced in 2008 and was terminated in April 2011. There was a pressure drop as gas was produced and CO_2 reinjected. A comparison of volumetric flow from 4D seismic monitoring showed 80% of injected CO_2 flowed into the higher permeable sandstone (3,500 mD). Seismic monitoring has shown that reinjection has been safe and it has verified the storage, but there has been a revised injection strategy.

Injection of CO_2 into the lower reservoir caused the pressure to increase to a level close to the fracture limit. Injection was stopped and gas was extracted to reduce pressure. CO_2 injection was resumed but into the shallower and more extensive Stø Formation, which was identified as a backup reservoir. 1.6 Mt CO_2 has been injected to date and monitoring has continued. Part of the planned mitigation was not to exceed the injection pressure threshold. There is only one injection well which limits the injection rate and CO_2 injection is above the gas producing horizons.

Session 12: How Risk Information Informs Modelling – and Vice Versa

Quantitative risk assessment approach by NRAP: making probabilistic predictions utilising numerical models, Grant Bromhal, NETL and Rajesh Pawar, LANL

This project focused on the development of reduced order models (ROMs) and their linkage to (integrated assessment models) IAMs. Sensitivity analysis is used to identify key variables that control component behaviour. The developed ROMS are then validated against simulations.

A science based quantitative risk assessment approach for geologic CO_2 storage sites is being developed. IAMs that can be used to quantify risk profiles for CO_2 leakage related risks have been developed. A systems modelling based approach, and the behaviour of system components, are captured through abstractions from detailed process level simulations. Developed risk profiles are being used to answer questions related to CO_2 storage site feasibility and long-term effectiveness. IAMs can be used to help quantify uncertainty and identify most sensitivity parameters for leakage. For low wellbore spatial densities, wellbore cement permeability is the most important factor. This effect is independent of sandstone or carbonate aquifers even if their underlying processes (flow and chemical reactions) are taken into account. For higher wellbore spatial densities other factors, such as the shallow aquifer porosity and permeability, had a more significant effect.

Higher confidence in modelling should be possible with long term modelling which will be necessary to predict CO_2 behaviour over 1,000+ years. Modelling will also be needed for leakage prediction. With increased heterogeneity it is difficult to predict CO_2 movement. Evidence shows CO_2 plumes move further and faster than predicted. Uncertainty therefore needs to be incorporated into projections. The range and type of errors that are to be expected need to be identified.

The use of models can lead to uncertainty but greater data acquisition will help to verify predictions. Variability and uncertainty need to be properly understood. The industry and regulators should not get distracted on simplistic scenarios. They need to have a broader perspective of CCS. Educating regulators to ensure that they fully aware of the current status of CCS is essential. This already happens in Norway and the US.

Minor issues, for example, raising ground levels by mms is of concern to land owners and developers so their needs have to be taken into consideration.

There needs to be a long-term repository for monitoring and data acquired from CCS sites to ensure continuity and good knowledge transfer. Learning from more demonstration sites, and the interpretation of data from different investigative techniques and processes, especially seismic, geomechanics and plume movement will build greater confidence in long term storage development.

How Modelling Fits in Risk Management, Rajesh Pawar, LANL

Modelling can provide information at various stages for different stakeholders, such as site feasibility calculations (e.g. capacity, injectivity), permit applications (to determine AOR) and site design parameters (injection rate, no of wells). Modelling can also be used to develop monitoring strategies (identifying which techniques that can be deployed and timing of their application). Mitigation strategies (development of leak/ impact mitigation approach), as well as post injection site closure (how long should it be monitored), can be developed from modelling. This will help to build confidence in long term strategies. However, it is necessary to understand how a quantitative risk assessment can be applied to ensure a high degree of confidence in modelling approaches and the magnitude of associated uncertainties.

A common uncertainty in model performance is plume development, which is generally under-predicted. The challenge of model application is the level of confidence that can be placed on predicted CO_2 behaviour and the timing of different processes. The extent to which different parameters affect uncertainty adds further complexity and ideally needs to be understood.

Iterative interplay between numerical simulations and risk assessment, Phil Jagucki, Schlumberger

At various points during a project there will be opportunities for input from new information. Results of calculations can be updated and model parameters adjusted. Any re-evaluation should always require expert judgement. A group of experts were asked to evaluate porosity and permeability from well offset data. The results they produced were all very different.

If a plot of the relative frequency of an occurrence against a specific parameter (e.g. plume diameter) is generated, a narrow band of the most likely outcomes will not encompass the majority of outcomes; whereas a broadband of options is more likely to contain a more realistic solution.

Making decisions when monitoring data confronts the model, Charles Jenkins, CSIRO

Monitoring data is likely at some point to give false positives. Expert judgement is therefore necessary to decide when an action needs to be made. Decisions need to be based on which of the risks are more probable in light of the available data. Specific predictions are required to determine what will happen if the risks eventuate.

It is necessary to be aware of sensitivity and false alarm rates. The probability of the various risks is relevant and should be include. More reliable data are needed to give credence to an a priori unlikely event. Statistical information (distribution of errors) is extremely relevant and should have as much empirical backing as possible. Understanding background variation is important especially if there is an anomaly. Pre-characterisation is therefore essential. There is also a requirement for a long-term repository of monitoring data from CCS sites.

More integration from different investigative techniques, including seismic and geomechanics, will help build collective understanding of phenomena such as plume development.

Session 13: Panel Discussion: When does Uncertainty Matter?

Update from NRAP Stakeholder meeting, Grant Bromhal

NRAP activities are aimed at reducing uncertainties and include several aspects including: the estimation of potential release volumes by evaluating a range of scenarios; the determination of potential groundwater impacts by assessing a range of scenarios and aquifer types; the localised impacts on the atmosphere deduced from the evaluation of coupled processes; and the clarification of potential release volumes.

The introduction of Class VI regulations for wells has caused an increase in monitoring costs, mostly due to the requirement for a 50 year post-injection monitoring period. This will need to be taken into account as part of risk assessments.

Stakeholder feedback included: a learning curve for agencies and reviewers; uncertainty in calculating Agent object Relationship (AoR) modeling; field consolidation; PISC length, the length of insurance and risk as a function of injection quantity. The feedback also considered what could authorization to inject look like and what does authorization for closure look like. It was concluded that there is always going to be uncertainty.

Panel Discussion - When does Uncertainty Matter?: Phil Jagucki, Schlumberger; Grant Bromhal, NETL, Charlie Gorecki, EERC; Andy Cavanagh, Statoil; Rob Trautz, EPRI; Jørg Aarnes, DNV

There are a number of uncertainties now impinging on CCS. For a utility perspective uncertainty has slowed progress. Only one new coal fired power plant was commissioned in 2012. There is no federal carbon trading system or climate change legislation or regulatory framework for CCS. Costs have also continued to increase. The estimated cost for a 1,600 MW coal fired power station has risen from $US4.4B to $US11B if CCS is included. Utility companies could consider the use and sale of CO_2 for EOR, fertilizer production or other applications. But selling into three different markets, all with different technical and commercial criteria, creates complications for any investment strategy. Investing in CO_2 storage also causes difficulties for a utility because there is a strong possibility of uncertainties created by natural heterogeneity within the site. Consequently it may not be possible to guarantee storage capacity or limit it to more conservative thresholds. There is a broad range of well costs of between 40 – 70% further adding to future uncertainty in cost.

Projecting the costs and performance of new sites will be speculative unless there is sufficient data and site characterisation. However, the understanding of the technical challenges should improve through time. Uncertainty will be greatest at the start of the project but diminish as injection and monitoring progress. There are examples where risk has been judged to be too high and caused potential projects to be abandoned. For example, Fort Nelson, where CO_2 was to be injected into the water leg of a depleted gas field. The movement of the CO_2 into the gas field was considered to be too risky and the project has not proceeded.

From a project manager's perspective, modelling objectives are different for different projects and for different stakeholders. For one project disposal of CO_2 from a gas processing operation into a gas field in close proximity was under consideration. There was a high degree of certainty that the aquifer was far enough away from the gas field, due to a large enough pressure sink, but to give a 100% certainty of no interference the storage site was shifted further away. For another project, there is uncertainty with compartmentalisation. In this case could injected CO_2 affect a nearby oilfield. Uncertainty is not necessarily bad, but there is concern where it could prevent good decisions or where there is a perceived consequence.

Uncertainty in plume shape and direction can affect the monitoring design. There needs to be intelligent interplay between modelling and risk assessment and modelling needs to encompass these uncertainties. If there is leakage the ability to detect it will depend on where it occurs and the rate of leakage. If there is uncertainty in storage capacity assessment needs to be based on how factors affect the capacity limit.

A reward system needs to be in place to encourage investment in new projects, but this incentive is only in place in Norway. If there is potential for a large upside, then operators will need to be prepared to incorporate uncertainties and manage risks, but the business philosophy around CO_2 storage requirements is different from the oil and gas industry. The majority of uncertainty is not technical but political, economic and regulatory. There are tools and methods, which can be adapted and updated, so it is important to be able to communicate technical understanding to financial, political and regulatory stakeholders.

Leakage can be detected through a containment monitoring programme, but the sensitivity of the programme needs to be considered to ensure detection of low levels of leakage. The detection threshold will depend on the number of wells and the scale of the CCS site. It will be necessary to monitor the extent of plume development especially if there is a risk that it will extend beyond the permitted boundaries. Predicting movement needs to be part of any mitigation strategy. Modelling can be used to manage uncertainties for example plume development over time. However there will need to be a high degree of confidence that the CO_2 remains in place.

Future CCS programmes need to take account of the unavailability of insurance. Insurance is not offered because the uncertainties are too high. Under these circumstances liabilities associated with CCS become federal government liabilities. In the state of New Mexico there is a carbon tax to fund liabilities associated with CCS.

If there is a lack of reward then projects are unlikely to proceed. BP have now moved away from a number of projects. The company was actively engaged in one offshore Australian project but this has not proceeded because of geological uncertainty. Norway is the only country where there is an active incentive to proceed with CCS. The Snøhvit CO_2 reinjection was driven by a business case i.e. avoiding a penalty for CO_2 emissions.

An example was given of a permit for the use of CO_2 for EOR. The oil company has no intention of using the depleted reservoir as a Carbon sequestration site. This would mean transferring the site from a Class II to a Class IV permit with a series of additional requirements. (but if CO_2 is used for EOR would the technical issues be the same depending on the capacity of the EOR programme). This example also raises the question of whether CCS liability can be transferred across different jurisdictions for example between different states. It would be useful to raise these issues with financiers to get the perspective of potential investors.

The use of CO_2 in EOR also needs to take account of reservoir compartmentalization. Uncertainty needs to be evaluated but it should not lead to bad decisions or no decisions.

Risk evaluation depends on a number of components which need to be assessed as inter related issues i.e. a bow-tie approach.

Session 14: Risks due to Geomechanical Effects

The majority of induced seismicity observed from different sites has been mostly of a low magnitude, however, microseismic monitoring has been found to be particularly useful at a number of sites by enabling previously unmapped structures to be identified. It has also aided the assessment of caprock integrity. There are lessons from other industries where induced seismicity has occurred including mining and geothermal. Induced seismicity potential should be part of the risk assessment. It can be managed by effective reservoir and injection engineering and by careful and effective site characterisation and selection.

The NRAP programme has been looking at a common method that can be used. A phased approach has been suggested.

Integrated microseismic monitoring and injection history analysis at In Salah CO_2 storage site, Algeria, Bahman Bohloli, NGI & Volker Oye, Norsar

There was a sharp uplift at the start of the injection period and indications of slight subsidence a few months after injection stopped. Microseismic events were recorded, but they were very small, the largest being M1. The occurrence of seismic activity before injection is not known.

Geophones were lowered into a shallow well but only one detector at 100 m worked. This makes identification of the location of seismicity very difficult. 200 events per day were recorded at the height of the injection programme and over 5,000 microseismic events were detected during the microseismic monitoring period. There was a high correlation between the occurrence of microseismic events and the injection rate. Only 1 – 2 events were recorded post storage. RSQSim code was used for modelling natural seismic events. The technique proved to be effective and provided valuable information particularly the detection of a fracture that extended into the caprock.

Probabilistic Seismic Risk Assessment for CCS, Josh White, LLNL

Work from NRAPs induced seismicity working group was presented. A typical scenario considered is a relatively small CO_2 plume surrounded by larger plume of pressurised brine. An existing well-oriented fault that caused concern is reactivated. It is too small to have been characterised but large enough to produce felt earthquakes. There will always be irreducible uncertainties associated with the seismic behaviour of a field, although it is possible to choose sites that are less susceptible to this phenomenon. Four key risks considered are damage risk, nuisance risk, brine leakage risk and CO_2 leakage risk. Each of these risks has nuances that should be considered separately.

Seismicity deserves attention when the characterisation, monitoring and mitigation plans are developed. A phased approach, combined with good contingency plans, can reduce cost while still addressing risk. Probabilistic seismic risk assessment provides a rigorous, quantitative framework. Significant progress has been made adapting it to induced seismicity, but some important gaps in the science still exist.

Induced seismicity, and its associated impacts, can be regarded as a nuisance factor. In areas which have a direct economic link to industries which cause seismicity, such as mining, there is a greater degree of tolerance. Communities which have not been exposed to seismicity are likely to be less tolerant for example in Basel. Compensation might be a solution but there would be a financial implication for CCS. The necessity for a baseline is also important.

Microseismicity at the Aneth Field, Grant Bromhal, NETL

Injection at the Aneth field started in 2007 and is ongoing. Geophones to monitor microseismicity (as well as VSP) were installed three months later. The events were small (~-1) and initially increased with amount of CO_2 injection, although there is a better match when compared with salt water disposal. Event rates have now stabilised over the last year to around 10 per day. Microseismicity was able to reveal structures not seen in the initial seismic surveys. These were NW-SE striking structures confined to the reservoir.

Evidence from this injection programme shows that microseismicity (natural and induced) occurs almost everywhere. Most seismic and microseismic events are associated with pre-existing faults and low permeability zones. The phenomenon can help to identify geological features, such as critically stressed faults. Induced seismicity can be controlled through effective reservoir and injection engineering; and careful and effective site characterisation and selection.

Discussion – Induced seismicity discussions after Zoback's paper

The discussion session was introduced by Tim Dixon, IEAGHG and Charles Jenkins, CSIRO.

A recent IEAGHG report on induced seismicity suggested that understanding of the phenomenon and its associated risks would be improved by:

1. Increasing the induced seismicity catalogues publically available for development and testing of physical and statistical models,
2. Undertaking more systematic studies of sites populated by well constrained subsurface information and seismicity catalogues that are completely recorded down to small magnitudes,
3. Improving the physical reality of physical models by modelling such factors as poroelastic effects, multiple species of fluid, and non-critically stressed systems,
4. Studying the scaling effects associated with a move from pilot projects to full commercial implementation of CO_2 storage,
5. Developing standard risk management procedures and guidelines for induced seismicity for CCS projects,
6. Filling induced seismicity knowledge gaps in the CCS community by collaborating with seismologists working in other industries.

The discussion firstly focussed on what was covered in the report as many of the examples given were in granitic rock which is not relevant to CO_2 storage. There is also a distinction between induced seismicity related to shale gas and that to CO_2 storage, although the most relevant to CO_2 storage is likely to be waste water injection. Zoback has not been critical about seismicity related to shale gas extraction. He has some interest in this industry.

It was agreed that the paper was useful in bringing the topic to public attention and throwing light on current research related to induced seismicity. The debate has kick started several discussions on the subject. There have been several recent reports on the subject, including the national academy of science report, which may have gained more attention (in the scientific community). Zoback has provoked the CCS community to take induced seismicity more seriously even though he might have given CCS a negative image that is unjustified. In the US microseismicity has attracted media attention which has been highlighted by Zoback's views.

It was suggested that induced seismicity is likely to be more of an issue for felt earthquakes, rather than causing leakage. There is a broader question. What are the properties of faults especially in shales and other caprock lithologies and how do they respond to pressure increases. This is an area for future research.

Session 15: Meeting Conclusions

Modelling

The focus has changed from models to modelling approaches and comparisons, including the need to understand what datasets are important for different models. There has also been more work looking at sensitivity and bounding as opposed to processes. The outcomes of benchmarks and toolsets are also of interest. Key uncertainties on how modellers set up problems and approach them bring understanding to the modelling process.

Models will under predict plume expansion and may struggle to accurately predict actual migration patterns. Models have improved with greater data and can be useful in helping to predict long-term behaviour and retention of CO_2. Heterogeneity within reservoirs will cause variations in migration.

Risk Management

Mitigation and remediation should have a greater focus, possibly using experience from other industries, such as gas storage. There is much to be learned from recent projects such as the unexpected behaviour of CO_2 and how has this been managed. Crisis management at the Decatur project is a good example which could be applied to other projects. Previous meetings have had more discussion of competing risk assessment methodologies; however, different methodologies have been applied successfully. Different methodologies may be useful to show different aspects, for example Bowtie is easy to visualise whereas the Tesla method is good for managing uncertainties.

Work in communication has progressed. Communication needs to be instigated from the start and the current focus is on how to send out clear messages. There is a requirement to discuss the balance between risk verses benefits and not just risk in isolation.

There are many issues with policy, especially in the US, where Class VI regulations are halting research projects.

There are a number of outstanding issues to be resolved. Can long term liability be quantified? If the liability of a storage site can be transferred what are the criteria for handover? Some of these issues are handled in the EU guidance documents, but the post closure period remains uncertain. There is a longer term question over the reliably of leakage detection over the next 4,000 years and how this should be specified in guidelines and regulations.

Overall

Managing public perception needs to take account of local issues and their relevance to CCS. Greater public awareness and education is necessary to put CCS into context with other options and energy supply.

There is a significant benefit from real projects because new phenomena can be observed and a better understanding of changes induced by CO_2 injection can be determined (i.e. pressure changes, induced seismicity, fracture propagation). When the injection does not go as predicted, there is actually benefit from more learning.

The behaviour of faults exposed to CO_2 induced stress needs to be better understood especially as faults and fractures could act as conduits or seals.

There is a difference in the perception of risk between different authorities and organisations. For example investors may not view risks associated with CCS compared to utility companies.

The feedback from monitoring and mitigation is very important to risk assessment modelling.

Uncertainty matters when the consequences are perceived to matter to 'decision-influencers'. In dealing with uncertainty, many had concluded that a 'phased approach' enabled progress to be made in a structured and rationale manner to arrive at appropriate conclusions.

Evaluating technology options to mitigate greenhouse gas emissions

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