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IEAGHG

Risk Management and Monitoring Networks Combined Meeting Report

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IEAGHG

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Leading the way to net zero with advanced CCS research. IEAGHG are at the forefront of cutting-edge carbon, capture and storage (CCS) research. We advance technology that reduces carbon emissions and accelerates the deployment of CCS projects by improving processes, reducing costs, and overcoming barriers. Our authoritative research is peer-reviewed and widely used by governments and industry worldwide. As CCS technology specialists, we regularly input to organisations such as the IPCC and UNFCCC, contributing to the global net-zero transition.

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The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate is twofold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy. The IEA created Technology Collaboration Programmes (TCPs) to further facilitate international collaboration on energy related topics.

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Steering Committee, Hosts & Sponsors

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- Nikki Clarke, IEAGHG (Co-chair)
- Sam Neades, IEAGHG (Co-chair)
- Marcella Dean-Elsener, Shell (Host)
- Charles Jenkins, CSIRO
- Filip Neele, TNO
- Katherine Romanak, GCCC, BEG, UT
- Marcia Coueslan, Vault 44.01
- Owain Tucker, Shell
- Philip Ringrose, NTNU
- Sue Hovorka, GCCC, BEG, UT
- Thomas Le Guenan, BRGM
- Ziqiu Xue, RITE

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Contents

Executive Summary

Two IEAGHG expert networks, the Risk Management Network and the Monitoring Network, held a combined meeting from 27th to 28th August 2025 in The Hague, The Netherlands. Both networks have been convening for 20 years, and this meeting, hosted by Shell at the Shell Centre, represented the 11th Risk Management and the 15th Monitoring meeting.

Bringing together over 75 experts, comprised of regulators, operators, research and academic staff, this meeting span across two days to discuss new ideas and probe for deeper insights. The workshop was augmented by a dinner sponsored by Shell and EBN at the Mauritshuis Museum and a post-workshop field excursion to tour the Porthos project.

The purpose of the workshop was to explore the latest thoughts, ideas, developments and technologies related to risk management and monitoring of geological CO_2 storage sites. The dedicated Steering Committee curated each session and the overall flow of the workshop.

On day 1, session one explored ways to maximise storage resources: with a consideration of well abandonment protocols; looking at how classification of aquifers according to regulations influences their availability as a CO_2 store; and how management of surface infrastructure from other industries is critical, especially in the marine environment. Session two included experimental work testing CO_2 injection into a fault and exploring monitoring technologies; and fault risk assessment workflows were presented from the DETECT project. One of the biggest risks to a storage site is the presence of legacy wells; session three focused on quantification, measurement and materiality of leakage via legacy wells. This included control-release experimental work developing near-surface monitoring, case studies of leaking methane wells from British Columbia, crossflow issues between legacy wells and cement channels and quantifying leakage magnitude. Continuing the theme of wells, the final session of day 1 honed in on well designs and operations, a timely update from the Decatur Storage site was followed by well design practices in the US and Norway and material choices to manage corrosion. Finally, a new technique of applying a cement integrity sleeve was described and its potential to preserve self-sealing properties was described.

The second day kicked off with a deep dive into novel monitoring solutions, including down well fibre-optics, seabed fibre-optics, using shear waves as a potential monitoring technique, gravity field monitoring on depleted fields and the latest advances in sparse and cost-effective monitoring. Session 6 continued to explore risk factors with the goal of investigating what might act to reduce the risk profile of a project through time. Two case studies were presented one on an established project (Quest) and one on a project in planning (Porthos). Multi-physics models were shown to demonstrate how hard it is for CO_2 to migrate from a reservoir, and experimental work was presented on the potential of

shale creep to aid CO_2 containment. How the scale up of CO_2 storage might impact resource allocation, risk factors and what monitoring strategies might be employed was the focus of session 7. This is an area where regulators are focusing considerable attention. The themes of the talks ranged from the risk of induced seismicity from multiple stores, using natural seismicity records to create a unified database and some of the challenges in doing so in the North Sea, monitoring strategies (e.g. using pressure monitoring and fibre-optic strain sensing), and strategies for maximising resource allocation. The final session was a panel discussion focused on the role of insurance and finance in CCS at the project level. The panellists addressed definitions, risk allocation, financial guarantees, and innovative insurance solutions relevant to project developers, lenders, insurers, and regulators and engaged in a detailed discussion session with the audience of technical experts.

The workshop concluded with a dedicated closing session aimed at distilling the learnings and promoting action points for further recommendations as outcomes of the meeting. These are summarised at the end of this report.

Risk Management and Monitoring Network Delegates

Session 1: Safeguarding Future Storage Needs – Risks & Opportunities

Chair: Owain Tucker

Risks to damaging future stores – well abandonment practice

Gwilym Lynn, Shell

The presentation emphasised that legacy well abandonment practices are almost as critical as the geology itself in ensuring long-term containment of CO_2. Many wells were not abandoned with CCS in mind, and since storage can introduce pressure regimes different from those anticipated at the time of abandonment, this can pose risks to containment. Effective abandonment relies on having verified barriers in place, yet existing wells in potential storage sites may not meet CCS requirements, meaning costly remediation or a higher tolerance of risk may be necessary. A key challenge is the need for early identification and engagement, fostering a common understanding of storage and seal definitions and ensuring all parties work together. Importantly, the issue extends beyond current CCS licence areas, as unidentified future stores may also be compromised if abandoned in unsuitable ways. Ultimately, the clear message was that there can be no storage capacity without containment.

The discussion that followed highlighted the complexity and balancing act of well abandonment in the context of future CO_2 storage. Not every geological horizon will have a plug in place, making feasibility assessments essential, and in some cases remediation cannot realistically be enforced. Participants noted growing conversations around new storage resources, such as mineral wells, and the need to engage regulators on how plug and abandonment (P&A) requirements should apply to these, potentially at depths of 1000m. Financing was recognised as a major challenge, with underfunded and overstretched groups responsible for P&A, raising questions about how to accelerate activity independently of CCS to create a more level playing field for the energy transition. Suggestions included drawing on oil and gas funding, while recognising that in the US operators are legally obliged to fix insufficiently plugged wells regardless of ownership. Technical aspects were also discussed, particularly the risks of wells within CO_2 plumes where pressure and corrosion could be issues. While there is little guidance, the greater concern was seen as inaction. Cement placement, including effects in the outer annulus, was highlighted as important, alongside geological factors, with creeping or swelling shales potentially enhancing barriers. However, such effects require site-specific testing, raising questions about whether results can be translated across wider basins or only applied on a field-by-field basis.

Classification of reservoirs, e.g. as USDWs and implications for use

Katherine Romanak, GCCC, BEG

This work aims to determine if there is a technical case for Class VI exemptions for storage in brackish water < 10,000 PPM; to determine the technical impacts of injecting $scCO_2$ into less-saline water and determine if brackish water exists at the depths needed for CO_2 storage, considering other potential priority uses such as desalination for drinking water. The influence of CO_2 on metals in aquifers is generally considered limited, with only minimal concentrations typically released, and natural processes mitigating these once CO_2 levels decline. In aquifers with lower salinity, long-term trapping mechanisms such as residual trapping, dissolution, and mineralisation are expected to be enhanced. However, these reservoirs also carry a slightly greater risk of CO_2-enriched brine migrating up the wellbore due to lower critical pressures, though this can be effectively managed through deeper injections and adherence to existing regulations on storage pressure and monitoring.

At depths greater than 800 metres, where CO_2 storage is most viable, brackish water is widespread and may provide a valuable resource for CCS projects, particularly in regions with limited alternatives. Where aquifers contain high mineral saturation or elevated concentrations of elements such as arsenic, boron, fluoride, or iron, desalination can be costly or impractical. In such cases, these reservoirs may be better suited for geological CO_2 storage, helping optimise resource allocation.

The discussion focused on regulatory approaches and perspectives between the US and Europe. In the US, a distinction is made between risk and hazard, with Class VI wells required to have cement extending to the surface – an approach not mirrored in Europe. This was explained as a precaution driven by the Safe Drinking Water Act to protect largely onshore drinking water resources. It was noted that CO_2 in brackish water occupies very little space and that the real risk lies in pressure rather than contamination. Participants suggested reframing the issue in terms of co-existence in the subsurface, emphasising that synergies such as shared infrastructure could be viewed positively, particularly as subsurface competition becomes more relevant. On defining areas of exemption across large regional aquifers, it was clarified that regulations designate only portions of an aquifer rather than the entire formation, and for CO_2 this would be determined within the Area of Review (AoR).

Competing surface infrastructure

Adrian Topham, The Crown Estate

This presentation noted the competition between offshore wind and CO_2 storage in the UK, particularly in the North Sea. The Crown Estate aims to coordinate action across sectors, using the Marine Delivery Routemap to map out the best use of the seabed and coastline to speed up energy projects and infrastructure, and spark investment in the UK. The Offshore Co-location Forum's Project Co-locate will use systematic, technically informed consideration of the types of carbon storage project and the monitoring requirements relative to other seabed constraints (notably offshore wind) to delineate the areas where CS projects can co-locate. The Forum's Project Anenome will engage with relevant stakeholders to create a common understanding of the regulatory and approval pathways for collocated projects, and the operational opportunities and challenges associated with colocation. The Crown Estate recognises that managing the seabed around England, Wales and Northern Ireland – as well as 50% of the coastline – means taking a holistic and long-term view of this vital resource, helping catalyse the UK's transition to net zero while playing an important role in stewarding the marine environment.

The discussion following The Crown Estate's talk on competing surface infrastructure centred on the challenges of early engagement and coordination between projects. Participants noted the difficulty of getting involved early enough to resolve colocation issues, as many commercial organisations are focused on progressing their own projects quickly, though bringing all parties together upfront was seen as the best approach. Technical solutions exist for managing overlaps with wind farms, and there appears to be some willingness to cooperate on shared monitoring solutions, though not all arrangements are fixed. On managing acreage and licensing rounds, it was explained that The Crown Estate works closely with the NSTA and maintains a shared evidence database. However, a recurring challenge is the inherent uncertainty until projects are underway, with time pressures often compounding these difficulties.

Discussion

The wide-ranging discussion brought together themes of co-location, resource protection, monitoring, risk, and public perception. On co-location, participants reflected on the challenge of balancing protection of drinking water and maximising resources. Views of "perfection" varied: integrating multiple uses under one project, restoring environments to their original state, or focusing on stakeholder understanding and communication.

On monitoring, there was agreement that early projects tend to be over-engineered, with a tendency towards excessive monitoring. While some argued this creates unnecessary burdens, others stressed the importance of understanding exactly what needs to be monitored. Over-monitoring was seen as partly a legacy of other industries and may risk creating public concern rather than reassurance, yet it also provides opportunities to demonstrate safety, support expansion, and build business confidence. Participants noted the balance between conformance, containment, and confidence, and emphasised that "less is more" in shallow monitoring where natural variability complicates results.

Competition with other subsurface uses such as lithium extraction and geothermal was recognised, though synergies may also exist. The discussion also touched on ALARP (as low as reasonably practicable), with calls for a broader view of minimising total environmental impact and for stronger incentives for collaboration. Managing projects that combine different subsurface uses was flagged as an unresolved regulatory question.

Public perception was identified as critical, with the need to engage communities before projects arrive in their vicinity and to communicate CCS as a positive activity. Participants reflected on how legal, financial, and environmental risks differ, stressing that actual environmental risks are generally very small compared to public perceptions. Geological storage was seen as far more permanent and reliable than many other CO_2 removal options, a point that should be more widely communicated.

Other themes included the potential for restrictions on activities like bottom trawling in storage areas, the importance of coordination between regulators and consenting bodies to enable joined-up approaches, and the need for a strategic, cross-sectoral view of subsurface management to avoid risk aggregation. Ultimately, the group reiterated that there can be no capacity without containment, and that effective communication, proportionate monitoring, and collaboration are essential to realising CCS safely and at scale.

Session 2: Faults – How Risky Are They?

Chair: Gloria Thürschmid

DETECT fault leakage risk assessment project findings

Jeroen Snippe, Kevin Bisdon, Nino Cilona & Marcella Dean, Shell

Jeroen presented the DETECT project, a fault leakage risk assessment developed to answer the following questions: how to estimate current fault conductivity based on available subsurface data, how to estimate storage operations impact on fault conductivity, what might the range of potential CO_2 leak rates and fate of CO_2 be in shallower formations and how to best monitor fault leakage during operations. The DETECT project was an ACT project which ran from 2017-2020 with Shell, Heriot Watt University, Aachen University and Risktec, initiated to create a predictive methodology to quantify fault leakage potential. The modelling and monitoring barriers were incorporated into a qualitative bowtie risk assessment framework. The outputs are a range of tools from quick screening to full field scale modelling, which produced fault leakage quantification (with uncertainty quantification) on effective permeability and conductivity, CO_2 breakthrough time, and steady-state volumetric and mass leak rates. Utilising regular subsurface data as inputs to the model (fault structure, pre-injection stress state, mechanical matrix properties of seal etc). DETECT integrates single-fracture permeability with the fracture network connectivity and topology. Using the example of Green River, Utah, USA[1] DETECT demonstrated model predictions of surface leak rate over time are in line with observations. This site is a fault-bound natural CO_2 reservoir, and has been extensively studied. Another example from a natural gas cloud above a reservoir as imaged on seismic, DETECT matches the average leak rate and estimates the system close-off time. In a third example DETECT is employed to apply fault leakage scenarios to account for an observed above zone elevated pressure response, with the conclusion that it is highly unlikely the monitoring signal can be attributed to fault leakage.

A question was posed about the role of sub-seismic faults; knowledge from global datasets and outcrop data can be helpful, but even when you fill the model stochastically with smaller faults it doesn't affect the results.

Investigating fault risk and associated monitoring technologies at In-Situ Lab

Ludovic Ricard, CSIRO

The In-Situ Lab project was co-funded by the Australian Government and CSIRO in 2018 and since 2023 part funded by the Research Institute of Innovative Technology for the Earth (RITE) of Japan. The project aims to investigate fault leakage risk at pilot scale by injecting fluids into a fault zone and monitor the migration of these fluids across time and space to inform the risks. The evolution of this project from initial 2010 risk assessments on regional faults to the present-day plans for water and CO_2 injections into the specific F10 fault were explored by Ludovic Ricard[2] . While investigating the CCS fault leakage risk, it is important to consider the wealth of information about faults, fault networks, their sealing capacity, migration potential and stress status amassed by the oil and gas industry.

In 2016, the team started to look at fault juxtaposition, what if CO_2 had access to a fault and ran models to explore the variables and design of early experiments. This led to the 2018-2019 CO_2 shallow control release experiment into a fault zone. The fault was identified on seismic, 200m wide with a 1000m offset. 1.1km of core samples collected by drilling the Harvey 2 well was subject to geological interrogation (core, porosity, permeability, facies analysis, gamma ray, palynology). The Harvey 2 well was repurposed

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[1] Snippe, J., Kampman, N., Bisdom, K., Tambach, T., March, R., Maier, C., Phillips, T., Inskip, N.F., Doster, F. and Busch, A., 2022. Modelling of long-term along-fault flow of CO2 from a natural reservoir. *International Journal of Greenhouse Gas Control*, *118*, p.103666.
[2] Ricard LP, Xue Z, Dautriat J, Hashimoto T. (2025) Towards an improved understanding of fault systems behaviour in a CCS project. Australian Energy Producers Journal 65, EP24260. https://doi.org/10.1071/EP24260

as injector and instrumented and a second well drilled and instrumented, the observations showed that the injected CO_2 barely moved.

In 2023, in collaboration with RITE, the fault zone was imaged with an additional two 2D seismic lines and reprocessing of a 3D original seismic survey from 2014. This re-imaging increased the confidence in interpreting the position of fault structures and well placement which allowed for the planning of a new series of tests. Two scenarios for the new tests are imagined, either CO_2 migrating within the fault zone or CO_2 migrating along the footwall.

In 2024, a new deviated monitoring well (Harvey 6) was drilled crossing fully the F10 fault zone and instrumented with fibre-optic sensing cables optimised for acoustic and strain sensing. In 2025, an injection well (Harvey 5) was drilled with three perforation zones within the fault and footwall, in preparation for water and CO_2 injection testing planned for 2026 and 2027. Meanwhile, a shallow water injection test was run at 18-24m depth in a superficial aquifer to test pressure and strain propagation. This showed a direct relationship between pressure and rate, and the strain is not distributed uniformly consistent with heterogeneity of the formation while tiltmeters data show a direct correlation of direction and timing.

In the post talk questions Ludovic expanded on some of the details of the experiment. The injected CO_2 (less than 500t, which will be trucked in) will be in the gas phase in the top interval and just into the footwall, and the bottom interval is designed to be in the supercritical phase zone. The fault is a very major fault and has been stable for many years, we are not expecting a change of pressure so it should be fine. They are currently working on numerical models for the planning of the experiments.

Water and CO_2 injection into fault experiment

Ziqiu Xue, RITE & Charles Jenkins, CSIRO

Ziqiu presented work undertaken at the CO2CRC Otway site at the Brumbys fault (a near vertical strike slip fault) with a water and CO_2 injection test. This fault has been well characterised, and a static and dynamic model created to predict the migration behaviour of CO_2 injection for a range of scenarios[3]. This CO2CRC–RITE collaborative project investigated the role of fibre-optic strain sensing in two monitoring wells (Brumbys 3 and 4) located either side of the Brumbys fault in a water injection (2 hours via injection well Brumby 1 and 3 into the fault) and CO_2 injection at ~70m (via Brumby 3). Brumby 3 and 4 were instrumented with Distributed Temperature Sensing (DTS), Distributed Acoustic

[3] Feitz, A., Radke, B., Ricard, L., Glubokovskikh, S., Kalinowski, A., Wang, L., Tenthorey, E., Schaa, R., Tertyshnikov, K., Schacht, U. and Chan, K., 2022. The CO2CRC Otway shallow CO2 controlled release experiment: fault characterization and geophysical monitoring design. *International Journal of Greenhouse Gas Control*, *118*, p.103667.

Sensing (DAS), and Distributed Strain Sensing (DSS) Fibre Optic Sensing, and soil gas monitoring was also carried out. For the CO_2 injection, 16T was injected over 8 days (2024). Some of the observations showed that CO_2 was detected by soil gas monitoring from day one around surface cracks. Strain response from the monitoring well (Brumby 4) showed that initially CO_2 accumulated under the Hess Clay (seen to be an impermeable seal horizon) then moving to deeper layers (~40m) in an abrupt episode. The results point to the fault not being the leakage pathway for water or CO_2, the Hesse clay is not a perfect seal and cracks create leakage pathway for CO_2 accumulation under the Hesse clay. The main conduit is a high permeability area located away from the fault.

When asked about the strong daily signal and variation in strain, Ziqiu responded that this is due to the baseline which was set at the beginning of injection, we need to consider the drift and then finalise the magnitude of changes. Other details such as the signature of the CO_2 arrived at the surface are held by Geoscience Australia.

Discussion

During the discussion, participants asked what the application of these research findings were to real life scenarios or industrial settings. The DETECT project's methodology and correlations are documented in a final report (available on the ACT website), making them accessible for industry use. Shell's in-house simulator can incorporate many parameters; however, real-world scenarios (e.g., natural gas) are highly sensitive to specific conditions (tensile vs. compressive regimes). The Shell in-house simulator predicts significant mass loss when simulating CO_2 migration up a fault, particularly in the primary seal. CO_2 solubility, which depends on salinity, there is a lookup table on the DETECT website. Both anisotropy and fault orientation are key factors: vertical faults may result in greater impacts, whereas horizontal faults can promote CO_2 pooling – though outcomes remain highly site-specific. When asked how far well fault sealing is currently understood and estimated, it was agreed that this remains a weak point. In hydrocarbon systems, the availability of extensive data provides better constraints, however in the absence of real cases or test cases our understanding is still somewhat limited. Many experiments are shallow, and a large dataset is needed to validate any model. Fibre optics can be useful, if we can detect formation waters, it could provide an early warning signal to operators.

The issue of downward vertical fluid migration was also raised, and although not specifically examined in the DETECT project, it could be applied. The main considerations would be to avoid pressure build-up at a fault and whether that fault reached basement.

On regulatory and operational implications, forward modelling (like DETECT) can inform regulatory responses and mitigation strategies but requires accurate geological and physical data. Research experiments have different permitting requirements than commercial projects.

The discussion turned to the challenges of scaling up beyond single-site storage and potential implications for the stress state. Although the DETECT team hadn't considered this, the first recommendation would be to revisit the bow-tie analysis. In principle, a high-level change in pore pressure would be required to change the effective stress, and a large shift in effective stress to change the outcome, However, experience in the Permian Basin with water disposal operations has shown that inadequate well completions can lead to issues such as cross-flow and downward flow, which have proven costly for the operators and challenging for the regulators.

Session 3: Legacy Well Risk – Thresholds of Detection - What is Material?

Chair: Gwilym Lynn

Thresholds of detection: what is material, lessons from the literature, computer and field

Aaron Cahill, Benjamin Pullen and others, Heriot-Watt University

Given the ample documented evidence that legacy wells can and do leak, both onshore and offshore and that integrity failure is complex, with all aspects needing better understanding. Aaron presented some of the work from a recent IEAGHG-funded project (with Scottish Carbon Capture & Storage (SCCS)), developing a robust, evidence-based framework to decide which legacy wells might require remediation (or avoidance) for safe and effective CCS deployment. The first defined criteria estimated leakage rates for legacy wells and was evaluated by looking at the literature, which revealed most are based on modelling exercises with a huge spread in rates. This was compared to a model Q-WellRATE developed by HWU (Heriot-Watt University) with SCCS, which was more conservative but still with large variability. The range of tools, methods and sensitivities for detecting leakage in the onshore and offshore realm was compared with the range of literature-derived and QWellRATE modelled flux levels. Most tools might detect the literature minimum rates, but only the most sensitive would detect the lowest rates as calculated by QWellRATE, for slow, chronic releases. Detection remains a challenge. Lastly, a field example of a leaking well was presented from British Columbia, with leakage estimates benchmarked against the theoretical estimates. They demonstrated that methane oxidation is a key process that might lead to false positives in CCS projects. A key take-home message is that there is an urgent need for more field data.

During the post-presentation discussion, Aaron expanded on details of the fieldwork. The well in question was plugged and abandoned (P&A'd) in 2007 in accordance with the regulations at the time. Although it should not be leaking, low-level leakage has been detected, evidenced by crop rotation uncovering stunted plant growth. This year, alfalfa is being grown, and it will be informative to observe whether it is similarly affected.

Atmospheric measurements have not yet been undertaken, though methods such as eddy covariance using a drone would be valuable, but is currently outside of the project scope. The methane appears to originate from the production reservoir, with a trio of gases that convert to each other; it's very site-specific, with room for error. No previous work has examined these wells in such detail and there is potential for false positives, so careful data interpretation is essential.

Determination of a risk-based AoR and risk of leakage to USDWs

Marcia Coueslan, Vault 44.01

Marcia presented work from a US perspective on their class VI applications. Although a risk assessment is not required for a class VI application, the definition of the AoR will impact project economics, for example, by necessitating funding of any corrective action on a legacy well that could pose a problem. Financial assessments and guarantees need to be provided prior to submitting a permit application and can be obtained via insurance or through an escrow account. Therefore, a risk-based AoR is a sensible approach to evaluating the area where hypothetical brine leakage would cause minimal impact to the underground source of drinking water (USDW)[4]. Using a case in the Illinois Basin and the Mt Simon Sandstone, the deepest legacy wells penetrate the St Peters, which although qualifies as a USDW, is unlikely to be used as a drinking water supply due to depth and salinity, and any brine leakage would be very difficult to detect. They evaluated emergency and remedial response (ERR) risks, the risk of a leakage event and what the cost of remediation would be using a Monte Carlo approach, assuming one hypothetical deep well, which provides an upper bound on projected costs. With this modified approach the risk-based AoR significantly reduced in size (98% reduction) due to a low delta pressure and a deep USDW.

Quantifying leakage magnitude in legacy wells considering cement channels

Al Moghadam, TNO

This work looks at the results of modelling to account for cement channels in a well annuli that might provide pathways to upward flow of CO_2. Recent experiments have demonstrated a significant decline in cement stress as it cures. A thermos-hydromechanical staged FEA model has been developed (CREST) that couples the cement's hydration reactions with its mechanical response. Cement hydration reactions should be considered to predict micro-annuli formation and size. A previous geometry of the CREST model modelled the development of micro-annuli and leakage from a CO_2 plume into a permeable layer above a plugged seal horizon. This scenario was expanded

[4] underground source of drinking water – an aquifer <10,000 mg/L of total dissolved solids

to include more realistic leak paths, including via micro-annuli, cement channels, or via formation fluid to accumulate beneath a shallow plug with eventual leakage to the seabed. The pressure relationship (storage formation and plug pressure) is explored and annular fluid depth. As storage pressure increases, so does the migration rate. Initially all the fluid migrating out of the storage ends up at the surface, however, as storage pressure reaches 234 bar the annular fluid reaches the overburden and the surface rate remains constant. This may have implications for MMV plans and risk assessments. A future project Eloquence will be launched in the autumn of 2025 to develop a comprehensive leakage assessment tool that considers a broader spectrum of physical processes to predict the most likely leakage pathway and leakage rates.

Further clarification of the model and results during the questions indicated that the cement is Portland cement, and that chronically overstressed cement is problematic. The CREST model considers two-phase flow.

Cross-flow in legacy wells: Between data and uncertainty

Anna Peksa, Shell

This presentation covered Shell's work evaluating the crossflow of brine in legacy wells onshore. The onshore setting impacts both communities and ecology, therefore could be significant and requires careful assessment. Using a bow-tie method to explore the threat of vertical brine flow through legacy wells that might result in release to the surface or into a drinking water supply, highlighting the need to understand the barriers such as integrity of the well, injection pressure management, geological overburden and conformance monitoring and corrective action. Receptor mapping and sensitivity analysis are also key activities e.g. proximity to built-up areas, water resources and regulatory regimes, for example. Anna outlined the necessary requirements for assessment, including current wellbore condition, local reservoir and fluid properties, pressure and temperature conditions and well characterised aquifer. Self-healing processes and assumptions about baffles and barriers are also vital to understanding. Modelling the results and defining what is permittable is a key step along the journey. The conclusions drawn were that applying a bow-tie mindset from the outset helps identify, manage and fix risks early. Early action is critical, very few wells show leakage, and the system is largely intact, but monitoring and pressure control are key tools for active risk management.

During questions Anna stated that they planned to monitor pressure in other layers.

Near-surface monitoring – a controlled release simulating a failed well

Susan Hovorka (GCCC), Sahar Bakhshian (Rice), Arya Chavoshu (UT), Mahdi Haddad (BEG, UT), Hassan Dashtian (BEG, UT)

Legacy wells are the most likely leakage pathways for CO_2 and brine. Sue presented the results of a project to design a cost-effective monitoring system for long-term surveillance of P&A'd wells to act as an early detection method. This was tested by executing a shallow release experiment and surveillance via a monitoring package to identify changes in the vadose zone. By applying machine learning to the data, they were able to separate well-failure signal from other environmental anomalies. The sensors used were a TxSON soil sensor, casing temperature and a weather station sensor (ATMOS 41). Sue described the experimental setup at the Brackenridge Field Laboratory at UT Austin. Background data (weather, soil and casing temperatures) were collected for three days and captured diurnal effects. 5 controlled release episodes (hot water, CO_2, CO_2 and hot water) were conducted over seven months, and at each leakage event a distinct and rapid spike in electrical conductivity (EC) was observed, demonstrating that it is a highly sensitive and immediate indicator of fluid migration. After the leakage event, the EC values typically plateau then decline gradually, and the level of EC increase during CO_2 leakage depends on soil moisture content. Machine learning models were applied for automatic anomaly detection with tree-based models (Random Forest, XGBoost, LightGBM) significantly outperforming traditional methods like Logistic Regression and SVM.

Following the talk there was a discussion on the importance of baseline measurements in shallow gas monitoring, and signal identification. Ultimately, a baseline assumes that these original conditions won't change unless you have a signal, however in the shallow subsurface and surface many other factors may be of influence e.g. daily, seasonal and longer-term climate changes – it is highly complex and underestimated. The same variations are not seen in the deeper zones. An outlier should send a signal – but needs to be validated. A spike in these measurements still needs to be checked, but it can be cheaper alternative to re-entry. Machine learning has value but is not going to solve all our problems.

The term characterisation was preferred over baseline, and it was felt that years of pre-injection data was unnecessary. You need to know enough to be able to make an attribution case.

Discussion

The discussion session covered how to transfer learnings to the regulators, costs, differences in experiments and how to ground truth modelling studies.

There are variations between regulators; in British Colombia the regulators funded the research presented earlier by Aaron and are receptive and forward-looking. There was a feeling that in the US, more dialogue could be had. There are plenty of opportunities to create information workshops for the Ground Water Protection Council, whose internal experience varies widely. Sue Hovorka has some funding from the EPA to do short courses.

Regarding finances, financial assurances are required (in the US) on application. Marcia also clarified that in their project, the costs just included the emergency response and remediation only and not re-entry and plugging. There are no well penetrations in their storage formation aside from their own wells.

Sue clarified how their experiment differed from the ZERT experiments, explaining that their approach focuses on engineering the site above the well rather than sampling the natural environment, as this is the most likely place for leakage to occur. Regarding the use of soil monitoring, it was noted that generally the key is to identify the most appropriate tools and techniques for each site while avoiding overly arduous or complicated monitoring approaches.

When asked about methods for ground-truthing modelling efforts, Al Moghadam noted that leak rates are very hard to quantify. Methane wells are a good source of data, particularly when sourced from a good geographical distribution. Conducting mini case studies on individual wells was suggested as a useful way to test geomechanical and flow models.

Session 4: Well Designs and Operations

Chair: Marcia Coueslan

Decatur Storage Site – an update

Randy Locke, Illinois Geological Survey

This presentation provided a timely update from the Decatur Storage Site in Illinois, USA. Although not speaking on behalf of Archer-Daniels-Midland Company (ADM), Randy presented current information based on 17 years of experience at the site. He also presented updated well completion diagrams that were provided by ADM. As a reminder, he stressed the importance of correct terminology. Leakage and migration are not necessarily synonymous. Leakage can be used as a general term to refer to a range of different fluid migration scenarios. It can also come with assumptions or preconceptions. In the case of Decatur, migration is a more appropriate term given that CO_2 still remains deeply buried and sequestered. The Decatur Storage Site is a pioneer, with the first two Class VI federal injection permits in the United States. Site design included comprehensive monitoring and subsurface characterisation. Risk management began 3 years prior to injection, was extensive, and continues to evolve throughout the operation.

The multilevel monitoring well designs were unique; were driven by operational, research, and regulatory objectives; were approved by industry, academia, and regulators alike; and are not replicated in other Class VI applications or permits. The multilevel completions allowed research and operational advancements that wouldn't have been possible otherwise. For example, after the initial 1 MT injection in CCS1, review of the multilevel pressure data guided the selection of a new injection horizon for CCS2 that reduced downward pressure translation into the Precambrian strata and greatly reduced induced seismicity.

Verification well 1 (VW1) had 28 packers and an 11-level completion in the initial installation. The completion was simplified in 2017 to a 3-level completion. Verification well 2 (VW2) (completed in 2012) was perforated in 5 zones, 4 in the target reservoir Mt Simon and 1 in the Ironton Galesville (overlying the caprock). Randy reflected that how you design your permit area is important, referring to Marcia's reference to dissipation zones. For the Decatur Storage Site, the storage complex only includes the reservoir and primary caprock. The fluid migration of brine and CO_2 occurred through the two deep monitoring wells (VW1 and VW2) and was a well integrity issue, not a geologic integrity issue. Brine and CO_2 migrated into the Ironton-Galesville Formation, a unit directly above the primary caprock that is used elsewhere in Illinois for natural gas storage but was not permitted for CO_2 storage at the Decatur site.

Randy outlined the timeline of events that triggered regulatory action by the USEPA under the authority of the Safe Drinking Water Act. USEPA concluded that migration of injected fluids out of the permitted zones had occurred, but at no time was it a threat to drinking water. There were still 1200m of vertical distance and multiple additional low permeability layers separating the USDWs used locally and migrated fluids. Migration was first detected in VW2 with intermittent instrumentation issues. Well interventions were necessary, and the tubing was pulled. The tubing has suffered corrosion and the integrity compromised, and an anomaly detected above the caprock was confirmed by sampling. Temporary bridge plugs were established to isolate the Ironton-Galesville from the Mt Simon. Remediation plans by ADM focused on the best long-term solution. ADM's fluid migration assessment of VW2 estimated the amount of CO_2-migration to the Ironton-Galesville Fm at 2,670 to 3,940 metric tons, and vertical migration will be negligible and stay below 4,960 ft after 100 years and remain close to the well. ADM are progressing with expansion plans with 5 new permits and an additional monitoring well.

The multilevel completions in VW1 and VW2 have been fully replaced by single level completions. This is a key factor. In recompleting the VW2 all zones have been squeezed off with CO_2 resistant cement and a new perforation in the Ironton Galesville. VW 1 was recompleted to a single zone completion with CO_2-resistant cement, which will be more robust. Randy also presented findings of ISGS Circular 611 (https://www.ideals.illinois.edu/items/132327), a detailed assessment of deep fluid monitoring from a 7-year period from VW1 with recommendations for suggested well operation and design.

Historic experience in managing well corrosion in the US

Sue Hovorka, GCCC

This presentation explored the material choices and selections made by industries such as CO_2 EOR, acid gas disposal and wastewater injection that have operated for decades and the learnings that might be transferred to a more nascent CO_2 storage industry, including corrosion of steel and cement. In the case of steel, there may be overreactions and the use of Chrome 25 in place of Chrome 13 might be advocated. Sue gathered opinions from across the industry (operators and researchers) and discovered a disparity in approaches. In general, CO_2 injection wells are usually dry and protected from corrosion, however under wet conditions e.g. CO_2 sourced from natural domes or reinjected may need corrosion protection. CO_2-EOR, produces CO_2 and brine, hydrocarbons and hydrogen sulphide (H_2S). From anecdotal evidence the operators are confident that if there is a hole in the well, they will see it in the production data immediately and there is a strong financial case for not wanting to lose fluid to shallower layers. Replacement, when needed, is an integral part of operations and may include replacing tubing, side tracking, liners and surveillance. Sue then documented a list of corrosion management methods for EOR producers (that will always be in contact with wet CO_2 and brine). These included: metallurgy and coatings, inhibitors, cathodic protection, use of non-steel tubulars and coated tubulars.

Chrome steel is used sparingly in EOR; it's softer than carbon steel. Threads can get damaged, which is the main cause of well leakage. It is not always readily available, is costly and corrosive to H_2S. Corrosion inhibitors are the workhorse of most wells; all wells use them with a broad market for them. They are engineered chemicals that form a film on steel tubulars and keep the corrosive material away from the steel, combined with a good cement job. Cathodic protection is used to protect the surface casings, using DC from solar panels. There is a discrepancy of opinion on the application of non-steel tubulars, such as fibreglass. These are commonly used in Class I hazardous wastewater disposal and used at Cranfield. There are issues, but they provide corrosion-resistant designs that are non-conductive and therefore open up options for electrical methods for monitoring. Fibreglass can also be used to coat the inside or outside of steel tubulars.

As a conclusion – and word of caution – Sue raised the issue of monitoring wells, which, in contrast to injection and production wells, are essentially idle, with static water levels and instrumentation that can be located inside and outside the casing. There is a need to employ these only when necessary and be aware of the additional risk.

Norwegian offshore CO_2 well design

Philip Ringrose, NTNU

Philip followed the US perspective by bringing together 29 years of operational experience from the Norwegian CCS industry. Over 27 Mt CO_2 has been successfully stored, and there are ambitions to grow this industry. There are many overlaps with the US experience, and some notable differences. For example, there are no liners or coatings, and they have been careful (e.g. using corrosion-resistant alloys for exposed sections) without excessive specifications. Wells are placed at the base of aquifers or in down-dip positions. Metals and elastomer components are selected with higher corrosion resistance (e.g. 13-25% Cr Steel), and there are stringent cementation and isolation procedures. Philip detailed the well design for the Sleipner and Snøhvit CO_2 injection wells with particular emphasis on the steel selection. High chrome (25% Cr Duplex) steel was used for the 7" injection tubing, sand screens and exposed sections of the 9 5/8" well casing, and other components used 13 Cr or 316. The Northern Lights project with a summary of the primary injection well (31/5-A-7 A) was given. 25% Cr Super Duplex Steel are used in components that are in contact with CO_2 and water i.e. tubing and completion elements, with standard steels used for other well components. The injection interval has been kept away from the caprock interface to avoid potential effects of cooling-induced fractures during injection.

One of the main differences between EOR in the US and CO_2 storage in Europe is the difference between the use of naturally mined CO_2 and anthropogenic CO_2, and the risk of pitting corrosion – that changes design processes.

CO_2 cement integrity sleeve performance, deployment methods and its capability to preserve self-sealing properties of standard class G cements

Walter Stam, Shell

This work by Shell looks at cement integrity sleeves that have the potential to mitigate against micro-annuli in cement barriers caused by shrinkage or damage. This can be of particular concern in depleted fields. The sleeves, which are placed over casing or tubing, typically at caprock level, have been used by Shell in unconventionals for many years and first applied to CCS wells in 2023. They have been shown to improve annular integrity by 80% and can provide a low-cost solution.

Walter described the performance test undertaken on the cement integrity sleeves including using rubber coupons to look at the swelling forces once CO_2 had been introduced. By using a CO_2 swellable sleeve, soaked in wet CO_2, with a cone in cone testing design within a pressure vessel they could apply certain size micro-annulus to test performance. The CO_2 outflow remained below the limits of detection with some self-healing properties observed. Further tests on cement seal integrity, undertaken by Tim

Wolterbeek, exposed cement plugs to wet CO_2, they applied a micro-annulus and evaluated the permeability through time. All samples showed a notable reduction in effective permeability due to calcium carbonate ($CaCO_3$) precipitation. Introducing sleeves can increase the residence time, thus preserve the self-sealing qualities.

Discussion

During the discussion, it was noted that in the onshore US, EOR experience is generally positive; it's easy to fix a well, however in an offshore setting more advanced wells are preferable, particularly those that can be monitored remotely via remote sensing and geophysical methods. In terms of material selection, participants highlighted that in Norway the principal concern in the injection well would be the potential backflow of brine into the well. The Quest project, for example, employs a non-return valve to prevent this. When only dealing with dry CO_2, the use of higher-grade materials such as 25 Cr is not necessarily required.

Discussion turned to the ADM monitoring well, and the use, placement and material choices of monitoring wells that will encounter a CO_2 plume. The EPA require monitoring wells and specify the materials to be used. In the ADM case, inhibitors were used and problems arose due to maintenance and fluid management issues which accelerated due to component malfunction and then fluid migration. Initial modelling was over simplistic and predicted that it would take 18 months for the CO_2 to reach the well; in reality, this took 3 months. There have been many lessons learned in the communication aspect, particularly in relation to emergency response planning. The automatic shutdown of injection activities during a response can cause concern among stakeholders and the public. Having spaces to hold conversations with the public and allow them to ask questions is important.

Finally, the discussion addressed well design in areas of natural seismicity. It was believed that large earthquakes are generally not expected to compromise well integrity, as seismic waves typically pass through without causing disturbance. However, under the EPA's stoplight process, seismic events of a certain size would require operators to suspend operations and investigate well integrity.

Session 5: Novel Monitoring Solutions

Chair: Marcella Dean-Elsener

Adapting multiparameter measurements with distributed optical fibre sensor for CO_2 storage monitoring: A case study in North Dakota

Takahiro Nakajima & Ziqiu Xue, RITE

This project stores CO_2 captured from an ethanol facility in a deep saline formation (the Broom Creek Formation) at a depth of ~1950m. Injection started in June 2022 and ~500kt of CO_2 has been injected as of June 2025. The aim of this work was to explain the status of monitoring by optical fibre cables (DAS: distributed acoustic sensing, observation) at the site, and through this observation aim to demonstrate sustainable monitoring techniques for geological storage. Monitoring is done using surface orbital vibrators (SOVs) and a vibroseis source, then matching with the CO_2 injection simulation.

The results from the SOVs showed changes at reservoir depth, and the vibroseis source (2D survey) recognised a tendency towards expansion of the plume size. Simulation results were consistent with the monitoring data (DAS / VSP (vertical seismic profiling)). Future work will continue the monitoring to check that the CO_2 injection is being conducted safely, and more precise matching between the monitoring results and flow simulation.

Seabed fibre optic cables for CO_2 storage monitoring: status and next steps

Estelle Rebel, TotalEnergies

This talk highlighted the potential of using existing seabed fibre optic cables for CO_2 storage monitoring. Since fluid injection can induce microseismic activity, the main goal is to improve the safety of operations. Fibre-optic cables, already widespread offshore, act as passive seismic sensors requiring no power and little operational effort, and they complement onshore monitoring networks. Challenges include their horizontal orientation, which raises questions about sensitivity to vertical wave propagation and P-waves, as well as the very large data volumes generated in continuous monitoring, requiring real-time processing. Early results show promise, with offshore fibre networks detecting around three times more earthquakes than conventional systems. The use of machine learning further reduces false detections, improves accuracy, and enables real-time monitoring.

The discussion raised the question of whether regulators should be encouraged to support the expansion of fibre optic networks as part of spatial planning. Ms Rebel noted this could present a valuable opportunity, with the potential to leverage fibre installed for other uses, such as wind farms, to also support monitoring for CO_2 storage.

Shear wave resonance effects and potential use for CO_2 monitoring purposes

Martin Landrø, NTNU

This work looks at shear wave resonance monitoring and whether it can be used for cost effective monitoring. Two earthquakes at different locations give good repeatability – and an indication that a small shift caused by CO_2 injection into a resonance layer can be observed using a fibre optic cable at the seabed, and this demonstrates it is possible to estimate the thickness of the sediment column and the s-wave gradient within the sediment layer using data from Svalbard fibre optic. An external source is needed to measure shear wave resonance, such as earthquakes, seismic shooting, or background noise; there is enough minor earthquakes in the North Sea. F-x plots of earthquakes are dominated by S-energy due to source and strong conversion from P to S that resonates – frequency range of 0-15 Hz. Resonance modelling shows that a shear velocity decrease of 50 m/s leads to detectable time lapse changes, and repeatability tests for the Svalbard data set (with two different earthquakes) are promising.

Changes in reservoir pressure are clearly detectable, but monitoring focuses on what is happening in specific locations, raising the question of whether this can provide useful spatial information. To achieve the necessary resonance effect, the fibre cable must be close to the plume, which presents some limitations and ambiguity. A series of wind farms equipped with a 3D fibre optic array could help address this issue, though it would generate very large datasets. However, participants noted this should not be seen as a problem, as machine learning can be used to extract useful information from large volumes of data. Terabytes of data were described as manageable, with computational costs not considered a major barrier since edge computing can be employed to filter the data and extract only what is most relevant, such as earthquake signals.

Resonance effects were also discussed, with the distance from the event and from S- and P-waves influencing the signal, while sediment layers can amplify the resonance.

Gravity field monitoring, Viking and Morecambe CCS

Martha Lien, NORCE

This talk discusses the feasibility of field-wide gravity for monitoring CO_2 injection in depleted gas reservoirs, using two case studies in the UK: Viking and Morecambe CCS. Like conventional seismic methods, the acquisition of 4D gravity and seafloor deformation data is survey-based, with each survey producing field-wide maps of relative gravity and water depth. By repeating these surveys over time, changes between successive maps reveal insights into reservoir dynamics. This approach delivers two independent types of data: gravity variations, which directly reflect mass changes within the reservoir, and relative water depth changes, which indicate seafloor uplift or subsidence and thereby provide information on subsurface pressure changes.

Both studies of the feasibility of gravity field monitoring over depleted gas fields indicate strong potential for mapping CO_2 migration patterns in depleted gas fields. Time-lapse gravity is well suited to map the CO_2 plume, and at Morecambe, seabed uplift signals also provided insight into pressure evolution during injection. Alternative scenarios have shown potential for monitoring secondary containment by using polarity differences in the 4D gravity response. Key factors for feasibility include the magnitude of density change—where CO_2 replaces void space in depleted gas fields, directly reflecting injected volumes—and target depth, as shallower reservoirs enable higher resolution and detection of smaller volumes.

The discussion focused on the practicalities and value of gravity and seafloor deformation monitoring. It was noted that once concrete pads are in place, data collection using an ROV or vessel can be completed in about a week, depending on burial depth. At the Viking site, monitoring is expected to capture around 5–6 million tonnes of CO_2, with maximum seafloor displacement of about 4 mm considered measurable given the quiet seafloor environment and the use of repeated surveys and calibration points to detect relative changes. Questions were raised about the added value of gravity monitoring when pressure gauges are already in place; however, it was argued that gravity data can help resolve uncertainties around pressure communication in the field and serve as a valuable tool for confidence monitoring, though financial justification remains a consideration.

Advances in sparse, cost-effective monitoring

Don Lawton, CaMI

Key challenges in monitoring, measurement, and verification (MMV) for CO_2 storage include establishing an adequate baseline, the risk of missing transient events, and ensuring access for repeat time-lapse surveys. Surface and near-surface conditions also pose difficulties, such as population density, cultural features, topography, seasonal variations, and high ambient noise levels. Additional challenges are 4D seismic noise, repeatability, resolution limits, monitoring well requirements, pore space trespass, and induced seismicity. Finally, cost is highlighted as an overarching issue affecting all these factors. Advanced multi-physics sparse (AMPS) monitoring is continuous or semi-continuous if technically achievable, can be automated and real time, is sparse, cost-effective, and phased-proximal.

A phased approach to MMV is suggested to reduce cost and effort, with the ultimate aim of achieving automated, sustainable surveillance. Early monitoring should be focused proximal to the injection wells, while later phases would shift to a sparse surveillance plan, supported by multi-physics and chemistry monitoring nodes once the CO_2 plume extends beyond the range of VSP imaging. Pressure plume monitoring is considered equally important as tracking the CO_2 plume. Long-lived, remotely operated technologies with accessible maintenance are essential, and any anomalies should trigger more targeted, high-density surveys. All monitoring data should be integrated with reservoir simulation to refine the geomodel and fluid properties, with the sparse program demonstrated at a deep injection well project.

Discussion post-talk noted that a sparse seismic approach would deploy observation nodes progressively as the plume migrates; this can be optimised by first seeing how the plume develops and using reservoir simulation to guide where nodes are laid out. On tools, running fibre optic behind casing in an offshore well was viewed as difficult: fibre in tubing suffers poor signal-to-noise, and in deviated wells the lack of centralisers can introduce gravity coupling that degrades data quality.

Discussion

The discussion emphasised the importance of a 3D seismic baseline, with several participants considering it mandatory for effective monitoring. While legacy data, such as seismic surveys from the 1990s, can be reused if reprocessed carefully, new surveys may be preferable, as older datasets are often challenging to adapt directly. This is especially true for storage in depleted reservoirs. A reliable baseline was seen as essential to prepare for issues and ensure repeatability.

Participants also considered the potential for combining monitoring technologies, such as using offshore wind farm infrastructure, though wind-related low-frequency noise may not provide a sufficient seismic source. Horizontal fibre optic cables were noted as useful for shear-wave detection, with positive results from trials at CaMI and Otway, though their effectiveness depends on near-surface velocity conditions.

The conversation further explored detection limits and permanent monitoring sources, with industry improvements needed in signal-to-noise ratios and frequency range. Permanent sources could help bridge the gap between early observations and the first 3D monitored seismic surveys, improving confidence in models. Comparisons were made between SOVs and vibroseis trucks, with cost and land access identified as key differences.

Finally, it was noted that early projects are currently spending around $4–5 per tonne for monitoring, which remains a benchmark figure.

Session 6: Risk Profile Through Time – Positive Risk Reduction Factors

Chair: Tim Dixon

MMV evolution at Quest

Marcella Dean-Elsener, Shell

The talk on MMV evolution at the Quest CCS project outlined five key performance requirements for CO_2 storage: capacity, containment, transport and injectivity, monitoring and remediation, and stakeholder engagement. Quest has adopted a risk-based, site-specific, and adaptive MMV approach to ensure both short- and long-term safety. The use of a bowtie framework provides a structured method for managing credible risks, and the project's MMV plan has continued to evolve, with significant updates in 2023. These include enhanced seismicity monitoring and risk assessment, casing assessments, changes to pulsed neutron logging, and increased utilisation of deployed fibre optic technologies. Machine learning is also being applied to improve the value of monitoring data and insights.

Insights from Quest highlight that a risk-based, site-specific, and adaptive MMV plan, supported by technology tiering, can be successfully implemented for CCS projects. Operational MMV should continue evolving to enhance effectiveness, incorporating new technologies and adapting to changing risks and regulatory requirements. After ten years of operation, well integrity at Quest remains excellent, with fibres cemented behind casing and downhole gauges performing reliably. Time-lapse DAS VSP has proven valuable in verifying containment and demonstrating conformance. The project also showed that MMV can be effectively deployed through wells and facilities management processes adapted from hydrocarbon operations. Fibre optic technologies have demonstrated clear utility, and machine learning offers further opportunities to increase the value of monitoring data.

Questions after the talk focused on alternatives to VSP, with Shell noting that while 3D surface seismic is available and more could be acquired, it must be justified by need and is subject to ongoing discussions with regulators and stakeholders, often on a five-year review cycle. Concerns were raised about competing CCS projects in the same storage zone, and Quest explained that work is underway to integrate such projects into planning, with new technologies being developed to manage pressure interference and associated risks. On fibre optics, it was emphasised that the current shallow configuration works well and avoids risks of damaging cables during perforation, though site-specific feasibility studies are needed to guide future designs. Finally, in response to US regulatory expectations for direct in-well measurement, Shell explained that drilling additional wells through the seal is undesirable. Instead, pressure monitoring was achieved through existing wells, flow material balance, and history matching, which together provided robust assurance without additional penetrations.

Sequential multi-physics trapping models (Markov chains)

Philip Ringrose, NTNU

This work proposed an Invasion Percolation Markov Chain (IPMC) approach to model CO_2 migration events, creating a probabilistic framework for assessing containment risks and using the Sleipner project to prove the hypothesis. The study demonstrated that migration of CO_2 at Sleipner does follow a Markovian model, with the probability of later migration events highly dependent on the probability of preceding events and revealing the importance of vertical feeders and/or faults. In terms of CO_2 migration enablers and resistors, there are good models and data on some areas, whereas other areas (such as thermal fractures, wellbore migration and earthquakes – the enablers, and shale creep and carbonate precipitation – resistors) need more work.

This work concludes that the geological system has a strong tendency to absorb, retain and hold-back CO_2 injected into the subsurface. IPMCs are a good and validated way of estimating migration pathways and risks. Geochemical processes mainly have a positive (inhibiting) effect as they interact with geomechanically controlled potential leakage pathways. However, there are many remaining challenges in understanding coupled processes, such as rates: geomechanical processes in the rock system typically operate in the range of minutes to days, and geochemical processes operate over periods of months to tens and hundreds of years.

The discussion following this talk explored how to communicate CO_2 migration to stakeholders, noting that while the public often imagines storage in caverns; in reality CO_2 moves differently in the subsurface – if it leaks from one layer, it is likely to become trapped in another. On geochemistry, it was emphasised that care is needed as common reservoir rocks such as sandstones, shales, and mudstones are not very reactive, and long-term geochemical reactions remain uncertain. Questions also focused on applying insights to wells, with current work examining faults across multiple layers, where the same mathematical approaches could be adapted to wellbore leakage.

Impact of shale creep on CO_2 containment

Pierre Cerasi, SINTEF

This presentation emphasised that CO_2 storage is a proven and safe technology, but geomechanics can quantify conditions for which leakage could occur; stress changes due to pressure changes in the reservoir could lead to failure of the caprock seal, reactivation of geological faults, or micro annulus formation at wells. The failure of the caprock seal is less of a risk, but large-scale fractures might play a role. The presentation showed that shale exposed to brine tends to soften, and sorption of dry CO_2 reduces its strength. CO_2-saturated brine can also introduce pH effects, although there was no significant difference observed between brine and CO_2-saturated brine. In terms of caprock behaviour, fractures in shale may heal over time due to shale caprock creep, weakening of the caprock, or decreasing fracture fluid pressure. Fractures within the fault process zone, or more generally within the caprock, may either close or remain open in the long term. Shale softening can promote fracture closure through increased deformation, but it also reduces the ability of crack boundaries to resist pressure, potentially limiting the effectiveness of this healing process. The study concluded that further research is required to fully understand these mechanisms.

A question was raised about the impact on organic content and whether differences between HCl (hydrochloric acid) and CO_2 molecules had been considered. In response, it was noted that Shell has been carrying out detailed work on these interactions. For shale creep specifically, Equinor has developed strong knowledge of which shales are effective and which are not, but correlating behaviour directly with mineralogy is not straightforward.

Porthos – a discussion on risk

Willem-Jan Plug, Porthos

The Porthos project is working towards the first large-scale CO_2 transport and storage infrastructure in the European Union, paving the way for other CCS projects. With a 37 million tonne / 2.5 Mtpa capacity, construction began in 2024 with operationality planned for 2026. The various challenges and risks that have or would in the future need consideration, such as delays and interdependencies along the full CCS chain, growing the organisation and need for internal alignment within, stakeholder management and existing underground infrastructure needed thought for the onshore pipeline aspects, different cultures between the project team and contractors, technical items such as material selection for the offshore pipeline, delays due to re-use of old platform and well equipment, and potential reservoir damage due to workovers.

The subsequent questions covered several aspects of the Porthos project. On public communication, it was explained that around four to six full-time equivalents (FTEs) are dedicated, including advisors to regulators, with at least one person focused specifically on engagement with the public. Regarding the recent pipeline issue, activities were halted for two to three months due to a defect caused by tension; although this risk had been anticipated, one of the ship's tools was not functioning properly, underscoring the need to ensure equipment compatibility with pipeline materials.

On CO_2 composition, the project is based on specifications similar to the CO_2 supplied to greenhouses in western Netherlands, with additional thresholds applied for sulphur, water, and oxygen content. Legal challenges were also discussed, with reference to both Aramis and Porthos. Porthos faced an appeal in 2021 against its environmental permits, resulting in a two-year delay. The experience highlighted the importance of keeping projects moving during such setbacks and being ready to scale up quickly once positive rulings are secured. Wider political issues such as the nitrogen crisis in the Netherlands were also noted as influencing the permitting context.

Finally, participants stressed the importance of keeping sight of CCS's main objective: tackling climate change and achieving CO_2 neutrality by 2050, which remains the core driver for the project.

Discussion

The discussion began with shale creep, where it was acknowledged that while the process looks promising for sealing, uncertainties remain around defining which shales creep and at what rate. Laboratory testing requires months to confirm true creep behaviour, and high stresses are needed to accelerate deformation and sealing.

On risk assessment, it was noted that while the methodology (such as bowtie analysis) remains consistent across projects, the threats and challenges differ between newly built CCS sites and those using existing infrastructure. Depleted hydrocarbon fields, for example, provide more data but also present residual gas risks, so assessments must be adapted to site-specific conditions.

Questions on infrastructure raised the point that fibre cannot be installed within existing pipelines but could be placed alongside them. More broadly, decisions around reuse and new developments should consider requirements for each site, with trade-offs between lower carbon footprint, cost, and material quality.

Community and legal challenges were also discussed. Lessons from Barendrecht underscored the importance of proactive, transparent engagement, as its cancellation stemmed from stakeholder and communication failures. Quest avoided such issues by engaging early with locals and landowners, while other projects faced difficulties when surveys were conducted before community dialogue. Positive examples included ADM in Illinois, which goes beyond state requirements by holding regular open engagement sessions, and Porthos, which has developed a full communications scheme informed by earlier lessons.

Participants agreed that outreach remains challenging, with success depending on choosing the right stakeholders and allies, maintaining honesty, and recognising that people under existing pressures may resist further change. Despite the difficulties, continued, proactive engagement was seen as essential, with Barendrecht providing enduring lessons for CCS communications.

Session 7: Pressure Plume Risk

Chair: Philip Ringrose

Induced seismicity risk from multiple stores

Stephen Bourne, Shell

This presentation explored the seismic hazards and risks of induced seismicity in storage sites, particularly where there are multiple stores. Fluid injection or extraction has the potential to induce earthquakes as pore pressure changes it increases shear stress on faults. A general framework to manage induced seismicity risks is common across these settings and includes characterisation, monitoring, forecasting, hazard assessment, risk assessment and the development of controls. Controls might include favouring ductile top and bottom seals in the site selection process; avoiding critically stressed or large throw faults in well placements; sufficient monitoring; the continual assessment and reassessment of probabilistic risks through forecasting; and pressure control to control seismicity. By using a case study on the Groningen gas field, Stephen was able to demonstrate how a forecast model was trained[5] during steady gas extraction and rising seismicity rates, as gas extraction declined and eventually ceased the decline in seismicity response was accurately matched by the forecast model. Hazard and risk maps were also presented which showed a local personal risk for each of the 500,000 residents exposed in 250,000 buildings.

Subsurface geometries influence induced seismicity, it's the biggest faults you need to worry about, and they are the ones you can see, although as faults are generally undersampled we don't know their initial stress through conventional methods. Through some worked examples, Stephen demonstrated scenarios on how well placement in relation to proximity and geometric arrangement of faults might impact seismicity events and event rates through an injection and closure period. Three scenarios compared a base case injection scenario adjacent to a fault whose location and injection rate were forecast to significantly exceed the operating envelope of annual probability (using a hypothetical threshold of $M>3.5$). By reducing the injection rate, increasing the distance and increasing the distance and rate they were able to demonstrate that the expected seismicity would be reduced to within acceptable limits.

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[5] Acosta, M., Avouac, J.P., Smith, J.D., Sirorattanakul, K., Kaveh, H. and Bourne, S.J., 2023. Earthquake nucleation characteristics revealed by seismicity response to seasonal stress variations induced by gas production at Groningen. *Geophysical Research Letters*, *50*(19), p.e2023GL105455.

Cooperative strategies for maximizing storage capacity of gigatonne-scale regional resources

Sarah Gasda, NORCE

Sarah Gasda set the scene of her talk by framing the trilemma associated with striving towards gigatonne storage: the balance between the scale and urgency of the climate emergency; the need for industrial innovation, economic growth and good jobs; and physical laws and geological reality. Regional scale pressure (on injection of CO_2) is a concern for a variety of reasons, pressure increases far beyond the CO_2 plume, hydraulic diffusivity in the aquifer is relatively fast, multiple pressure pulses are additive and there is potential to increase risks in 'no man's' land'. Good aquifers, although rich in pore space and reservoir quality, are not unlimited, they have boundaries and are likely to attract many operators. Therefore, there is competition for finite resources, and to ensure that CCS is profitable, it's important to differentiate between the value of a few great projects or many good-enough projects.

The work presented defined three storage licences in a cooperative game whereby each agent's objective is to maximize profits, the objectives are in conflict, any partnerships are only to gain advantage and geomechanical constraints are limited. Reservoir simulations and multi-objective optimisation (MOO) runs showed all possible efficient allocations and demonstrated that there is not one single perfect solution. However, there are 'utopia points' that gets each coalition as close as possible to their individual targets. In a grand coalition, with mutual compromise, each licence stores less than their individual targets but together achieves the greatest total. The model was tested on a first-come, first served basis. In this scenario the first agent out-competes the others for space and the next best outcome occurs if the second and third agents to partner up. Game theory can help us to move towards smart collaboration, for example in identifying strategies that might reduce risks and maximise total storage efficiency e.g. negotiated injection rates and shared monitoring costs. Ultimately, pressure interference will become a fact of life, and there are questions over who will act as a third-party facilitator to coordinate a transparent allocation of pressure space to multiple parties. In a competitive environment can actors accept sub-optimal resource for measurable gains in basin-wide efficiency.

Light-touch pressure monitoring: keeping an eye on a multi-actor system without breaking the bank

Alex Bump, Susan Hovorka & Angela Luciano, GCCC, BEG

Alex highlighted growing competition for CO_2 storage space in the US Gulf Coast, where dense clusters of emitters overlap with ideal geological conditions. Closely spaced CCS leases risk pressure interference and brine displacement, potentially endangering underground sources of drinking water (USDWs) through elevated pressures in legacy wells – especially those not considered in single project AoR definitions.

The talk centred on regional reservoir pressure monitoring methods, e.g. a network of monitoring wells and passive seismometers might be effective, but placement, responsibility and maintenance are unresolved and not defined. Using a case study from Pergan-Marshall's Class I waste disposal wells in Marshall, Texas. Injection began in the 1980s, but nearby saltwater disposal (SWD) wells ramped up significantly between 2006–2008. Using EASiTool, observed bottom hole pressure data matched closed-boundary models, showing pressure increases and merging AoRs by 2011. Annual pressure fall-off tests for Class I wells proved effective for tracking reservoir pressure without new infrastructure. These fall-off tests offer cheap and reliable reservoir pressure monitoring requiring no new wells, however they do require shutting in an injection well.

A second case study introduced coda wave interferometry (CWI), a highly sensitive ultrasonic method for detecting micro-damage and pressure changes[6]. Used in the Los Angeles basin to monitor groundwater recharge, CWI demonstrated sub-psi accuracy across various depths. The challenge lies in adapting it for deeper reservoir applications.

The session concluded with a discussion on aligning pressure tests with maintenance schedules and comparing CWI to shear wave techniques, exploring their potential for deeper subsurface imaging.

Fibre optic strain sensing from Japan and Otway

Ziqiu Xue, RITE

The presentation covered the use of distributed fibre optic sensing (FO) technologies—DTS (temperature), DAS (acoustics), and DSS (strain)—to monitor subsurface conditions in CO_2 storage projects. These systems detect backscattered light variations (Rayleigh, Brillouin, Raman) and are capable of tracking caprock and well integrity, plume and pressure fronts, and seismic activity.

A lab experiment was shared where FO cables cemented around a rock core (reservoir-caprock pair) in a pressure vessel, and using X-ray CT scanning, revealed CO_2 accumulation and pressure front migration. Strain data closely matched saturation profiles, with early strain signals indicating pressure movement ahead of CO_2 saturation—suggesting DSS as a viable method for detecting CO_2 migration into a caprock.

Field applications were discussed, including fault zone monitoring at the In Situ Lab (South Perth) by RITE and CSIRO using FO strain, temperature, and acoustic sensing. DSS

[6] Chen, J., Zhu, C., Pu, Y., Rui, Y., Liu, B. and Apel, D.B., 2025. A systematic review of Coda Wave Interferometry technique for evaluating rock behavior properties: From single to multiple perturbations. *Earth Energy Science*. https://doi.org/10.1016/j.ees.2025.03.002

was also used in a water injection test to map reservoir heterogeneity, showing strong correlation between strain and particle size.

At the Otway site (Victoria, Austria), DTS, DAS, and DSS were installed at the CRC-8 monitoring well to monitor a 10,000-ton CO_2 injection into the injection well CRC-3. Strain remained stable during injection, with post-injection pressure release observed in high-permeability zones. Collaboration with Stanford University is comparing DSS data with pulse neutron logs, which confirm CO_2 arrival but show DSS provides more detailed insights. Work continues to refine interpretation methods for storage performance.

Natural seismicity in the North Sea: the benefits and limits of unified seismological data

Tom Kettlety and others, University of Oxford

Tom presented on behalf of a consortium including Norsar, TU Delft, BGS, GEUS, the Dutch Meteorological Institute, and NGI, sharing outcomes from the ACT SHARP Storage project[7].

Despite low seismic hazard, the North Sea experiences frequent small to moderate earthquakes. With growing CO_2 storage activity, attributing seismicity is critical for regulatory compliance and public confidence. Historical examples (e.g. Groningen, Basel, Castor) highlight the risks of induced seismicity to project viability.

The team compiled and harmonised seismic data from multiple national agencies up to July 2022, storing it in IASPEI Seismic Format. The cleaned dataset includes 9,792 events, revealing both artefacts (e.g. coastal detection bias) and tectonic features like the Viking and Central grabens. Improvements in detection since 1980 were noted and must be factored into interpretation.

Merging catalogues enhanced event location accuracy, especially with offshore PRM data, though depth resolution remains limited without near-field stations. Variability in magnitude calculations across agencies was addressed, enabling uncertainty quantification. Additional outputs include refined focal mechanisms, a new ground model, and an updated seismic hazard map.

The work underscores the value of cross-border collaboration. The upcoming SAFE-C project will focus on harmonising data at the point of collection and integrating fibre optic sensing. Norway and Oxford are exploring broadband array development, though UK participation in CETP projects is currently limited by funding.

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[7] https://sharp-storage-act.eu

Recommendations emphasised the need for greater data sharing among agencies to support harmonisation efforts.

Discussion

When asked about any obvious showstoppers in his work, Tom Kettlety referred to a case from July involving a cluster of four earthquakes in the southern North Sea close to a licence block. If such events were to occur after injection had commenced, they could present significant challenges, both in terms of operational response and public perception. In the US, saltwater disposal has been subject to a relatively light-touch regulatory approach, introducing additional uncertainty. Instances of induced seismicity have led to the shutdown of saltwater disposal and deep injection operations in Texas, prompting operators to switch to shallower injection targets. However, this approach increases the risk of interactions with legacy wells, creating a trade-off between depth and safety. The issue of induced seismicity extends beyond technical considerations, encompassing public perception and communication. Accurately determining the depth of seismic events is also critical. In the U.S., landowners who receive revenue from saltwater disposal have tended to be more accepting of induced seismicity.

Regarding competing pressure plumes, cases were given where two separate applications were made in California to the EPA, where each party was initially unaware of the other's project and therefore potential overlap in AoR. The regulator identified the issue and notified the applicants, prompting discussion on whether this should be the regulator's role or if a more proactive approach is preferable. It was agreed that reliance on the regulator to identify such issues is not ideal; operators should be encouraged to develop a regional understanding and address potential interactions in advance. While this requires considerable additional effort, responsibility for coordinating such work remains unclear. Another example from North Dakota illustrated a more collaborative approach: two developers encountering proximity issues were able to meet, discuss their respective projects, and jointly approach the regulator with a proposal demonstrating that both operations could coexist within the same area: an orderly development approach. Although approaches to allocation vary by country, efforts are ongoing to improve alignment. As noted, similar frameworks already work effectively for groundwater management, and while challenges remain, this is not viewed as a showstopper.

Regarding baseline data, collecting microseismic data is seen as a priority in the Texas Gulf Coast and is taking significant budget to do so, but is seen as an important insurance policy.

When discussing what would constitute an ideal monitoring network for the North Sea, participants highlighted the advantages of the fibre-optic networks presented in Session 5. Even the installation of single seismometers above each licence area would provide valuable data. This would require an integrated data approach and collaboration between operators, but working together would ultimately reduce costs. Another question raised concerned the best methods for predicting regional-scale seismic risk zones, with suggestions including the use of probabilistic analysis or downhole pressure gauges in wells.

It was also noted that valuable learnings could be taken from the Tomakomai project, particularly regarding the importance of having a clear response plan in the event of induced seismicity. Communicating effectively with a non-technical public and maintaining project safety are key.

Session 8: Discussion Panel – Role of Insurance & Finance

CHAIR: Franz Hiebert

Hiroyasu Konno, Nishimura & Asahi; Jan-Erik Berre, DNB; Ian Catterall, Howden; Lesley Harding, Liberty Mutual

This panel discussion focused on the role of insurance and finance in carbon capture and storage at the project level, and in terms of general industry development and scaling. The panellists addressed definitions, risk allocation, financial guarantees, and innovative insurance solutions relevant to project developers, lenders, insurers, and regulators and engaged in a detailed discussion session with the audience of technical experts.

The panel opened with Hiroyasu Konno, who grounded the discussion in the legal framework of Japan's CCS Business Act. He emphasised that leakage must be defined in measurable, regulatory terms and underscored the role of insurance as a mechanism to compensate for monetary damages from external events. Jan-Erik Berre brought the banking perspective, stressing the importance of long-term cashflow security and highlighting the EU's requirement for financial guarantees covering three months of injection capacity. He cautioned that excessive guarantees could undermine borrowing capacity and become project killers, urging a balance between regulatory demands and financial feasibility.

Ian Catterall, representing the broker's view, explained how brokers bridge project finance and insurance markets. He introduced innovative solutions such as parametric policies, which pay out based on triggers rather than events, and bespoke leakage coverage designed to support cashflow and debt capacity. He stressed the importance of information sharing and the development of archetypes to build insurer confidence. Lesley Harding, speaking from the carrier's perspective at Liberty Mutual, broadened the lens to include the Geneva Association's work on barriers to clean-tech financing. She emphasised the limited capacity of the insurance sector, the need for government backstopping, and the importance of holistic risk management across all phases of CCS projects, from design to decommissioning.

Audience questions and discussion lasted for over 50 minutes. Industry voices from Norway and the U.S. suggested that leakage risks may be exaggerated compared to seismic, pressure plume, or political risks, while regulators highlighted the importance of trust funds and surety bonds to ensure resilience. Harding reinforced that insurance is not the only vehicle for risk financing, pointing to alternatives such as captives, mutuals, and government support. Together, the panellists painted a picture of CCS risk management as a layered ecosystem requiring collaboration across insurers, financiers, regulators, and governments.

Much discussion among participants centered on clarifying definitions of leakage, debating whether small deviations should trigger penalties, and questioning how monitoring data could be standardised. One asked whether leakage should be contextualised against average human emissions, while others raised concerns about the scarcity of data and the difficulty of pricing risks without broader industry experience. Questions also probed how insurance policies could reflect existing mitigating measures, whether risks should be covered across the entire value chain or selectively, and how government guarantees could be structured to avoid stifling early projects. The exchanges revealed both the complexity of CCS risk allocation and the urgency of building confidence through shared definitions, pooled data, and collaborative governance.

Conclusions

The following key messages and conclusions have been drawn from the meeting.

Session 1

- It is important to take care in well abandonment and ensure that CCS requirements are considered, both onshore and offshore.
- Exemptions to Class VI regulations to utilise aquifers too deep to be considered as a drinking water supply but with a salinity slightly below the threshold value required by the UIC Class VI of 10,000ppm, could potentially optimise resources and open up areas hitherto inaccessible. The intersection of drinking water requirements and storage regulations might serve as a cautionary note to countries with more immature regulations.
- Management of competing uses of the seabed is achievable, as shown in the UK with offshore wind, but new challenges and benefits are emerging, such as lithium extraction in Western Canada and its potential advantages for pressure management.

Session 2

- Tools such as DETECT are available for fault risk assessment.
- Field experiments with faults provide valuable insights, particularly in determining which directions of fault migration are most consequential.

- There is much more we need to understand in terms of fault sealing in CO_2 storage sites, in the absence of case studies and deeper fault experiments, fibre optics can be useful and show promise.

Session 3

- There are important lessons to be learned from methane leakage at abandoned wells, and real case scenarios are vital to ground truth sophisticated modelling studies.
- Regulatory approaches and expertise across jurisdictions can vary widely. Where necessary, to appreciate the limitations of regulators' capacity and to provide them with appropriate support.

Session 4

- An update was provided on the Illinois Decatur Storage Site, with an outline of events that triggered action by the EPA due to fluid migration above the permitted zones. There are lots of learnings from this project as a FOAK project and the unique research wells turned into a commercial project.
- Although in some regulations monitoring wells that penetrate the reservoir may be a requirement, penetrations to the storage reservoir, especially multi-zone sampling wells, should be limited, and exposure to the CO_2 plume should be limited.
- Well material selection is critical, especially on exposed sections, and there are multiple views and options for corrosion control from the EOR community.
- Portland cement is a sufficient barrier, and in general, specialised cements are not necessary.

Session 5

- Sparse monitoring is more cost-effective, and skills are improving, particularly with fibre, service operation vessels (SOVs), and fibres of opportunity such as telecoms cables.
- SOVs, or other permanent remotely operated sources, present an economic opportunity.
- Natural earthquakes provide free data that can be recorded via fibre-optic cables and utilised for imaging and detection.
- Large data volumes should not be a concern, as edge processing can be used effectively.
- Machine learning is highly valuable, enabling more accurate real-time detection of seismicity with fewer false detections.
- Pre-injection 3D seismic, where possible, provides significant value. However, there is also an opportunity to supplement temporally frequent data for more infrequent spatial data.

- Gravity data on depleted fields can help resolve issues around pressure communication and serve as a valuable tool for confidence monitoring.
- Environmental aspects of monitoring should be considered.
- Baseline studies should be seen as a characterisation step rather than simply “baseline”, with shallow environments more variable and deeper formations more stable.

Session 6

- MMV plans can and should evolve as operational knowledge from projects increases.
- Machine learning is proving useful, but it is still a work in progress.
- Thermal effects in the reservoir must be considered, as cold injection can pose a significant risk.
- Markov models and real-life examples demonstrate that the subsurface has a strong natural tendency to retain CO_2.
- Project value chains often involve different actors who need alignment on aspects such as health and safety and risk tolerance.
- Shale creep is a promising mechanism for CO_2 containment, but there remains uncertainty about rates and mechanisms.
- Additional learnings are emerging from project operations, including differences between new developments and re-use of existing infrastructure.

Session 7

- Frameworks already exist to manage induced seismicity risks; while pressure changes may cause minor earthquakes, their magnitudes and rates can be controlled.
- Comprehensive seismicity catalogues are needed to support the management of induced seismicity risk, especially in areas with multiple agencies collecting data around a shared sedimentary basin e.g. North Sea.
- Pressure interference will be unavoidable, but unitisation and allocation can help to manage this risk. Open discussions with operators and regulators can help manage problems before they arise.
- Pressure monitoring will be essential when multiple actors operate in close proximity.

Session 8

- Quantification protocols are important, including methods for reversals, such as those developed in Alberta, while the EU follows IPCC guidance.
- Definitions matter: clear, measurable regulatory definitions of leakage are essential to ensure consistency and confidence in CCS risk management. Leakage

should be assessed alongside other risks (seismic, plume, political) and possibly benchmarked against average human emissions.
- Balanced financial guarantees: While guarantees are necessary to secure long-term cash flow, excessive requirements risk undermining borrowing capacity and project viability.
- Innovative insurance solutions: Parametric policies and bespoke leakage coverage can strengthen cashflow security and bridge gaps between finance and insurance markets.
- Holistic risk management: Insurance capacity is limited, requiring government backstopping and integrated risk strategies across all project phases.
- Layered ecosystem approach: Effective CCS risk allocation depends on collaboration among insurers, financiers, regulators, and governments.
- Alternative risk financing: Captives, mutuals, trust funds, and surety bonds complement traditional insurance mechanisms.
- Confidence through collaboration: Building trust requires standardised definitions, transparent monitoring, and cooperative frameworks to avoid stifling early CCS projects.

Recommendations

- Formalised communication routes should be established for data sharing with stakeholders.
- All available seabed telecom fibres, including those linked to windfarm infrastructure, should be mutualised.
- MMV plans and risk management plans should evolve as project operational knowledge increases.
- Projects should address not only technical risks but also non-technical risks at an early stage.
- Local stakeholders should be engaged early, with preparedness for potential negative responses.
- IEAGHG should facilitate the sharing of new learnings emerging from project operations, including differences between new developments and re-use of infrastructure.
- Probabilistic seismicity prediction is needed as a function of pressure increase at a regional scale.
- A dialogue is required between the insurance and technical communities to define what constitutes leakage, as interpretations vary globally, and greater precision is needed on which definition is applied.
- Regulators should act as coordinators to manage the interference of pressure plumes.

- There is growing recognition that CCS is the most permanent method of storing CO_2.
- Requiring an annual fall-off test would help better manage reservoir pressure and could be aligned with plant shutdowns.

Poster Presentations

No.	Title	Presenter(s)	Affiliation(s)
1	**Mafic and Ultramafic CO_2 Storage: A Look at Known and Unknown Risks**	Rachael L. Moore	CarbStrat
2	**Advancing Quantitative Risk Assessment for CO_2 Geological Storage: Experience from the PilotStrategy Project**	Thomas Le Guenan	BRGM
3	**Co-location and CCS Surveillance: Addressing the Maze of Operability and Acceptability in the Dutch North Sea**	Nour Michael	Spot Light
4	**Containment Risks and Insurance Implications for a Notional CO_2 Store**	S. Daniels[a], L. Hardiman[b], D. Hartgill[b], V. Hunn[a], R. Jones[a], D. Cook[c], J. Gluyas[a]	[a]GeoEnergy Durham, [b]Black Goldfish, [c]WSP UK
5	**Impact of Subsurface Setting on CO_2 Storage Leakage Risk: Implications for Financial Responsibility and the Insurance Industry**	Argenis Jesus Pelayo Nava	M.S. Energy and Earth Resources, The University of Texas at Austin. *Supervisors: Susan Hovorka, Sahar Bakhshian, Seyyed Hosseini*

Field Trip

On the 29th of August, around 25 delegates took an excursion to the Rotterdam Harbour to view the onshore and offshore elements of the Porthos CCS project from capture facilities along the onshore pipeline to the compressor station and views out to the P18 platform offshore. Willem-Jan Plug of Porthos was generous in giving us a bespoke guided tour. We concluded with lunch at the Portlantis experience.

Field trip to the Porthos CCS project.

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