Evaluating technology options to mitigate greenhouse gas emissions

ieaghgriskmanagementnetworkand environmentalresearchnetwork combinedmeeting

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An IEAGHG combined meeting, hosted by the National Oceanography Centre

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Front & back cover images: Delegates at Bridport Sands / Delegates enjoying an informal discussion at the workshop / RRS in front of NOC / Lulworth Crumple / Group shot in front of ship

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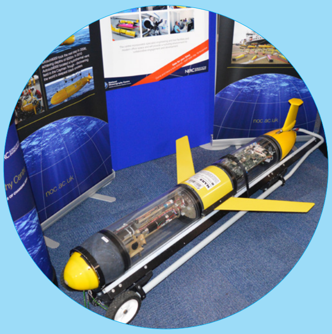
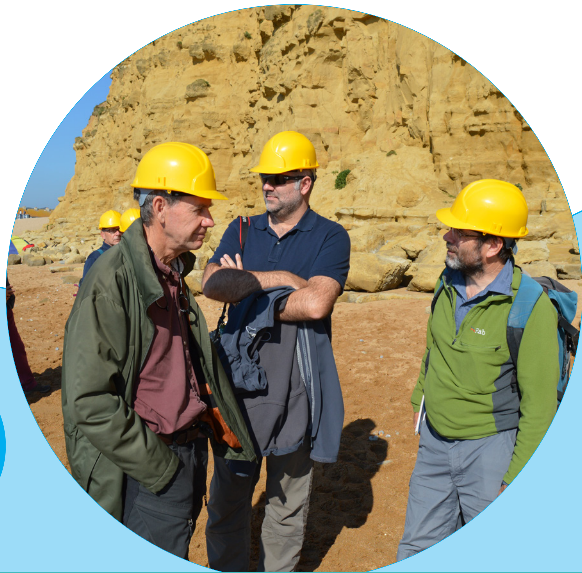




Automomous Underwater Vehicle (AUV) / Lulworth Crumple / Delegates at Bridport Sands

Risk Management Network and Environmental Research Network Combined Meeting 2015

The three days of presentations and discussion in the Risk Management Network and Environmental Research Network meeting had an offshore theme, and was hosted by the National Oceanography Centre in Southampton. The sixty attendees discussed over 38 presentations on the latest work on topics including risk assessment methodologies, mitigation strategies, projects' risk management, impacts of CO_2 in the ocean, natural variability in environments, pipeline environmental impacts, formation fluid release, overburden features, international initiatives, and environmental impact assessments.

Of particular note was a session on formation fluid release into the marine environment, and the development of sensors for marine monitoring. Attendees were given tours of the AUV workshops (autonomous underwater vehicles). One of these is being kitted-out for Carbon Capture and Storage (CCS) monitoring research. Great advances in offshore monitoring are being developed and applied.

The meeting concluded that the risk assessment for CO_2 geological storage is maturing, recognising that with leaks from storage, if they occur, are likely to have low environmental impacts. Wellbore issues are still the predominate risk, and although this is an area of known technology solutions, more work to test and apply these alternatives was suggested. There are great developments in understanding environmental aspects in the marine environment. A sense of perspective was also seen by comparison of potential impacts caused by CO_2 with those from other activities. Further work looking at formation fluid releases was encouraged, and field tests of new sensors eagerly anticipated.

Overall good progress has been made in all areas and the meeting facilitated constructive discussions and the development of new collaborations.

Introduction

The IEAGHG's Research Management Network and Environmental Research Network held a combined meeting at the UK's National Oceanography Centre (NOC), in Southampton. The meeting was attended by 62 delegates from 11 countries. The three day meeting included themes on risk assessment methodologies, risk communication and mitigation strategies as well as environmental research. There was an emphasis on potential impacts of CO_2 in marine environments, natural variability and the unscheduled release of CO_2 from pipelines. Coverage also included formation fluid release, overburden features, international initiatives and environmental impact assessments; notably the Peterhead – Goldeneye project.

Delegates at Bridport Sands

After the meeting some of the delegates visited two key sites on Dorset's Jurassic Coast.

Day 1 – Risk Management

Session 1: Welcome; Professor Ed Hill, NOC Executive Director, Ian Wright, NOC Director of Science and Technology and Tim Dixon, IEAGHG

The Executive Director of the UK's National Oceanography Centre (NOC), Professor Ed Hill, opened the meeting. Professor Hill stressed that the centre is at the forefront of marine science and research in the UK and is ranked third or fourth in the world. He remarked that oceanography is becoming an increasingly important subject particularly in the context of a resource that can sustain a global population of nine billion people and the impact that they have on ocean ecosystems. The impact of climate change on oceans is an additional factor that needs to be taken into consideration hence the importance of offshore storage. The Director welcomed delegates and stressed the interesting and varied programme.

Ian Wright then addressed the meeting outlining the intensive effort by the European countries including the UK into CCS supported by the European Union (EU) as well as the UK's Department of Energy and Climate Change (DECC) and the Energy Technology Institute (ETI). Ian stressed that the meeting is a timely opportunity to present and discuss risk management and environmental research with an emphasis on marine conditions.

Tim Dixon concluded the opening remarks by also referring to the offshore theme. He observed that this was the eighth risk management meeting and the third environmental research meeting. Tim later then mentioned that 2015 marks the 10^{th} anniversary since the publication of the IPPC special paper on CCS. IJGGC has recently published 17 review papers on advances in CCS since 2005.

Session 2: Risk Management Updates from Projects — *Chair: Charles Jenkins*

Peterhead – Goldeneye - Owain Tucker, Shell

Shell's Peterhead – Goldeneye project planned to use an amine post combustion capture technology from a gas-fired power plant on the coast. This was planned to be the world's first full-scale CCS project linking a power plant to an offshore depleted gas field and would have tested a broad spectrum of technical and non-technical risks including duration, regulation and political risk. The project planned to capture 10 to 15 million tonnes of CO_2 over a 10 to 15-year period (90% CO_2 capture from one turbine). The initial site selection depended on the technical and commercial opportunities offered by the depleted gas field including reservoir capacity, seal integrity and infrastructure. The ability to monitor the project and demonstrate compliance with regulators is also an essential requirement. A comprehensive risk register had to be devised and was designed to be actively managed.

The comprehensive risk assessment programme has been designed to determine the level of uncertainty of specific risks and then the measures that are needed to mitigate or counter them. The basis of the risk register is evidenced supported logic. For example, is there supporting evidence that CO_2 can be contained by the caprock. Shell have instigated a series of bow-tie workshops to identify risks at each stage in the project. The evidence for a risk is then compared with the evidence against the impact of a risk. If uncertainties still remain further investigation is initiated. Monitoring has been then been designed to detect, for example, leakage routes and to inform the corrective actions that might be necessary. The detailed risk assessment programme has been used to identify which monitoring techniques are most suitable for specific leakage risks. Shell have conducted a validation exercise with the BGS and Herriot-Watt University and shared their knowledge with a wider academic community.

Risk Management for a CO_2 Superstore - Mervyn Wright, National Grid and Richard Metcalfe, Quintessa.

National Grid are setting out to create a CO_2 transportation business based on a large secure offshore reservoir linked to multiple carbon point sources in the Don Valley area of Yorkshire and Humberside. National Grid have been working with the Don Valley and White Rose projects to link CO_2 sources with a potential sink. The company identified a suitable structure, Endurance (previously known as 5/42), within an offshore deep saline aquifer (DSA). The reservoir is located close to the shore and has a large storage capacity. In 2013 an appraisal well was drilled and a comprehensive data set acquired including cored caprock. The wellbore also provided a section through the overburden which has provided information for a regional model of the seal, reservoir and connected aquifer. The primary seal is halite, but there are a series of secondary seals which extends to the top of the Lias.

A Quantitative Risk Assessment (QRA) based on a three value logic model has been developed to build confidence for and against projected outcomes. The aim of QRA is to identify the impact of uncertainty. The QRA can be used to demonstrate how risk assessment has been conducted and what specific measures could be applied. QRA is also useful for analysing specific uncertainties and what their impacts could be. Data is collated and specific features identified. The expected evolution of the store's development was then composed. Alternative scenarios, associated risks and impacts were also considered even if there was a low probability of such occurrences. The QRA was checked against the EU CCS Directive to ensure that all the selected scenarios met regulatory requirements.

The risks were categorised within a matrix defined by a scale of least to worst possible outcomes compared against a probability scale from very low to very high. The risk assessment decision tree developed for the project can be tracked back to the underlying evidence. By embedding the rationale for the QRA, confidence can be built with stakeholders and investors.

In conclusion the risk assessment has produced a very high level of confidence in the long term containment of CO_2 and that the system will achieve long term stability which are key requirements of the CCS Directive. The commercial prospects for the UK CCS industry are based on the development of a very large and secure offshore storage. High levels of confidence in a large store needs to be communicated to potential follow on power generation and industrial CO_2 sources to offer them a long-term solution for captured emissions.

Risk Management updates from Tomakomai - Jun Kita, RITE

The Tomakomai demonstration project, 800km north of Tokyo, will be in operation in 2016. A costal onshore site has been selected which will capture CO_2 from an oil refinery hydrogen facility and will inject 100kT / year into two offshore reservoirs: a sandstone layer at 1,000 – 1,200m; and a volcanic formation at 2,400-3,000m depth, via two deviated wells.

The regulation that covers offshore CO_2 storage in Japan is the Act for the Prevention of Marine Pollution and Maritime Disasters which is based on guidelines from the London Protocol 1996. The Act stipulates that CO_2 must not cause an adverse impact from a leak. The Act also requires an environmental impact assessment (EIA) including migration into the overburden and CO_2 dispersion into the sea. Selected scenarios using TOUGH2 with ECO2M (LBNL) have been run over different periods of time to simulate migration through virtual faults. Leakage dispersion into the sea has also been simulated including dissolution of CO_2 bubbles in sea water. Simulations have been run for summer and winter to evaluate oceanological seasonal impacts. Marine organisms showed varying degrees of response to high-CO_2 environment. Overall evaluation suggests that a pCO_2 increase of 100-200µatm can be a safe level for ecological impacts. The monitoring plan must be able to demonstrate conformance, containment and contingency. The Act also demands that a three tiered monitoring plan must be implemented depending on the severity of changes that could occur following CO_2 storage. Normal time monitoring defined as no indication of leakage or change from natural variability; suspicious time monitoring where possible leakage is suspected and should be confirmed; and Abnormal time monitoring where leakage has occurred and the extent of any impact should be known. The biggest concern for the project is technical not political.

The Value of Multiple Rounds of Risk Assessment to CCS Project Planning: The Fort Nelson CCS Project as a Case Study - Nick Azzolina, PCOR

Fort Nelson, situated in the north-east of the Canadian provience of British Columbia, is one of several CO_2 storage projects within the Plains CO_2 Reduction (PCOR) Partnership region. The project will inject 2.2Mt/year of CO_2 from the Fort Nelson Gas Plant into a saline aquifer 2,100m deep.

This presentation reviewed the process and results from two rounds of risk assessments that were conducted for the project in 2009 and 2010. An iterative approach from initial site characterisation to CO_2 injection was adopted. In 2009 a risk assessment was conducted based on two reference periods consisting of 50 years of injection followed by 50 years of post-injection monitoring. 32 risks were identified of which 20 related to containment, four each to injectivity and strategic issues, plus three related to capacity and one to seismicity. Expert opinions were solicited from a group of experts to derive frequency and severity estimates for each risk. Values for these two parameters were cross plotted to produce a Risk Criticality Score which compares the relative ranking of each risk and helps identify moderate- to high-criticality risks. During the first round of risk assessment, several moderate- and high-criticality risks were identified related to containment, injectivity and capacity. This process then led to a requirement for additional information and alternative measures to understand the risks in greater detail. The risks were then re-assessed in a second round risk assessment in 2010.

The 2010 risk assessment included a detailed geological and laboratory assessment; a geostatistical model and numerical simulations; an assessment of an alternative CO_2 injection location; and a Monte Carlo simulation. The improved site charaterisation led to the formulation of a new model. New simulations at the alternate injection location showed that there was a reduced chance of CO_2 having an impact on pre-existing gas pools. This re-evaluation has indicated that the risk of leakage and seismicity are very low. The risk assessment was also used to define the monitoring, verification and accounting (MVA) programme. For example the locations of potential monitoring activities were developed in relationship to predicted CO_2 plume geometries from the simulation studies.

The second risk assessment led to risks and probabilities that were better defined. Shifting the injection location 5km to the west of the original location significantly reduced the risks of impacts to pre-existing gas pools. The process used at the Fort Nelson site illustrates the value of multiple rounds of risk assessment to CCS project planning.

Session 2 Discussion: How do we Better Communicate Risk Management Plans to Regulators?

The evidence of the examples presented in this session indicates that as more information becomes available the initial perception of the magnitude of some risks is reduced. However, oil industry experience shows that risks can increase when more detailed information becomes available. For example projects that were thought to be viable can turn out to be uneconomic with greater technical investigation. It is also clear that uncertainty is not the same as risk and the distinction between the two needs to be clearly communicated. Expressing risk in terms of likelihood can be misleading therefore the phraseology needs to be carefully presented to convey the severity of risk.

The interaction of developers with regulators was raised. Shell has explained the results of risk assessments to regulators but they rely on specialist consultants to explain the process of risk assessment. Regulators will not have a detailed background in the relevant technology but all background information is open to them. Examples from the oil industry can help. The Canadian system based on investment where risk assessment is tied to financial assurance can successfully mitigate risks.

Peterhead – Goldeneye Bowtie Model. Sheryl Hurst, Risktec Solutions

The bow-tie method of risk assessment has its roots in the chemical and the oil and gas industry. There is a reference to its application by ICI in 1971. The methodology is now widely adopted globally throughout the oil industry, and in the UK's railway industry and offshore wind power industry, as well as being referenced in risk assessment standards and guidance. The assessment starts with building a bow-tie diagram with the primary hazard, CO_2, and then the subsequent consequence which could be loss of containment or control. Possible causes of the loss of control are illustrated on the left of the diagram, together with engineered, geological and procedural preventive measures. To the right of the diagram are the potential mitigation measures which could limit the impact of the consequence. This framework provides a structure that can be used to collate potential hazards, link them to preventive and mitigation measures to reduce their impacts, and evaluate the effectiveness of such measures in managing the hazard. Qualitative effectiveness gradings can be indicated by a colour-coded traffic light system and displayed on the bow-tie. Issues which might undermine specific preventive or mitigation controls are termed escalation factors, and trigger additional measures that might be necessary.

For the Peterhead-Goldeneye project, a preliminary bow-tie risk assessment initiated in 2011 has been progressed to a refined, semi-quantitative bow-tie model consisting of seven separate but interlinked bow-ties. The methodology has been communicated to stakeholders and peer reviewed by BGS and Herriot-Watt University.

The bow-tie analyses covered releases at different depths, and releases arising from geological and geomechanical causes, and via injection and abandoned (legacy) wells, such that all possible release paths were assessed. The bow-tie method allowed the multi-disciplinary risk assessment teams to not only to identify causes and consequences but also to spot any gaps or weaknesses in the prevention and mitigation measures. The effectiveness grading for each mitigation/prevention measure is supported by detailed documentary evidence linked to the bow-tie diagrams.

The bow-tie workshops also investigated the potential for further risk reduction. The teams tested the effectiveness of each risk reduction measure and the cost/effort involved in its implementation. This approach was also used to determine the most effective monitoring.

In the semi-quantitative assessment, each bow-tie cause is given a numerical score ranging from very likely to statistically insignificant. The overall frequency of a loss of control arising from a specific cause is determined by the cause likelihood multiplied by the probability of failure of each independent prevention measure. Similar calculations on the right side of the bow-tie, allowing for dependencies between detection and mitigation measures, provide a numerical estimate of the likelihood of each defined consequence.

Plots of each bow-tie consequence arising from the different causes and the effectiveness of mitigation measures/monitoring are plotted through the lifetime of the project to show changes with time. The model has been compared with published data for well leak frequencies and shown to be in good agreement.

The outcome from this risk assessment shows that the likelihood of a release of CO_2 from the storage complex is judged to be low. The semi-quantitative analysis suggests that the injection wells would make the biggest contribution to the risk of a CO_2 release until they are abandoned and, after this point, the abandoned wells make the biggest contribution. The model also shows that the probability of CO_2 release decreases after cessation of injection.

Session 3 Discussion: Do we need Probabilities from Risk Assessments or does ALARP (as low as reasonably practicable) Suffice?

Regulators and other stakeholders like bow-tie analysis because it illustrates hazard scenarios and the related prevention / mitigation measures in an easy-to-understand graphical format, and clearly shows where there are gaps / weaknesses. It is also possible to use qualitative bow-tie analysis to demonstrate that risks are reduced to ALARP levels. The bow-tie assessment used for this CO_2 storage project is comparable with oil and gas analyses of major accident scenarios, in terms of the number of bow-ties and level of detail. However, could there be an issue with providing too much information, particularly to non-risk specialists, inadvertently giving the impression (e.g. by a large/complex bowtie) that the risks are high? (refer to Session 4 discussion on the following page).

The confidence that can be placed on risk is informed by the probability of its occurrence. There is not much quantitative data for CO_2 storage projects, particularly for release paths which do not involve well- and equipment-related failures, so accurate, fully quantitative risk assessment is difficult and risk assessment needs to be based on qualitative information. There is an interdependence of different risk assessment techniques so it is important to identify the covariance of risks.

Commercial entities based on CO_2 storage operations will have business models that include the impact of risks. Quantitative measures will be necessary to underwrite financial risks. Quantification is also necessary to estimate the amount of money to set aside for mitigation or barrier implementation.

In some cases, ALARP could lead to overdesign of some mitigation barriers, whereas they only need to mitigate in proportion to the actual risk level (which is computed from the probabilities and severities).

Session 4: Risk Communication — *Chair: Bob Dilmore*

Risk Management Approach for CO_2 Storage: Focus on Risk Assessment in an Uncertain Context - Thomas Le Guénan, BRGM

The first goal of risk management is to prevent harm to the environment or people and to earn the trust of stakeholders. For example the risk and impact caused by induced seismicity may be very low but this can be difficult to explain to stakeholders who are wary of technical experts. Therefore, experts need to know what the magnitude of these risks are and how to explain them. Understanding the natural environment is complicated by spatial heterogeneity and temporal variability but there may also be epistemic uncertainties (i.e uncertainties related to our knowledge). With limited access to data or model limitations risks may be difficult to quantify but improvements are possible. Communication needs to convey how risk management is conducted beginning with context, identification, analysis and concluding with treatment. This is a two-way process leading to further refinement.

The risk assessment adopted by BRGM had 11 main events which were developed into generic bow-tie diagrams. These were then adapted to a studied site to develop a risk register. The next step was the application of an example of a risk analysis for a simulated brine leak for an abandoned well caused by pressure increase in a reservoir. Every possible probability distribution from different parameters was input into a model. Then all the uncertainties were propagated to produce a span, representative of epistemic uncertainty, from a worst case scenario (a cumulative distribution) to a best case scenario. A standard probability distribution will not represent a span of probabilities.

Risk evaluation depends on the stage of project development. Risk reduction may require more technical evaluation. The results can be difficult to understand so uncertainties need to be explained without maths.

Perspective of Environmental Impact Modelling of CO_2 Leakage for Public Acceptance - Toru Sato, University of Tokyo

Natural seismicity in Japan means seismicity is a very important consideration for CCS development. Public attitudes are important in Japan and vary depending on location. Local fisheries associations, in particular, are not enthusiastic about CCS. Consequently bigger storage prospects, further offshore, are now being considered to avoid confrontation. Ship transport would be used as an alternative to pipelines. Further offshore, low temperatures and relatively high pressures favour the formation of gas hydrate within the hydrate stability zone which could act as a barrier to migrating CO_2. Using a numerical model to predict potential impacts is good tool for EIAs but models need to be verified. There is a natural analogue in the form of a submarine volcano where CO_2 emissions can be compared with a modelled release. However, it can be difficult to detect the location of a seep. A joint probability can be used to determine the location of seeps.

JQICS is the next phase of a planned controlled leak experiment in deep water.

Session 4 Discussion: Is Risk Communication Effective and can Negative Perceptions be Counter Balanced?

The large investment in risk assessment and risk management should increase public confidence in CO_2 storage, but this needs to be positively communicated. There could be a mixed message from the use of a detailed bow-tie risk assessment which shows that although the risks are low they might be perceived by non-experts as high. Public reaction to new technology can be irrational, for example, shale gas fracking. Using more positive terminology such as "increasing confidence and understanding" instead of negative terms such as "reducing uncertainty" should help to convey a balanced perspective.

Experience shows that informed regulators do understand risk assessment methodologies, however, in a relatively new industry there is less full-scale experience for comparison. Clear and unequivocal communication to explain risk is therefore essential. What needs to be stressed is the key motivation for CCS, that is climate change mitigation, and the risks should CCS not be adopted, alongside discussion of the risks associated with CCS. The value of demonstration projects to test the technological validity of the concept at full-scale, and therefore advance its deployment, needs to be emphasized. Risk perception is partly cultural for example the comparison between Japan and UK on seismicity. In the UK minor seismic events invoke worry because the population has limited experience of earthquakes. In Japan familiarity with large earthquakes mean minor events do not cause adverse reactions.

Shell have been actively engaged in stakeholder engaged with the Peterhead – Goldeneye project. Their experience with the proposed Barendrecht storage project in The Netherlands focused on direct engagement with local political representation, however, the project lacked local support and did not proceed. This experience suggests communication needs to be clear and simple. Initial consultation could benefit from less detailed material, supported by more detailed technical information to address any public concerns that might arise. Public perception can lack scientific rationality leading to an emotional response especially if community livelihood is affected. Local issues like water supply or detrimental effects to properties are often major concerns so local issues need to be understood and addressed. It is also important to convey that there may be uncertainty however low. If there is any misdirection then a negative perception can easily take hold so it is important to present a positive image early on.

Session 5: Mitigation strategies — *Chair: Lee Spangler*

MiReCOL project - Filip Neele, TNO

If significant irregularities occur, as defined by the EU Storage Directive, such as CO_2 migration through the overburden then mitigation measure must be implemented. The aim of the MireCOL project is to provide background information on mitigation measures to rectify CO_2 migration out of a storage complex or wellbore. The project has developed a toolbox of techniques to mitigate and remediate undesired migration or leakage of CO_2 within the deep subsurface. The project also aims to support the definition of corrective measures plans and help build public confidence in deep subsurface storage of CO_2. Currently available techniques include pressure management, the back production of CO_2 and well remediation techniques. Other techniques such as immobilisation gels and foams have also been investigated. Data from field tests at the Ketzin site and the offshore K12-B will be used to develop specifications for remediation techniques. In one hypothetical exercise foam was injected along a spill point. The effectiveness of the blocking mechanism was modelled which showed the CO_2 migration could be controlled. The concept of the mitigation approaches was tested to determine whether the unmitigated risk was reduced by intervention. The mitigated risk was then re-evaluated to determine whether the level of risk had been improved.

The project will study mitigation and remediation techniques on a range of real or realistic storage complexes, to derive a series of site-specific results, from which more general conclusions will be drawn. A workshop is planned for Spring 2016 probably at the Open Forum event in Venice to present the results of the project and explain when to implement mitigation measures.

NRAP Approach to Quantifying Wellbore Leakage Risk - Bob Dilmore, NETL

The National Risk Assessment Partnership (NRAP) is a collaborative research effort led by the U.S. DOE and comprising researchers from five National Laboratories focussed toward developing defensible, science-based methodologies and modelling tools to quantitatively assess environmental risks associated with long term, large-scale geologic carbon storage (GCS). Risks of primary concern include potential release of CO_2 or brine from the storage reservoirs, and potential ground-motion impacts caused by the injection of CO_2.

The programme is focussed toward modelling critical behaviour of this complex engineered natural system using an integrated assessment approach. Numerical models of key system components (including storage reservoir, caprock, wells, fractures and fault, groundwater aquifers, and atmospheric leakage) are developed; many realizations of those numerical models serve as the basis for development of computationally efficient reduced order models (ROMs). ROMs of various system components are then linked within an integrated assessment model (IAM) to predict whole-system risk performance.

Field and laboratory data can then be used to validate and calibrate both IAM and component models. Model predictions allow strategic monitoring protocols to be developed to verify system performance.

NRAP have developed seven different tools to evaluate different system components including storage reservoirs, caprocks, faults and seismicity, wellbores, thief zones, ground water aquifers and leakage to the atmosphere. Of particular relevance to legacy well leakage performance are NRAP's Integrated Assessment Model for Carbon Storage (NRAP-IAM-CS), and the Well Leakage Analysis Tool (WLAT). NRAP's Integrated Assessment Model for Carbon Storage (NRAP-IAM-CS) simulates long-term full system behavior from reservoir to receptor, and can used to produce risk profiles, estimate storage permanence, and identify key drivers of risk. For example, evolution, over time (e.g., 1000 years) of risks of atmospheric leakage or groundwater impacts in response to wellbore leakage can be calculated for different storage site configurations and wellbore scenarios, including: open wellbore, cemented well with discrete effective permeability (with or without a thief zone to attenuate leaking fluid), multi-segmented wells, and CO_2-saturated brine flux through fractured well cement with geochemical alteration. In another example leakage into a thief zone has been incorporated into a ROM. The WLAT is a stand-alone tool – decoupled from reservoir and receptor ROMs – that can be used for rapid performance assessment of well leakage over time.

NRAP is actively seeking interested individuals from the GCS community to serve as beta testers, to evaluate the effectiveness and useability of these tools. NRAP continues to improve the tools by addressing science gaps, developing more robust ROMs, and incorporating feedback from beta testers into a new version of tools. NRAP will advance its risk assessment tools and methodologies to incorporate mitigation and monitoring for risk management and uncertainty reduction.

Well Assessment at Cranfield Field - Andrew Duguid, Battelle

CO_2 EOR implies a significant number of wells need to be quantified for field scale risk assessment. The risk of well leakage is a significant consideration for CO_2 storage in association with EOR. This collaborative research project, including the University of Louisiana at Lafayette, Battelle, and Schlumberger, conducted a comprehensive risk quantification that involved logging, testing and sampling to quantify wellbore properties over the same zone. Data acquisition could then be used in well-scale and field-scale risk assessments. The research was centred on SECARB's Phase II Gulf Coast Stacked storage project from the Cranfield Field, Mississippi. One of the three wells used in the study, Ella G Lees #7 (EGL7), is 70 years old. Evaluation used different cement bond logs (CBLs) and other logging tools. The two newer wells, CFU31F2 and F3, are monitoring wells that have fibreglass cased sections. EGL7 has had a lot of work overs since it was first drilled in 1945 including cement squeezes. The wells were first logged to find zones of interest to test. Reservoir saturation tools were run to detect the extent of CO_2 saturation in the reservoir.

Sidewall cores from more recent wells were taken for analysis. One sample has a noticeable vertical crack in cement. A sample of cement cored from a production level has CO_2 within it that caused it to break. Highly altered cement from the EGL7 well shows evidence of carbonation but this was not caused by CO_2. Well construction or materials choice not CO_2 reactivity is the probable reason for the alteration of the cement.

The constriction in the fiberglass casing in the injection zone in CFU 31F3 is likely to be related to CO_2 interaction with the casing. Cement mapping tools can be used to identify defects but cannot by themselves quantify pathway sizes in three dimensions. The existence of defects in some places within a well does not mean that the overall integrity is problematic but it might indicate that further investigation is required.

Session 5 Discussion: How Could we Evaluate Mitigation Strategies and are there Gaps?

Experience from CO_2 EOR operations can provide an insight into mitigation practices. Some operators do manage CO_2 movement to minimise losses and complete wellbore workovers before EOR. Others wait to see what happens in the field before taking action. The approach depends on how risk averse the operators want to be. There are well established techniques that can be used to minimise CO_2 leakage. DOE are about to launch a series of new projects on pressure management leading to field demonstrations over the next year. Salt Creek in Wyoming is an example of where all the wells were fixed before flooding to minimise leakage. For first of a kind it pays to be risk averse to ensure CCS can be deployed effectively. In the future when injection rates are ~200Mt/year then a plethora of techniques will be required to fix problems if they occur because of the scale of injection required.

Plugged and abandoned (P&A) wells could present problems. The status of casing and completion records might give an indication of the wellbore integrity. There may be evidence from adjacent wells. Ultimately individual wells may need to be re-entered if serious deterioration is suspected. Pulse Neutron (PN) logs can detect leakage. Large scale anomalies at reservoir or field scale will require monitoring wells. With small leaks that are undetectable then mitigation may not matter. Remediation techniques that can guarantee a solution to a leak would be ideal. A very high level of confidence in an ameliorative measure is necessary otherwise potential storage candidates may have to be ruled out. Legacy areas could present a significant risk if legacy wells cannot be remediated.

Session 6 Panel Discussion: How is the Importance of Leakage Risk, Environmental Impact and Storage Capacity Balanced.

Panel: Ian Wright, Owain Tucker, Filip Neele and John Frame

CCS will still be required to minimise CO_2 during cement or steel production even if CO_2 capture is not implemented for power generation. Small-scale leakage is not likely to be dangerous given the evidence from natural seeps in Italy. The technology could be much more expensive if additional mitigation or treatment measures like desalination are required.

Experience from Australia shows that environmental protection does allow some degree of flexibility. The regulator and developer can abide by the same legislation provided there is no evidence for leakage into adjacent resources. Otway is a good example where CO_2 injection has not had any impact on a higher aquifer or buildings which are protected by legislation.

The EU Regulations are very strict on CO_2 containment and therefore operators have to learn to live with minimal leakage as a condition of any permit. The depleted P18-4 gas field has already been identified as a potential demonstration site for the ROAD project. Depleted gas fields are a logical choice but the selection will be driven by economics.

The first demonstration projects need to be successful and have a very high level of containment to avoid negative perception. Risk management needs to be thorough but operator error and technical failure is still a remote possibility. If an operator goes bust then mitigation will not be possible and a negative perception becomes ingrained. Regulators will not want to pick up costs. One solution is to insist on investment bonds to pay for any contingency. A contingency budget is a requirement of the EU CCS Directive. Mitigation measures need to be clearly documented and there needs to be transparency in any decision making.

Even with present day remote sensing technology it is only possible to quantitatively measure about 90% of the CO_2 stored in the deep subsurface under 2km of rock. The EU regulations recognise the technical and practical limitations of remote sensing measurement of CO_2 in reservoirs. The CO_2 that is injected needs to be metered to a very high degree of accuracy at the surface prior to injection, and there needs to be a monitoring programme to track the overall behaviour of the CO_2. If modelling and monitoring evidence suggests that the CO_2 is secure then a zero leakage assumption is judged to be valid under IPCC green-house gas guidelines 2006. This principle is reflected in the European regulations and UNFCC system.

The European EC Directive is thought to be complex and demanding but the proposed monitoring programme for the ROAD project is relatively simple and has been accepted. This example demonstrates that there are feasible solutions that allow a CCS project to proceed. The P18-4 field of the ROAD project is an 8Mt site, but the future challenge will be the development of 800Mt sites in the southern North Sea. This could mean that characterisation of larger sites with features such as faults which may or may not be transmissive. In these circumstances fault properties would need to be ascertained with a targeted monitoring programme. The extent to which CO_2 migrates across faults could be tested by injecting into small leaky reservoirs. This has been proposed in the US but the plan was not approved by regulators.

A key question to address is how to balance the cost and risk of CCS compared with the impact on climate change caused by unabated CO_2 emissions. IPCC models for 2100 projections of CO_2 reduction assume that capture rates of 85 – 90% will need to be reached. The overall development costs for a CCS project may lead to the avoidance of poor quality wellbores. If credit is available then full project economics will be improved. Regulators might want excessive monitoring to cover project risks, however, this could be moderated by regulatory discretion. Experience from Canada shows that the regulations for CO_2 storage are more stringent compared with the demands placed on acid gas disposal. Acid gas (H_2S) has been successfully stored which shows that CO_2 storage can be controlled. Disposal operations have not needed reservoir models or modified wells despite the gases' corrosive and toxic properties. Gas in reservoirs is not actively monitored.

In Germany current environmental regulation favours other uses for subsurface resources over CO_2 storage.

Research proposals should include deliberate injection to induce migration under controlled conditions. A second potential project was also proposed for a social science approach to gauge risk assessment of CO2 storage compared with the impact of anthropogenic climate change. One objective of this proposal would be to develop language that can be understood by the wider public starting with local primary schools.

Wrap -up: Charles Jenkins / James Craig

Highlights

- Maturity of risk assessment methodology (even probabilities!)
- Clarity about the prominence of wellbore risk
- Beta test for NRAP assessment tool
- Biofilms

Gaps

- Diagnosing wellbore risk
- Remediating wellbore risk
- Setting thresholds ("normal" -> "suspicious")

Summary

- Bow-tie methodology clearly demonstrates highly detailed assessment of different risks and barriers but this perception can lead to an unintentional negative perception.
- Risk Communication - Phraseology needs to be carefully presented to convey severity of risk.
- MiReCOL and NRAP are developing predictive tools that need to be road tested.
- Legacy wells which have been plugged & abandoned could present significant challenges. There is a need to be sure mitigation measures work.

Day 2 – Environmental Research

Session 7: The Impact of CO_2 in the Ocean: what is the Magnitude of the Impact and how Would Marine Ecosystems Respond

Chair: Doug Connelly

Relationship between Sea Floor Emission Rate and Environmental Perturbation - Jerry Blackford, PML

The impact of CO_2 on the marine environment needs to consider two components: biological sensitives to high CO_2 concentrations; and secondly the chemical and spatial extent of plausible scenarios. The CO_2 footprint in the ocean depends on leak rate and how is it dispersed, especially by tidal mixing. Plausible scenarios of leakage still have large uncertainties.

The following three scenario classes have been widely discussed in the literature:

- Abandoned well 0 – 1t/day hard to detect, potentially long-term.
- Leakage via a geological feature 10 – 500t/day on a decadal scale if not mitigated.
- Pipeline scenario ~5,000 t over a short time span and very sudden.

Hydrodynamic modelled scenarios have tested impacts over several orders of magnitude of leak rate. Modelling reveals that post leakage, chemical recovery is rapid provided mixing occurs as is the case in the North Sea which has high tidal mixing. Most CO_2 is eventually released to atmosphere and is not retained in the sea.

The area of impact has been plotted against different leakage rates. For small leaks (<1t/d) impacted area (as defined by a change of pH exceeding 0.1 pH units) ranges from cms to 10s m, trivial on a scale of an area of the North Sea. Leakage rates of 10 – 1000t/day would impact 1 – 100km^2. The annual impact of trawling in the North Sea is two to three orders of magnitude greater (~100,000km2).

Any plume of dissolved CO_2 will move radially with tidal mixing and the resulting pH perturbation can be rapidly and cyclically variable. The biological impact is less clear under these circumstances. Episodic exposures on fauna have not been widely researched.

On the basis of this research we can assess that all but the largest leak events would be very unlikely to impart significant regional environmental impacts. The primary environmental impact of large scale CCS development, which mitigates climate change, would be hugely positive.

Chemical Transformations in Shallow Sediments associated with Leakage - Henrik Stahl, Zayed University, Dubai

Chemical transformations within shallow marine sediments were monitored before, during and after the QICS in situ release experiments. 4.2t of CO_2 was released over 36 days. Sediment was sampled to a depth of 30cm around the release point and from a reference site. Surface sediments have bacteria, epi-fauna (star fish) and macro fauna that respond to changes in pH caused by the release of CO_2.

Seepage of bubbles through the sediments into the water column was observed. An estimated 15% of released CO_2 reached the sea. 85% was retained in pore water forming carbonic acid and calcium carbonate in solution. Alkalinity increased post injection reaching a maximum one week after injection. At D42 high dissolved inorganic carbon (DIC) saturated the pore water. By D54 a rapid decrease in DIC had occurred which might be caused by advection or even biological irrigation processes. Spatial variability within the sediment may also influence these observations. The change in pH did lead to some iron and manganese ion mobility but there was no increase in the mobility of heavy metals which are present in very low concentrations. This controlled release experiment, and subsequent chemical analyses, have demonstrated that chemical transformations in sediments could be a good indicator of CO_2 leakage.

Predicting the Impact of Sub-Seabed Leakage of CO_2 on Benthic Microbes and Microbially-Driven Processes: Lessons Learned from Mesocosm and Field Studies - Karen Tait, PML

Key indicator taxa that are sensitive to the presence of a CO_2 leak within coastal environments were detected at the QICS site. Changes were observed in benthic communities in samples exposed to CO_2 at the QICS release point and also at progressive distances from it. There was a reduction in biological diversity at the release site but, contrary to previous reports showing impacts to ammonia oxidation with decreasing pH, elevated CO_2 stimulated an increase in ammonia oxidation.

Two groups of microbes are responsible for ammonia oxidation. In an Arctic sediment mesocosm, it was shown that ammonia oxidising archaea are tolerant to pH changes but ammonia oxidising bacteria were sensitive to the CO_2 change and their activity declined. This suggests that the impact of CO_2 on local nitrification may depend on the ratio of archaea:bacteria present.

Ammonia oxidation in burrowing shrimp burrows was investigated to assess how changes in CO_2 concentration might affect this process. The animal draws oxygenated organic matter into its borrow leading to increased ammonia oxidation when compared to surface sediments. Elevated CO_2 has a strong and significant effect on nitrification rates in burrow wall sediment but not in the surface sediment. This is attributed to the shrimp's irrigation behaviour.

A microphytobenthos bloom (identified as cynobacteria, together with diatom species) was caused by CO_2 reaction within pH range 7 – 7.5. Carbon concentrating mechanisms are evident in some microbes and observed in mesocosm experiments. Field observations from a site in the Mediterranean revealed an increase in microbe activity but not in abundance suggesting that although CO_2 can affect photosynthetic kinetics other mechanisms can restrain growth. To be certain that CO_2 is affecting microbes the effects need to be stronger than any natural background variation. Indicator species may be useful as a monitoring tool but impacts may only be temporary.

Responses of Key Benthic Megafauna to Real and Simulated CO_2 Leaks in the Marine Environment, with Implications for Establishing Environmental Baselines - Chris Hauton, University of Southampton

A biodiverse, resilient, and productive ecosystem is seen as a key indicator of Good Environmental Status (GES) (EC Marine Directive Article 3). GES descriptors include: maintenance of biodiversity, an integral sea floor that supports a functioning ecosystem, and contaminant concentrations which produce no effects on marine organisms. Furthermore, and as stated with high certainty in the Millennium Ecosystem Assessment of 2005: 'biodiversity, including the number, abundance, and composition of genotypes, populations, species, functional types, communities, and landscape units, strongly influences the provision of ecosystem services and therefore human well-being.'

Research has shown that increases in sea water pCO_2 can impact the physiology and performance of marine organisms, and so influence biodiversity. It is therefore essential that, before sub-seabed CO_2 storage becomes widely adopted, the potential risk to the marine environment is quantified in the unlikely event of any leakage.

In situ field experiments have shown that larger faunal species living at the surface of the seabed, including species such as mussels and scallops, do not suffer detectable impacts when subject to limited releases of CO_2, which mimic a short-lived and small scale release from a reservoir. This has been attributed to the rapid dispersion of the CO_2 plume by tidal forcing.

Mesocosm and laboratory based experiments, with more extreme perturbations in environmental pCO_2 (up to 20,000 ppm), have demonstrated significant impacts to marine species including severe spine dissolution in epifaunal urchins and shell etching of infaunal bivalves, including cockles. Often these exposures have been accompanied by behavioural avoidance of the CO_2 plume, either seen as escape behaviours or reduced activity of infaunal species. Infaunal species emerging from sediment in response to CO_2 exposure will be prone to predation from scavengers.

In general, infaunal species in sediments appear to be more impacted by CO_2 releases whereas epifauna are less impacted. In all cases, however, the larval and juvenile stages of marine species are more susceptible to exposure to elevated pCO_2 than adult life stages. The response of organisms to elevated pCO_2 also varies as a function of the nutritional status of the affected individuals. Well-fed individuals may have sufficient energetic reserves to tolerate periods of elevated pCO_2, whilst starved individuals may be more susceptible to exposure. As a consequence of both of these factors, the season in which a leakage occurs may be pivotal to the magnitude of the impact of that leak.

Ultimately, however, the marine benthic system represents a dynamic environment that does not necessarily respond linearly or predictably to natural or anthropogenic forcing. Therefore, in order to accurately discriminate natural changes in benthic ecosystems from the impacts of CCS reservoir failure, and so ensure that operators are protected from wrongful litigation, it will be necessary to establish multiple 'reference sites' to compare against the biological community overlying any injection reservoir. Any directional change in the composition of the biological community at an injection site will need to be compared to the directional changes simultaneously recorded for multiple reference sites to definitively identify impact. As a consequence, it will be imperative that all reference sites will need to monitored for as long as economically possible, both during and after the injection phase.

Megafauna Responses to Chemical Transformations in the Sea - Jun Kita, RITE

The response to the CO_2 release on benthic megafauna were also monitored at the QICS site. Sea ferns, sea stars, snails, crabs and juvenile fish were observed using time lapse cameras. Sea stars and crabs were frequently observed next to a bubble stream for many hours without discernible abnormal behaviour. No adverse effects on fish were observed during the CO_2 release phase. They even swam amongst bubble streams. Changes in brown mats of microphytobenthos at the release site, and a control site, were caused by natural variations.

Multi-dimensional scaling (MDS) plots showed that chemical changes at the QICS site were not severe enough to have adverse effects on megafauna. A hermit crab recorded adjacent to CO_2 bubbles seemed attracted by a bubble stream.

Japanese flounder were exposed to elevated CO_2 at 10,000µatm, 30,000µatm and 50,000µatm for 72 hours in a laboratory. This experiment demonstrated that fish can compensate blood acidosis by taking bicarbonate from surrounding seawater. In other experiments the tolerance levels of ivory-shells were tested. In the adult stage a high degree of tolerance to CO_2 is observed but the larval stage of this species is sensitive to acidification.

CCS has potential as a climate change mitigation option if leaks are small, rapidly detected and occurring in more resilient habitats even should it leaked. Thus appropriate base-line surveys on marine environment are essential in site selection procedures and monitoring programmes for CO_2 storage reservoirs.

Session 7 Discussion: What Further Research is Needed?

There is a research requirement to improve the understanding of the mechanisms that cause infaunal responses to changes in conditions. Physiological and behavioural responses may be induced by increased CO_2 concentrations or other pollutants. Formation water and brine change could be more important than changes in CO_2 concentration. A reduction in pH will also have an impact leading to an increase in H_2S inducing infaunal movement.

Field observations show both avoidance and attraction to bubble streams which might be induced by vibration. However, the limits of this stimulus are unquantified. Evidence also reveals that mega fauna display diverse responses to CO_2 in marine environments. Automated imagery to analyse infaunal responses is a potential area for development.

In tidally dominated regions induced mixing leads to highly dynamic plumes, therefore the environmental response of fauna to rapid cyclic change is an important topic for investigation. Many organisms have the ability to tolerate short periods of environmental stress. However, if conditions become chronic through prolonged exposure then physiological stress could be detrimental. Some work has suggested that oscillating exposures could impart additional challenges for organisms as they continually need to adjust to changing chemistry. The evidence from both controlled release sites and natural CO_2 seeps shows that impacts are highly localised.

Reference risk cases which researchers could use to analyse the magnitude of impacts would be a helpful starting point for simulations. This approach would be more relevant than hypothetical and unrealistic scenarios. Multiple reference sites would provide background evidence of spatial and temporal variability.

A second stage QICS type project, over a longer time period (~50 t release), would be able to demonstrate impacts and monitoring techniques over a greater scale. Community acceptance could still be a challenge even with rapid dispersion. The broader question of environmental impacts from leaks needs to be put into context. The probability of leakage is very low ~1:10,000,000. The probability of climate change and increasing ocean acidification will continue without intervention. Consequently the impact of simulated releases should be emphasised to the wider public (~10-5 per year) to put the risk into context.

Session 8: Understanding Natural Variability and CO_2 Impacts: how can Natural Variability be Distinguished from Induced Anomalies in Environments?

Chair: Jerry Blackford

Natural Variability of Biological Communities in the Temperate NE Atlantic and North Sea - Steve Widdicombe, PML

Seasonality is a key influence in the marine environment. In spring rising temperatures plus nutrients increase biological productivity causing phytoplankton blooms. In the north-east Atlantic and North Sea stratification also occurs between the warmer surface waters and deeper cooler waters. Then in the autumn storms break down stratification and nutrients are brought to surface resulting in a second annual bloom. Stratification and therefore biological productivity is partially governed by depth. Shallow waters in southern North Sea and eastern English Channel are regularly mixed and not stratified. Detailed site-specific sampling at the L4 observatory station in the English Channel off the coast of Plymouth has also revealed a stratification pattern observed elsewhere. 2012 observations from this site showed that it was the most productive year since records began several decades ago. Macrofaunal abundance co-incides with the spring bloom leading to an increase in diversity which can be used as an indicator of change. Oxygen demand caused by blooms can lead to hypoxic depletion. In abundance some marine organisms are better able to tolerate abnormalities therefore tolerance to environmental stress will depend on the time of year. This seasonal cyclicity also varies on a yearly and even decadal scale. Stochastic events like storms can also have big impacts. Consequently, additional impacts such as elevated CO_2 concentrations will depend on the time of year, locality and climate.

Climate change is creating biogeographical changes in the coastal seas around the UK leading to an increase in the prevalence of warmer water species. Changes induced by CO_2 could be different in 20 years' time. There are broader environmental changes which CO_2 releases will not affect, for example the diminution of cold water corals from acidification.

Environmental assessments of the impacts that might be attributed to CO_2 releases in the ocean need to be fully conversant with natural variability and be able to distinguish this phenomenon from any change induced by CO_2 leakage.

Environmental Variations in Dissolved CO_2 Offshore Gippsland related to Equivalent Leaks from Storage - Charles Jenkins, CSIRO

There is ample power generation potential from brown coal in the Australian state of Victoria. There is also offshore CO_2 storage potential in the Bass Straight off Victoria's coast which also has important ecological and fisheries interests. Consequently a CarbonNet research project has investigated the impact of a CO_2 leak and the natural occurrence of dissolved inorganic carbon (DIC).

Water samples were taken from a ship transporting cars to Melbourne over a five year period. DIC is very variable over the seasons, changes of up to 100µmole/kg are common DIC is also spatially variable. Samples show DIC fluctuates to the east but is more stable to the west. The dip in DIC values is related to an annual front.

A hypothetical leak on the scale of 20kt/year into 40m of water was modelled in coastal waters. The cumulative distribution of DIC signals from the leak shows virtually nothing above ~10µmole/kg. Windy conditions in the Bass Strait cause mixing and any change induced by CO_2 is likely to be very minor. Naturally-caused DIC changes are much larger than those resulting from an intense, spatially-concentrated leak. The environmental impact is therefore not likely to be a large risk. The results also suggest that finding leaks from marine chemistry changes will require sensitive measurements.

A new way of Looking at Baselines - Katherine Romanak, BEG

A new approach to baseline monitoring in the unsaturated vadose zone in the near surface is essential. Environmental impact is greatest in this zone as it affects the general public, and land owners, and it is the interface onshore which defines leakage to the atmosphere. Research is showing that there is a need to rethink baseline monitoring especially following the Kerr Farm allegation at Weyburn.

The standard approach to leakage detection is to compare pre-injection CO_2 concentrations to post-injection concentrations to discover if an anomaly signals leakage or is in line with natural variability. However, background measurements at all locations are not always possible, weather parameters need to be taken into account, complex statistical analysis needs to be performed and baselines can be spatially dynamic over the lifetime of a project.

As an example, monitoring at the Weyburn Project involved rigorous research with a very high temporal and spatial sampling density. It also included rainfall measurements and geostatistical analysis. A landowner claimed leakage from the CO_2 injection. Three teams investigated the leakage: one funded by the operator, a BGS-led team as part of the Weyburn-Midale Project and an IPAC-CO_2 team involving the University of Texas and others.

CO_2 measurements at Weyburn, Kerr Farm and background locations could, by themselves, be interpreted as leakage. However, CO_2:O_2 and CO_2:N_2 ratios measurements clearly showed that anomalies were consistent with biological respiration. This was confirmed by radiocarbon and noble gas analyses. This example highlights the importance of having a method for signal attribution that is accurate and timely for responding to public claims quickly. Subsequent research at the ZERT site has revealed leakage patterns which can be differentiated from natural patterns of CO_2 release using simple ratios. The approach has now worked at 3 – 4 different sites. Although concentrations of these gases change the ratios remain consistent.

Differentiation between Natural Processes and Induced Leakage in an Offshore Environment – Bio-Oceanographic Approach to CO_2 Leakage Detection. Latest Research Findings - Jun Kita, RITE

Monitoring CO_2 in seawater is essential for leakage detection near offshore storage sites. Exogenous leakage needs to be distinguished from naturally occurring background CO_2.

Photosynthesis in the water column leads to high O_2, low CO_2 and high pH in surface waters. In contrast, degradation in the proximity of the sea floor leads to low O_2, and pH, but high CO_2 concentrations. This stratification becomes pronounced during the summer when biological activity increases. pCO_2 measured in Tokyo Bay was relatively uniform during the winter (200 - 300µatm) but revealed a vertical gradient from 100 – 900µatm in summer. The high measurements in summer mean that it would be more difficult to distinguish leakage from background observations. An appropriate methodology is therefore needed to detect leakage.

Environmental monitoring in Osaka Bay has been conducted for over 30 years. Bay waters have been sampled for a series of parameters including salinity, dissolved oxygen (DO) and pCO_2. Alkalinity was calculated from a linear relationship with salinity. TCO_2 / DO have a weak statistical relationship, but a log pCO_2/ DO% saturation plot shows that a quadratic trend-line is evident. This relationship can be used to detect leakage.

The natural background of pCO_2 has been measured at a depth of 50m near Niigata off the west coast of Honshu. pCO_2 concentrations are regularly high at mid-night and low at mid-day when the sun's radiation is strongest. Photosynthesis influences pCO_2 even at a depth of 50m. This fluctuation is also evident from the high concentration of benthic phytoplankton during June and July. The fluctuation in daily pCO_2 concentration declines from August. Although the pCO_2 / DO% correlation can be used for leakage detection, background characterisation deduced from site-specific monitoring is essential. Leakage monitored at release sites shows a distinctive pattern that can be distinguished from natural background trends.

Session 8 Discussion: What are the Main Drivers on Environmental Impacts?

Marine site characterisation will depend on location, depth and season.

Regulators will want to know if a signal is a leak or whether it can be attributed to background variability. A minor CO_2 leak may not have a significant impact on the environment. Moreover, the scale of the impact needs to be determined. Regulators will become concerned if a catastrophic leak occurs which leads to environmental change or damage to a specific receptor. Regulators could demand an impact assessment.

The uses of tracers might be an option but tracking them and CO_2 through 1000s of meters of overburden might be impossible. CO_2 will react with some of the mineral content in the overburden formations and could be retained in traps. Tracers are also expensive. Data from QICS and other marine sites could be used to see if natural variables can be distinguished from leaks. Variability can be addressed by statistical treatment of covariation between different variables associated with natural processes, but not leaks. But natural variability takes place over multiple timescales, and co-variability may be partially uncoupled in space or time, making this more challenging than initially hypothesised. A geophysical parameter could offer an alternative to variable biological parameters. Key reference sites or habitats could be used to compare changes that might occur elsewhere.

Other biogeochemical parameters could be refined to demonstrate natural baselines especially in a marine environment, i.e. establishing ratios between DIC, O_2, nutrients etc. This approach could help to overcome the difficulties of distinguishing an anomaly from spatial and temporally variable natural baselines. Processes are complex in a marine environment and need to be better understood. Mesocosm experiments to test whether ratios can be used to define natural conditions is one possible solution, models can also provide insights, but there will be no substitute for high frequency multivariate time series with both a seasonal and spatial coverage.

COOLTRANS Project - Julian Barnett, National Grid (NG)

The National Grid COOLTRANS research programme was a three year Research and Development (R&D) project which took place from 2011 to 2014 and was co-funded by the EU. It started with considering the CO_2 pipeline specifications, then identified gaps in technical knowledge and what R&D was relevant to dense phase CO_2 pipeline transportation. A series of R&D work streams were set up to address these gaps. Experimental work including a programme of over 100 tests into above and below ground releases, simulated pipeline punctures at full scale and full scale fracture propagation tests were conducted. The results were used to develop best practice and safe long term CO_2 pipeline transportation.

National Grid has also completed an environmental impact assessment (EIA) for a proposed pipeline across the Yorkshire and Humber regions. The EIA follows the UK Planning Act for the planning of major infrastructure projects in England and Wales. The company has also consulted with statutory authorities, non-statutory consultees including the general public. One example of the care and attention applied to the planning of the proposed pipeline is the routeing of the pipeline under a possible archaeological site which could be a medieval village.

A series of field and laboratory experiments by Nottingham University have also been conducted. Controlled releases on crop plants have been used to monitor the impact of CO_2. DNV-GL has carried out similar experiments on sphagnum moss with no observable detriment effects. The level of impact depends on the area of exposure, rate of release and its duration. Computational Fluid Dynamic (CFD) models of atmospheric dispersion of CO_2 from venting operations have formed part of the R&D programme. CFD models have been refined after comparison with observations from experimental releases to improve future simulations.

An unplanned release of CO_2, although very unlikely, has been simulated. Third party interference is a risk, which might lead to a failure mode such as a small leak from a puncture although standard pipeline procedures will be adopted to manage this risk. The impact of a major event such as a pipeline rupture has also been considered. A comprehensive Quantified Risk Assessment (QRA) has now been developed for CO_2 pipelines which meets the principles of UK design codes and the prevailing legislation.

Quantitative Hazard Assessment for CO_2 Pipelines. Solomon Brown, University College London

Concern over pressurised CO_2 pipelines has led to EU funded research to assess hypothetical risks of ruptures. A sudden release of CO_2 would 'flash' (vapourise from supercritical state). Solid CO_2 would also be released and then disperse from the rupture. Experimental campaigns were conducted to represent CO_2 releases at different scales including a 256m length of experimental pipe at a Chinese test site in Darlean. Transient conditions were measured during these experimental releases. Pipeline decompression can occur followed by a risk of ductile and brittle fractures. The modelled CO_2 release episodes are then linked to the dynamic modelling of ductile fracturing. This approach can then be used to influence pipeline design.

FLACS high fidelity simulation to predict the impact of a CO_2 plume across ground has been produced by HSE. The impact of CO_2 can be highly topographically dependent. The model output has been used to produce risk assessment guidelines for pipelines.

Subsea release simulations have been conducted by the research team. Rapid Decompression can lead to the loss 15,000 kg/sec and the uncontrolled release of 10,000s tonnes of CO_2 followed by the ingress of seawater before remedial action can be undertaken. Impurities, particularly noncondensable gases, will influence fracture propagation.

High Pressure CO_2 Pipelines: CFD Simulation of the Consequences of Puncture and Rupture - Christopher J. Wareing, University of Leeds

Research at the University of Leeds has concentrated on the near-field sonic dispersion (2m from the release point) of CO_2 from high pressure pipelines. Thermodynamic conditions of solid and liquid phases are not in equilibrium at the time of release. Consequently a novel complex equation of state is required. Mach Shock, turbulence models simulate the sudden release of CO_2 which requires a dense grid and is computationally demanding. Dense phase release escapes at 500m/sec at 177.8 K -80°C 4m above the vent. The models were validated against experimental observations. In the gas, phase good agreement between the model and experiment was also achieved.

Conditions that might be experienced with underwater pipelines are a key knowledge gap. There is also the question of the formation of hydrates and solid CO_2 and CO_2 dispersion in the water column. A full-scale rupture at 13.5 MPa at -100°C, would create a release at 100m/s. A 0.6m diameter submarine pipeline, 100 km in length, would release 100,000 tonnes of CO_2 before the shut off valves were activated. This equates to a 10% concentration CO_2 gas cloud 7 miles in diameter. A research proposal is being prepared to seek fundamental scientific research funding from the UK EPSRC. This ERUPT proposal is designed to address the key knowledge gap regarding offshore CO_2 pipelines and the risk of their rupture. Interested stakeholders are invited to become involved.

Session 9 Discussion: Can Environmental Impacts caused by a Leak from a CO_2 Pipeline be Quantified?

Large CO_2 releases from pipeline ruptures can be limited by safety procedures. At Quest the pipeline is shut down automatically if there is a large pressure drop. National Grid has pipeline controls to shut down systems using remote valves. Experimental work has aided the understanding of CO_2 releases. A plume will entrain air and therefore dilute the CO_2 before it eventually disperses. Natural turbulence will cause CO_2 dispersion even on a still day, although wind will facilitate more rapid dispersion. Venting would only be done on windy days to ensure safe dispersion.

Full blown pipeline fracture tests have been conducted by National Grid. Results have been used to define a minimum toughness test, equivalent to a 250 Joule pipe. The material standard for a future pipe would be in the order of 300 Joule. National Grid have also simulated a digger accidentally damaging a pipeline.

Session 10: The Impact of CO_2 in the Terrestrial Environment: Magnitude of Impacts and Baseline

Chair: Katherine Romanak

A Review of Recent Research on Potential Environmental Impacts of CO_2 in Terrestrial Environments - Dave Jones, BGS

Legislation stipulated in EU Directives and the US Class VI wells means that operators need to be aware of the consequences of leakage on terrestrial ecosystems despite the very low risk of leakage. The effects of elevated CO_2 on soil microbes and plants has been investigated at a number of different test sites and laboratory experiments, plus naturally occurring CO_2 seeps, including CO_2GeoNet, RISCS, CO2 Field Lab, ZERT (USA), Ginninderra (Australia), Ressacada Farm (Brazil), MUSTANG and PISCO$_2$.

Results from a Norwegian site trial showed that with high soil CO_2 oat growth was reduced. The CO_2 flux was correlated with a stressed vegetation index. At the ASGARD test site in the UK autumn-sown barley showed stress after two weeks exposure to CO_2. However, autumn-sown oil seed rape was not strongly affected because the plant was well established before exposure to CO2 but there was a greater impact on spring-sown oil seed rape. Modelling at the ASGARD site is consistent with discreet CO_2 migration pathways through the soil. A natural CO_2 seep site at Florina in Greece revealed a plant species distribution based on the degree of tolerance of plants to CO_2 exposure. The effect of CO_2 on microbial activity was also evident at this site but could not be separated from seasonal effects at ASGARD.

The overall conclusions from these experiments is that different species have varying degrees of tolerance to elevated CO_2 levels in soil. Impacts are restricted spatially to a few meters to 10s of meters. The development stage of plants, as well as seasonal and annual variation, influences the effects of CO_2. The impacts appear to be manageable compared with climatic factors or pests.

Assessing the Potential Consequences of CO_2 Leakage to Freshwater Resources: from Experiments to Predictive Models - Julie Lions, BRGM

The potential impacts of CO_2 on a shallow ground water aquifer could be compounded by direct and indirect consequences including brine migration, the presence of immiscible hydrocarbons and the modification of the geochemical equilibrium within an aquifer. CO_2 may lead to acidification and the release of trace elements or sorption of trace elements from minerals. Modelling changes induced by CO_2 shows a large variability in published results.

Further research has attempted to improve the understanding of CO_2 impacts on groundwater quality. CIPRES is a French national project to evaluate these impacts. One objective was to identify geochemical reactivity to examine the significance on temporal and spatial impacts induced by CO_2 intrusion. Laboratory experiments were combined with modelling using the Albian Greensand formation within the Paris Basin as a case study. This formation is a strategic reserve for drinking water supply. The iron-rich phyllosilicate glauconite within the formation has high surface properties that are sensitive to changes in pH. Isotherms on glauconite were used to test the dissolution of glauconite and ion exchange properties of nickle, zinc and arsenic. Laboratory data was used to build geochemical models that include the kinetic dissolution of minerals and surface processes. Two different processes were modelled: ion exchange; and a surface complexation process. CO_2 changes the pH and therefore both reaction processes need to be correctly assessed to improve the prediction of trace element mobility. Surface complexation is sensitive to pH and water chemistry while ion exchange is mainly controlled by water quality.

A 3D reactive transport model was used to simulate the progression and impact of a leak. Three different leakage rates (0.001 to 0.1 kg/s) were modelled over a 100 year timescale. Above the leakage point gas saturation and the dissolved inorganic carbon (DIC) accumulates at the top of the aquifer. Downstream the density effect of the dissolved CO_2 causes the plume to accumulate at the base of the aquifer, but after 100 years the plume has almost completely dispersed. pH buffering is very low within the aquifer in the absence of carbonates. Even if gas saturation recovers to zero, the pH does not revert to a neutral level. Good geochemical characterisation is essential before any monitoring programme to determine the presence of a leak. Initially there will be changes in gas saturation and pH, but in the longer term a drop in pH will cause dissolution of glauconite and an increase in ions such as aqueous silica. The delay in the response of the water chemistry is controlled by the kinetic dissolution of silicates that is relatively slow. Such indicators could therefore be used to detect a CO_2 release. The correct assessment of geochemical reactions in aquifers, caused by potential CO_2 leaks, is important to aid the design of monitoring plans. The location and separation of sampling points and the frequency of monitoring could be estimated with a 3D reactive model if the hydrogeology and the geochemistry is known.

Session 10 Discussion: What are the Most Important Terrestrial Impacts and which Impacts Lead to the Greatest Concern?

The evidence to date from controlled releases on crops shows that elevated CO_2 concentrations have limited impacts. There is also limited evidence from soil sampling that microbial communities can respond to a rise in CO_2 levels in some locations although it is not clear if longer term fertility could be affected. Surface changes are the most visible to the public but these are likely to be spatially limited. CO_2 or brine impacts are the greatest concern especially in the USA where shallow aquifers are a major source of drinking water. There is evidence that water quality will not be adversely affected by a leak from a well 100m away. However, it could be very difficult to detect the impact of CO_2 on a potable water supply from a monitoring well. Consequently, the monitoring location does not necessarily mean a change in water quality will be detected.

There is currently an EC funded CO_2Quest project which has an objective to track CO_2 with heavy metals to model/monitor their dispersion within an aquifer in the Paris Basin. Despite the close proximity (20m) of the monitoring point it was very difficult to detect the presence of released CO_2 which had fallen to 10% of the concentration at the injection point.

Greater public debate about brine ingress into fresh water aquifer would be beneficial. Monitoring potassium mining, and the associated brine disposal operations, has provided a useful insight into the impact of brine disposal on ground water.

Wrap-up Day 2: Ian Wright and Lee Spangler

Terrestrial

Potential environmental impacts caused by CO_2 leaks in terrestrial locations are highly localised and relatively limited. Evidence from controlled release experiments suggest rapid recovery is likely to occur but further research is necessary. It is clear that saline water ingress is a key issue.

Pipeline safety is a key public concern given the scale of potential impacts. Catastrophic failure such as a rupture will have a big impact but over short period of time. Minor leaks caused by corrosion might affect vegetation in the vicinity of pipelines.

Marine

Research suggests that small leaks in a marine environment will have a limited localised empheral effect. Natural turbulence induced by currents will cause mixing and dispersion dissipating the impact of released CO_2. The approach to base-line monitoring needs to take account of site-specific conditions. It may be better to use molecular ratios to distinguish the origin of CO_2 rather than more complex methods which could be less effective.

Pipeline rupture in a marine environment needs further investigation. Biochemical changes induced by CO_2 within shallow marine sediments and the water column is another area for further investigation.

Day 3 – Risk Management and Environmental Research Combined Themes

Session 11: Fluid Production and Release into the Marine Environment: Management, Issues and Impacts

Chair: Ian Wright

A Perspective on Hypersaline Fluid Management Introduction - Ian Wright, NOC

Ian Wright introduced this section. He made three key points:

- In the North Sea and other offshore petroleum provinces there are natural seeps of brine and other fluids from aquifers including hydrocarbons,
- CO_2 injection into saline aquifers may displace brine in the far field,
- To go beyond 1% injection into saline aquifers, brine is likely to require extraction i.e. produced waters.

Impacts of Formation Water Release on Benthic Ecosystems – Preliminary Findings - Ana M Queirós, PML

In the North Sea 50% of the aquifers are saline and about 30% are hypersaline. This has important implications for CCS because of the potential impact of the release of saline formation fluids into the marine environment. A series of mesocosm experiments were conducted at the NIVA Marine research station in Oslofjord, southern Norway as part of the EC FP7 project ECO_2. Mesocosms can be used to test artificial simulations of biogeochemical conditions on different sedimentary assemblages and sediment types. The impact of CO_2 was measured over comparatively short periods of two weeks and over longer periods of several weeks. Exactly the same experiments were then conducted on the same communities but under hypersaline crossed with hypoxia conditions[1].

Formation salinity in the central and Northern North Sea varies from between six to nine times seawater and in some cases ten times sea water salinity. Hypersaline conditions were set up in a mesocosm to evaluate the effect on marine fauna. A control tank was established for comparative purposes close to the oxygen and salinity levels of the Oslofjord collection site. Three condition sets were tested and compared with control conditions: brine (48 ppt) with normal oxygen; low oxygen (hypoxia) conditions with normal salinity; and brine with low oxygen. A tidal influence was simulated by flushing an extra treatment set of tanks (with brine and low oxygen conditions) with controlled water conditions. A short term three week exposure experiment was conducted to see if there was any physiological stress expressed by the levels of fauna diversity, bioturbation (a process measuring the general activity of fauna and their health); and sedimentary chemical processes.

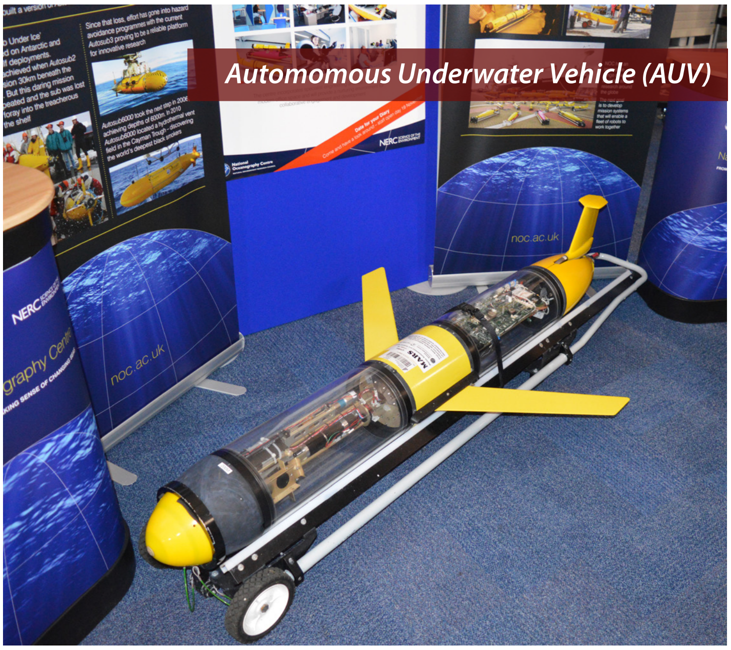
[1] AQ sea bed ecologist. First formation impact assessment from ECO2 projects. See IJGGC special paper V40 1-458 Sept 2015

Hypoxia led to an increase in sulphides suppressing biological conditions. Hypoxia limits ammonia oxidation in sediment whereas high salinity has the opposite effect. The activity of fauna was reduced by 50 – 100% under high salinity conditions compared with the control. The relative abundance of fauna was affected by high salinity after three weeks. The overall impact of hypersaline conditions after three weeks equated to that observed under extreme CO_2 leakage conditions (20,000 ppm) tested during a 20 week experiment. Only tested a moderate brine (48 ppt c.f. normal salinity of circa 35 ppt) was tested given the salinities observed in formation fluids across the North Sea. The combined roles of other components of brines could additionally be potentially detrimental, however dynamic flushing may have an ameliorating effect but this condition needs to be tested and supported by model development. Spatial modelling of brine dispersal and dissolution is the next step to gain a better understanding of brine impacts. The impact on different species and sediment types also needs further investigation.

Precursors of Leakage: Formation Fluid and Pore Water Release from a Leaking CCS Reservoir - Doug Connelly, NOC

Bubble detection is relatively simple using a number of shipboard acoustic approaches, but fluids can come from a variety of natural sources. Natural fluxes through pockmarks, geological fractures and submarine groundwater discharges are well known in the North Sea and other shelf seas. Chimneys observed on seismic images may reflect palaeo fluid migration routes, which may or may not be still active. In addition there is ~1M m3/day of formation fluids discharged into the North Sea from existing production operations. The source and composition of different fluids needs to be identified and characterised to avoid false positive association with storage sites.

Gaseous and dissolved CH_4 discharges are well known and have been detected by AUV surveys across the Hugin Fracture, thought to be 10M years old. These methane sources may be biogenic or thermogenic in origin and may indicate a link to a submerged hydrocarbon reservoir, or simply a pocket of natural gas. Pore waters displaced ahead of a rising deeper fluid have distinctly different chemical signatures from seawater and can be monitored using chemical approaches as a precursor of leakage.



Automomous Underwater Vehicle (AUV)

The release of formation fluids from reservoirs may indicate overpressure in the storage complex, and displacement of the fluids. The composition of Sleipner and other North Sea formation fluids can be very similar to seawater, making simple monitoring more difficult. Formation fluid composition also changes as it ascends due to gas dissolution. Carbonate mineralisation can remove metal ions and under reduction condition the fluids may increase the concentrations of trace metals. Additional hydrocarbons may also be released along with the fluids allowing these trace contaminants to be used as an indicator of release. Minor elements (Si, Li, B), not present in sea water in the same concentration, can be used as tracers in released formation fluids, but can be expensive to analyse. In the case of the Hugin Fracture fresh water, probably of meteoric origin, is being emitted which clearly distinguishes it from Sleipner formation fluids. In conclusion it is important to characterise formation fluids, pore waters and background chemical conditions and variability in seawater to understand if a leak has occurred.

The use of Biochemical Sensors to Monitor Fluid Emissions - Matt Mowlem, NOC

The primary chemical signatures associated with a CO_2 leak are pCO_2, DIC increase and pH decrease. Natural seasonal and diurnal fluctuations have the potential to mask any signal caused by an increase in CO_2. The team at NOC have been developing a multiparameter and spatial and temporal filtering system to distinguish natural variability from an anomaly. An illustration of a simple anomaly detection algorithm was demonstrated at a subsea hydrothermal vent site using a Eh sensor. The Eh measurement can be analogous to a CO_2 leak signature and can show significant temporal and spatial variation. The signal can be processed using a temporal filtering (high pass filter) to enable unambiguous location of the vent site.

Multiparametric assessment could be used to separate naturally occurring (e.g. biological activity) DIC anomalies from a leak derived signal. For example observation of oxygen, nutrients (phosphate and nitrate) and the carbonate system (two of DIC, Total Alkalinity or pH) can enable prediction of the portion of DIC signal that is attributed to biological processes through the use of Redfield ratios, or other established or measurable stoichiometric ratios for natural processes. Any deviation from expected stoichiometric relationships would then be attributable to a suspected leak. This approach has been demonstrated in natural marine CO_2 vent sites as well as at terrestrial CO2 storage sites.

In a marine CO_2 storage context, a very small leak will be hard to detect unless the sensors (and host vehicle / platform) pass directly through the plume. Depending on the turbulence (mixing) and vertical mass transport (advection) at the site, a small leak expressed as a DIC plume may spread across, or near the sea floor. For example in the North sea in typical conditions the plume might only be detected 2 – 3m above the sea floor and therefore would not be detected at the surface. However, a persistent leak may lead to accumulation when tides result in the same water masses repeatedly moving over the leak (typically leading to an elliptical plume). This condition would aid detection, and because of the increased time for vertical transport, may enable detection at or near the surface.

A further complication is that formation fluids may vent at the seabed, and may have an effect on DIC and stoichiometric ratios. However, the effect of this may be mitigated by measurement of the chemical signatures associated with formation fluids, which might include increases in salinity, Eh, Sr, Si, Li, B, Cl but a decrease in SO_4 ions. This signature is different to both CO_2 leaks and biological activity, and hence multiparametric measurement should enable discrimination between these processes.

There are a number of sensors available to measure these parameters. DIC can be measured routinely in the lab, and by prototype submersible sensors to an accuracy of 2µM which is sufficient to detect a small leak. The submersible sensors are in their infancy, and are slow (minutes) limiting their use as the primary sensor for plume detection. In contrast current electrochemical (ISFET) pH sensors are mature, fast (0.5Hz) and can resolve <0.001 pH. However, they can suffer from instrument drift and can take several days to produce a stable signal. This can be mitigated by using spatial / temporal filtering (as above with the Eh sensor) and / or by combining with a drift free and accurate pH sensor such as the slower (minutes) spectrophotometric technology. pCO_2 can be detected by mature commercially available sensors but the response (minutes) is not as fast as for pH.

In terms of contextual sensors for multiparametric assessment oxygen levels can be accurately detected to micromole level with either optical (optode) or electrochemical commercially available sensors. Nitrate measurement via UV spectroscopy currently lacks the precision and accuracy required in this application. The NOC nitrate and phosphate analysers do have sufficient metrology performance, but are too slow (minutes) for use as a primary plume characterisation tool. Eh signatures can be measured effectively with commercial and research sensors.

Instrumentation now available varies in Technology Readiness Level (TRL) from 3 – 8. NOC are currently integrating detection equipment into different platforms and automomous underwater vehicles (AUVs) for marine survey work. A number of different chemical parameters and salinity can be measured simultaneously within a self-contained unit to enable multiparametric sensing for unambiguous leak detection.

Session 11 Panel Discussion: Formation Fluid Leakage and Release into the Water Column: Risks and Mitigation Strategies

Led by Owain Tucker

There are pre-existing fluid releases from natural sources as well as formation water discharges from production facilities. There can be significant contrasts in salinity and temperature between some formation fluids and sea water. These factors plus the quantity of discharged fluid need to be taken into account to determine the risks and mitigation that might be necessary. An injection rate of ~1M t/year of CO_2 equates to 2,500 t of CO_2 per day. To keep a reservoir pressure neutral ~3,000m3 i.e. 3k t of formation fluid per day would need to be discharged, equivalent to an Olympic size swimming pool. As a rule of thumb 1-2% of the pore volume in a reservoir can be used for storage without any extraction before the tensile strength of the caprock is approached. Sites can generally accommodate small injection volumes of around 30Mt (although it is all dependent on the geological and hydrodynamic conditions) without pressure relief, however, storage volumes are required, say over 100-200M tonnes, then pressure relief will reduce the number of injection sites required.

The scale of any impact on the environment will depend on the composition of produced water as well as the volume. These fluids can also be oxic/anoxic and can contain trace elements. The rate and pattern of dispersion can mitigate impacts. In a tidal driven system such as some areas of the North Sea, dilution can be achieved relatively quickly but only if sufficient near bed mixing occurs, which may not be the case particularly in deep areas. Localised accumulations of dense/highly saline fluids are possible. Local conditions as well as fluid composition needs to be understood and modelled so that the pattern of dispersion can be predicted. Model development is needed to support this.

Produced water today from oil and gas platforms tends to be discharged at or close to the sea surface. This ensures mixing and homogenisation, but future operations might involve discharge at the sea bed. The fluid could be denser and hotter than the surrounding sea water causing convection induced mixing. Dispersion of saline formation fluids is not accurately simulated by current models and therefore further research will be useful.

There are potential analogues, particularly reverse osmosis desalination discharge which creates hypersaline conditions, that could be tracked to study the pattern of dispersion and mixing. The impact of salinity depends on fauna or ecosystem within the vicinity of discharges. Some species are more tolerant of high salinity conditions and could be potential environmental indicators. These species are unlikely to occur in deep environments where salinity tends to be stable. The magnitude and variation in saline discharges, and the extent of mixing and dispersion, needs to be known. One possible solution to manage saline discharges is to manage wells on duty cycles that allow periodic releases to allow mixing and dispersion at different states of tidal cycles.

The monitoring strategy needs to be designed with specific objectives and needs to provide public reassurance. The impact of discharges on broader ecosystems or fisheries is still unclear. A good example is the analogy of the spillage from the Macondo well blow out in 2010. The genuine impact on commercial fisheries is unclear particularly in the context of natural seeps in the Gulf of Mexico.

Session 12: Overburden Features - What do these Represent and how do they Affect risk — *Chair: Robert Dilmore*

Seismic Imaging and Environmental Monitoring of Chimneys in the Gulf of Mexico - Implications for Geologic CO_2 Storage - Tip Meckel, BEG

There is growing interest in potential prospects for storage options in the coastal waters and inner continental shelf of the Gulf of Mexico. Approaches to addressing near-offshore risks on continental shelves are different compared with onshore. One major difference is that the risk of CO_2 leaks to marine environments has been shown experimentally to be minor, whereas concern about CO_2 interactions with onshore water resources (updip salt water encroachment) and resource competition remains moderate. Shallow sediments are not of commercial interest and therefore not well investigated historically, despite their importance for CO_2 storage permanence. Sediments are still accumulating on the continental shelf, compared to onshore, where surficial erosion is dominant. This results in an active sediment compaction regime in which pore fluids (sea water and hydrocarbons) are expelled. Current or geologically-recent leakage points from the compacting basin can be more readily identified than the equivalent relict leakage points onshore. Existing technologies such as sidescan sonar can identify "pock marks" where fluids are leaking and shallow high resolution 3D seismic can identify "gas chimneys" where fluids may have damaged stratification during escape provide evidence of long-term containment performance. This relative ease of leakage path determination is a major risk reduction mechanism for offshore storage.

The Gulf Coast Carbon Center (GCCC) at The University of Texas at Austin has focused on a near-shore area where Miocene sandstone formations with very high capacity have been documented in recent multi-year capacity assessment studies. It is important to recognize that existing technologies are very useful for reducing storage risks by interrogating the overburden above potential storage reservoirs. The GCCC team have been deploying novel P-Cable high-resolution 3D seismic acquisition to further characterize the overburden above potential storage prospects. Initial interpretation shows that some reservoirs are devoid of hydrocarbons either because seals have been compromised or the reservoirs were never charged. Higher resolution data in the overburden reveal shallow features such as minor faults, and their role in historic fluid migration and future performance during CCS projects can be interpreted. In some settings, detailed investigation suggests salt dome intrusion probably disrupted natural seals. Consequently, some potential storage reservoirs in those settings are unsuitable. High resolution seismic, near the coast, has revealed fluvial channels ~140,000 years old. Chimney structures and faults are also evident. At least one fault has an offset of 3-4m and extends to within a few meters of the seafloor. There is also evidence of shallow gas accumulation which contributes to our understanding of long-term fate of migrating fluids, although the time-frames of migration are less clear. Shallow seafloor sediment cores with low concentrations of methane have been taken from a survey vessel in water depths of 15m above shallow anomalies identified in high-resolution 3D seismic data. The CH_4 isotope ratio signature suggests a thermogenic source plus some biogenic interaction. CH_4 from depth suggests gas migration to surface over geologic timescales. The underlying structures in this specific setting are therefore less suitable for CO_2 storage, while other settings without such feature become more prospective. Further investigation is required to check storage potential especially as there are small scale features that are potential natural conduits. Migration rates are also open to question from relatively rapid to geological timescales.

Near Surface Characterisation of the Goldeneye CO_2 Storage Site using High Definition Seismic Data and Attribute Analysis. -Owain Tucker, Shell

Shell have investigated the shallow overburden to characterise Pleisticene-Pliocene sediments in the upper kilometre of the overburden. Although these features are too shallow to ever come near the storage complex, they do form natural pathways for migration of shallow gas, and also cast seismic "shadows" on the deeper formations making. The lateral boundaries of the storage complex were defined by potential migration distance of CO_2 after 1,000 years were half of the stored volume to migrate were it introduced into secondary storage volumes. High definition reprocessed seismic has been used to identify features within the most recent succession. This has revealed a Pleistocene tunnel valley channel 240m deep. Lensing effects of this valley have generated a seismic image artefact which could be misinterpreted as a chimney. This investigation has demonstrated the importance of differentiating seismic image artefacts from defined features.

Palaeo sea floor peircements within shallow sediments are also evident. These pockmarks in the seafloor represents points where gas has or could be escaping. These features could be channels for CO_2 migrating from a deeper reservoir. High definition reprocessed seismic has also revealed ice-scour marks produced by continental-scale glaciers. Large outwash glacial channels were also formed. Seismic interpretation has revealed the complexity of these channels which might influence potential shallow migration pathways. The detailed picture of glacial and post-glacial phenomena then influences the future monitoring strategy.

The Internation Ocean Discovery Program (IODP) is to explore shallow attribution for overburden features pertinent to CO_2 storage.

CO_2 Retention and Migration in Shallow Marine Sediments QICS - Jon Bull, NOC / Melis Cevatoglu, University of Southampton

QICS was a shallow marine controlled CO_2 release experiment at a site off the west coast of Scotland[2]. The release point was 11m beneath the sea bed. A controlled release (~100skg/day) was conducted over 34 days. 2D high resolution seismic was implemented before, during, and two years after the release. Soon after release, on Day 1 amplification at the H_2 horizon revealed the presence of trapped CO_2. On Day 2 a columnar structure leading to a small pockmark on the seabed became evident. At Day 12 a chimney structure had become established and by Day 34 the chimney structure was fully developed from release point to surface. A survey two years later showed that the chimney structure had disappeared. Observations during the release experiment showed that the gas flux varied through each tidal cycle. Comparison of observed gas in the water column and the amounted released showed that ~15% reached the sea. Evidence from reverse polarity of post release seismic images indicates that CO_2 is still trapped. After 100 years all CO_2 will be dissolved.

Surveys from the North Sea show that a large number of chimney structures are present in the South Viking Graben 300-600m in width and ~800m – 1km deep. These structures could act as migration paths. The internal permeability of chimneys is unknown and could be a topic for future research. Coring part of a chimney might reveal some of its petrophysical properties but this might be technically challenging. The use of seismic anisotropy is another possibility.

[2] Blackford et al. 2014 Nature Climate Change - doi:10.1038/nclimate2381.; Cevatoglu et al. IJGCC - doi:10.1016/j.ijggc.2015.03.005

Polygonal Faulting across the Petrel sub-Basin, Australian shelf and its relevance to CO_2 storage - Eric Tenthorey, Geoscience Australia

Polygonal faulting, particularly in the context of fluid migration pertinent to CO_2 storage, has not been the subjected of detailed investigation.

Polygonal layer bound non-tectonic faults are created by elevated pore pressure during dewatering and compaction. These phenomena are very common in continental marginal basins including the Bonaparte basin off the north-west coast of Australia. A few occur onshore in North America and Australia. They cover large areas of 100,000s km^2. The Petrel sub-basin near Darwin has natural gas reservoirs high in CO_2 hence the interest in potential storage reservoirs in the basin[3]. The seal, the Bathurst Island Group, is a micaceous mudstone approximately 700m thick. It is heavily polygonally faulted. Fault length is ~1.5km but they strike in all directions. These structural features tend not to propagate between stratigraphic tiers, although this can occur. Displacement is similar to tectonic faults with maximum displacements of 40-50m. Faulting occurs sequentially as each tier of sediment builds. Fault position tends to determine the position of overlying faults. Hydraulic connectivity will depend on permeability. A rare onshore example from the Cretaceous Khoman Formation in Egypt exhibits polygonal faults with carbonate mineralisation. The multiple generation of mineralisation suggests a series of conductive fluid migration episodes, but over geological timescales. The presence of voids also suggests that dilation occurred.

A gas leak in 1969 created acoustic turbidity in seismic sections which shows what a large scale leak might look like. There is some evidence of vertical gas migration via polygonal faulting in the Petrel sub-Basin but on a geological timescale. It is unclear if these features are significant conduits for CO_2 and further research is needed.

Some thoughts on Potential CO_2 Migration along pre-existing Fluid Flow Pathways in Overburden Successions - Andy Chadwick, BGS

Seal by-pass systems (SBS) could consist of faults, chimneys/pipes or even naturally injected bodies such as sand diapirs or igneous intrusions. Whether these systems could compromise storage sites over sufficiently extended timescales is a key question.

Fault flow properties will depend on the effective stresses and pore pressure which determines fault permeability. Reactivated faults could become transmissive if tectonic stresses interact with pore pressure changes. Chimneys and pipes are clearly evident from seismic surveys. They reflect upward migration of fluid due to pressure decrease or gas expansion but their current flow properties are not well understood. Faults are likely to be the main SBS in the syn-rift overburden succession in the southern North Sea, but significant faults are rare in the post-rift sequence in the northern North Sea. Chimneys are likely to form the main conduits in this area. The hydromechanical response to overburden loading-unloading cycles, caused by successive glaciations, is a significant factor, but whether chimneys are still active with high permeability pathway networks or, more likely, dormant at roughly hydrostatic pressures, is less clear.

There is evidence of a small chimney feature above the Sleipner CO_2 plume, evidenced by a CH_4 accumulation within the overburden. The CH_4 has in the past flowed into the overburden due to a combination of advection buoyancy and diffusion through the mudstone, but the accumulation has not changed since CO_2 injection began in 1996, suggesting that no high permeability pathways currently exist. Modelling suggests advection through intact caprock would lead to CO_2 progressing 17m in 3 million years. Diffusion in the aqueous phase would take CO_2 3 million years to reach the sea floor. This rate of migration equates to 2 - 68 mm / century through advective transport and 23 – 100 mm/ century via diffusive and advective transport depending on the assumed scenario. In conclusion there is no current evidence of CO_2 out-of-reservoir migration at Sleipner along presumed earlier fluid flow pathways.

Session 12 Discussion: Overburden Features - what do these Represent and how do they Affect Risk?

Permanent storage implies retention of CO_2 within a reservoir but over what timescale. There are features within overburden successions, for example, polygonal faulting which could potentially act as conduits for CO_2 if it leaked from a reservoir. Vertical migration via faults is hard to determine and based on the stress regime across and along the fault as well as the

[3] Marine & Petroleum Geol 60 (2015) 120-135 Hannu Seeback, Eric Tenthorey, Chris Consoli, Andrew Nicol

lithology. Otway modelling shows little movement of CO_2 across a fault at low pressure rates. Natural migration rates are not known and only estimated from oil source lithologies to reservoirs. Evidence from gas storage in natural reservoirs is successful indicating that secure retention is feasible. Some tentative modelling suggests multiple conduits and seals where there is transgression enroute to surface shows little evidence of rapid migration to the surface. Capillary migration is also slow on a human scale. Multiple barriers are critical as they avoid dependency on any single barrier.

One possible description of secure storage is the retention of CO_2 in a defined storage complex within a given time-span. Safe storage within 10,000 – 100,000 year time span would be significant in the context of climate change mitigation.

Two analogues that that may provide some useful insights for CO_2 storage fluid migration are: hydraulic fracturing and steam injection into bitumen deposits (i.e., steam assisted gravity drain process). The creation of new routes, or augmentation of existing pathways for unwanted vertical fluid migration (fractures and faults) by hydraulic fracturing in unconventional reservoirs with low-permeability matrix (e.g., shale), may provide insights into how stress-dependent permeability changes can impact leakage performance. Steam injection into bitumen deposits might also provide some indication of fluid movement rates. 4D and 3D / VSP seismic surveys can provide reassurance but this adds to the cost of monitoring an entire storage complex. VSP is especially helpful for checking potential leakage from a well bore, however, this is not an option for legacy wells that have been plugged.

Session 13: International Risk Management Activities and Initiatives – Offshore Environmental Research

Chair: Thomas Le Guénan

Initiative for an Offshore Demonstration Project in the Gulf Of Mexico - Tip Meckel, BEG

The US, and some other countries, are interested in an initiative to develop an offshore demonstration project. US DOE cannot afford to fund a demonstration alone and is therefore seeking international involvement but not necessarily in the Gulf of Mexico. BEG has selected 10 potential offshore basins. Most have or are near large oil and gas fields. In the Gulf of Mexico there are suitable candidate sites with old platforms in near-shore locations that could be linked to EOR. CO_2 storage in the Gulf of Mexico might help with the decision to allow the extension of the Keystone pipeline which could, in future, bring oil from Canada and northern US to the US Gulf coast. Other offshore candidates include: oil fields off the coast of California near Los Angeles; the Pearl River mouth basin an area of ~185,000km2 off the coast of Guangdong province, China; the GlaciStore IODP bid: Joint drilling programme project to core glacial overburden in the North Sea; the Brazilian Lula CO_2 EOR development; the Petrel Basin which forms part of Australia's north-west shelf; and Tomakomai in Japan.

An international collaborative demonstration project could investigate commonalities relevant to all offshore storage such as integration and association with CO_2 rich gas fields, post-closure monitoring, leakage scenarios and demonstrate containment. International co-funding could reduce costs as well as sustain the global discussion on CCS as an atmospheric emissions mitigation option.

International Offshore Initiatives within the CSLF - Katherine Romanak, BEG

The Carbon Sequestration Leadership Forum (CSLF) is a government-level international climate change initiative with a mission to facilitate development and deployment of CCS. The CSLF identifies research directions and reports to a policy group on required actions. It also makes recommendations to its ministerial group to provide policy and technical direction. In November 2013, the Bureau of Economic Geology at The University of Texas at Austin brought a proposal to the CSLF to form a task force to assess barriers and technology needs for offshore CO_2 storage with the ultimate aim to create multinational collaborative field tests. A finalised report reviewing technical barriers and R&D opportunities in offshore CO_2 storage was presented in November 2015 at the CSLF in Saudi Arabia. Seven countries including the USA, UK, Japan, Australia, China, Norway, and the Netherlands all contributed to the final report which concluded that significant opportunities exist to increase understanding of offshore storage; and that there is a growing wealth of research developments and practical experience in offshore storage. It also made the following recommendations and needs:

- National storage capacity assessments at the basin level
- Investment in offshore transport infrastructure
- R,D&D into offshore CO_2 EOR

- Expand knowledge of CO_2 impact in the marine environment
- Monitoring technology development
- Improvement in quantification and shallow-focused monitoring
- International knowledge sharing through workshops and international collaborative projects

To act on the recommendation for knowledge sharing, an international workshop was held in April 2016 at the Gulf Coast Carbon Center at the BEG to build a community of countries interested in deploying offshore storage and to move towards multinational collaborative projects.

Discussion: Building a Framework for International Initiatives and Cooperation – what are the Next Steps?

There will be an EU call for pilot projects valued at 10 – 15 M €. These plans include a new project called STEMM-CCS (Strategies for Environmental Monitoring of Marine CCS) which will build on from the ECO_2 project. This new project will develop and test offshore monitoring techniques for offshore site environmental characterisation, leakage detection and quantification. A test release of CO_2 will be used in the seabed 100m under the North Sea to test the monitoring techniques, so it will be like a deeper version of the QICS project, and will involve use of sensors mounted on AUVs (autonomous underwater vehicles). The project is to be led by NERC's National Oceanography Centre, and involves Shell, Geomar and ten other partners.

There is offshore potential in developing countries and opportunities to develop big projects but getting the right direction is imperative. The aim is for a generic approach that helps developing countries invest in CCS. The UK's COOLTRANS experience shows that there was a specific issue, understanding the impact of a sudden release of CO_2, that was clearly addressed with a £1M project, including full-scale experiments to find out key issues.

One of the key aims for a good demonstration project in a target developing country like China or India is to motivate investment in CCS. The perception is that CCS is too expensive in developing economies and therefore there is a need to show that the technology can be implemented successfully. Where there are commercial projects novelty research can be tested at a demonstration site. However, novelty has to have potential for cost saving and low risk. R&D needs to identify key aims that should also be specific to achieve successful outcomes.

Session 14: Environment Impact Assessments — *Chair: Tim Dixon*

An Operator's Perspective; Shell Goldeneye - Paul Wood, Shell

The environmental impact assessment (EIA) for the Peterhead – Goldeneye project covers the full chain from capture to storage. The key permits include onshore planning from the local authority, the Pipeline works authorisation (PWA) and Marine Licence for offshore operations.

The leak path scenario includes routes from the wellbore, directly through the caprock and laterally within the formation adjacent to the reservoir. CO_2 is not expected to leak. The greatest risk is through a plugged and abandoned (P&A) well or up the side of a wellbore annulus. The survey plan includes P&A wells as well as the platform. A risked based approach to assess risks of these wells has been implemented. Geochemical probes of the seafloor sediment-gas flux have been conducted to establish baseline data and avoid a potential false positive. A mid-life survey is planned unless down hole logging shows an unusual indication of irregularities or leakage. A survey to look for the presence of bubbles would be conducted. Side-scan sonar would also be used for reassurance.

The EIA was submitted to DECC 9th January 2015 and then to the European Commission on 24th August 2015. The EIA is in the public domain although the monitoring plan is not.

An Australian Perspective of EIAs - John Frame, EPA Victoria

The regulator for CCS in the Australian state of Victoria is the Environmental Protection Authority (EPA). CO_2 storage is based on the Otway test site. The EPA's main remit is to set standards and encourage high performance and act as a monitoring authority. Australia has two levels of environmental protection legislation and is subject to many laws. The first stage of an application is to start with the proposal and then compare it to the standards that might be required. Additional assessment may be necessary before approval if not the proposal is rejected. The regulator is concerned with the detail but regulators do not have time to read every document. There could also be multiple regulators who may not know what best practice means and the terminology is not always explained. CO_2 is already in the environment and is difficult to treat. Standards are not always quantitative and processes can occur out of sight. The other main consideration is that CO_2 storage will be for a long time (10,000s of years). There is also the possibility that CCS is confused with other industries.

To get a permit the site must be low risk and must be fit for purpose. It must have plans, procedures and monitoring in place. Indicators can be good surrogates of environmental quality. Mitigation measures should be included before a permit can be granted.

Offshore legislation is dealt by the Federal government in Australia and state legislation is then identical. There is no national environmental regulator but there is a federal petroleum regulator.

Session 14 Discussion: What are the gaps in EIAs?

In Europe a review of EU CCS Directive concluded that the directive was fit for purpose and did not need to be re-visited.

For EIAs the best approach would be to integrate international experience. The Global CCS Institute has been trailing a regulatory tool kit in the CarbonNet project in Australia, Scotland, Trinidad and Tobago. When trialled in Scotland the tool kit was refined down to ~70 permits from over 200.

The EIAs for Gorgon, Goldeneye and Otway found no significant gaps and all applications have been approved. Regulators check that EIAs comply with regulations. There is an assumption that in granting a permit the operator will implement EIA measures.

Emissions from formation fluids into sea are not covered. Goldeneye is a sub-hydrostatic pressure reservoir because it is a depleted gas field so no fluid exclusion is likely. The Gorgon EIA specifies that formation fluids will be reinjected into a different formation. In the USA, formation fluids are covered by water EPA criteria to avoid contamination of fresh water resources under Class VI regulations.

Session 15 Panel Discussion: Mitigation: How do we decide when to Mitigate? - The route to making decisions on appropriate mitigation. Panel: Filip Neele (Chair), Paul Wood, Robert Dilmore, Lee Spangler, John Frame

Appropriate mitigation contingencies need to be planned before a project is approved. Within the Area of Review it is possible that brine and/or CO_2 could migrate to and contaminate an underground source of drinking water (USDW). The potential fluid migration routes need to be adequately characterized, and performance of candidate remedial actions need to be understood. If there is no receptor of concern (e.g., no underground drinking water aquifer) no action need be taken. The likelihood and magnitude of potential impact on receptors also needs to be predicted. Environmental regulators emphasize the critical importance of protecting groundwater resources, and require assurance that storage activity will not result in their impact. This calls for deep level monitoring to detect early difficulties, and allow effective interventions to mitigate unwanted conditions before receptors are impacted.

Experience from CO_2 EOR has provided confidence in CO_2 injection and field management. The practice of steering plumes and reacting to leaks has provided valuable experience in fluid flow control. The monitoring regime needs to be of sufficient quality to detect fluid flow and understand conformance of model predictions to real-world performance so that impactful deviation can be identified and mitigation can be implemented, if required, in a timely and effective manner. Corrective measures are applied on the basis of monitoring information and can include a cessation of injection.

In the case of CO_2 storage there is a relatively low risk from leakage outside casing and induced seismicity. A traffic light system alerting operators to the risk of this phenomenon is necessary to avoid felt seismic events; there may be value in augmenting traffic light protocols with site-specific forecasting tools. Induced seismicity should be anticipated from monitoring and modelling of subsurface risks; effective and probabilistic methodologies and predictive tools are being developed to support such assessment.

Session 16: Overall Meeting Conclusions/Gaps/Recommendations. Panel: Tim Dixon, Ian Wright, Charles Jenkins

- Risk assessment for CO_2 storage sites has matured significantly, as compared with five years ago. Wellbores still represent the most-likely pathway for unwanted fluid migration in most storage scenarios.
- Very substantial work on pipeline safety has been achieved. Pipelines have the potential to cause big acute impacts or small leaks.
- Field experiments indicate that, in the event of CO_2 leakage to the surface, terrestrial environmental impacts are likely to be low.
- The discharge from offshore storage sites needs to be kept in proportion. 1Mm3 of hypersaline brine is discharged daily by Saudi desalination plants.
- Fluid discharges from the oil industry and natural seeps need to be distinguished from leaks. Natural seeps also occur in Australia, the USA and Europe.
- Environmental assessment in the marine environment can leverage great scientific understanding, datasets and techniques.
- Environmental impacts of CO_2 leakage at the seaflore are localised and fast recovery is evident in shallow, coastal areas with tidal flushing. The complexity of natural variations in marine environment is a significant factor when attempting to establish a baseline and monitoring programmes.
- Chimney characterisation is better understood. Pockmarks often represent palaeo fluid channels. The absolute value of sub-surface permeability, and relative differences inside and outside a chimney structure, is poorly defined.
- CCS in comparison with other industries is being held to higher standards.
- Reference risks cases should include cases with probabilities.
- The potential impacts of scaled-up impact need to be placed into context i.e. risk per mega tonne of mitigation should be a parameter.
- New sensors are under development and will need to be tested and reviewed.

Identified Further Work and Opportunities

- A serious full-scale experimental investigation of wellbore leakage (like the COOLTRANS model).
- Structure research on impacts to be better connected to risks, and vice-versa. Reference to risk cases would be helpful.
- There is a need for a consistent narrative about relative risks (climate, other environmental impacts vs CCS). In this context, there needs to be a clear understanding what baselines are, and how they will be applied (for leakage signal detection over background variability, or for measurement of impact, or both).
- Scaling up to large deployment needs more attention.
- Wellbore risk and remediation needs more detailed investigation.
- Unlike onshore pipeline failure, where entire projects (e.g. COOLTRANS, CO2PIPEHAZ, CO2QUEST) have now achieved considerable understanding through comparison of simulations and experiments, offshore CO_2 pipeline failure has not been studied and is not well understood. An opportunity exists to rectify the current knowledge gap.
- Formation water leakage – monitoring, impacts, EIAs, of analogous releases would be beneficial (eg produced water from oil and gas operations).

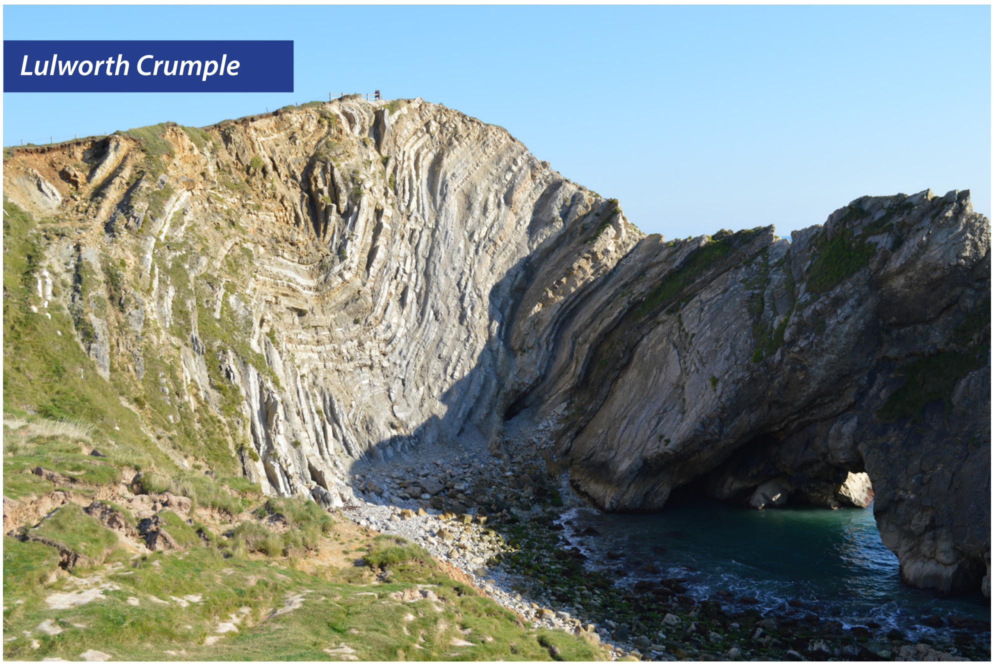
- Empirical research on the characterisation of brines, their potential impact on natural systems and modelling of their dispersion in marine environments needs further research.
- Sensors for formation fluid leaks are being developed and will need to be field tested. A review of new sensors and their potential benefit to early detection is recommended.
- Effects of leakage on soil fertility are not yet known.
- Development and testing of new ratio-based techniques (aka process-based) offshore to distinguish leakage from natural activities.

Recommendations

- Address the further work above.
- More R&D attention on the performance of alternative mitigation and other corrective measures?
- Net Environmental Benefit Analysis (NEBA) for CCS in event of leaks? A NEBA is a methodology for comparing and ranking the net environmental benefit associated with multiple mitigation alternatives to an environmental incident such as a CO_2 leak.
- Further research is required to quantify the impact on the CCS chain and marine environment of an offshore CO_2 pipeline failure.

Tours of The National Oceanography Centre's technical facilities and the field trip to Dorset's Jurassic Coast

Throughout the three day meeting, the director of the National Oceanography Centre (NOC), Ian Wright, and other staff, conducted tours of the centre's technical facilities particularly its compliment of Autonomous Underwater Vehicles (AUVs). NOC can deploy advanced AUVs that depending on their design, can drift, dive or glide through the ocean without real-time control by surface operators. AUVs are capable of simultaneously testing sea water for key parameters such as Eh, pH, DIC and then recording data that can be download for later analysis.


Lulworth Crumple

After the meeting some of the delegates visited classic geological sites exposed along the Jurassic Coast beginning with the Bridport Sands. Thes extensive cliff exposure of this formation shows clear evidence of bioturbated horizons within a shallow marine shoal sandstone. These horizons are known to coincide with low porosity calcified bands. This formation is an important reservoir rock for the Wytch Farm Oilfield further to the east near Bournemouth. The reservoir properties of this formation have revealed that the calcified bands act as baffles. Subsequent tectonic events have created vertical fractures which could allow vertical migration. These features are important to understand because they influence fluid movement and help to explain the challenge of monitoring CO_2 injected into similar reservoirs.

Delegates then visited Lulworth Cove where there is a succession from the Portland Limestone of the Upper Jurassic through the Purbeck Beds into the Cretaceous Wealden, Gault Clay, Greensands and finally Chalk. The location also displays evidence of significant folding caused during the Alpine Orogeny known locally as the Lulworth Crumple. These two locations, and other exposures along this World Heritage coast, enable geoscientists to gain a broader insight into subsurface complexities which are inferred from geophysics and wellbore sequences. The identification of secure, long-term storage reservoirs for CO_2 ultimately depends on understanding such geological complexities.

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Evaluating technology options to mitigate greenhouse gas emissions

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