THE CCUS HUB

EAST COAST CLUSTER

Review of six technical documents related to Net Zero Teesside and the Northern Endurance Partnership, parts of the East Coast Cluster

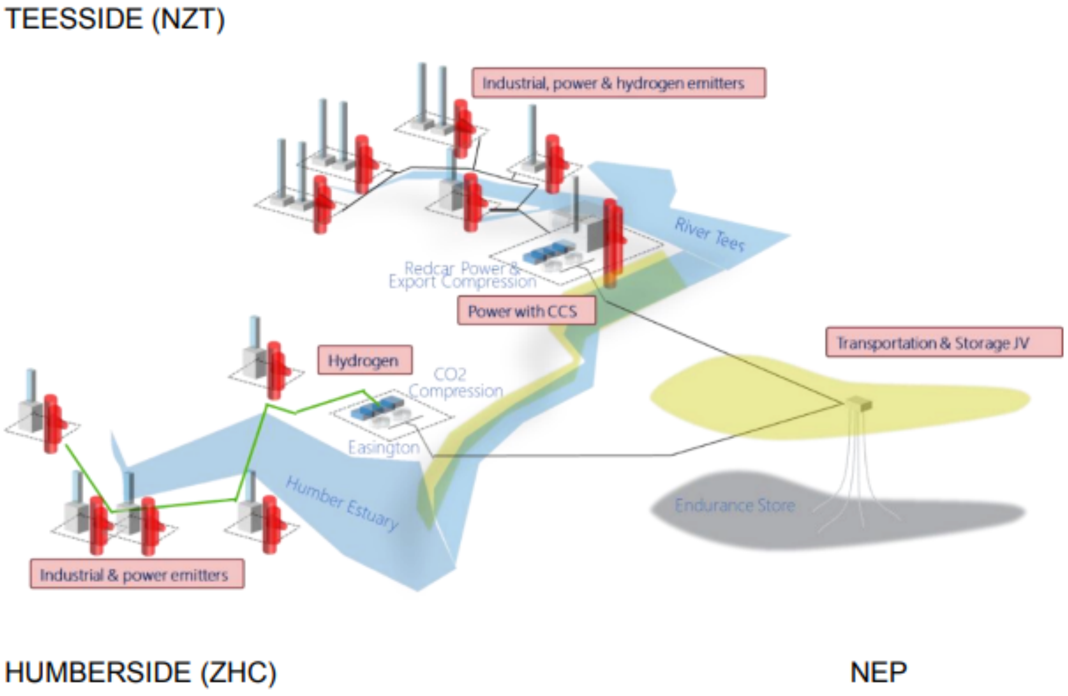
TECHNICAL LESSONS

TECHNICAL DOCUMENTS - EAST COAST CLUSTER

The six technical documents reviewed here relate to Net Zero Teesside and the Northern Endurance Partnership, parts of what is today known as the East Coast Cluster. The Cluster aims to go into operation from 2027, storing CO_2 from a range of industries in a series of saline aquifers in the southern North Sea, offshore UK. Phase 1 injection via the Endurance store is estimated at 4 MTPA potential ramping up to higher volumes later in the life of the facility.

More about the hub

The East Coast Cluster is one of the initial two hubs selected by the UK government for development, in order to meet the UK-wide target of 20-30 MTPA by 2030. It consists of two adjacent clusters, Net Zero Teesside and Zero Carbon Humber, which represented the Teesside and Humber industrial areas during the UK government's CCUS Cluster Sequencing process. The two clusters share the Endurance storage reservoir which is operated by the Northern Endurance Partnership (NEP).

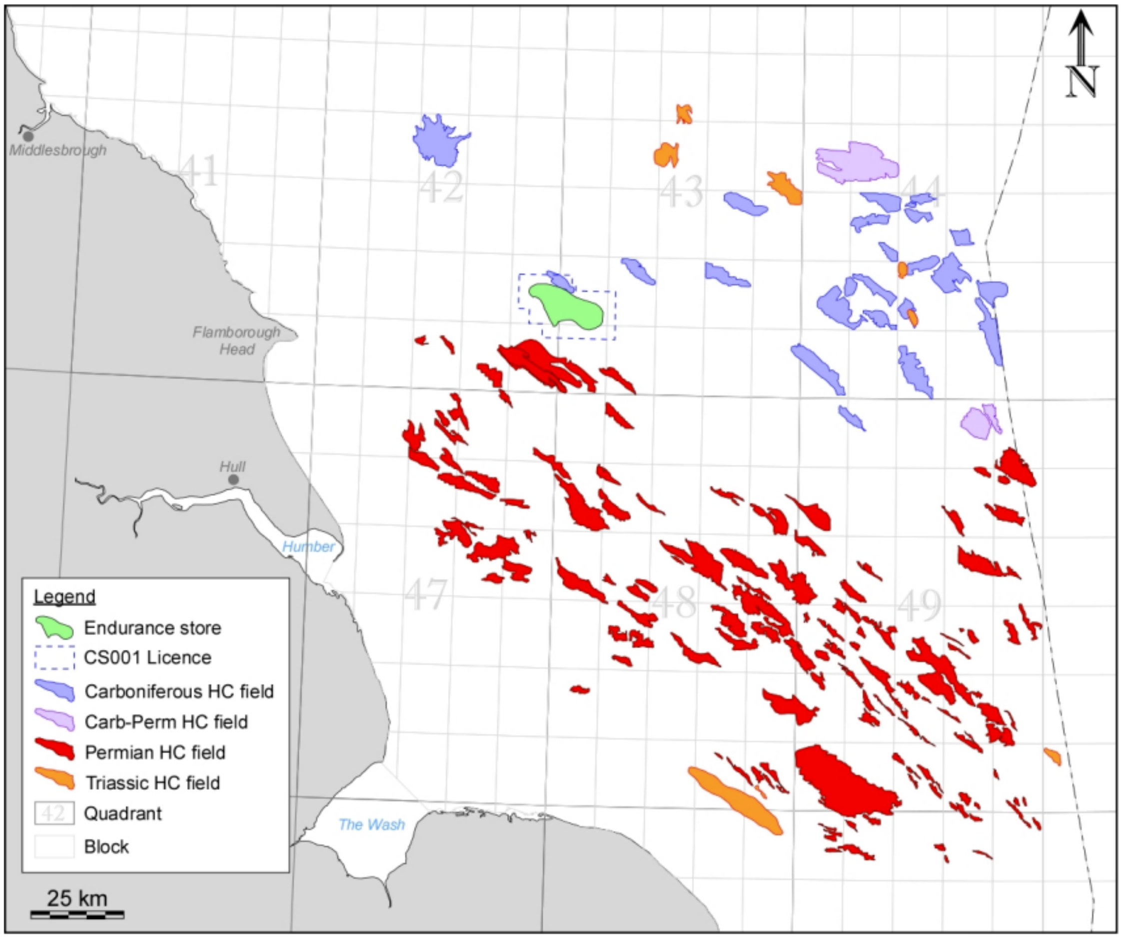


From Primary Store Geophysical Model and Report

Net Zero Teesside is anchored by a gas-fired power plant with carbon capture that will provide low carbon flexible power to the UK grid, complementing intermittent renewables. The plant's CO_2 emissions will be collected by the Northern Endurance Partnership and transported by pipeline to the offshore Endurance store, along with the captured emissions of other industrial companies in the area.

The Endurance structure

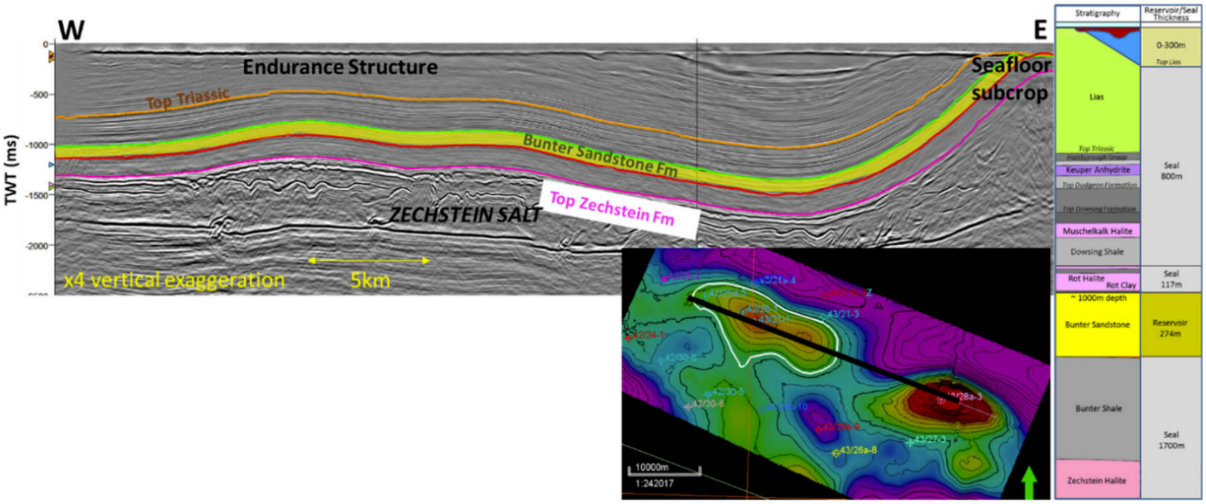
The Endurance structure is an anticline approximately 145 km offshore and approximately 1000m below the sea floor. The structure could be used for CO_2 disposal into a saline aquifer. The target for CO_2 disposal in the anticline is the sandstone of the Triassic Bunter Formation. The Bunter sandstone can be a prolific oil and gas reservoir but, in this structure, there are no hydrocarbons present and any porosity is filled with saline water. The CO_2 would be pumped into the Bunter sandstone saline aquifer displacing some of the saline water. Carbon dioxide is less dense than water and would rise to the top of the anticline and be trapped in the subsurface.



Location map of the Endurance anticline (green polygon) with respect to oil and gas field in the southern North Sea. Unlike the other fields on the map, the Endurance structure contains no hydrocarbons but is filled with high salinity salt water (saline aquifer). From Primary Store Geophysical Model and Report

The Endurance field is a large well-defined anticline, approximately 20 km long and 10 km wide. The anticline is evident even on older seismic data and the crest was drilled in 1970 by Mobil well 43/21-1. This well discovered the anticline but the Bunter sandstone reservoir only contained saline water with no hydrocarbons. In 1990 BP drilled a second well, close to the crest of the structure, 42/25-1 to assess deeper targets in the anticline. The well was unsuccessful in finding hydrocarbons, but it did confirm the wet Bunter sandstone. In 2013, National Grid Carbon drilled a third well down flank on the structure as part of a previous evaluation of the structure for CO_2 disposal. This well was part of the White Rose CO_2 storage project which was cancelled in 2016. However, some of the data and analysis for the White Rose project have been used in the Endurance project.

Well 42/25d-3 is important as it recovered 190m of core in the Bunter Sandstone. Because the Endurance structure is 1000m below the sea floor much of the data used to build up a picture of the Endurance structure is indirect or inferred. Core data is important because it allows direct examination and measurement of the physical properties of the actual reservoir rock. There are numerous other wells drilled around the structure which can be used to help characterize the Bunter sandstone through the incorporation of well log information. As the Bunter Sandstone is an important economic formation in a large area of western Europe there are many studies, reports and analyses which can be used to help characterise the formation within the Endurance anticline.



Geophysical section through the Endurance anticline. The Bunter sandstone is indicted in yellow and is the potential storage formation for CO_2***. The crest of the structure is at approximately 1000m below the sea floor. The deepest part of the Bunter sandstone (spill point) defines the limit for*** CO_2 ***storage (outlined in white on the map). To the east of the spill point the Bunter sandstone sub crops on the ocean floor, this has important implications for pressure management and potential*** CO_2 ***storage volumes for the project.*** From Primary Store Geophysical Model and Report

Review material

This technical review covers six reports related to the evolution of Net Zero Teesside and the Northern Endurance Partnership. The documents were submitted in 2021 by BP (on behalf of the other partners) for review by the Department of Business, Energy and Industry Strategy, a UK government department.

All the reports represent a summary of the considerable amount of work done under each of the headings. We selected six of the reports to review in detail the purpose, methodology and conclusions associated with each one. Report 1 was selected as it describes some of the different technologies examined for CO_2 capture and tackling CCUS scale up. Reports 6-10 were selected, as a group, as they effectively aim to describe the storage container for CO_2 (the Endurance anticline) and what might happen when CO_2 is injected into that container. The other reports are important and contain valuable information on the project but were outside the scope of this initial review.

It should be emphasized that there is a considerable amount of detailed technical work summarised in these documents which represents a very thorough analysis of this particular reservoir and location for CO_2 disposal. The technical work is a very good example of what can be done with respect to analysing all the available subsurface information. However, the reports should not be taken as an exact template for how to analyse all saline aquifers for CO_2 disposal in every location around the globe. This is a very large project and one of the first hence a considerable amount of work was undertaken to decrease risk and uncertainty. As more projects become operational and learnings are shared, evaluation methodologies will evolve. The data requirements and technical work required for future projects will have similarities to the workflow presented for Endurance but will be tailored to each specific project.

Technical documents available – those included in this review in bold

Report	Title	No of pages
1	**Net Zero Teesside and Northern Endurance Partnership Technology Plan**	63
2	NEP and NZT Environmental Management	32
3	Multi Store Development Philosophy	20
4	Endurance-Storage Development Plan	74
5	NEP_NZT Endurance Field Well Integrity Risk Assessment	105
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8	**Primary Store Geological Model and Report**	70
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11	Endurance Well Injectivity Fracturing Study with REVEAL	44
12	MMV Plan for Endurance	32
13	Preliminary Wells Field Basis of Design Summary	177
14	Alternative Stores and Notional Development Plan	133
15	Hewett Conclusive Report	544
16	Endurance Field Wells Cost Estimate	26

Net Zero Teesside & Northern Endurance Partnership Technology Plan

Key Knowledge Document NS051-EN-PLN-000-00007

This is a 63-page document that focuses on the management of technical risk associated with operating a full-chain CCUS hub with first-of-a-kind integration of emerging technologies. The document was provided by BP Exploration as part of what is now known as the East Coast Cluster.

What is a technology plan and why is it important?

The Technology Plan aims to systematically identify and manage unproven technologies to reduce associated risks. This is achieved by recording and tracking each technology's progress, outlining mitigation strategies and contingencies. Regular reviews of the project technology plan ensure that all relevant technologies are captured, and risk mitigations are progressing.

This paper demonstrates a systematic approach to acknowledging, classifying, and quantifying the technology risks associated with implementing the Net Zero Teesside and Northern Endurance Partnership projects.

The document starts with a clear understanding of the project's objectives, scope, and intended outcomes. It highlights the goal of decarbonizing the Humber and Teesside industrial clusters and the expected phased development of the project.

The project philosophy on technology emphasizes early identification and mitigation of risks, market engagement, knowledge sharing, and alignment with industry standards. This approach ensures that the project remains up to date with industry developments and optimizes the proposed concept.

The document highlights the challenges in areas such as full chain dispatchability and scale-up. It acknowledges the first-of-a-kind nature of the project and the need for proper management of proprietary data and intellectual property to ensure that the project's innovations are protected and leveraged effectively.

Anyone planning the technical implementation of a CCUS Hub or interested in the maturity of CCUS technology would benefit from reading this paper.

Technical summary

The Technology Plan focuses on the management of technical risk associated with operating in full-chain dispatchability and with first-of-a-kind (FOAK) integration of emerging technologies. Both the integrated carbon capture plant and the gas-fired power plant will turn on and off to support intermittent renewables. This dispatchability requires new approaches to design and operating procedures.

Key technology risk areas are associated with full chain dispatchability, first-of-a-kind (FOAK) integration and subsurface safety valves (SSSV). Technologies supporting those risk areas are categorized as either enabling or enhancing. A scale of Technology Readiness Level (TRL) is provided, ranging from "unproven concept" level 0 to "field-proven" level 7. Unproven technologies with a TRL of at least 3 are identified, and several 2-page documents are used to track the qualification milestones, mitigations and contingencies of each.

The paper documents several technologies that have been discounted as their risk level initially identified is no longer credible, or the technology is too underdeveloped. These discounted risks include:

a. Exhaust gas recirculation
b. The use of exotic materials and welding techniques on the heat recovery steam generator
c. Selective catalytic reduction
d. Autonomous monitoring for seabed
e. Pipeline leak detection on the gathering network
f. Rig and LWIV qualification for CO_2 intervention and in-fill drilling
g. Permanently installed pressure monitoring sensor behind casing
h. Hermetically sealed compact compressors (HSCC)
i. CO_2 gas phase fiscal metering

The two-page summaries of technology opportunities include completed fields for classification, independent verification subject matter experts, qualifying party, technology description, value proposition, relevant bp/industry experience, current status, TRL milestones, key risks, mitigations, contingency plan and associated key documents. There are fields within the two-page summaries that have been removed or not completed in the document such as the qualification cost estimate.

Full Chain Technology Opportunities includes 2-page summaries for full chain dispatchability and FOAK integration.

Facilities Functional Technology Opportunities includes 2-page summaries for flue gas diverters, flue gas blowers, use of a large absorber and quencher unit, solvent scale-up, O_2 removal, ductile fracture propagation on offshore pipelines, corrosion mechanisms in gathering network and offshore pipeline, qualification pf non-metallic materials with dense phase CO_2, CO_2 detection onsite, all-electric subsea control, and H-class combined cycle gas turbines (CCGT).

Wells Technology Opportunities includes 2-page summaries for subsurface safety valves for CO_2 injection wells and distributed acoustic sending (DAS) in subsea wells.

Subsurface Technology Opportunities includes 2-page summaries for in-well gravity survey, optimized 2DHR seismic for 4D monitoring, and permanent landers for seabed monitoring.

This document demonstrates a practical approach to reducing risk of new technologies within the CCUS application, by acknowledging how risks impact project planning, and by systematically categorizing and summarizing each technology risk. Other projects could use a similar approach to understand, reduce and manage technology risk.

Technical comments for possible future work

The risk reduction and management process can include a dynamic risk register to regularly update and track risks, allowing for more effective management and mitigation of new risks as they emerge. Periodic reviews and audits can be conducted to ensure that risk management processes remain effective and adapt to changes in the project or industry landscape.

For the project overview section, including quantitative targets for decarbonization provide a clearer picture of the project's ambitions and success metrics. Additionally, offering more details on the collaboration and partnership structure between stakeholders can facilitate better coordination and alignment of efforts.

When it comes to technology philosophy, cross-functional collaboration and communication should be encouraged to enable a more holistic understanding of technology risks and opportunities. Adopting agile methodologies and iterative approaches to technology development and integration will allow for more rapid adaptation and learning in response to changing project needs or industry trends.

The intellectual property strategy could include a more detailed framework for managing intellectual property, with guidelines for sharing information with external stakeholders and handling disputes or conflicts. Establishing clear criteria for evaluating and prioritizing intellectual property investments will ensure that resources are allocated effectively.

Lastly, as new projects emerge, lessons learned from other projects or industries about addressing key technology risks can be incorporated. Developing contingency plans for key technology risks will ensure project continuity and resilience in the face of unforeseen challenges or setbacks. By incorporating these suggestions, the document will be better equipped to address potential challenges and provide a more robust framework for managing risks, technology development, and intellectual property.

Document Information

Document Name: Net Zero Teesside & Northern Endurance Partnership Technology Plan

Reference Number: NS051-EN-PLN-000-00007

Document Length: 63 pages

Topic Area: CCUS Hub Technology Risk Management

Project: Net Zero Teesside / Northern Endurance Partnership

Original Report Date: July 2021

Original Author: BP Exploration Operating Company

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Reviewer Organization: International CCS Knowledge Centre

Date of Review: April 2023

Keywords : flue gas diverter, flue gas blower, use of large size absorber and quencher unit, solvent scaleup, O_2 removal, ductile fracture propagation on offshore pipelines, corrosion mechanisms in the gathering network and offshore pipeline, qualification of non-metallic materials with dense phase CO_2, CO_2 Detection onsite, electrical subsea control, H Class Combined Cycle Gas Turbine (CCGT), subsurface safety value SSSV for CO_2 Injection Wells, Distributed Acoustic Sensing (DAS) in subsea wells, In-well gravity survey, Optimized 2DHR seismic for 4D monitoring, Permanent Landers for Seabed monitoring, Exhaust gas recirculation, Hermetically Sealed Compact Compressors, welding techniques, Heat recovery steam generator, Selective Catalytic Reduction, Autonomous monitoring for seabed, Pipeline leak detection on the gathering network, Rig and LWIV Qualification for CO2 intervention and in-fill drilling, Permanently Installed Pressure Monitoring Sensor behind Casing, CO2 gas phase fiscal metering.

Primary Store Geomechanical Model & Report

Key Knowledge Document

NS051-SS-REP-000-00012

This 78-page technical report focuses on the Northern Endurance Partnership's approach to building a subsurface geomechanical model for CO_2 sequestration in the Endurance structure in the southern North Sea.

What is a geomechanics model and why is it important?

Geomechanics focuses on the mechanical behaviour of rocks. It involves studying the physical and mechanical properties of rocks, such as their strength, elasticity, and deformation behaviour, under different loading conditions. This information can be acquired through a variety of tests that take place during drilling, as well as laboratory testing of core samples which provide data on the mechanical properties of the rock.

Geomechanics is crucial for carbon capture and storage (CCS) operations. During the CO_2 injection process into a saline aquifer, the pressure of the reservoir will increase due to the poor compressibility of the original saline water in the formation. This pressure increase will be greatest close to the wellbore and decrease away from the wellbore. The magnitude and behaviour of this pressure decrease away from the wellbore relates to the injection rate and reservoir properties, such as porosity and permeability, as discussed in the dynamic model review. How the increase in pore pressure will impact the mechanical behaviour of the reservoir rocks and possible surrounding formations is examined in the geomechanical model. As CO_2 is injected, it will cause changes in the pore pressure and stress distribution within the rock mass, leading to possible deformation, fracturing, and potential damage to the overlying rock formations.

Understanding the mechanical behaviour of rocks in the storage formation and the overlying rocks is essential for predicting and preventing potential hazards that may arise during and after CO_2 injection. By analyzing the properties of the rocks and the stresses applied by the injected CO_2, geomechanical models can help predict the behaviour of the reservoir and surrounding rock, including their deformation and potential failure mechanisms. This information can be used to design safe and efficient storage sites and to develop monitoring and mitigation strategies to prevent or mitigate any adverse impacts on the associated rock formations. In CO_2 storage projects, the risks of increasing pore pressure in the subsurface are possible fracturing of the reservoir, possible fracturing of the overlying seal rocks, changes in ground or seafloor elevation and ground slope angle due to increased pressure at depth. These factors are generally detrimental to a CO_2 storage project and a geomechanical model attempts to model what will happen at different injection scenarios so these problems can be mitigated before injection takes place.

This report relates to other key documents as reviewed here. The *Primary Store Geological Model and Report* presents a field scale geological model which is built based on the substantial geophysical data *The Primary Store Geophysical Model and Report*. Then, the geological model is integrated into the dynamic model with a series of engineering data, for instance fluid properties, relative permeabilities, well design information. Finally, the dynamic model *The Primary Store Dynamic Model and Report* lays out the foundation for simulating reservoir fluid flow, which allows the geomechanical model to be effectively coupled to validate the containment of the stored CO_2 and assess the possibilities of rock failure within the Endurance structure during injection.

Modelling of geomechanical properties in the subsurface and calibrating this to dynamic models is evolving quickly and due to the amount of data and size of the area studied the models become large and complicated. It should be noted the actual models were not available for review, but the extensive discussion of workflow and results presented in this study is a thorough and comprehensive analysis of the geomechanics in the Endurance structure.

Technical summary

This document focuses on applying geomechanical models and simulations to the static and dynamic models discussed in previous reports (). The geomechanical workflow uses SLB's Petrel Reservoir Geomechanics software and VISAGE finite-element geomechanics simulator. The workflow investigates the stress/strain changes within and above the Bunter Sandstone storage formation resulting from injection-induced pressure increases. The primary focus is to assess the potential impacts on four key areas due to the pore pressure increase caused by CO_2 injection:

1) Failure of the Röt Halite and Röt Clay sealing units through tensile or shear failure.
2) Tensile or shear reactivation of faults mapped in the overburden of Endurance down to Top Röt Halite.
3) Uplift and tilt of the seabed.
4) Tensile or shear failure of the Bunter Sandstone.

In poro-elasticity theory, the effective stress applied on reservoir rock skeleton is equal to the total stress minus the pore pressure multiplied by a correction factor (Biot coefficient). The total stress is normally denoted as “S” and the effective stress is normally denoted as “σ”. For geomechanical studies we are concerned with rock failure which is often visualized Using Mohr Circle theory. The rock failure envelope and Mohr circle theory are based on the effective stresses “σ“ on the rock matrix.

The reservoir fluid flow simulation results are exported from NEXUS software (Halliburton) and then imported into the Petrel Sim Grid to get ready for coupling with VISAGE (SLB). Three key pressure cases relating to 3.5, 5 and 10 Mtpa of CO_2 injection from the NEXUS dynamic model were simulated in VISAGE for 25 years injection, utilising different combinations of fault and matrix properties. The conclusion from all the work outlined in this report was that none of the simulations, using these key pressure cases, display any failure or reactivation of faults. Therefore, demonstrating probable effective CO_2 containment.

It should be noted that since this modelling has been carried out as a one-way coupled process, VISAGE uses the outputs from the reservoir simulator to calculate the stresses and strains in the discrete time step. In geomechanical modelling there are one-way and two-way coupling solutions between reservoir fluid flow and geomechanics modules. In one-way coupling, pressure and temperature changes are passed from the reservoir code to the geomechanics module, but no information is passed back. In two-way coupling, iteration is carried out between the reservoir and stress solution at every timestep until the pore volumes and permeabilities calculated from the stress model and those used by the reservoir model agree. However, the two-way coupled method requires much larger computing resources, longer simulation time, and higher costs. In early modeling stages, one-way coupling is often used to solve the problem and understand the risk severities. In general, a two-way coupled method is only required when there is a high possibility that the changes in porosity and permeability are pronounced, or the rock is close to its failure conditions. In this report, one-way coupling methodology is considered sufficient but two-way coupling may be incorporated for further work.

The geomechanical grids and properties are built over the Endurance structure and outcrop area including the target Bunter Sandstone reservoir and all the overburden sequence up to the seabed. The geomechanical model is derived from that property grid but only built over the Endurance structure (also called the Phase 1 area in this report). As noted in the geological and geophysical review no faults were observed from the available seismic data to indicate there were any faults penetrating through the top seal into the Bunter Sandstone. For containment of CO_2 the lack of visible faulting on seismic sections is encouraging, as faults can be potential leak points. However, to the east of the Endurance anticline nearer to the subsea outcrop of the Bunter Sandstone, faults extending down into the upper Bunter Sandstone are observed. Therefore, the potential for sub-seismic faulting in the Endurance anticline was investigated. Five of the imported faults were copied and manually edited to extend down into the upper few layers of the Bunter Sandstone Z6 unit in the Phase 1 area. This methodology models the potential occurrence of faults, that can not be detected on the available seismic data.

As part of building the geomechanical model the mechanical properties of the geological formations of the Bunter Sandstone and cap rocks were calculated. This study integrates seismic interpretations of horizons and faults, well logs, geomechanical core data and fracture tests from the Endurance area for the whole stratigraphic section from seabed down to the base Zechstein salt (underlying the Bunter Sandstone unit). These data were used to create the geomechanical grid and properties in the 3D Petrel model. It is important to note that:

- There are six wells located within the Endurance structure. The three within the spill point contain key stress and geomechanical property data used during the modelling.
- P wave or compressional sonic data (used to calculate Young's modulus for rock mechanical properties) is present in most wells but only Well 42/25d-3 contains S wave or shear sonic data (for shear modulus calculation). S wave sonic and density are created using correlations to P wave sonic.
- Well 42/25d-3 drilled in 2013 is a dedicated appraisal well for this CO_2 storage project and includes a significant amount of geological, reservoir engineering and geomechanical data specifically acquired for CO_2 storage appraisal. The key elements of the geomechanical data acquisition and analysis program are:
    1) Multiple confined core tests of static elastic parameters, static compressive strength and tensile strength plus acoustic velocities.
    2) Openhole logs, image logs and advanced sonic logs to determine in-situ dynamic elastic and strength parameters and in-situ stress azimuths and horizontal stress anisotropy.
    3) Formation Integrity Test (FIT) in the Röt Halite to determine minimum halite stress.
    4) MicroFracture tests in the Röt Clay and Bunter Sandstone to obtain the minimum principal total stress, regarded as Sh_{min}, which is in the horizontal minimum stress direction.

The three principal stress directions (Sv, Sh_{min} and Sh_{max}) also need to be measured or estimated to initialize the model, these estimates were based on the following data. The bulk of the dedicated in-situ stress tests were taken in well 42/25d-3, Formation Integrity Test (FIT) and Leak-off Test (LOT) data are also available in several other wells. FIT and LOT data indicate that an Sh_{min} value of 0.80 psi/ft or 0.182 bar/m is a reasonable estimate at the base of the Lias Group which is approximately 500m above the Bunter Formation at levels of -530 to -713 mTVDss. Density log derived estimates of the vertical principal total stress (Sv) indicate values of 0.99 to 1.03psi/ft from the base of the Lias Group to the Base of the Bunter Sandstone Formation respectively.

From the Sonic Scanner analysis in well 42/25d-3 and regional considerations, the Sh_{max}/Sh_{min} ratio within the Bunter Sandstone is estimated at approximately 1.05. In general, shales have higher Sh_{max}/Sh_{min} anisotropies than sandstones so a Sh_{max}/Sh_{min} of 1.10 is regarded as more reasonable for the Röt Clay. The Röt Halite and Zechstein halites are regarded as lithostatic where $Sv = Sh_{max} = Sh_{min}$.

The reservoir simulation grid (Sim Grid) and associated properties are imported into the working Petrel project for generating geomechanics grid. This geomechanics grid includes data for all overburden above the Bunter sandstone to the sea floor. The 'Overburden All' grid is derived from the Sim Grid with the addition of extra surfaces in the overburden sequence. Three separate grids were created to incorporate the overburden section above Endurance. This is required to accurately model the stresses, strains and displacements occurring in the matrix and on the mapped faults from the top of the Bunter Sandstone, which is the upper limit of the modelled injection pressures, to the seabed. The grid of the Phase 1 modelling area is created by extracting a subset area of the coarser Overburden All Grid using the Phase 1 area. Then, the model is upscaled to create a new larger grid with that Phase 1 area embedded within it.

For the geomechanical property modelling process, sonic and density logs were upscaled to and distributed within the Overburden Grid and then upscaled into the Geomechanical Grids. These are then used to create geomechanical properties. The log derived, elasticity and strength, geomechanical properties are matched to core data and/or in-situ stresses at Wells 42/25d-3, 42/25-1 and 43/21-1 before populating the whole model. The sideburden and underburden outside of the phase 1 grid are created to stabilize the initial stresses after initializing boundary conditions. The geometric expansion of cells in the sideburden and the underburden minimizes large changes in cell dimensions.

The geomechanical properties of salt are quite different to the geomechanical properties of sandstones and shales and must be correctly accounted for in any biomechanical model. Salt layers are identified in the original geomodel so they can be assigned correct properties in the geomechanical model. The distributions of elastic and Mohr Coulomb properties including Young's modulus, Poisson ratio, shear modulus, bulk modulus, unconfined compressive strength, tensile strength cut-off, friction angle, dilation angle, are populated in clastic rocks and salts. Salts are difficult materials to model as they are typically less dense than surrounding rocks and deform by creep mechanisms on geological timeframes leading to lithostatic stress states. By using an equivalent elastic medium approach, a Poisson's ratio of 0.495 is assigned to ensure a near lithostatic stress state and low shear stresses. A Young's Modulus value of 0.75 GPa is calculated from the measured bulk modulus of approximately 25 GPa, from logs, with the assigned Poisson's ratio of 0.495. Since salt is effectively self-sealing, pore spaces will tend to be isolated and surrounded by creeping salt with lithostatic pressures. The pore pressures are therefore set as not to contribute to the effective stress calculation in VISAGE.

The imposed boundary conditions group of methods were the primary choice used to generate predictions of the initial in-situ stresses for assessing how well these initial stresses match with the available data. This is considered a normal geomechanical workflow if there is sufficient data. Setting Young's Modulus of 0.75 GPa and Poisson's ratio of 0.495 attains the lithostatic stresses within the salt units. This leads to relatively large negative strains in the overlying units, particularly above Röt Halite and very low Sh_{min} values (particularly in the shallow sequence). This negative strain may lead to erroneous results in the model. Therefore, two separate imposed boundary condition initializations were created to mitigate this situation. The two boundary conditions were then merged to create a more robust stress initialization used in the subsequent simulations. The results indicated a good match between measured data and the initialized stresses from the model.

A 2D Mohr circle diagram of a notional failure envelope and Mohr circles for stress were developed to help understand the simulation results. In summary, as the pore pressure increases, this poroelastic coupling will tend to shrink the Mohr circles and decrease the principal effective stresses during CO_2 injection but not enough to cause mechanical failure.

A series of model scenarios were simulated with different combinations of injection pressures, fault properties and extents, and matrix properties. The initial pressure plus injection pressures for five steps between years 2025 to 2050 and one post injection monitoring pressure at year 2500 were simulated in all cases. Simulated injection schemes are 3.5 Mtpa with no brine production, 5.0 Mtpa with brine production and 10.0 Mtpa with brine production. None of these reference cases had any failure during injection. The highlights are summarized below.

- The pressures equilibrate rapidly in the high permeability Bunter Sandstone. This means that differences in the number and placement of injectors are less important to Endurance Bunter Sandstone reservoir pressures than the total material balance of CO_2 injected compared to the brine produced.
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- The Bunter Sandstone unit displays a clear poroelastic response with the total horizontal principal stresses increasing during CO_2 injection. This reduces the likelihood of failure in this unit by reducing the differential stress and keeping it below the modelled failure envelopes despite the effective stresses decreasing.
-
- Modelled maximum uplift at the seabed occurs over the Endurance structure crest and ranges from 0.17m to 0.19m, which are toward the high end of expectation. It is likely some uplift will be absorbed within the overburden.
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- Horizontal in-situ stress reductions above the Bunter Sandstone are expected from the elastic inflation and stretching of the Bunter Sandstone during injection. The VISAGE modelling indicates a slight decrease in the Röt Clay Sh_{min} (-0.01 to -0.03 psi/ft) and a maximum change of -0.078 psi/ft in the Quaternary over the Endurance crest. These shallow stress reductions are not regarded as a significant issue for Endurance, as they are likely to be absorbed by the overburden.
-
- Modelled maximum tilt values of the seabed in all cases reported here are below 0.002° and generally found on the flanks of the structure. This is unlikely to cause significant issues with the planned Hornsea 4 windfarm and other infrastructure.

Technical comments for possible future work on the geomechanics model

This study presents an advanced workflow by coupling geomechanics and reservoir simulation resulting in a thorough analysis of the effects of increased pressure caused by injection CO_2 on the geomechanical properties of the Endurance structure. The geomechanical model provides a useful exploration of the possible rock mechanics properties and in-situ stresses expected within and above the Endurance structure including the overburden fault system. After integration with a comprehensive data gathering and monitoring program, it is concluded that risks of seal breach or adverse seabed uplift and tilting effects are considered low in the planned CO_2 injection schemes of up to 10 Mtpa with brine production where necessary. This reduces the likelihood of failure in this unit by reducing the differential stress and keeping it below the modelled failure envelopes despite the effective stresses decreasing. However, the elastic strain estimates reported here can be used as input to surface facility designs, data gathering and monitoring program design or for further modelling to provide more detailed characterisation.

The one-way coupling is a reasonable geomechanical workflow for an initial review of the field. To investigate possible failure scenarios in more detail two approaches could be taken.

1. Röt Clay failure could be investigated by dual porosity/dual permeability models that explicitly couple the geomechanical effects with the potential for fluid ingress from the Bunter Sandstone to the Röt Clay via joints or small faults. This is a classic analytical approach for seal breach analyses and a conservative assessment of cap rock integrity.
2. Two-way coupled models could be used where some criteria for changes in the Bunter Sandstone reservoir pressures and stresses lead to a revised permeability and pore pressure in the adjacent Röt Clay unit. Using this methodology if a scenario was run where failure did occur the failure and the resulting fluid flow could be modelled more accurately.

Document Information

Document Name: Primary Store Geomechanical Model & Report

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Topic Area: Geomechanical model for CO_2 sequestration

Project: Net Zero Teesside / Northern Endurance Partnership

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Primary Store Geophysical Model and Report

Key Knowledge Document

NS051-SS-REP-000-00013

This is a 69-page document summarizing the methodology and results of the geophysical work applied to the proposed Endurance saline aquifer CO_2 disposal site. The document was provided by BP Exploration as part of the Northern Endurance Partnership project.

What is a geophysical model and why is it important?

The geological structure which has been proposed to store CO_2 in Endurance is 1000m or deeper below the seafloor. Therefore, the structure is not directly visible and mapping of the structure (size, depth, shape and thickness) is done by indirect means. This is the function of using geophysical techniques specifically seismic methodology. Seismic data involve generating acoustic (seismic) waves at the surface, the seismic waves travel into the subsurface and are reflected back from layers in the subsurface. The complicated arrays of reflections are recorded at the surface and processed through sophisticated geophysical interpretation software to build a model of the rock layers in the subsurface. These data can show the top and base of formations, give an indication of shape and continuity and if there are any faults cutting through the layers. Seismic data can be shot as a line resulting in a cross section through the subsurface (2D seismic) or as an area which results in a three-dimensional model of the subsurface (3D seismic). Depending on how data are acquired, physical properties within the reservoir rock may be inferred from some seismic data and not just the top and base of the formation.

These types of data have been used in other CO_2 sequestration projects to detect where CO_2 has been injected into the reservoir. If the same type of data is collected over set time intervals, for instance every 2 years, the size and location of where CO_2 has travelled in the subsurface can be monitored (4D seismic). Where possible seismic data are always integrated with any well data drilled in the areas where the seismic has been acquired. The wells are usually the only data available where the rock has been analysed using well logs and/or directly sampled by taking a rock core. These data are used to calibrate and validate the seismic interpretations.

With respect to carbon sequestration activities, seismic data are key in assisting in the following:

1. Identify locations where geological structures and reservoirs in the subsurface are suitable for CO_2 storage. This would include identifying the appropriate geologic intervals and geographic locations that are of the appropriate scale and quality to accommodate and contain the required volume of CO_2 proposed to be sequestered. Essentially this is the size, shape and location of the underground storage container.
2. If the seismic data are of sufficient quality some inferences can be made to the physical properties within the target formation such as porosity and degree of cementation.
3. Identifying favourable geologic formations above the targeted reservoir which can act as seals preventing migration of CO_2 out of the structure. Seismic data can also be used to identify any faults cutting across the formation which may also cause potential containment risks.
4. Observe the effectiveness of CO_2 storage through monitoring the injection and migration of CO_2 in the storage reservoirs over time. Introduction of CO_2 into a saline reservoir alters the seismic response allowing for the identification of areas where CO_2 has been introduced.

Technical summary

The Endurance Geophysical Report consists of a thorough review of the geophysical data, specifically focusing on the use of seismic, and its application with respect to the Northern Endurance Partnership Project. How these data are utilized, and the methodologies employed to build and characterize the structural framework for the Endurance structure and its suitability with respect to carbon sequestration is discussed in detail. Limitations with respect to the data and the resulting interpretation were identified and quantified with respect to the impact on the subsurface model. Recommendations for potential future seismic acquisition, to assist in mitigating these limitations and monitor the effectiveness of the project were also discussed.

The Endurance project and regional structural understanding was defined using multiple seismic datasets. These datasets consist of:

1) Regional 2D seismic of varying vintages, used predominantly to assist in building a regional understanding of the basin
2) 1997 3D seismic (OBC), which consists of a sparse lower resolution 3D
3) 2013 3D seismic (Polarcus), which consists of a higher quality seismic 3D

Although it was recognized that these seismic datasets were designed and processed for deeper targets, and therefore not optimally designed to image the Triassic stratigraphy of the Endurance structure, the quality was sufficient to assist in building the structural framework for the project. Recognizing the limitations of the seismic datasets it was determined that to optimize the imaging of the key Triassic stratigraphy of the Endurance structure, reprocessing of the higher quality Polarcus 3D was warranted. Focusing on image quality and noise reduction at the Triassic level, CGG was engaged to undertake a post-migration reprocessing project. Although an improvement in data quality was observed following reprocessing, the challenges with respect to data quality from non-optimal design and acquisition could not be completely rectified.

Utilizing all available well ties, the key stratigraphic intervals including the primary seal of the Rot Halite and the targeted reservoir of the Bunter sandstone were identified and interpreted with high confidence. Although the interpretation resulted in a robust structural framework the data quality was determined to be insufficient to resolve and characterize subtle stratigraphic variations within the Bunter sandstone. Outstanding data quality issues due to multiples, 60Hz noise and acquisition footprint were specifically identified as issues that negatively impacted the seismic resolution. As a result, it is suggested that a new 3D seismic program be executed designed specifically to optimize the imaging of the Triassic stratigraphy. A new 3D seismic shoot would also be critical in developing a thorough MMV (Measuring Monitoring and Verification) plan to monitor CO_2 plume migration after injection commences.

Identification of potential faulting was also key in quantifying potential containment risk for the project. Following reprocessing it was determined that the data could resolve faults with offsets down to 10-15m. Multiple faults could clearly be imaged in the stratigraphy above the Endurance structure. Although limited by the resolution of the seismic data, faulting does not appear to extend below the Rot Halite into the Bunter sandstone reservoir, minimizing risk of faulting impacting containment.
A layer-based depth conversion of the seismic data and interpretations was undertaken with the resulting structural framework used as input for the static geological model (LINK) subsequently incorporated in the dynamic, geomechanical and geochemical models. A thorough review of the depth conversion methodology and associated uncertainty analysis was summarized and determined to be appropriate. Following a detailed uncertainty analysis, confidence in the Endurance structure is high in that variations did not have a large impact on the overall structure.

The impact of CO_2 on the seismic response was also reviewed, focusing on the ability to detect CO_2 using seismic data. The application would monitor both CO_2 migration and containment within the targeted Bunter reservoir. Seismic modelling was undertaken specifically to evaluate what CO_2 saturations are detectible seismically. Modelling strongly supports the ability to see low concentrations of CO_2 in the reservoir. Although excellent at identifying the introduction of low concentrations of CO_2 at a particular location, the ability to resolve variations in its concentration would be limited. The ability to resolve the presence of CO_2 was also shown to be highly dependent upon seismic data quality, i.e., higher frequency and lower noise content required, with the ability to resolve CO_2 migration in thinner beds requiring the acquisition of a higher resolution 3D survey.

Monitoring the migration of the CO_2 would require the repeated acquisition of high-resolution 3D seismic over time. This technique is referred to as 4D seismic and would be of value not only to monitor CO_2 migration but also could be used to confirm and monitor containment within the reservoir. Prior to the initiation of injection, a high-resolution 3D survey would be required to act as a baseline and the timing of any subsequent 3D's would be based upon injection volumes and reservoir modelling.
Overall, the Primary Store Geophysical Model and Report is a very thorough document. The methodologies and analysis align with industry standard workflow and the resulting conclusions and recommendation can be supported.

Technical comments for possible future work on the geophysical model

Within the report it was recognized that the existing seismic data are not optimal for investigating the Bunter sandstone reservoir and associated sealing formations. The report concludes that a new 3D seismic survey be acquired designed specifically for this project. We strongly agree with that approach.
A new survey specifically designed for this project could be used to better define the structural framework and possibly provide information about the physical properties and stratigraphic variability within the reservoir formation and of the adjacent sealing formations.
Modelling indicates high quality seismic should be able to resolve the migration of CO_2 within the Bunter reservoir. This new 3D is critical to establish a baseline to compare any future seismic data that could be used to monitor and map CO_2 migration and containment.

Document information

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Primary Store Geological Model & Report

Key Knowledge Document

NS051-SS-REP-000-00013

This 70-page technical report focuses on the Northern Endurance Partnership's approach to building a a subsurface geological model for CO_2 sequestration in the Endurance structure in the southern North Sea.

What is a geologic model and why is it important?

Building a geological model is critical to understand the potential storage volumes available for CO_2, to assess risk and uncertainty in parameters defining the storage container and to identify data gaps. Essentially a model is built to represent, as accurately as possible, the shape and physical properties of a subsurface volume, in this case the Endurance Anticline. Geological models are generally built from information obtained from seismic data and well data. Since these data are often sparse, geological interpretation between the data points must be made to model the whole structure. The complexity of a geological model is related to the available data. If lots of good subsurface data are available, then a higher level of detail can be expected, along with a decrease in the uncertainty of the model.

Considering the location of the Endurance anticline, 145 km offshore and approximately 1000m below the sea floor there is a relatively good set of data available to build a geological model. These data are derived from several seismic studies, wells, and published material. More data could always be used but the combination of three wells drilled into the structure, seismic data and extensive published regional work is sufficient to characterise the structure for initial modelling work. The method used to construct the model followed industry standards and was very thorough, the analysis suggests the structure is ideal for injecting and containing large volumes of CO_2.

This report is related to other key documents reviewed here. *The Primary Store Geophysical Model and Report* forms a critical part of the geological model as the geophysical data is used to define the upper and lower surfaces of the storage reservoir. Once a geological model is constructed it can then be integrated into a dynamic model that can be used to model fluid flow, pressure, and uncertainty within the structure (*Primary Store Dynamic Model and Report*) . The dynamic model is critical for field development modeling and to help develop a CO_2 monitoring plan. As more data becomes available through future drilling, seismic acquisition, and CO_2 injection both static and dynamic models should be continually updated and refined.

Technical summary

In this document BP summarizes the work and methodology for construction the geological model of the Bunter sandstone reservoir in the Endurance anticline. This model is constructed using various vintages of 2D and 3D seismic, information from three wells drilled into the structure and information from offsetting wells and published work. The report outlines industry standard modelling workflow resulting in a very thorough and geologically reasonable model.

The depositional environment of the Bunter sandstone, core analysis, petrophysical analysis, facies analysis and upscaling are all critical in developing a geological model and are all thoroughly reviewed in the document. The result of the analysis demonstrates that the Bunter sandstone is a thick sandstone (average 275m) pervasive across the whole structure. The sandstone has a high net to gross (average 94%) indicating most of the interval is available to store CO_2. The net sandstone has high porosity (average 22.5%) and high permeability (average 300 mD). The Bunter sandstone in this location would be considered a high-quality reservoir when compared globally to other potential reservoirs. There is variable cementation in the sandstone causing a decrease in porosity, but this has been captured in the model. The sandstone is relatively homogenous with some evidence of internal baffles. The extent of these baffles is not known and has been considered in the uncertainty of the model.

Critical to CO_2 containment is a seal on top of the Bunter reservoir to prevent upward migration of CO_2. The primary seal unit above the Bunter sandstone is approximately 10m of Rot Clay and on top of that approximately 100m of Rot Halite. Like the Bunter Sandstone the Rot Formation is laterally pervasive and appears remarkably consistent in thickness and lithology. Salts such as the Rot Halite are exceptionally good seals as the porosity and permeability of the salt is extremely low and its rheological characteristics make open fractures (conduits for CO_2 leakage) within the salt very unlikely.

There appears to no identifiable faulting cutting through the reservoir or faulting across the top seal which is critical for CO_2 containment. Where large faults are identified it is in the geological section above the seal. There may be some small-scale faulting at the very top of the reservoir which have been incorporated into the geological model. No large-scale faults affecting the entire reservoir or seal have been identified and therefore none have been incorporated into the static model.

Mapping the top and bottom surfaces of the Bunter sandstone and assessing any structural features such as faulting is reviewed in the *Primary Store Geophysical Model and Report* ()

The relatively thick sandstone with high porosity and permeability makes the Bunter sandstone an ideal target for CO_2 disposal. The anticline is a large structural feature, and the aerial extent and height of the structure indicates it can store a considerable quantity of CO_2. The halite seal above the target reservoir is thick and laterally pervasive and no large-scale faulting has been identified in the reservoir formation or seal which is critical for containment.

An unusual feature of the Endurance anticline is that the Bunter sandstone within the anticline may be in hydraulic continuity with an outcrop of the formation on the seabed approximately 20 km to the east. If this is the case the result is a hydraulically open system which may be beneficial to pressure management. The saline water displaced by injecting CO_2 into the anticline may be able to dissipate, thereby decreasing the amount of pressure build-up. The CO_2 being lighter than water would remain trapped in the anticlinal structural. Pressure management is discussed further in the *Primary Store Dynamic Model and Report*.

Discussion of potential volumes of sequestration, and uncertainty analysis are not discussed in this document but are reviewed and summarized in *Primary Store Dynamic Model and Report*.
The static geological model, as presented, appears to be a robust framework to integrate into a dynamic model. However, it should be noted the actual geological model itself was not available for review just the methodology and descriptions in the Key Knowledge Document.

Technical comments for possible future work on the geological model
If more detailed study of the overburden is to be done, core analysis could be beneficial to determine more accurate porosity-permeability relationships, as well as more accurate density and neutron-based porosity measurements, as opposed to porosity derived from available data (i.e. resistivity) and estimated petrophysical (a, m, n) values. Regarding absence of mud, and provenance of carbonate in the system, additional work could be performed on core and additional wells to delineate areas of

cementation and determine carbonate source. Given the high Net to Gross (NTG) of the reservoir section (97-99%), Vshale percentages are small and PHIT=PHIE, but if heterolithic facies are to be included in the future, PHIE may be considered. Correctly the P10, Mean & P90 reservoir parameters have been chosen to represent the current interpretation of the Bunter Sandstone over the project area and beyond. These numbers could prove pessimistic as the few current logs and core within the structure have actual values that exceed the P10 case, NTG ~97-99%, PHIT ~20-24%, Permeability ~400-600 mD. This uncertainty would be decreased if more wells were drilled into the structure for disposal and/or monitoring.

NMR data shows very optimistic permeabilities, exceeding 1000 mD in the best quality sands. More work with these data could be done, with porosity-permeability crossplots for each electrofacies applied to future models. Low Net to Gross intervals could be included as well, resulting in an increase of modelled reservoir and injectable volume. If dynamic modelling shows fluid movement to the northwest, it would be beneficial to add additional area to understand pressure and CO_2 concentration beyond the spill point.

The two grids used, 2 million cell 'Coarse' and 100 million cell 'Fine' model, do an excellent job of testing the effect of vertical resolution on the distribution and concentration of CO_2 over time, in this case 400+ years. Runs on both models showed a difference of 3.5% CO_2 concentration at the ~200-year mark, this difference was no longer observed as the system equilibrated at the ~400-year mark. Moving forward, all modelling can be done using the coarse model, which will save static model building time as well as significant dynamic simulation time.

Variogram parameters used for petrophysical modelling are reasonable, and future versions will be able to further define the direction and extent of each facies based on 4D seismic and pressure data acquired during the life of the project.

Uncertainties in the model have been well defined and next steps could include further work on lateral continuity and architecture of baffles. The model is constructed such that more detailed modelling of low NTG intervals along with pressure data acquired in the future can easily be added to help delineate these baffles. Faulting has not been included in the current model, but has been considered and could be added if history matching requires it.

Document Information

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Primary Store Dynamic Model & Report

Key Knowledge Document

NS051-SS-REP-000-00015

This 71-page technical report focuses on the Northern Endurance Partnership’s approach to building a subsurface dynamic model for CO_2 sequestration in the Endurance structure in the southern North Sea.

What is a dynamic model and why is it important?

The static or geological model is a three-dimensional representation of the subsurface. The model contains physical characteristics which describe the subsurface. These characteristics include the thickness, porosity, and the permeability of the reservoir, rock composition and other properties depending on the available data. The geological model aims to show how these properties vary spatially within the subsurface. A dynamic model uses the static geological model as a foundation and introduces engineering parameters which allow flow, or movement of substances to be simulated in the model. Reservoir dynamic modelling has been used widely in petroleum engineering for many decades and is important for solving complex subsurface engineering problems associated with extracting hydrocarbons. The modelling for injection of CO_2 into the reservoir is built on similar theory and methodology. However, there is an important difference, CO_2 is injected rather than extracted as in the case of hydrocarbons. The injection generally causes a pressure increase within the reservoir rather than a pressure decrease. The fluid properties in the model will be based on CO_2 and water rather than oil-gas and water.

For CO_2 sequestration projects such as Endurance, it is important to understand how the injected CO_2 displaces the original pore water and moves from the injection well through the subsurface. This is one example of the use of a dynamic model. The size and extent of the CO_2 plume can be modelled over time which is critical in determining the efficiency of the project and also for developing a monitoring plan to verify the location of the CO_2 stored in the subsurface.

If there are sufficient data, modelling the dynamics of other properties can be done. These include heat flow, pressure, CO_2 solubility and many other properties that change over time. For instance, injecting fluid CO_2 into a reservoir already saturated with water will cause the pressure to increase in the reservoir. The magnitude of the pressure increase, how it changes away from the well bore and how quickly it changes can be modelled in the dynamic model. The models allow different scenarios to be tested within the computer simulation before injecting any CO_2 in the field. The model allows different scenarios of CO_2 injection and may help identify any problems that may arise from the injection. For example, we can model the injection of 1 MT of CO_2 per year into one hypothetical well. Would the reservoir properties allow that volume of CO_2 to be injected safely or would there be insufficient permeability causing a potential unsafe pressure build-up? If the pressure build-up was too high, could two wells be drilled and 0.5 MT/year be safely disposed of in each well? There is a limit to how much pressure increase a reservoir can safely withstand which ultimately limits the amount of CO_2 which can be injected. To further increase the CO_2 storage capacity of a reservoir, it is possible to extract the original pore water thereby increasing space for CO_2 storage. The original pore water is extracted using separate water extraction wells located away from the injector wells. However, the produced saline water must then be disposed of safely. This concept of pressure management or dewatering can be examined through the use of dynamic modelling.

Dynamic models can be very useful for testing uncertainties as input variables can easily be changed with numerous scenarios for establishing a range of outcomes. These models can also be used to highlight which data need to be collected to decrease the risk and uncertainty of the models. As with the underlying static models, dynamic models should be continuously updated throughout the life of the project as new information becomes available.

This report relates to other key documents as reviewed here. The *Primary Store Geological Model and Report* presents a field scale geological model which is built incorporating the geophysical data (*The Primary Store Geophysical Model and Report*). Then, the geological model is integrated into the dynamic model with a series of engineering data, e.g., fluid properties, relative permeabilities, well design information. Finally, the geomechanical model (*The Primary Store Geomechanical Model and Report*) is run based on the results of the dynamic model to validate the containment of the stored CO_2 and assess the possibilities of rock failure of the reservoir and overlying sealing formations during injection.

Technical summary

In this document BP summarizes the work and methodology for conducting the dynamic model of the Bunter sandstone reservoir in the Endurance anticline. After integrating the geological model, detailed fluid and rock properties and well completion information are entered to complete the initial setting of the dynamic reservoir model. Then, the model is run with a number of uncertainty factors, including: formation structure, segment transmissibility, porosity, permeability, aquifer connectivity, reservoir architecture, and displacement efficiency through relative permeability curves.

This is done to evaluate the P10, P50, and P90 cases of CO_2 storage capacity for the clustered and distributed development design. Lastly, the maximum CO_2 storage capacity of Endurance has been evaluated with an increased number of CO_2 injectors and surrounded brine producers. Integrating suitable pressure management through brine extraction, the amount of stored CO_2 is estimated to be more than four times (approximately 450MT) than the base case (approximately 100MT) with no brine extraction.

Overall, the report outlines the industry-standard workflow of dynamic modelling, resulting in a very thorough and exemplary CO_2 storage simulation. The uncertainty analysis is within reasonable engineering ranges and gives valuable insights of the lower and upper limits of the storage volumes, which lays out the foundation of the project feasibility.

Landmark Graphics reservoir simulator 'Nexus' is used for the dynamic modelling of CO_2 storage. Other simulators for fluid properties, CO_2 solubilities, thermal fracturing effects, and statistical uncertainty analysis are also used. For the dynamic modelling physical and chemical properties of the gas injected is assumed to be pure CO_2 with no impurities. An equation of state PR78 (Peng Robinson EOS) and water PVT table with CO_2 solubilities at different water salinities (Henry's Law) were developed using the CMG WinProp module. The equation of state is needed to estimate the solubility of CO_2 in water. Since the CO_2 solubility in brine for Endurance is low due to the hypersaline condition in the reservoir, immiscible CO_2 without solubility into brine has been mainly used for the dynamic modelling. Brine properties were obtained from samples from Well 42/25d-3 during drill stem testing. These samples indicate that there is a potential increase of brine salinity with depth, which could explain the relatively large pressure difference observed between Well 42/25d-3 and Well 42-25-1.

Reservoir energy is studied by incorporating the following properties: water compressibility (generated by REToolkit), rock compressibility, aquifer connectivity to the broader Bunter basin, and permeability contrast for areas of the Bunter sandstone where seismic phase reversal indicates lower permeability. How much of the Bunter sandstone outside the actual Endurance structure should be incorporated into a model and the methodology used to do this is discussed in the report. The broader Bunter basin aquifer is modelled both numerically through a pore volume multiplier at the edge and analytically through the Carter-Tracy model. The reservoir pressure responses for 4 MTPA CO_2 injection in various extended aquifer models are compared using both methodologies. This sensitivity study can give flexibilities and options in the later uncertainty analysis with intensive simulation runs.

Displacement efficiency is studied through a series of CO_2 – water relative permeability models based on measured values from Special Core Analysis (SCAL) tests on core plugs from well 42/25d-3. The ultimate residual water saturation (S_{wrg}) has been corrected to capture the slowly changed CO_2 and water saturations during post-injection due to gravity drainage and capillary pressure effects over geological time in comparison to the relatively short laboratory-based measurements.

Reservoir architecture is modelled by applying the different ratios of vertical and horizontal permeabilities, which are K_v/K_h = ~0.1 for good quality sandstone and lower values of K_v/K_h <0.01 which represent possible vertical baffles interpreted from drill stem test measurements.

Average injection rate is assumed to be 1 MTPA per well and a limitation for reservoir pressure not to exceed approximately 200 bars fracture pressure at the crest over the 25-year life of the project. This is based on benchmarking against analogous offshore CCS projects such as Sleipner, Snohvit, and Northern Lights. It is found that no brine production would be required for Phase 1 of the project as CO_2 injected volumes are not expected to exceed 100 MT over 25 years. Salt precipitation, mostly halite, is considered a significant risk to well injectivity over time for Endurance due to the high salinity of the brine and the creation of a dry-out zone in the near wellbore region. The water vaporization phenomenon during continuous CO_2 injection is modelled using CMG GEM (*Primary Store Geochemical Model and Report*). The injectivity loss becomes prominent at low injection rates. It is recommended to perform a pre-injection initial flush with fresh water to dilute high-salinity reservoir brine near the injectors followed by a one-to-two-day long freshwater flush per well per year to keep the integrity of well injectivity.

After test runs and calibrations, the fine-scale geological model is upscaled to a coarse-scale reservoir model. Numerous simulation runs are conducted through a Monte Carlo probabilistic workflow to understand effects of reservoir uncertainties on CO_2 storage capacity for Endurance in the downside, base, and upside scenarios. A list of selective subsurface uncertainties has been reviewed:

- Structural uncertainty: three distinct grids have been generated to represent different brine volumes above spill point.
- Fault transmissibility: faults in the overburden and extended into the Bunter reservoir are modelled in segments with varied transmissibility multipliers.
- Petrophysical uncertainty: global permeability and porosity multipliers are used to account for uncertainty in permeability prediction.
- Aquifer connectivity: pore volume multipliers at the edge of the model are used to numerically represent different volume of the broader Bunter basin aquifer.
- Reservoir architecture: three geologic models have been utilised to account for uncertainty in the extent and severity of the heterolithic-rich intervals.
- Displacement efficiency: as reflected by the end points of gas (CO_2)-water relative permeability curves.

The downside scenario does offer some degree of compartmentalization and limited connected aquifer. The upside scenario offers greater connectivity to the Bunter aquifer as well as improved vertical connectivity. A limited aquifer associated with some sub-seismic baffling will lead to rapid compartmentalization and therefore a requirement for active pressure management through brine production. On the other end of the spectrum, excellent rock properties for an extensive aquifer alongside favourable reservoir architecture (i.e. high K_v/K_h) would enhance the pressure dissipation and allow for longer injection periods without brine production. The pressurization of the structure at Endurance might also lead to the release of brine into the sea through the underwater Bunter outcrop 20 km east of Endurance. This is dependent on hydraulic communication with the Endurance structure. It is thought that the salinity of the water in the shallow depths of the outcrop will be similar to seawater assuming it is in static equilibrium with the seawater above the outcrop.

Ultimate storage capacity is impacted by well placement as a subsea development scheme can allow for the wells to be better distributed across the structure providing robust mitigation against any compartmentalization. Storage capacity for Endurance without brine management is at least 104 MT of CO_2 for a distributed well layout for the 25 year-long project.

The injected CO_2 is expected to reach 10-12 degrees centigrade at the bottom hole location, which indicates that injectors might be subject to thermal fracturing as the temperature of the reservoir is approximately 57 degrees centigrade. However, the cooled region is expected to be restricted to the near-wellbore region as shown by the results of CMG GEM with the thermal option turned on. The evaluation in REVEAL (geomechanics simulator coupled fluid flow) shows that the risk of vertical fracture growth is low with no cases presenting fracturing reaching the top of Bunter Formation by the end of CO_2 injection. On the other hand, skin build-up associated with salt precipitation can be offset by thermal fractures.

The technical limit for Endurance is studied with the increased number of CO_2 injectors and a suitable number of brine producers for pressure management. The maximum CO_2 storage capacity of Endurance is estimated to be approximately 450 MT (25 years at 18 MTPA or 30 years at 15 MTPA). Storage tipping point is around 18 MTPA, above which injection rates cannot be maintained to 2050 (25 years) without CO_2 breakthrough into brine producers. Before significant investment for brine production, the development case of 10 MTPA (14 CO_2 injectors + 10 brine producers) is recommended to achieve the CO_2 storage capacity of 400 – 450 MT. This may fall into Phase 2 of the project development.

The dynamic modelling is a vital part of a Monitoring, Measurement, and Verification (MMV) plan for the CO_2 storage project at Endurance. The MMV plan is created to explain how the CO_2 plume will be monitored and outline potential risks and mitigation strategies associated with CO_2 disposal.

Technical comments for possible future work on the dynamic model

This study presents reasonable end members in terms of the overall system connectivity and its associated response when CO_2 volumes are injected. It gives a solid guideline for the preliminary front-end engineering and design (pre-FEED). However, uncertainties can be reduced if more data can be obtained as the development continues.

The structural uncertainty can be reduced when more wells are drilled in the eastern side of the structure. Similarly, the petrophysical uncertainty can be reduced with more core data collection with any additional wells drilled. The acquisition of new, more detailed seismic data will allow better identification and quantification of the presence of any faults in the structure. More well tests can be conducted to have a narrower range of K_v/K_h ratio for reservoir architecture.

If the run time allows, it would be beneficial to incorporate near-wellbore permeability changes due to water vaporization in the field-scale model, which could affect the well injectivity and therefore storage capacity.

Although the expectation is not to see the thermal induced fractures in the vicinity of CO_2 injectors reach the top of the Bunter Formation, it would be valuable to understand how the CO_2 plume grows along the fractures. This work is recommended to be done in conjunction with further geomechanical work.

Document Information

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Primary Store Geochemical Model and Report

Key Knowledge Document

NS051-SS-REP-000-00016

This is a 34-page document summarizing the methodology and results of geochemical modelling for the Endurance saline aquifer CO_2 disposal site. The document was provided by BP Exploration as part of the Northern Endurance Partnership project.

What is a geochemical model and why is it important?

The premise of the Endurance CO_2 storage facility is to take CO_2 from industrial centres at Teesside and Humber and pump it into a saline aquifer 147 km offshore and approximately 1000m below the seabed. The Endurance field is an anticline and therefore provides a structural trap for the CO_2. The CO_2 will be pumped into the pore space of the Bunter Formation. At this location the Bunter sandstone has approximately 20% porosity, the field does not contain hydrocarbons and the porosity is filled with saline water. The salinity of the water is high at approximately 250,000 parts per million (ppm) (for comparison seawater salinity is approximately 35,000 ppm).

A geochemical model tries to simulate what will happen to the chemistry of the formation water as CO_2 is added and if that could affect the storage capability of the project. The CO_2 will be injected as a supercritical fluid into the Bunter sandstone displacing the saline water already in the pore space. The CO_2 will move away from the injection well as more CO_2 is pumped into the reservoir forming a plume of CO_2 around the well bore. The size of the plume will increase with greater injection volumes.

One of the consequences of injecting CO_2 into the saline aquifer is that the chemistry of the saline water already present in the aquifer will be altered. CO_2 will dissolve in water causing changes to water chemistry which may affect how the pore fluids react with the minerals in the rock. As a consequence of adding CO_2 to the pore fluid, some minerals could precipitate out of the pore fluid. Precipitation of minerals would occur in the pore space and would negatively impact porosity and permeability. Conversely adding CO_2 can also cause different minerals to dissolve, this may increase porosity and permeability but could potentially start dissolving salt layers which form the seal at the top of the sandstone. The seal is critical as it prevents any CO_2 from leaking upwards out of the reservoir.

Technical summary

The Primary Store Geochemical Model and Report explains the methodology used to investigate possible geochemical interactions between the pore fluids and the surrounding rock caused by injecting CO_2 into the saline pore fluids of the Bunter Formation. The geochemical methodology outlined in this report is well explained and is consistent with industry workflow used to examine aqueous geochemical processes.

It is tempting to assume that all geochemical interaction can be modelled anywhere in the system at anytime i.e. linking all the chemical interactions with the static and dynamic models to produce an integrated flow and chemical interaction model. However, this is not the case, since the data needed to do this is not available in the detail required. This would demand an extremely large data set that would include not only the thermodynamic properties of all potential interactions but also a set of kinetic data at different temperatures and pressures for a very saline aqueous solution. The data set would also have to include chemical properties of the minerals in the Bunter sandstone. This complete data set is not yet available. What can be examined are specific geochemical interactions that are known from experience to be important in similar reservoirs. These specific interactions can be modelled on a smaller scale. This is the approach used in this report and is standard practice.

There are many geochemical modeling software packages available to look at different aspects of the geochemistry. Some models focus on the stability of certain minerals as the chemistry of the water is changed indicating which minerals may dissolve or precipitate. Other models examine the change of chemistry combined with flow but usually in a limited area and with limited chemical interactions. Both types of models were combined in this study. PHREEQC (ph redox equilibrium) is freeware originating from the USGS, it is essentially an equilibrium saturation model. It can be used to establish what relevant minerals will be saturated or undersaturated with respect to the saline brine. This will indicate if a mineral has the potential to precipitate or dissolve. It is important to distinguish ‘potentially precipitate’ from ‘will precipitate’ and at what rate. The latter involve kinetic data that are not part of equilibrium thermodynamic modelling. PHREEQC will take into account the solubility of CO_2 into the brine and the changes in chemistry this will cause. It also has functionality that will estimate the effect of the very high salinity on the equilibria involved. Geochemist’s Workbench (GWB) is commercial software provide by Computer Modelling Group. GWB is fundamentally similar to PHREEQC in that it calculates thermodynamic equilibria but it has increased functionality when it comes to integrating the input and outputs with other geochemical tools and visualizing the results. Both models require a database of empirically measured geochemical/thermodynamic values. In the workflow, measures were taken to compare the results of both PHREEQC and GWB to ensure consistency. There are numerous problems associated with geochemical modelling of very high salinity fluids and these are discussed within the report and the methodology used is reasonable.

GEM is available from Computer Modelling Group and is a coupled fluid and reactive transport simulator. This involves a similar geochemical database to PHREEQC and GWB but can be used to investigate reactions coupled with fluid flow. This was used specifically to look at the problem of halite precipitation close to the injector well as CO_2 is injected into the well bore.

All geochemical models need a good understanding of the initial geochemistry of the rock and the initial geochemistry of the aqueous fluid within the pore space. The report presents full geochemical analysis of five brine samples taken from the 42/25d-3 well. These samples were taken as part of the previous White Rose project specifically for the investigation of chemical interaction when injection CO_2. The analyses appear to be of high quality with many more species analysed than is normal for a routine water sample for standard oil and gas activity. However, no detail on sampling procedure or analytical procedure is given. The samples indicate a pore water of very high salinity of approximately 250,000 mg/Kg Total Dissolved Solids (TDS).

Mineralogical analysis is presented from XRD analysis of core samples taken from the Bunter Sandstone and the overlying Rot Halite and Rot Clay. The Bunter sandstone is a relatively ‘clean’ sandstone and consists primarily of Quartz (56-75%) and Feldspar (10-15%) with minor amounts of illite-mica, chlorite, calcite, dolomite, halite and anhydrite.

The focus of the geochemical modeling concentrates on some specific questions which are considered the main geochemical problems caused by injection CO_2 into the system.

1. Will there be interactions between the CO_2 saturated brine and the Bunter Sandstone that will cause mineral precipitation or dissolution?
2. Will there be clay/halite interaction with the CO_2 saturated brine which will cause dissolution and therefore degradation of the top seal, the Röt Halite and Röt Clay?
3. Will there be chemical interaction immediately adjacent to the injection wells that will cause problems with injectability?
4. If pressure management (dewatering of the aquifer) is used to increase the storage capacity of the Endurance structure what would be the chemistry of the produced water?

The modelling presented in this report outlines the methodology and results associated with these questions. As CO_2 dissolves in water the pH decreases due to dissociation of the CO_2 to produce a weak acid. However, because the mineral assemblage contains some carbonate minerals (dolomite and calcite) these serve to buffer the pH and therefore no drastic change in pH would be expected. To buffer the pH, small amounts of calcite may dissolve, and small amounts of dolomite may precipitate. Even if the solution was not buffered, the drop in pH would have very little effect on the stability of the silicate mineral including the most abundant mineral, quartz. There is no indication quartz would precipitate or dissolve. The mineral stability calculated for CO_2 saturated brine also suggests that even if illite were added to the system, a constituent of the Rot Clay, it would be unaffected by increasing CO_2 levels. The most significant change is with respect to halite stability which becomes undersaturated and hence has the potential to dissolve. The seal immediately above the Bunter sandstone is the Rot Clay but if formation water breached this layer (possibly through fractures) the brine would be undersaturated with respect to halite may cause some dissolution of the Rot Halite. However, if the brine remains undisturbed, equilibrium would be established between the halite and the pore fluids resulting in a thin layer of saturated brine just below the Rot Halite. This layer of saturated pore fluid should prevent large-scale dissolution of halite. As a result of these findings, it has been suggested that the CO_2 should be injected in the lower part of the formation so as not to cause excessive fluid flow in the upper part of the formation. Also, supercritical phase CO_2 is less dense than water and as more is injected a layer of dense phase CO_2 will occur at the top of the reservoir underneath the Rot Formation. This will act as a barrier to halite dissolution as the dense phase CO_2 will contain very little water and be unable to cause halite dissolution.

What happens close to the well bore when CO_2 is injected is counterintuitive to the undersaturation with respect to halite discussed above. As CO_2 in the dense phase essentially dehydrates the surrounding rock, water dissolves into the CO_2 removing the water from the pore space around the well bore. This halo around the well bore is a function of rate of CO_2 injection as well as chemical reaction. This dehydration around the well bore has two consequences. It means that there is little chance the cement around the well bore will be dissolved by relatively low acidic formation water as the water has been removed by the flooding CO_2. This is positive as it maintains cement integrity around the well bore. It is also possible that this dehydration will cause halite precipitation directly around the well bore reducing the permeability and therefore the injection rate of CO_2. As most of the water is removed by the CO_2 the remaining water becomes increasingly saturated with respect to halite, as the Na^+ and Cl^- are not removed at the same rate as the water. Depending on the rate of CO_2 injection capillary pressure may be enough to add more saline water to the well bore area, which is further evaporated increasing the chance of extensive halite precipitation. This halite precipitation has been known to occur in other saline sequestration projects such as the Quest facility in Alberta, Canada. To study this phenomenon a coupled reactive transport geochemical model was built in GEM software. The results from the model indicate that halite precipitation will occur, but it is dependent on the rate of CO_2 injection. At high rates (50mmscf/d) porosity reduction by halite precipitation was minimal as the amount of CO_2 pushed the precipitation front away from the immediate well bore area. However, at lower rates (10mmscf/d) significant halite precipitation was modelled to occur close to the well bore. This information could be used to establish an injection strategy. To remediate halite precipitation, fresh water 'washing' of the near well bore area is a proven method to dissolve any precipitated halite and re-establish near well bore permeability.

The subject of dewatering the aquifer has been considered to increase the storage capacity of the Endurance structure. This could be done by drilling new dewatering wells and/or there is the possibility that the structure could naturally dewater due to the outcropping of the Bunter sandstone at the sea floor. The outcrop is beyond a deeper structural spill point that would keep the more buoyant CO_2 within the structure. It is assumed, but not explicitly stated, that the saline aquifer brine would be disposed of in the surrounding seawater. Preliminary work has been done to investigate if any of the dissolved chemical species in the brine would be harmful to marine life. There appear to be some heavy metal aqueous species that are considered toxic but they are in very low concentrations. If this dewatering were an option, more detailed work would be required to identify the species and their concentrations and compliance with all environmental regulations.

Technical comments for possible future work on the geochemical model

It is notoriously difficult to verify or test the geochemical reaction modelled to take place in the reservoir. Constant water samples and rock analysis would be needed to verify what was occurring in the reservoir and this is impractical for a large subsurface reservoir. Salt precipitation near the injection well bore could be monitored by well head or down hole pressure data, sudden increases in pressure may be due to precipitation of minerals near the well bore. This would be built into a full field development plan. It is unknown how many observation wells are planned as part of the MMV (Monitoring Measuring and Verification) plan. However, any new wells drilled into the structure should have a detailed plan of data gathering associated with them, one of the data sets to be collected would be more mineralogical and saline aquifer water analysis data. If monitoring wells were in place a regiment of water sampling would be useful to track any changes in water chemistry and also track CO_2 migration within the structure over time.

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