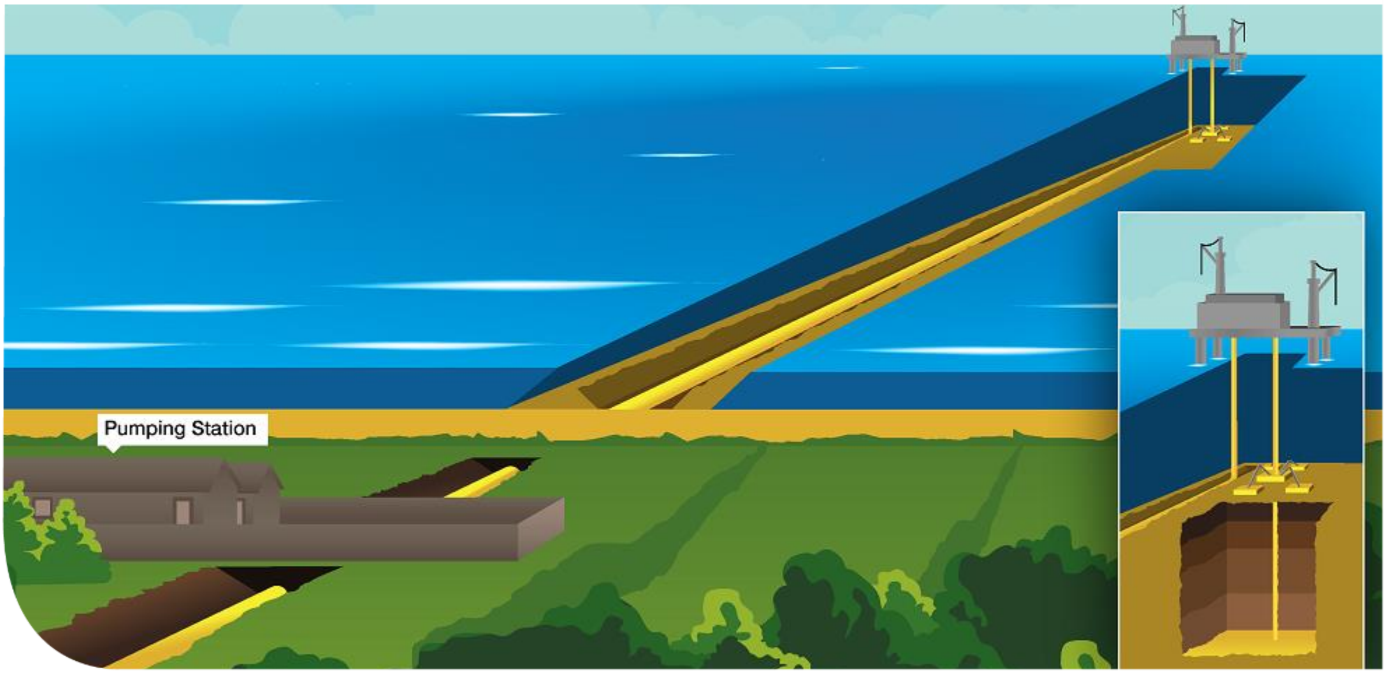
February 2016

WHITE ROSE

K42: Storage Risk Assessment, Monitoring and Corrective Measures Reports

Category: Storage



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Key Words

Key Words	Meaning or Explanation
Anticlinal structures	A fold that is convex up and has its oldest beds at its core
Bathymetry	The study of underwater depth of lake or ocean floors. Bathymetric maps may also use a Digital Terrain Model and artificial illumination techniques to illustrate the depths being portrayed
Bunter sandstone	Sandstone deposits containing colourful rounded pebbles, a lithostratigraphic and allostratigraphic unit (a sequence of rock strata) in the subsurface of large parts of west and central Europe
Bow tie approach	A diagram that visualises risk as an overview of multiple plausible scenarios. It is shaped like a bow-tie, creating a clear differentiation between proactive and reactive risk management
Carbon	An element, but used as shorthand for its gaseous oxide, carbon dioxide CO_2
Capture	Collection of CO_2 from power station combustion process or other facilities and its process ready for transportation
CCS Directive	European Union's Directive on the Geological Storage of Carbon Dioxide (EC, 2009, 2011)
Corrective measures plan	Describes actions, measures or activities taken to correct significant irregularities or to close leakages in order to prevent the release of CO_2 from the storage complex
Full chain	Reports described as 'full chain' would cover the complete process from the capture of the carbon at the emitter plant to its injection into the storage reservoir
Jurassic	(from Jura Mountains) is a geologic period and system that extends from 201.3± 0.6 million years ago to 145± 4 million years ago; from the end of the Triassic to the beginning of the Cretaceous
Key knowledge	Information that may be useful if not vital to understanding how some enterprise may be successfully undertaken
Liassic	The Lower Jurassic period of geologic time
Marine biota	Marine biota can be classified broadly into those organisms living in either the pelagic environment (plankton and nekton) or the benthic environment (benthos)
Monitoring, Measurement and Verification (MMV) plan	Provided to ensure that the operational parameters of the storage site and storage complex are adequately recorded in order to ensure conformance to its predicted behaviour and to verify containment of the stored CO_2
Permian	A geologic period and system which extends from 298.9 to 252.17 million years ago. It is the last period of the Paleozoic, following the Carboniferous and preceding the Triassic of the Mesozoic
Quaternary	A geologic period which spans from 2.588 ± 0.005 million years ago to the present
Rotliegend	Or Rotliegendes (German: the underlying red) is a lithostratigraphic unit (a sequence of rock strata) of latest Carboniferous to Guadalupian (middle Permian) age that is found in the subsurface of large areas in western and central Europe. The Rotliegend mainly consists of sandstone layers. It is usually covered by the Zechstein and lies on top of regionally different formations of late Carboniferous age
Storage	Containment in suitable pervious rock formations located under impervious rock formations usually under the seabed
Storage risk assessment	A quantitative risk assessment that considers the risks associated with underground aspects of CO_2 storage
Stratigraphy	A branch of geology dealing with the classification, nomenclature, correlation and the interpretation of stratified rocks.
Triassic	A geologic period and system that extends from roughly 252.17 to 201.3 million years ago, an interval of 51.04 million years
Zechstein	A unit of sedimentary rock layers of Middle to Late Permian (Guadalupian to Lopingian) age located in the European Permian Basin which stretches from the east coast of England to northern Poland

Executive Summary

This report is one of a series of reports; these ‘key knowledge’ reports are issued here as public information. These reports were generated as part of the Front End Engineering Design (FEED) Contract agreed with the Department of Energy and Climate Change (DECC) as part of the White Rose Project.

White Rose seeks to deliver a clean coal-fired power station using oxy-fuel technology fitted with Carbon Capture and Storage (CCS), which would generate up to 448MWe (gross) while capturing at least 90% of the carbon dioxide emissions. CCS technology allows the carbon dioxide produced during combustion to be captured, processed and compressed before being transported in dense phase to storage. The dense phase carbon dioxide would be kept under pressure while it is pumped through an underground pipeline to the seashore and then through an offshore pipeline to be stored in a specially chosen rock formation under the seabed. This Key Knowledge Deliverable (KKD) provides, in diagrammatical format, descriptions of the flows and processes associated with the overall system.

This document provides a summary of the contents of the Storage Risk Assessment; Monitoring Measurement and Verification Plan and Corrective Measures Plan for the White Rose Project.

Her Majesty’s Government (HMG) Autumn Statement and Statement to Markets on 25 November 2015 regarding the Carbon Capture and Storage Competition confirmed that the £1 billion ring-fenced capital budget for the Carbon Capture and Storage Competition was no longer available. This meant that the Competition could not proceed on the basis previously set out. A notice of termination of the White Rose FEED Contract was issued to CPL on 23 December 2015 and the FEED Contract was terminated on 25 January 2016; a date which was earlier than the expected completion date. The Government, CPL and National Grid are committed to sharing the knowledge from UK CCS projects, and this Key Knowledge Deliverable represents the learning achieved up to the cancellation of the CCS Competition and termination of the FEED Contract and therefore does not necessarily represent the final and completed constructible project.

1 Introduction

National Grid Carbon Limited (NGC) is a wholly owned subsidiary of the National Grid group of companies. Capture Power Limited (CPL) is a special purpose vehicle company, which has been formed by a consortium consisting of General Electric (GE), Drax and BOC, to pursue the White Rose (WR) Carbon Capture and Storage (CCS) Project (the White Rose Project).

CPL have entered into an agreement (the FEED Contract) with the UK Government's DECC pursuant to which it will carry out, among other things, the engineering, cost estimation and risk assessment required to specify the budget required to develop and operate WR assets. The WR assets comprise an end to end electricity generation and carbon capture and storage system comprising, broadly: a coal fired power station utilising oxy-fuel technology, carbon dioxide capture, processing, compression and metering facilities; transportation pipeline and pressure boosting facilities; offshore carbon dioxide reception and processing facilities and injection wells into an offshore storage reservoir.

CPL and NGCL have entered into an agreement (the KSC) pursuant to which NGCL will perform a project; the WR Transport and Storage (T&S) FEED Project, which will meet that part of CPL's obligations under the FEED Contract which are associated with the T&S Assets. The T&S Assets include, broadly: the transportation pipeline and pressure boosting facilities; offshore carbon dioxide reception and processing facilities and injection wells into an offshore storage reservoir illustrated in Figure 5.4.

A key component of the WR T&S FEED Project is the Key Knowledge Transfer process. A major portion of this is the compilation and distribution of a set of documents termed Key Knowledge Deliverables (KKDs), of which this document represents one example.

2 Purpose

The purpose of this document is to provide a report on the following aspects of the project.

- storage risk assessment;
- monitoring, measurement and verification plan; and
- corrective measures plan.

The storage risk assessment is a quantitative risk assessment that considers the risks associated with underground aspects of CO_2 storage throughout the lifecycle of the project. It was structured to address the risk assessment requirements identified in the European Commission (EC) CCS Directive and Guidance (EC, 2009; 2011). The assessed risks are divided into two categories: the risks to the protection of human health and the environment; and the risks to the permanent containment of CO_2 within the defined storage. The assessment covers only sub-surface aspects of the project and was undertaken by an independent mathematical and scientific consultancy.

The Monitoring, Measurement and Verification (MMV) plan is based on the characterisation of the storage site and storage complex and on the independent storage risk assessment and to ensure that the parameters of the Endurance storage site and storage complex are adequately recorded in order to ensure conformance to predicted behaviour and to verify containment of stored CO_2. The monitoring and measurement is designed to provide for the early detection and recognition of irregularities and thereby initiate contingent actions to be taken on their occurrence.

The corrective measures plan describes actions, measures or activities taken to correct significant irregularities or to close leakages in order to prevent the release of CO_2 from the storage complex.

The reports are prepared according to the guidance of the *European Union's Directive 2009/31/EC on the Geological Storage of Carbon Dioxide, Guidance Document 2*.

The WR Project, subject to the storage permit, intends to store CO_2 in the Endurance storage complex and, after 20 years of injection, expects to have stored a cumulative volume of up to 54Mt of CO_2.

The Endurance structure is a four-way dip-closure at top Bunter straddling quadrants 42 and 43 of the UK sector of the southern North Sea. This structure is a saline formation, approximately 22km long, 7km wide and over 200m thick.

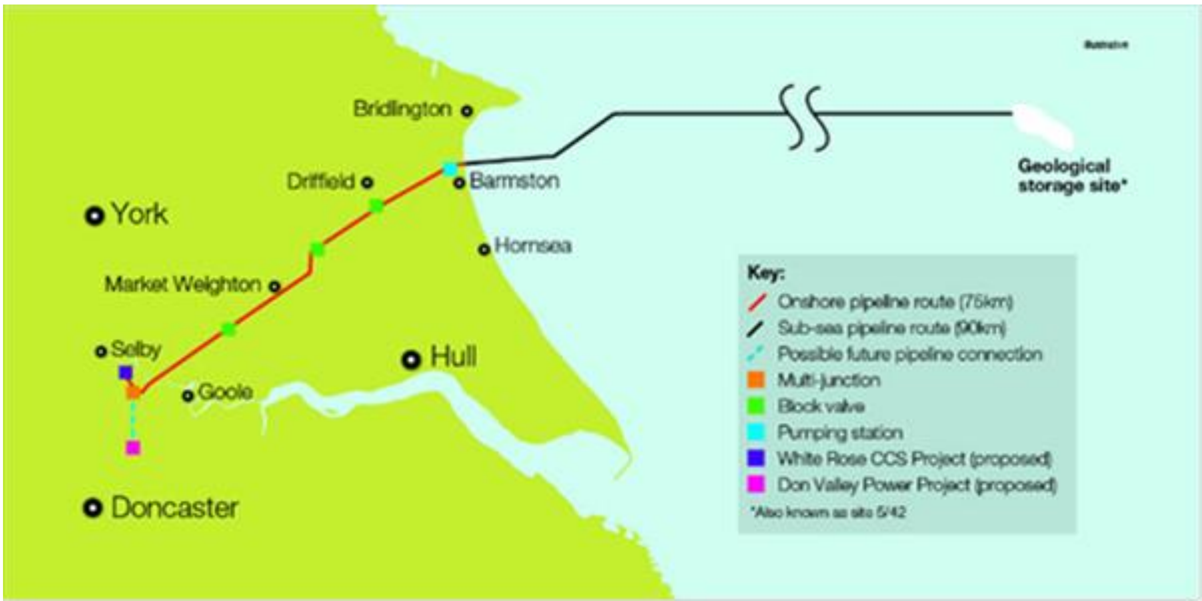
The storage complex is planned to be developed using a platform with six wells slots, through which three injection wells slots are to be drilled. The CO_2 will be delivered to this platform in dense phase through a 24 inch pipeline from the shore.

3 Overview

The White Rose CCS Project is to provide an example of a clean coal-fired power station of up to 448MW gross outputs, built and operated as a commercial enterprise.

The project comprises a state-of-the-art coal-fired power plant that is equipped with full CCS technology. The plant would also have the potential to co-fire biomass. The project is intended to prove CCS technology at a commercial scale and demonstrate it as a competitive form of low carbon power generation and as an important technology in tackling climate change. It would also play an important role in establishing a CO_2 transportation and storage network in the Yorkshire and Humber area. Figure 3.1 below gives a geographical overview of the proposed CO_2 transportation system.

Figure 3.1 Geographical Overview of the Transportation Facility

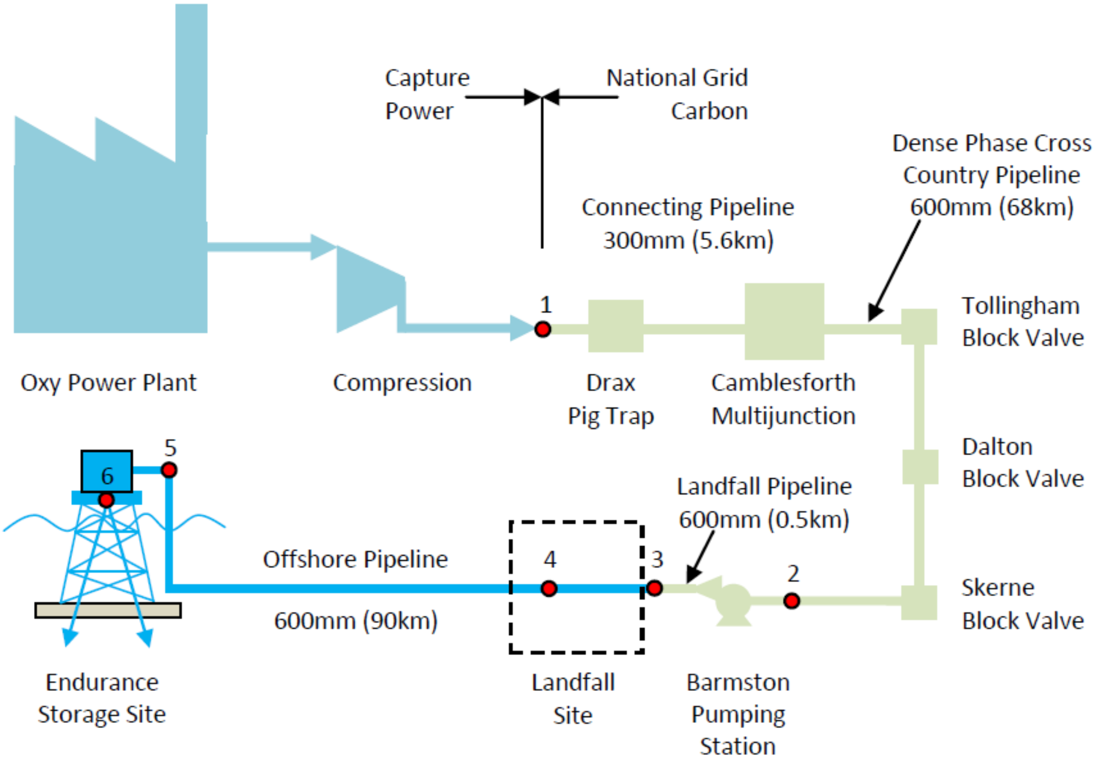


The standalone power plant would be located at the existing Drax Power Station site near Selby, North Yorkshire, generating electricity for export to the Electricity Transmission Network (the ‘Grid’) as well as capturing approximately two million tonnes of CO_2 per year, some 90% of all CO_2 emissions produced by the plant. The by-product CO_2 from the Oxy Power Plant (OPP) would be compressed and transported through an export pipeline for injection into an offshore saline formation (the reservoir) for permanent storage.

The power plant technology, which is known as oxyfuel combustion, burns fuel in a modified combustion environment with the resulting combustion gases being high in CO_2 concentration. This allows the CO_2 produced to be captured without the need for additional chemical separation, before being compressed into dense phase and transported for storage.

The overall integrated control of the end to end CCS chain would have similarities to that of the National Grid natural gas pipeline network. Operation of the Transport and Storage System would be undertaken by NGC. However, transportation of carbon dioxide presents differing concerns to those of natural gas; suitable specific operating procedures would be developed to cover all operational aspects including start-up, normal and abnormal operation, controlled and emergency shutdowns. These procedures would include a hierarchy of operation, responsibility, communication procedures and protocols. Figure 3.2 below provides a schematic diagram of the overall end to end chain for the White Rose CCS Project.

Figure 3.2 End To End Chain Overall Schematic Diagram



Key:

● FEED Terminal Points

4 Storage Risk Assessment

4.1 Context

A risk assessment of the subsurface CO_2 storage component of the project has been performed and is described in the following sections. The assessment is structured with sections describing the key steps of the assessment:

- **Context**: Specification of the assessment context, describing the background to and aims of the assessment and approaches to key aspects such as timeframes, classes of risks to be assessed, receptor identification and the relevant regulatory requirements; see Section 4.1;
- **Storage System**: Describing the storage system, its current condition and future injection plans; see Section 4.2;
- **Scenarios**: Development of risk assessment ‘scenarios’ covering possible evolutions of the system during and after injection, that reflect key risks and need to be assessed; see Section 4.3;
- **Analysis**: Analysis of those scenarios to assess the key risks; see Section 4.4;
- **Key Risks**: Description and analysis of the risks assessed; see Section 4.5; and
- **Risk Statement**: Development of a final risk summary statement; see Section 4.6.

The assessment addressed the risk assessment requirements identified in the 2009/31/EC CCS Directive and Guidance and was undertaken using a ‘top down’ approach accompanied by development of a robust audit trail, with the aim of facilitating the communication of outcomes and transparency of rationale to the benefit of all parties.

The risk assessment used outputs from a number of other activities commissioned by NGCL including:

- data acquisition, including seismic data and information from new and legacy boreholes;
- geological interpretations;
- reservoir simulations;
- geochemical investigations; and
- geomechanical investigations.

4.1.1 Purpose

The main purpose of the risk assessment was to analyse the risks associated with underground aspects of CO_2 storage throughout the lifecycle of the project and demonstrate that the risks are low and/or can be adequately managed by NGCL’s subsurface CO_2 storage activities at the Endurance site. The assessment considers the CO_2 volume to be limited to 54 megatonnes (MT) at a peak injection rate of approximately 2.68MTPA during a period of approximately 20 years.

The assessed risks were divided into two categories:

1. risks to the protection of human health and the environment; and
2. risks to the permanent containment of CO_2 within the defined storage complex.

NGCL will use the risk assessment to:

- finalise appropriate Monitoring, Measurement and Verification (MMV) plans;
- finalise appropriate plans for mitigating and managing identified risks and uncertainties to ensure the safety and effectiveness of CO_2 storage;
- inform financial provisions for meeting financial security and contribution requirements; and
- to support its licence application to DECC.

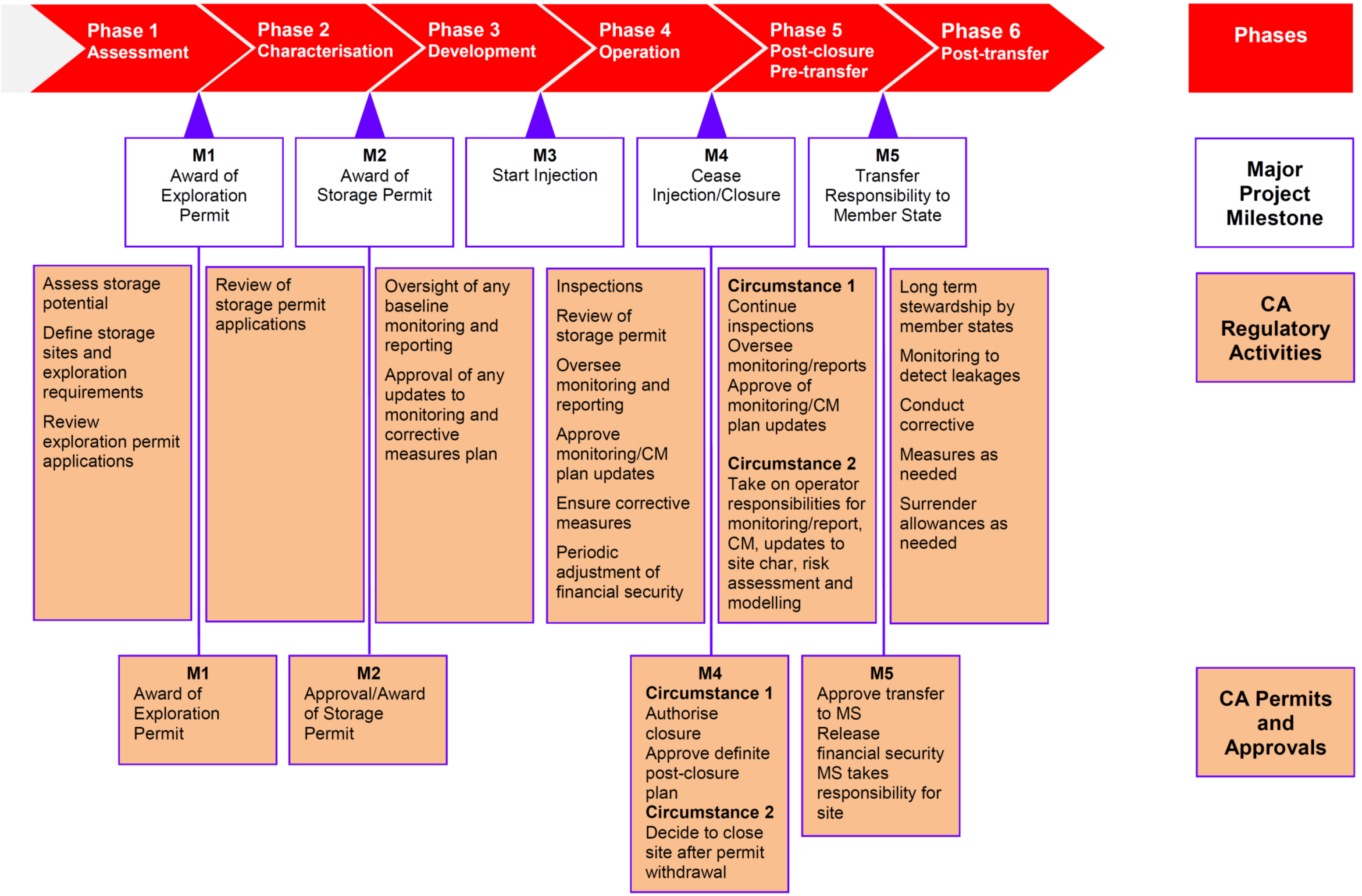
The licence application will be submitted by DECC to the European Commission, which will determine whether it conforms to the requirements of the European Union's Directive on the Geological Storage of Carbon Dioxide referred to as 2009/31/EC CCS Directive in this document.

4.1.2 Scope

The assessment covered the subsurface aspects of the project and considered:

- The storage site; the defined volume within Endurance used for CO_2 storage and associated wells and pumps;
- The storage complex; which includes the storage site, the associated infrastructure; injection wells, appraisal wells, legacy wells and the surrounding domains that may be impacted by leaking CO_2, displaced natural formation fluid and physical disturbances to the solid geosphere (these domains are between the Top Rotliegend c. 2896m to 3657m to the top of the Lias formation c. 52m to 63m);
- The pre-existing formation fluid, which will be displaced by the injected CO_2 and which will interact with the CO_2 by:
  - Dissolving in the dense CO_2 stream, leading to desiccation and possibly salt precipitation from the residual brine (likely to be close to the injection wells); and
  - Dissolving the $CO_{2;}$
- Injection boreholes and associated infrastructure;
- Legacy boreholes that might be contacted by any migrating or leaking $CO_{2;}$
- Actual and potential economic assets adjacent to the storage complex that might be impacted by any CO_2 that unexpectedly leaks; and
- The ecosystems in the region surrounding the storage complex that might be affected by any CO_2 that unexpectedly leaks or pre-existing formation fluids, that are caused to flow as a consequence of CO_2 injection.

Figure 4.1 Summary of CO_2 Storage Lifecycle Phases and Key Milestones (after EC, 2011)



Phase 1 Assessment

Phase 2 Characterisation

Phase 3 Development

Phase 4 Operation

Phase 5 Post-closure Pre-transfer

Phase 6 Post-transfer

M1 Award of Exploration Permit

M2 Award of Storage Permit

M3 Start Injection

M4 Cease Injection/Closure

M5 Transfer Responsibility to Member State

Assess storage potential

Define storage sites and exploration requirements

Review exploration permit applications

Review of storage permit applications

Oversight of any baseline monitoring and reporting

Approval of any updates to monitoring and corrective measures plan

Inspections

Review of storage permit

Oversee monitoring and reporting

Approve monitoring/CM plan updates

Ensure corrective measures

Periodic adjustment of financial security

Circumstance 1
Continue inspections
Oversee monitoring/reports
Approve of monitoring/CM plan updates

Circumstance 2
Take on operator responsibilities for monitoring/report, CM, updates to site char, risk assessment and modelling

Long term stewardship by member states

Monitoring to detect leakages

Conduct corrective

Measures as needed

Surrender allowances as needed

M1
Award of Exploration Permit

M2
Approval/Award of Storage Permit

M4
Circumstance 1
Authorise closure
Approve definite post-closure plan
Circumstance 2
Decide to close site after permit withdrawal

M5
Approve transfer to MS
Release financial security
MS takes responsibility for site

Phases

Major Project Milestone

CA Regulatory Activities

CA Permits and Approvals

At the time of writing, the project was undertaking phase 2 of the CCS storage project lifecycle specified in guidance to 2009/31/EC CCS Directive, which is illustrated in Figure 4.1. To support the licence application, the risk assessment considered the risks from subsequent phases and aspects of phase 2 that might impact upon these later stages. The risk assessment will require updating during the course of the CO_2 storage project to take into account information obtained.

The risk assessment considered the following timeframes:

1. between two and three years from phase 2, covering activities during storage system characterisation and development operations (phases 2 and 3 in Figure 4.1) that are likely to affect the risks following the start of CO_2 injection;
2. from c. 20 years after the start of injection, until the end of CO_2 injection operations (phase 4 in Figure 4.1);
3. an unspecified period between the end of CO_2 injection and responsibility for the CO_2 store being transferred from NGCL to DECC (the competent national authority under the terms of 2009/31/EC CCS Directive); and
4. a few thousand years following the transfer of responsibility for the CO_2 store to DECC.

The period for timeframe 3 is not well-defined but, in accordance with 2009/31/EC CCS Directive, sufficient for it to be shown that the stored CO_2 will be completely and permanently contained.

The period for timeframe 4 is open-ended but, in accordance with the 2009/31/EC CCS Directive which requires the CO_2 to be permanently contained it will be long enough that the storage system has become stable and its risk profile will not change. Such a timescale is likely to be many 1000s of years; Lindeberg (2002) calculated that to prevent climate change CO_2 should be retained in underground reservoirs for at least 10,000 years.

4.1.3 Legislative Framework

4.1.3.1 UK Legislative Framework Storage System

UK law has incorporated 2009/31/EC CCS Directive (Section 4.1.3.2) mainly through the Energy Act of 2008, Chapter 3 which covers CO_2 storage. This act promulgated a new regulatory framework to enable CO_2 to be stored in underground reservoirs offshore.

The Licensing Authority for CO_2 storage in the project, as defined in the Energy Act of 2008, is the secretary of state for energy and climate change. Pursuant to the 2008 Act, the secretary of state made the Storage of Carbon Dioxide (Licensing etc.) Regulations 2010. These regulations entered into force on 1st October 2010 and completed implementation of the 2009/31/EC CCS Directive in the UK.

An area in which CO_2 storage and associated activities are licensed may have its limits determined by reference to a Crown Estate lease. Such a lease must be entered into by the relevant developer with the Crown Estate Commissioners, the Crown Estate being the manager of the seabed out to the UK’s 12 nautical-mile limit and the renewable energy rights within the UK Economic Zone. The Crown Estate Commissioners have a duty to maximise the economic value of the Crown Estate and therefore are incentivised to prevent conflicts between CO_2 storage and other economic activities that may take place within the Crown Estate.

4.1.3.2 European Legislative Framework

The 2009/31/EC CCS Directive establishes a legal framework for the geological storage of CO_2 and is consistent with earlier legal instruments, as modified to remove legal barriers to CO_2 storage beneath the seabed:

- The 1996 London Protocol to the 1972 ‘Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter’ (1996 London Protocol); and
- The Convention for the Protection of the Marine Environment of the Northeast Atlantic (OSPAR Convention; OSPAR, 2007).

The 2009/31/EC CCS Directive defines environmentally safe CO_2 geological storage to mean permanent containment of CO_2 so as to prevent and, where this cannot be achieved, eliminate as far as possible negative effects and any risk to the environment and human health (2009/31/EC CCS Directive, Article 1). The 2009/31/EC CCS Directive is due to be reviewed by the EC during 2015. It is assumed for the purposes of this risk assessment that this review will not result in any changes to the requirements of the legislation that would have significant implications for the risk assessment.

The 2009/31/EC CCS Directive requires that a CO_2 storage project within a member state of the European Union should be regulated by a competent authority. In the case of the UK, the competent authority is DECC.

The 2009/31/EC CCS Directive gives the requirements that any CO_2 storage project must meet over its complete lifetime, including:

- storage site selection (Article 4);
- issuing of exploration permits (Article 5);
- Issuing of storage permits (Articles 6 to 10);
- obligations of operators and regulators (‘Competent Authorities’) during operation, closure and post-closure (Chapter 4); and
- transfer of responsibility from an operator to the competent authority (Article 18).

The 2009/31/EC CCS Directive defines six main phases in the lifecycle of a CO_2 storage project, separated by milestones, as summarised in Figure 4.1.

A risk assessment must be undertaken prior to a storage permit being issued at the conclusion of phase 2. Subsequently the assessment must be updated during later phases to take into account information obtained during the project.

Permit applications and supporting documentation should be provided by the competent authority to the EC, which may provide opinions. These opinions are non-binding, but if the final permit decision departs from them, the competent authority must explain why.

4.1.4 Regulatory Framework

The UK's regulatory framework is described in Section 4.1.3 above. Regulation of underground CO_2 storage offshore will be carried out by DECC in accordance with the relevant legislation and in particular the Storage of Carbon Dioxide (Licensing etc.) Regulations 2010. Of particular relevance to this risk assessment are the licensing regulations that require DECC to be satisfied that:

- the storage complex and surrounding area have been sufficiently characterised and assessed in accordance with the criteria set out in Annex I to 2009/31/EC CCS Directive;
- no part of the storage complex extends beyond the territories of the member states; and
- under the proposed conditions of use of the storage site, there is no significant risk of leakage or of harm to the environment or human health.

4.1.5 Assessment Endpoints

The end-point of the assessment was to present an assessed level of confidence that the storage system will perform as expected and that risks and impacts are low and therefore acceptable.

To achieve this it addressed the regulatory requirements described in 2009/31/EC CCS Directive and associated guidance, as required by the UK legislation, notably the Energy Act of 2008 and the Storage of Carbon Dioxide (Licensing etc.) Regulations 2010. Specifically the assessment addresses Article 18, Point 1 of 2009/31/EC CCS Directive by:

- providing evidence that the projected volumes of CO_2 to be injected will be stored safely and completely and permanently contained; and
- stating risks to complete and permanent containment (as a basis for developing monitoring and mitigation plans), including risks of exceeding any pressure limits and thereby threatening the maintenance of site integrity.

The assessment also contributed to addressing Article 19, Point 2 of 2009/31/EC CCS Directive by providing evidence that the storage site will evolve towards a situation of long-term stability following the completion of CO_2 injection.

The possible consequences of natural formation fluids being displaced by the planned volumes of injected CO_2 are also assessed.

4.1.6 Assessment Philosophy

The assessment philosophy analysed how the system was expected to evolve in future and also to identify alternative hypothetical 'what if' future evolutions of the system to identify risks and assess and bound potential impacts.

Multiple lines of reasoning based on qualitative and quantitative sources of evidence were used to support the assertion that the site will evolve as expected, with no loss of containment or unacceptable risk to receptors. Here receptors are components of the environmental system, whether living or not, that could be subject to adverse (or positive) impacts as a result of CO_2 leakage or be impacted indirectly as a result of the presence or movement of CO_2 in the subsurface.

Risks associated with what if projections of future evolution (for example associated with potential leakage) were assessed with the aim of showing that either impacts will be very low and/or very unlikely to occur; risks are low or very low.

The assessment therefore identifies and assesses a central Expected Evolution Scenario (EES) representing the expected future evolution of the system. Low likelihood what if situations were assessed by identifying a set of Alternative Evolution Scenarios (AES) and analyses of these different scenarios. These scenarios are described in Section 4.3 and assessed in Section 4.4.

Each scenario is a plausible description of the potential evolution of the CO_2 storage system according to the nature of its features and the events and processes that might act within and upon it. The AES together cover the range of lower likelihood but plausible system behaviours consistent with the uncertainties in data and understanding and thus represent deviations from the EES.

Assumptions made in the assessment were ‘realistically cautious’. This means that the assumptions associated with each scenario are on the one hand pessimistic, but on the other hand not so pessimistic that everybody would consider them sufficiently improbable as to be of no concern. In practice this means that the assumptions should be defined with the aim that few people, if any, would disagree that all the assumptions are cautious and at the same time, have not been combined unrealistically. ‘Realistically cautious’ also means that the assumptions would not violate any fundamental scientific laws or principles.

4.2 Storage System

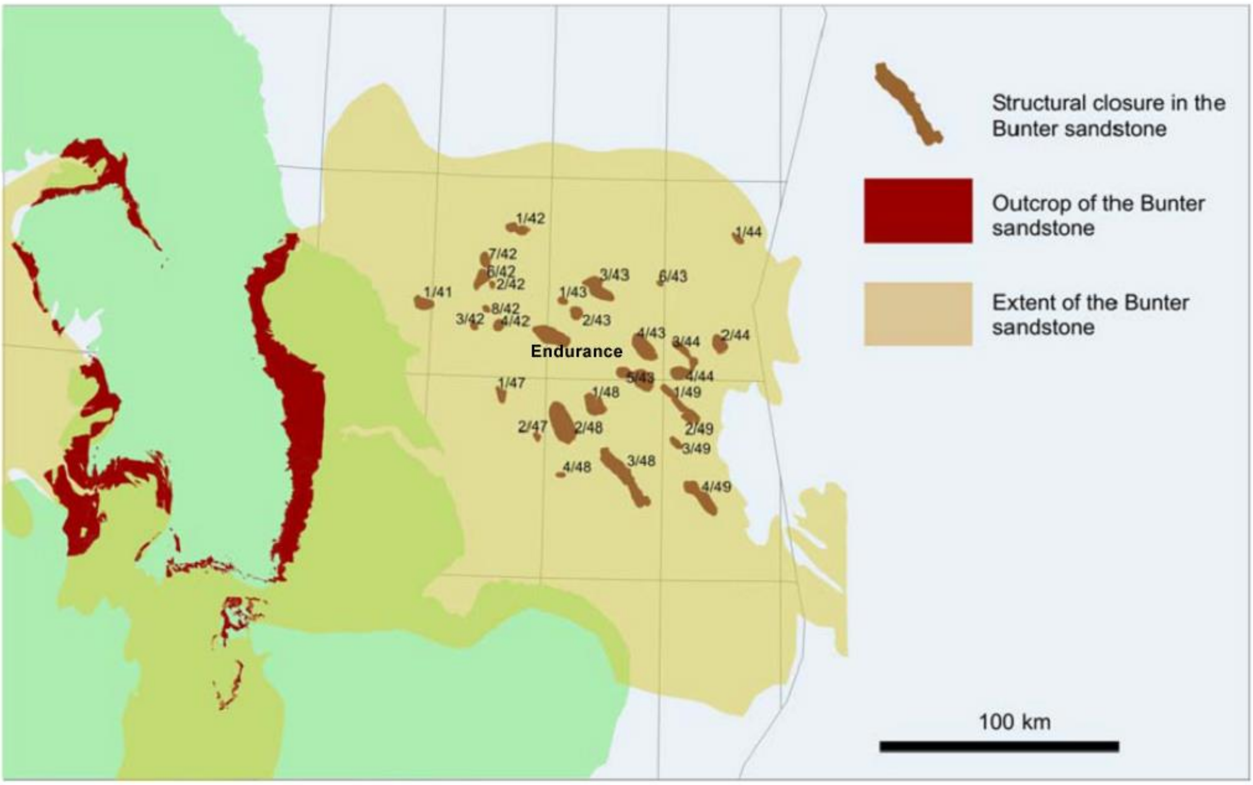
4.2.1 Overview

This section describes the key features of the storage system that are important from the perspective of the risk assessment. The description of the system provides the basis for identifying its expected future evolution and alternative possibilities, captured within the risk assessment scenarios in Section 4.2.2.

4.2.2 Location of the Storage System

The storage system is an anticlinal structure, a fold that is convex up and has its oldest beds at its core, called Endurance, which is in the southern North Sea and straddles Quadrants 42 and 43.

Figure 4.2: Extent of the Bunter Sandstone in the Southern North Sea, Alongside Structural Closures



The southern North Sea has been extensively explored and exploited for gas. The source rock for the hydrocarbons is Carboniferous and there are varied reservoir rocks, which depending upon the locality may be Carboniferous sands, Permian sands or Triassic Bunter sandstone; see Figure 4.3. Numerous fields and associated infrastructure exist, but in the region of the Endurance structure, gas reservoirs only exist in geologically deeper horizons, well below the Bunter sandstone.

Figure 4.3: Oil and Gas Fields of the Southern North Sea

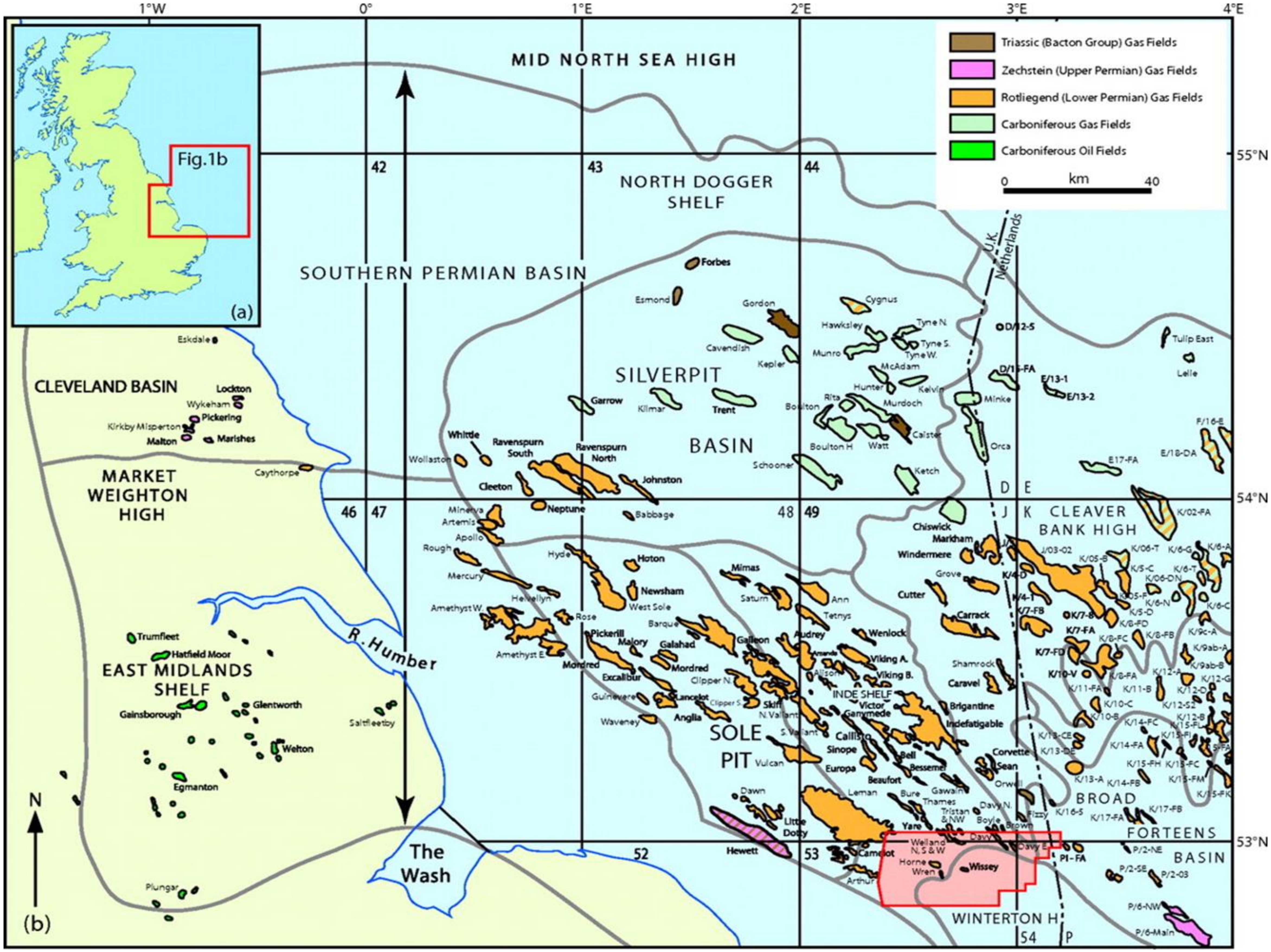
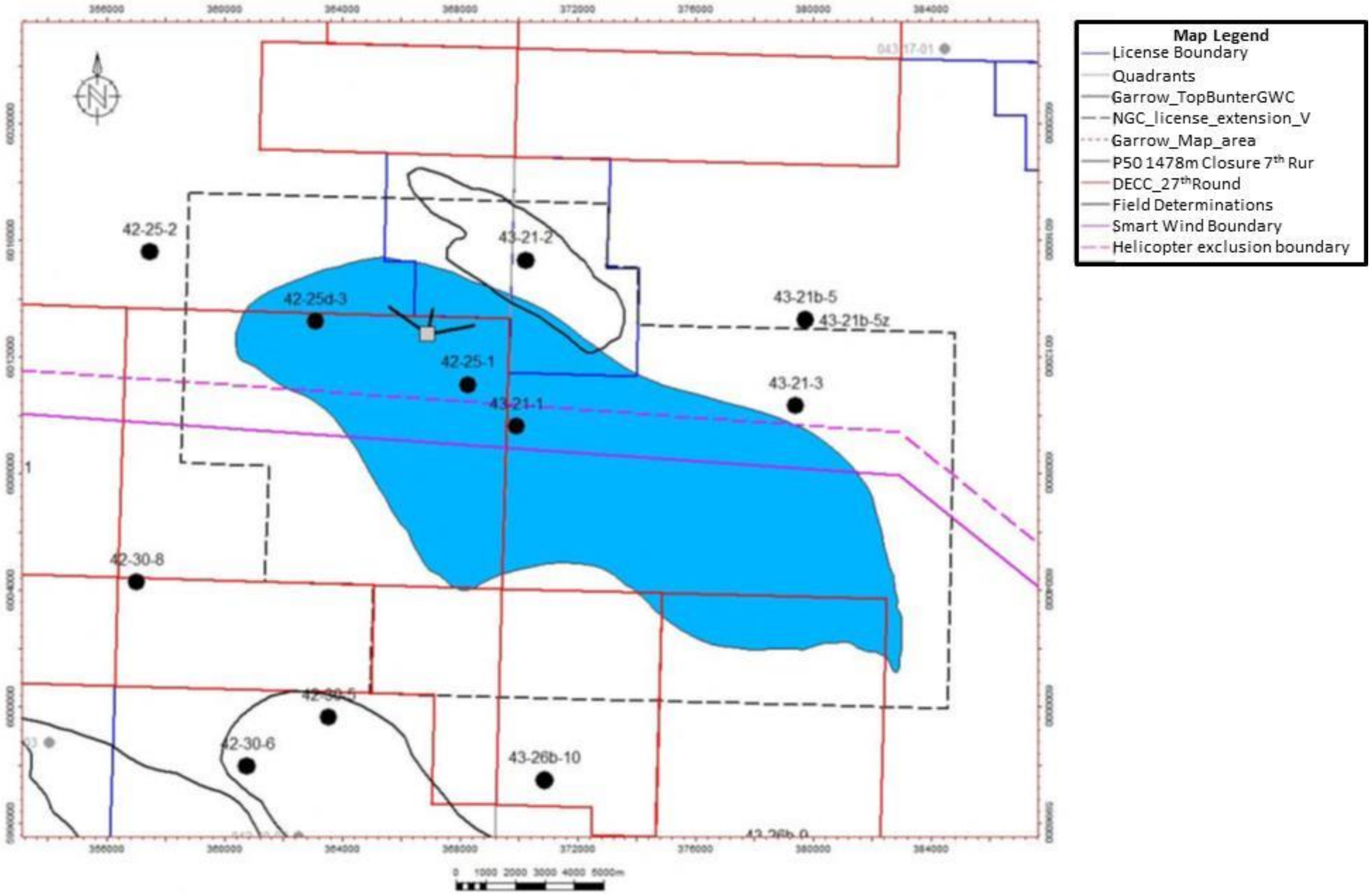


Figure 4.4: Offshore Licence Areas around the Endurance Structure

The Esmond Gas Field is located c. 50km to the north of the structure and the Hornsea zone (Smartwind project 3 boundary) overlies the southern part of the structure.



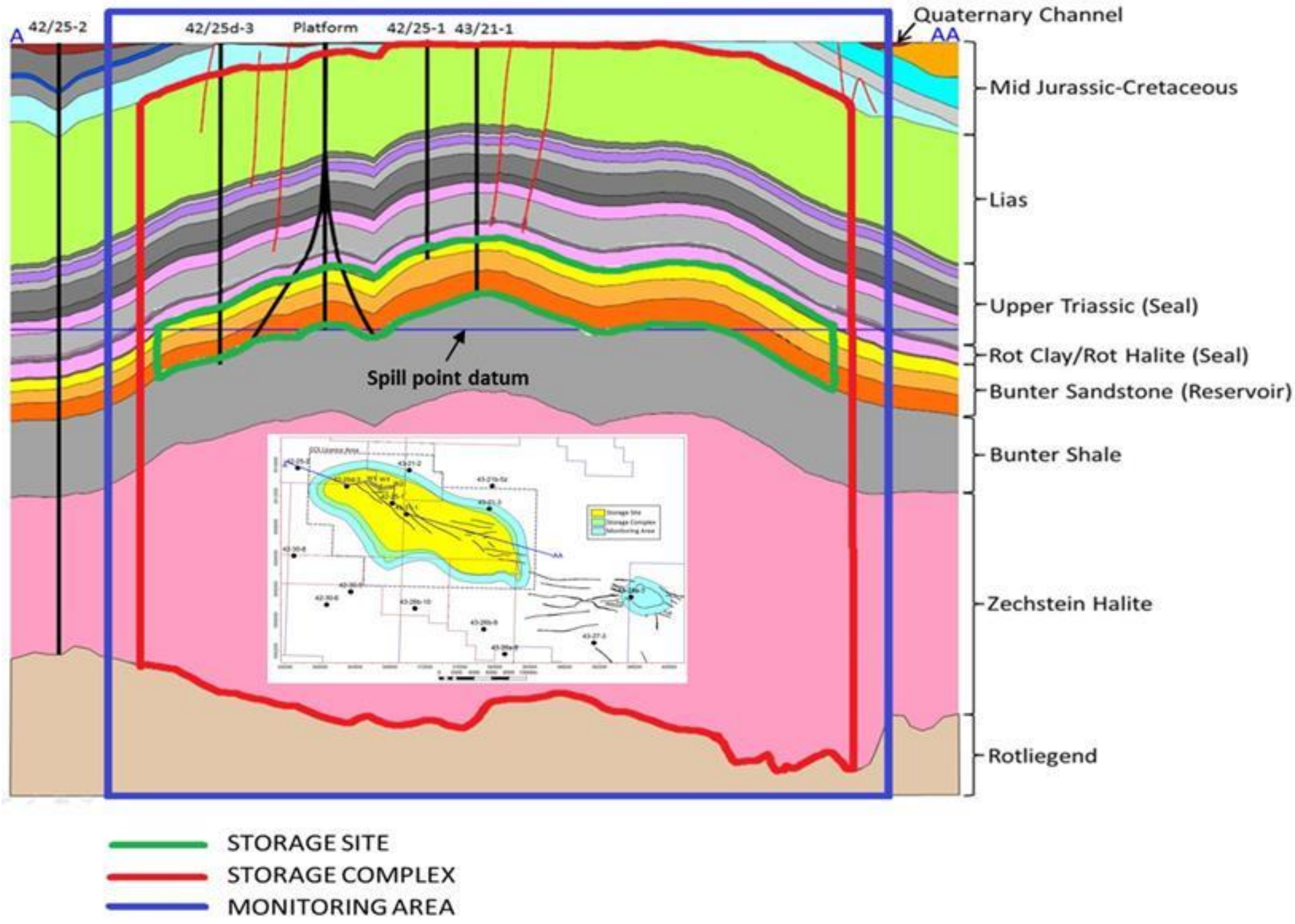
Licenses to build wind farms have also been granted in the southern North Sea and the Endurance structure is close to the Hornsea licence area see Figure 4.4.

The storage system comprises a storage complex and a storage site; these terms are defined by 2009/31/EC CCS Directive as:

- Storage complex
  The storage site and surrounding geological domain which can have an effect on overall storage integrity and security; that is, including any secondary containment formations; and
- Storage site
  A defined volume within a geological formation used for the geological storage of CO_2 and associated surface and injection facilities.

At the Endurance structure, the storage complex and storage site have been defined based on the stratigraphy (rock layers) and structure, see below (a larger version of the inset is provided as Figure 5.4.

Figure 4.5: Cross-section through the Endurance Structure Showing the Storage Site and Storage Complex



More details of the geology and structure are presented in Section 4.2.4, but a brief description of the storage complex and storage site are provided here.

The storage complex at the Endurance structure extends vertically from the top of the early Jurassic Lias formation, c. 60 - 350m True Vertical Depth Subsea (TVDSS), to the base of the Permian Zechstein formation, c. 2896m to 3657m TVDSS. This includes the target reservoir rock, two formations beneath this reservoir rock and the Triassic and Liassic overburden formations. The Röt clay is the primary seal and the overlying Röt halite is the deepest secondary seal. The lateral extent of the storage complex is currently defined as where the top of the Bunter sandstone is at a depth of 1553m TVDSS. This is calculated based on the deepest estimate of the spill point of the structure.

The storage site comprises Bunter sandstone which is approximately 275m thick. Laterally the storage site is defined where the contour of the top Bunter sandstone is at a depth of 1416m TVDSS as this is an estimate of the shallowest depth of the spill point.

4.2.3 Existing Infrastructure

Prior to NGCL acquiring the licence for Endurance there were two wells penetrating the structure:

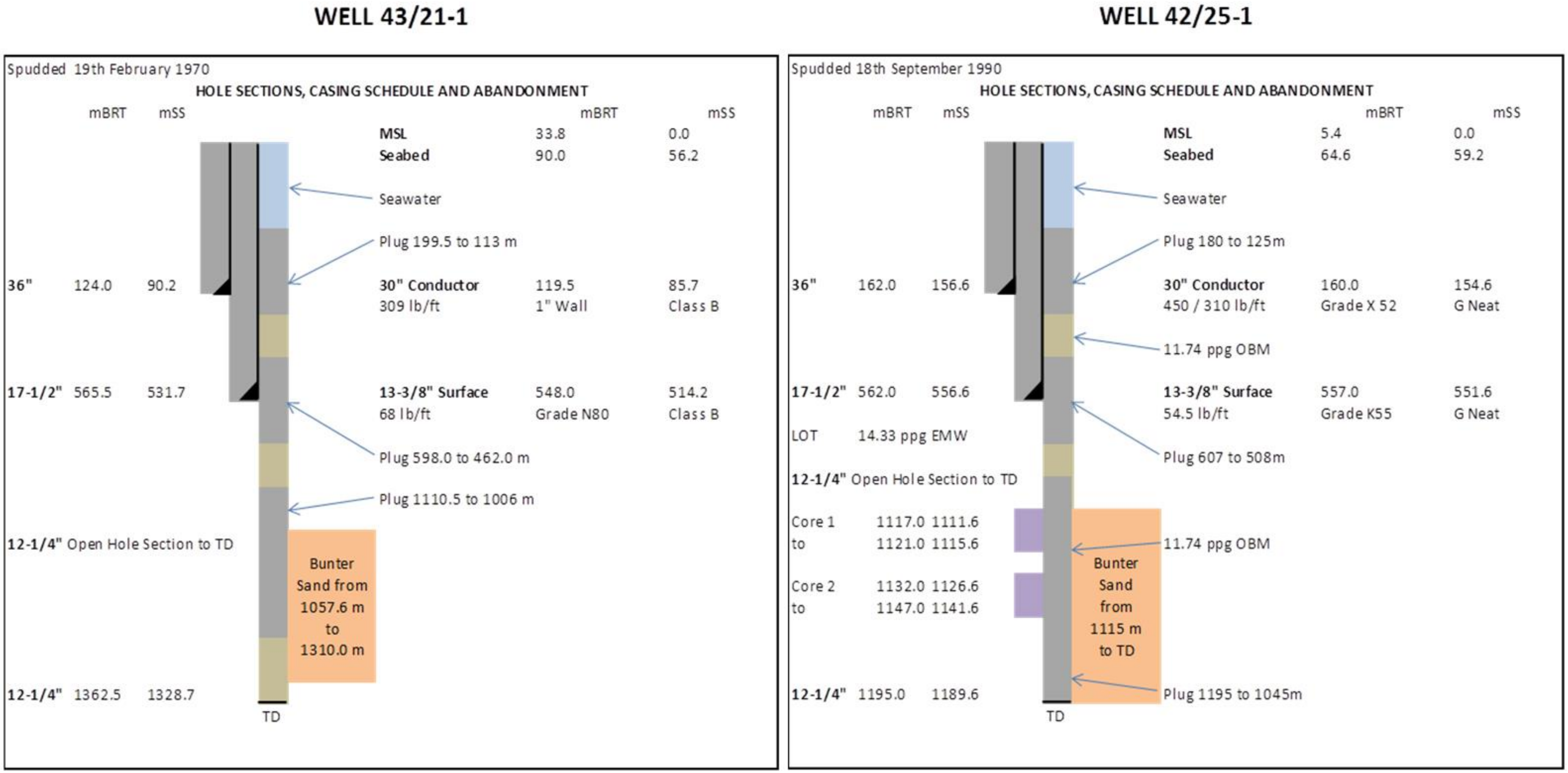
- 43/21-1 which was drilled in 1970; and
- 42/25-1 which was drilled in 1990.

Both of these wells are close to the crest of the anticline. NGCL has drilled a further appraisal well 42/25d-3 to the NW of the crest of the anticline. The locations of the three wells are shown in Figure 4.5 and Figure 4.9. The details of the well design have been taken from Webster (2014), Mobil North Sea Limited (1970) and BP Exploration (1990).

Well 43/21-1 was drilled to 1329m below the seabed and ends in the Bunter shale, see Figure 4.6. The shallower parts of the well were cased, but the 12¼in diameter section that passes through the Bunter sandstone is not cased. The cement used around the casings and for plugs in the well is Class B cement, based on API Specification 10A, which is similar to ASTM Specification C150 Type II cement. There are three plugs, two located at the shoe of the two casings and one across the top of the Bunter sandstone into the Röt halite. It is not known what the inter-plug fluid is, but the last section of the well was drilled with a salt saturated XC polymer system and it is possible that this fluid, or a cleaned and circulated version of this fluid, has been left in hole following abandonment of the well. If so, consideration should be given to the estimated stability of this fluid having been in-situ for over forty years.

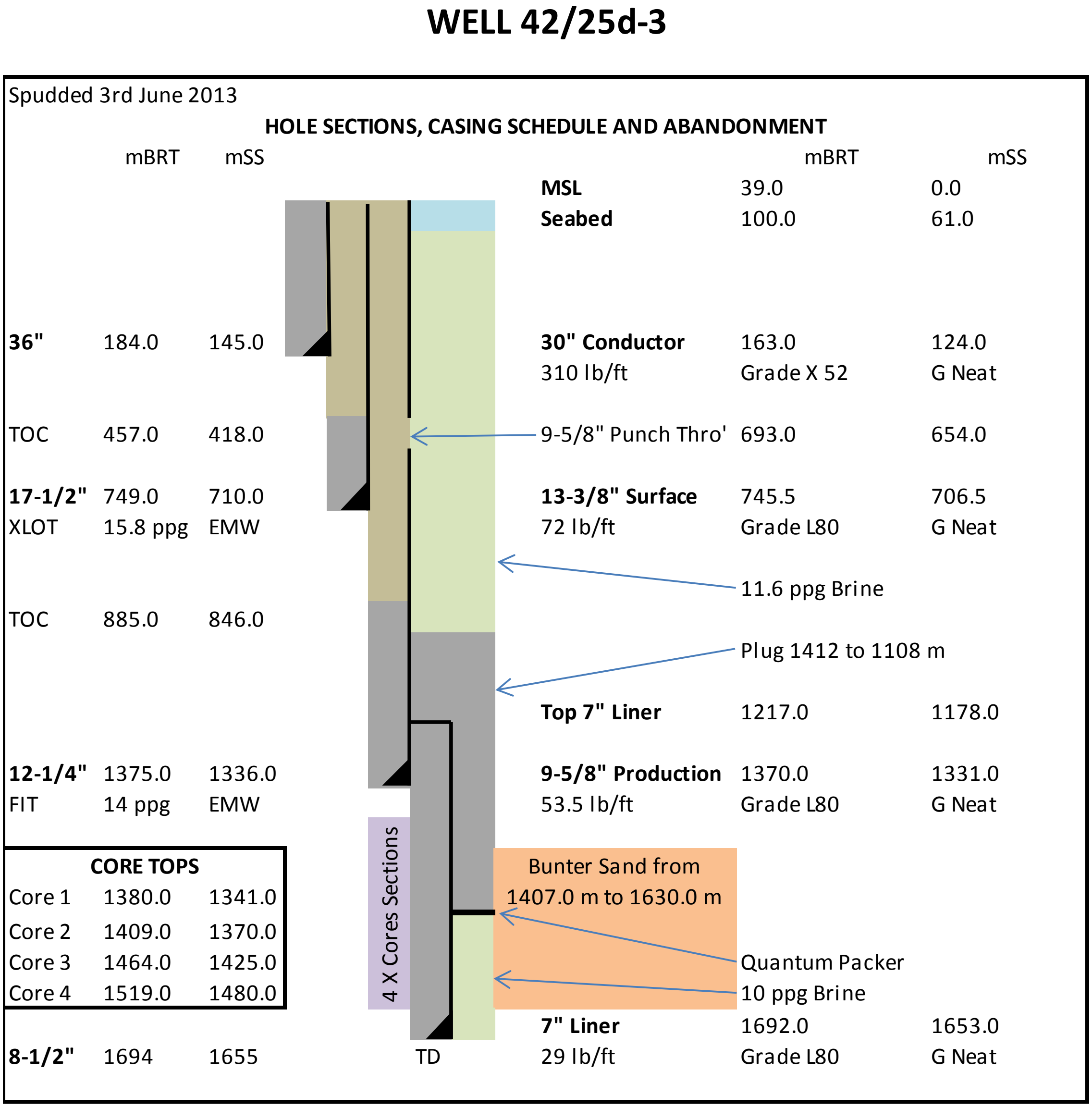
Well 42/25-1 was drilled to 1190m below the seabed and ends in the Bunter sandstone, see Figure 4.6. The shallower parts of the well were cased, but the 12¼in diameter section that passes through the Bunter sandstone is not cased. The cement used around the casings and for plugs in the well is Class G cement. There are three plugs, two located at the shoe of the two casings and one across the top of the Bunter sandstone into the Röt halite. The inter plug fluid is an oil based mud.

Figure 4.6 **Schematic Diagram of the Main Features of the Two Crestal Wells**



Well 42/25d-3 was drilled to 1655m below the sea surface and ends in the Bunter shale, see Figure 4.7. The well construction is a typical conductor/surface casing/production casing/liner design compared with the two exploration wells. The casing strings were cemented throughout with Class G cement, but only the conductor was cemented back to the surface. The other casings were cemented around the shoe, but the cement did not reach the shoe of the overlying casing string. The well was abandoned by placing a single plug from 1412m to 1108m on top of a quantum packer and the remainder of the wellbore left with 11.6ppg brine. This leaves approximately 25m of the Bunter sandstone below the packer exposed to the wellbore which at this depth is filled with 10ppg brine. It is also worth noting that the 9⅝in casing was punched through at 694m (above the top of the cement) creating a direct annulus to wellbore path.

Figure 4.7 Schematic Diagram of the Main Features of the Appraisal Well

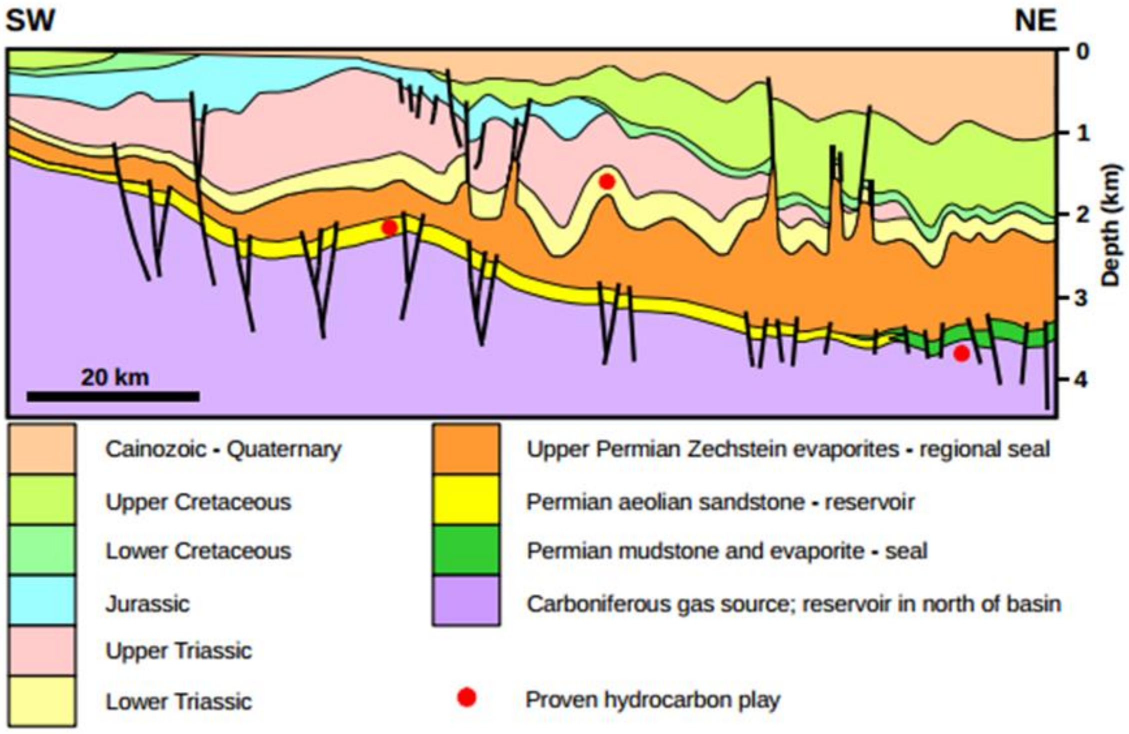


4.2.4 System Geology

4.2.4.1 Regional Geology

The southern North Sea Basin is underlain by a carboniferous sequence of sedimentary rocks which includes Westphalian coal measures, which are the source rocks for gas found in the southern North Sea, see Figure 4.8 below.

Figure 4.8 Schematic Section Illustrating the Geology and Structure of the Southern North Sea Basin



In the Lower Permian, the southern North Sea Basin shows a playa lake facies, including aeolian sands (shaped by wind activity) and muddy lake sediments all overlain in the Upper Permian by a thick evaporite deposit, which provides an excellent seal. In the Lower Triassic, sediment deposition recommenced leading to sandstones being interlayered with shales close to the present day shore line and the proportion of sand decreasing toward the east, where the sedimentary rock is shale. Above this shale layer is a clean, fluvial sandstone formed by rivers and streams, called the Bunter sandstone. The sedimentary sequence above the Bunter sandstone comprises successions of mudstones and evaporites through the Upper Triassic, which also provide an excellent seal. There are varying thicknesses of Upper Triassic to Upper Cretaceous sedimentary rocks across the southern North Sea, which are finally overlain by a variable thickness quaternary deposit.

The sealing properties of both the Upper Permian Zechstein evaporites and the Upper Triassic mudstones have been proven in gas reservoirs across the southern North Sea. The majority of the gas reservoirs have been found in the Permian Rotliegend sandstone, see Figure 4.3, demonstrating the sealing ability of the Zechstein halite. In a small number of reservoirs, gas has migrated into the Bunter sandstone, being trapped underneath the Upper Triassic mudstones and evaporites, proving the sealing capacity of these layers. Where gas is found in the Bunter sandstone, migration from the Carboniferous rocks can be explained by an absence or thinning of the Zechstein halite.

The whole sequence from the Lower Triassic to the base of the Quaternary has been deformed by salt tectonics into a series of anticlinal structures and salt diapirs (a diapir is a type of structural dome formed when a thick bed of evaporite minerals (mainly salt, or halite) found at depth intrudes vertically into surrounding rock strata). In some locations these structures coincide with faulting, see Figure 4.8. This process results in stretching (extension) of the overlying strata on the crests of the anticline which produces tensile stresses that can be sufficient to result in fracturing of the overlying strata. In some locations in the southern North Sea, these crestal faults may compromise the integrity of the seal above the Bunter aquifer, note that faulting is particularly prominent on steep-sided diapirs, where the tensile stresses will be high, but in low relief structures the faults have smaller offsets or are completely absent. In many cases fractures may have subsequently been sealed by the overlying Röt halite and sealed fractures have been found to prevent gas leakage even when the reservoir undergoes rapid changes in pressure.

4.2.4.2 Local Stratigraphy

The stratigraphy close to the Endurance structure is based on ten wells located in Quadrants 42, 43 and 44 and data from an appraisal well, 42/25d-3, drilled by NGCL on the western margin of the structure in 2013, see Figure 4.9.

A schematic stratigraphy of the Endurance structure based on seismic data and data from the three wells that have been drilled into the structure, shows the Bunter sandstone to be 27m thick and underlain by 430m of shale and over a kilometre of Zechstein halite, see Figure 4.10. Immediately above the Bunter sandstone is an 11m thick Röt clay layer followed by around 100m of Röt halite. There are two further evaporite layers in the over burden (Muschelkalk halite and Keuper Anhydrite) along with mudstones. There is currently no evidence to suggest that there may be any layer above the storage site that could provide secondary containment, reservoir formations. Only thin, discontinuous sands have been identified in the Liassic overburden.

There are six main facies types within the Bunter sandstone, representing six different deposition environments: aeolian; aeolian sand sheet and sandy sabkha; fluvial laminated; fluvial structureless; playa margin and floodplain; and playa mudstone. These six facies were identified and confirmed present at well 42/25d-3. The predominant facies found in the well is coarse-grained fluvial and aeolian with the individual mudstone beds that are present being thin. The only significant mudstone bed within well 42/25d-3 is around 10cm thick and there is a 45cm thick muddy siltstone. Both beds have irregular tops and bases suggesting that these layers are unlikely to be horizontally extensive (Blackbourn and Robertson, 2014).

The Bunter sandstone has also been divided into sub-units by chemostratigraphy, with three main units L1, L2 and L3. Close to the boundary of L2 and L3 is a horizon that is rich in calcite and this is associated with a large number of ooids (small spheroidal, sedimentary grains) at this depth. This calcite rich layer could present the most significant baffle to vertical fluid flow in the Bunter sandstone and would be relatively reactive.

There is an abrupt boundary between the top of the Bunter sandstone and the overlying Röt clay. The Röt clay is interpreted to have been deposited in a playa lake and the sediment contains both anhydrite nodules and a pervasive finely crystalline dolomite. At the thin section scale, there is a wide variation in the proportion of silt and cement along with small shrinkage cracks that are sometimes infilled.

The Röt clay is sharply overlain by the Röt halite, which is an evaporitic sequence composed mostly of coarsely crystalline halite with inclusions of anhydrite (a mineral). There are some beds of 1m thick siltstones which comprise accumulations of silt grade anhydrite accompanied by small volumes of dolomite.

Figure 4.9 Location of the Endurance Structure and the 42/25d-3 Well on the Top Bunter Sandstone Depth Map

Blackbourn and Robertson, 2014

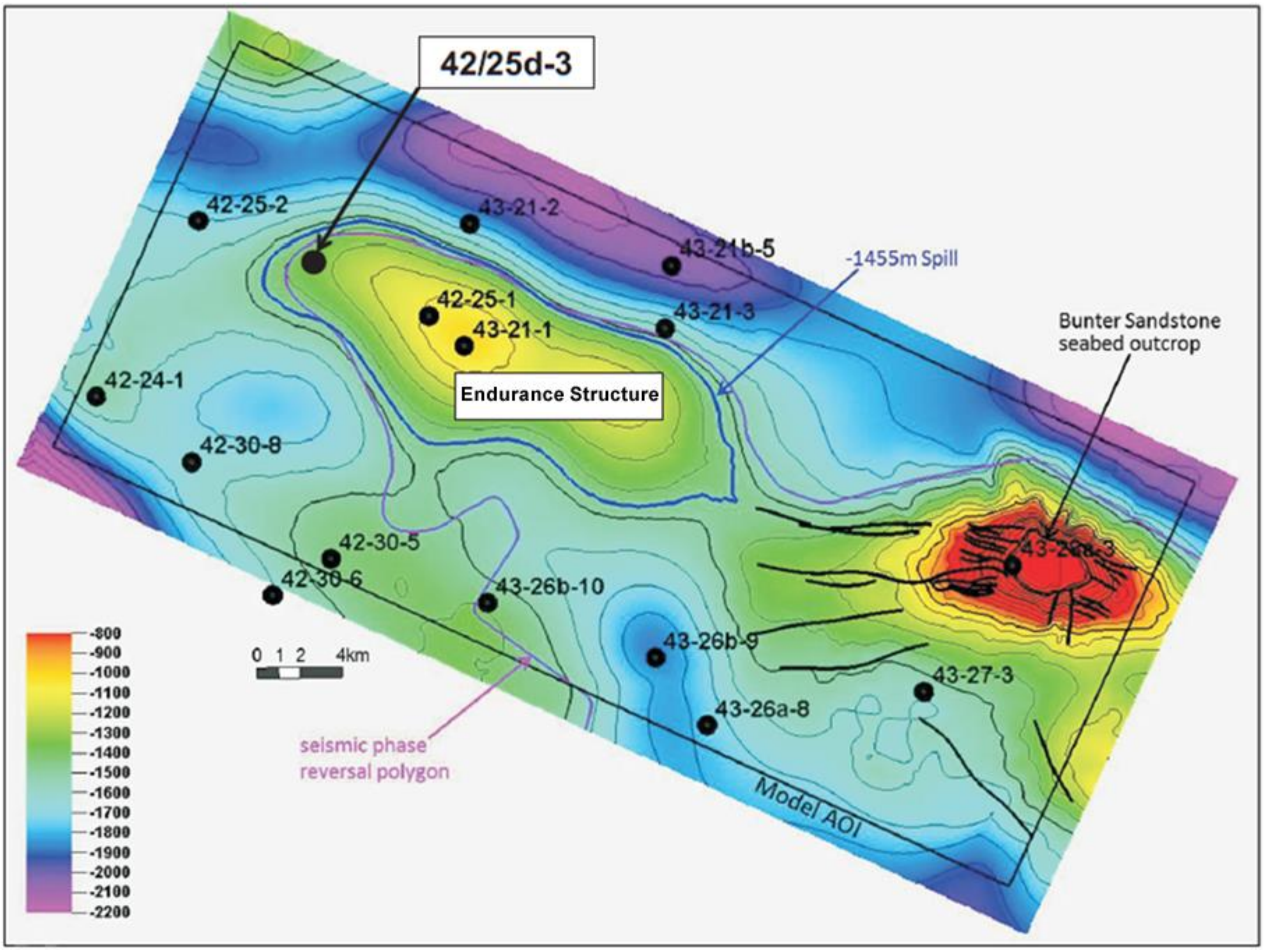
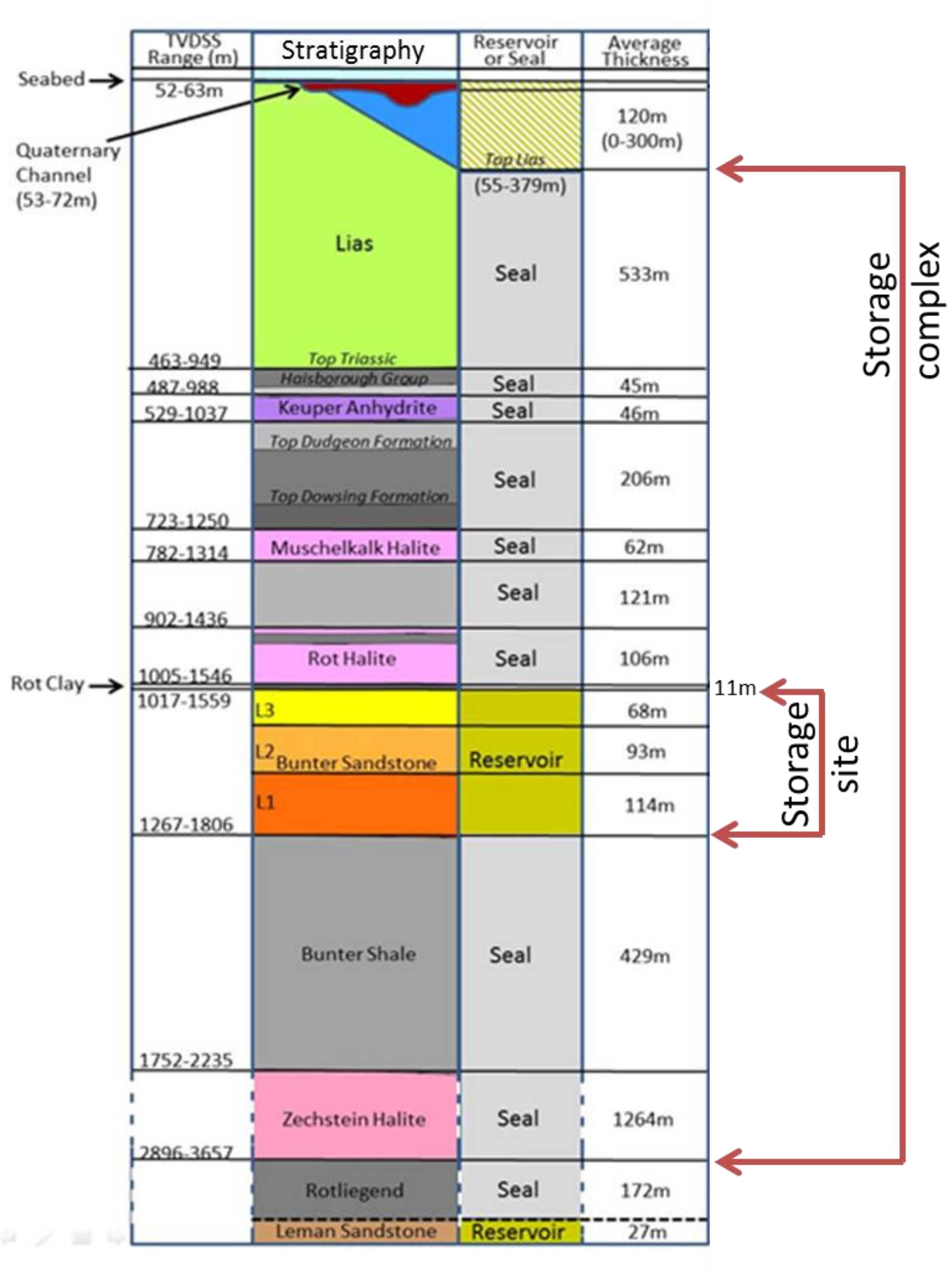


Figure 4.10 Stratigraphy at the Endurance Structure



4.2.4.3 Geological Structure

Endurance is an anticline with a four way closure formed by deformation of the Zechstein halite. The precise shape of the anticline is uncertain as it depends on the conversion of seismic two-way-time into depth. Note that seismic two-way-time uses reflected energy from interfaces between subsurface layers, recorded as down and back up travel times, to determine their configuration. However, it is a gentle anticline with dip on the limbs of 2˚ to 7˚. Many of the diagrams of the structure have significant vertical exaggeration, making the anticline appear much steeper than it is.

Probabilistic calculations, based on different best estimates of the top Bunter surface and additional error in depth conversions, were used to identify a maximum and minimum case for the spill point depth of the top Bunter sandstone. This corresponds to different depths of spill point, with the shallowest spill point at -1416m TVDSS occurring to the east of the structure and the maximum depth spill point at -1553m TVDSS occurring to the south of the structure (Figure 4.11). These values were used in defining the storage site and storage complex (Section 4.2.2).

Based on these different maps of the top of the Bunter sandstone, rock volumes and pore volumes of the Bunter sandstone reservoir have been calculated. The most likely gross rock volume has been calculated as $24 \times 10^9 m^3$ and the most likely pore volume as $4.6 \times 10^9 m^3$. There is significant uncertainty on this estimate of pore volume with the 10th percentile and 90th percentile values of $5.4 \times 10^9 m^3$ and $4.2 \times 10^9 m^3$ respectively. The main component of this uncertainty is the uncertainty in the depth of the top of the Bunter.

Approximately 15km to the east-southeast of the Endurance structure is another anticlinal structure in which the Zechstein halite and hence also the Bunter sandstone outcrop at the seabed (Figure 4.12). The extent to which the Bunter sandstone outcropping at the seabed is hydraulically connected to the Bunter sandstone in the Endurance structure is uncertain; however there are several lines of evidence that indicate they are connected.

The presence of faults above the Endurance structure has been interpreted from seismics (Figure 4.13). The faults do not penetrate through the Röt halite to the Bunter in the central part of the structure, but some faults penetrate close to the top of the Bunter sandstone on the south eastern flank of the anticline. However, this does not mean that the faults are open and in particular they are likely to be closed in the Röt halite.

Figure 4.11 Maximum and Minimum Surface of the Top of the Bunter Sandstone with the Spill Points

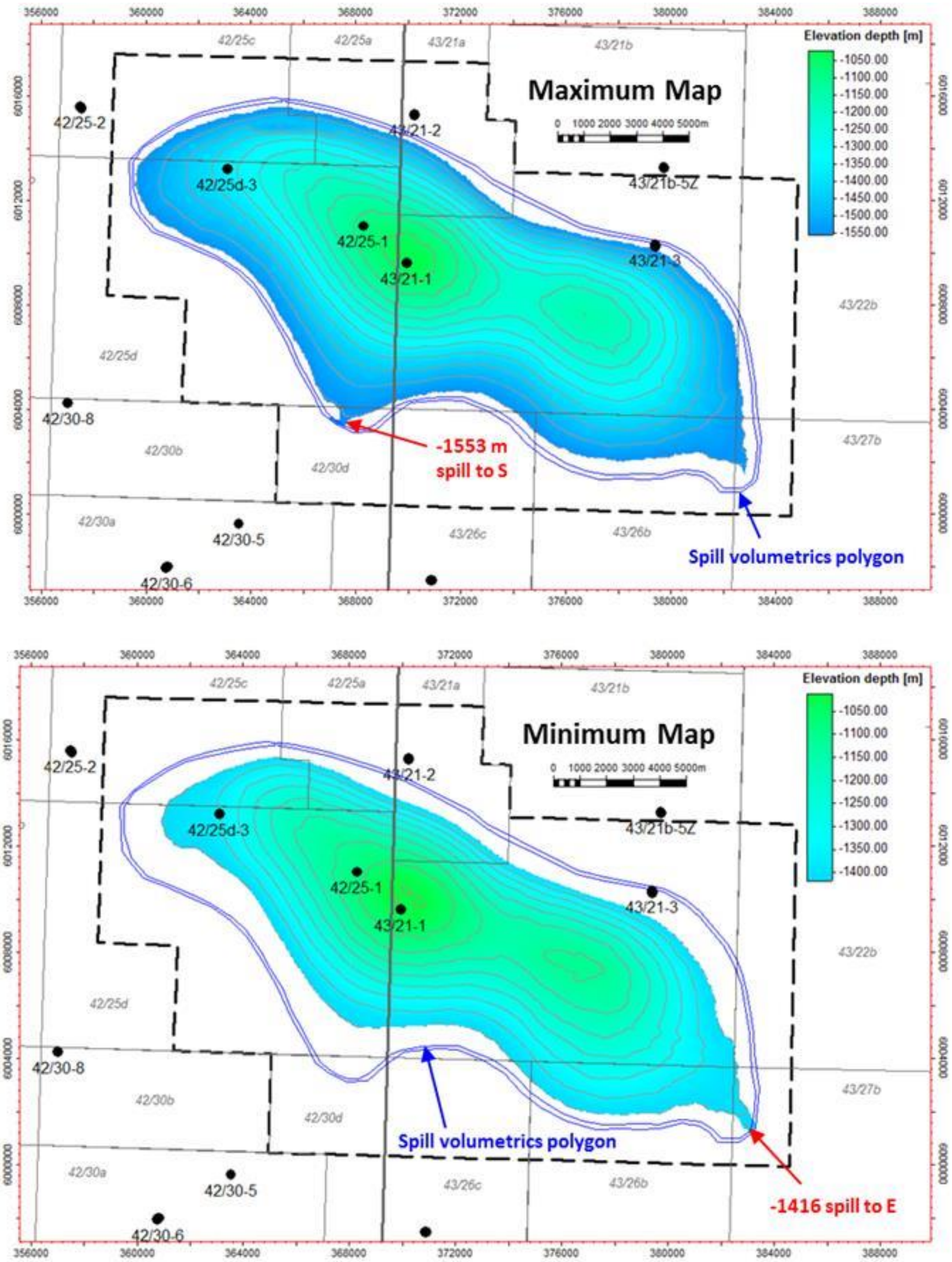
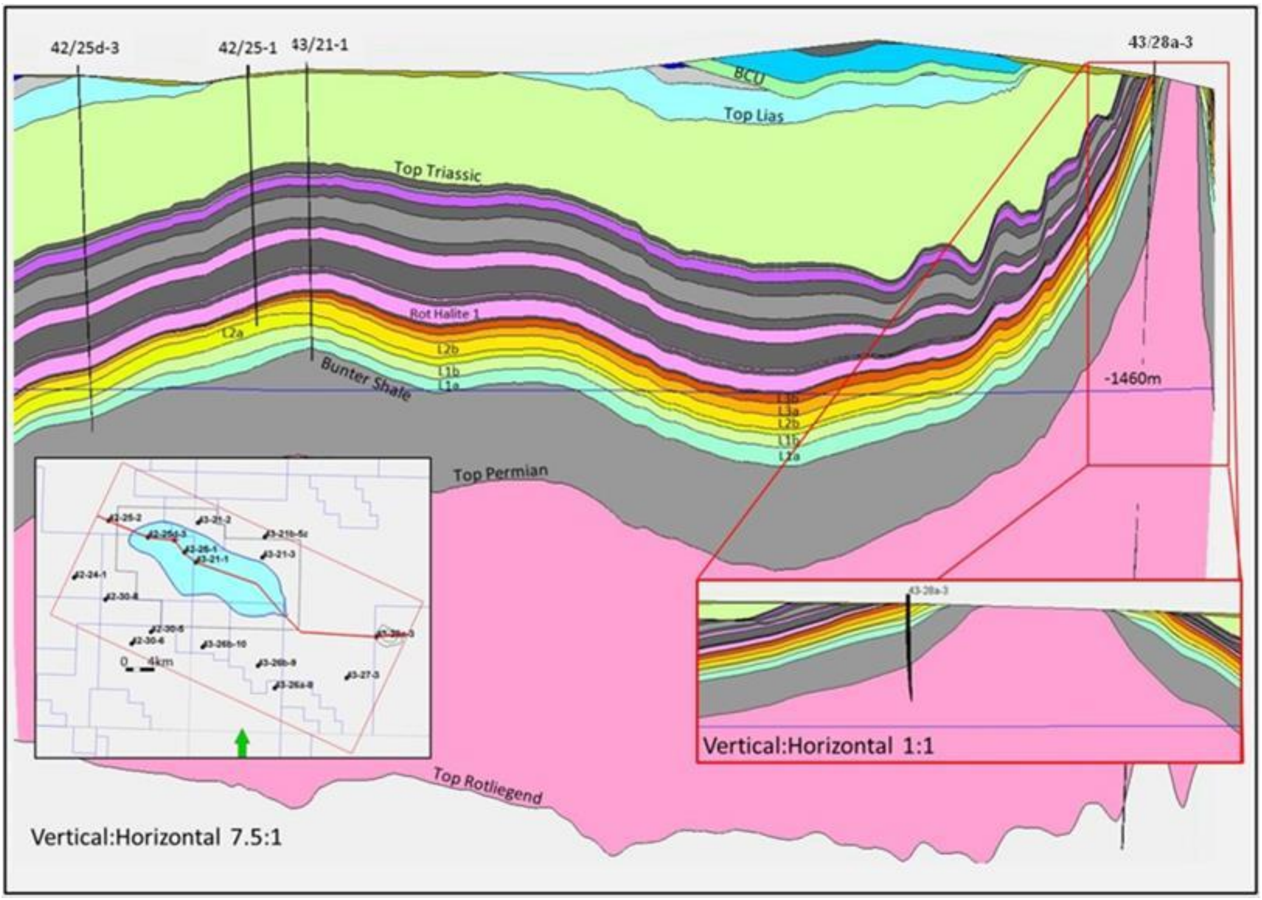
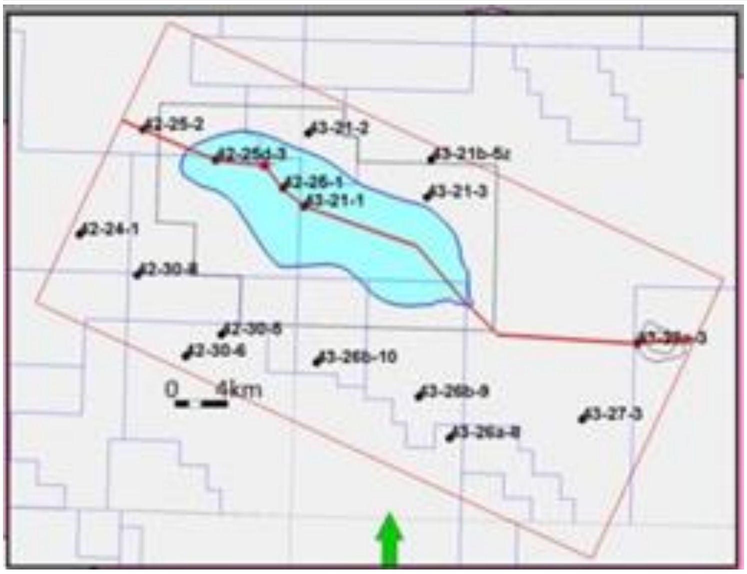


Figure 4.12 Cross-section through the Regional Structural Framework Model

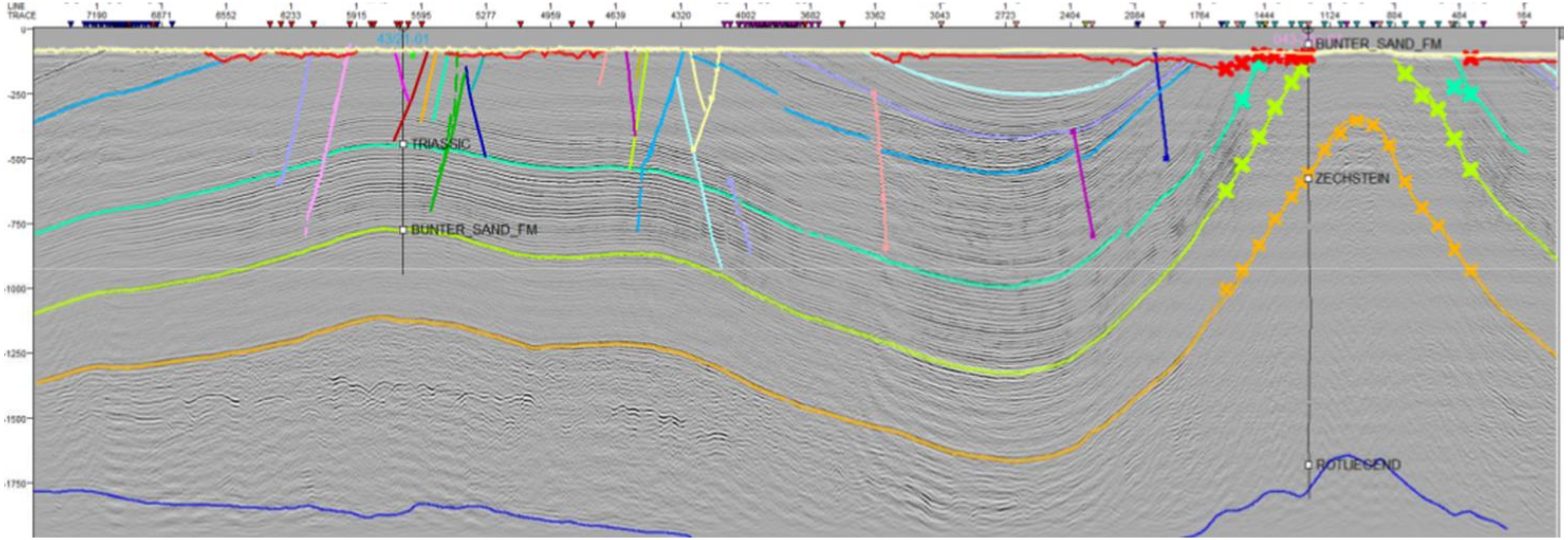




Inset enlarged.

The Bunter sandstone comprises the orange, amber and yellow layers.

Figure 4.13 2D Seismic Cross-section across the Endurance Structure Showing Interpreted Faults



4.2.4.4 Seabed Outcrop of the Bunter Sandstone

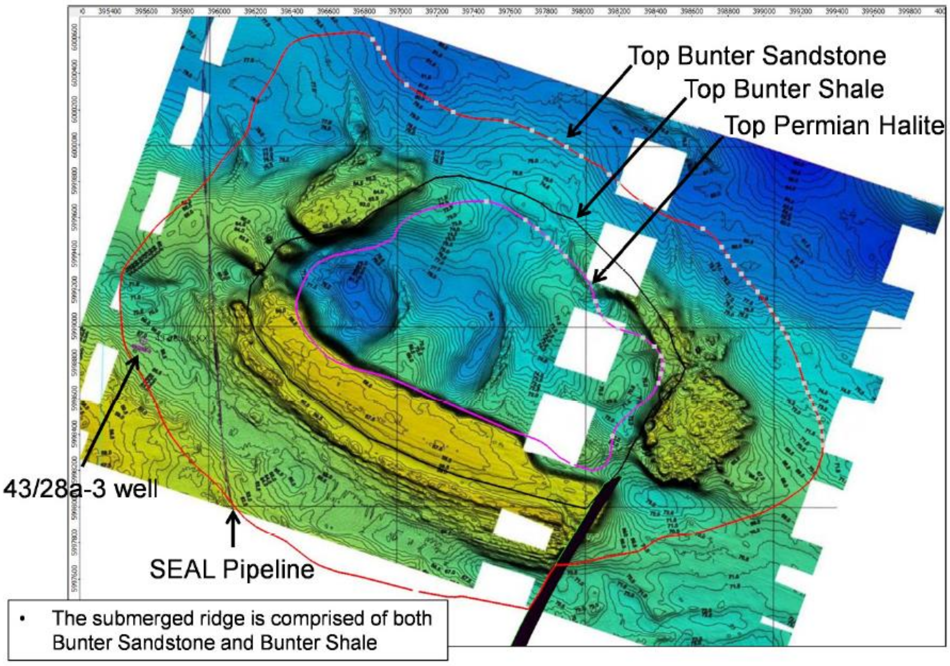
The outcropping Bunter sandstone and shale forms an approximately 10m high circular feature on the seabed (Figure 4.14). The slightly lower topography inside and outside the circular feature is associated with the outcropping Zechstein halite, Bunter shale and the Röt clay and Röt halite (Figure 4.14 and Figure 4.15). The outcrop area is covered by Holocene sands, which form dunes above the Endurance structure. Across approximately 70% of the Bunter outcrop (Figure 4.15), the Holocene sands are underlain by Quaternary clayey sand (Markham's hole formation) or stiff sandy clay (Swarte bank formation). Seismic data indicate that the total thickness of Quaternary and Holocene deposits is up to 15m.

There is some uncertainty as to the thickness of the Quaternary sediments. Cuttings from well 43/28a-3 (Figure 4.14) indicate that the Quaternary may be as much as 90m thick. At present, the explanation considered to be most likely is that dissolution of soluble salts such as anhydrite within the Röt clay and evaporite bearing portions of the Bunter sandstone has resulted in collapse structures that contain greater thicknesses of Quaternary deposits. Well 43/28a-3 may have intercepted one of these features. However, this uncertainty is not particularly important in the context of the potential impacts of discharge of saline water at the outcrop.

The Quaternary sediments are anticipated to be significantly less permeable than the Bunter sandstone and the Holocene cover sands. Therefore, discharge of water at the outcrop may be focussed through the areas where the Quaternary sediments are absent.

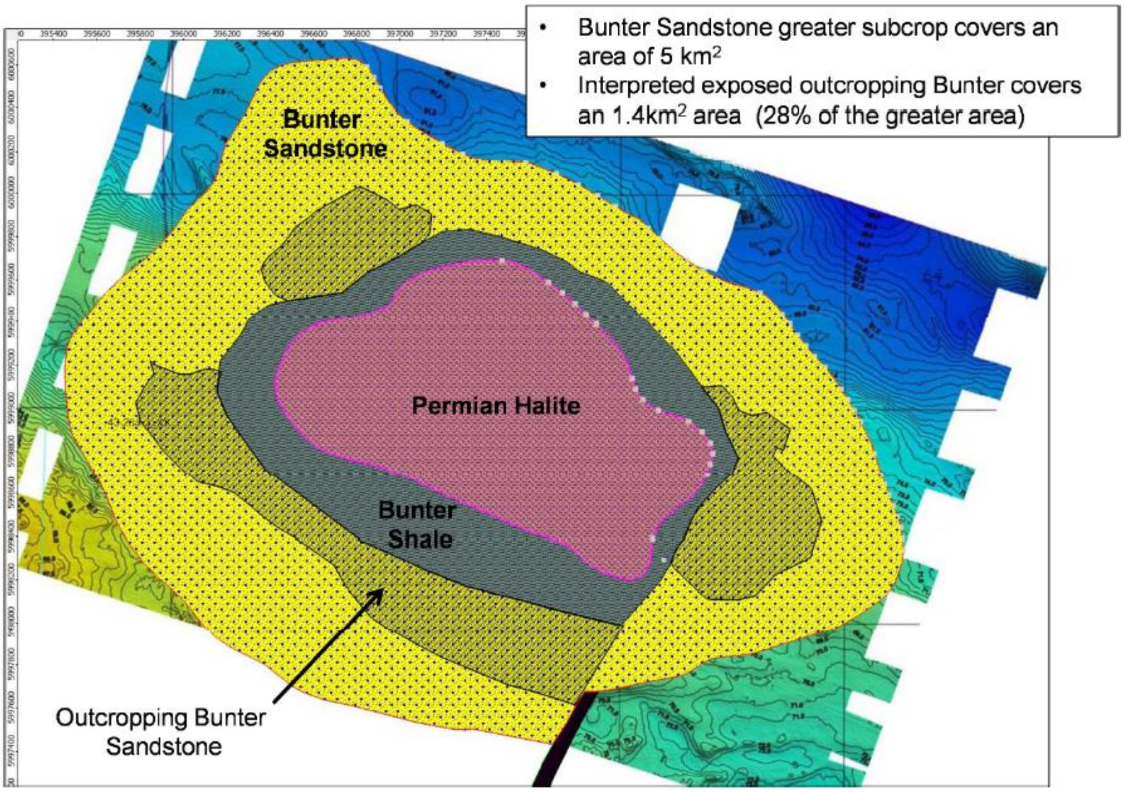
Figure 4.14 Outcrop Bathymetry

Bathymetry is the study of underwater depth of lake or ocean floors.



- The submerged ridge is comprised of both Bunter Sandstone and Bunter Shale

Figure 4.15 Quaternary Cover on the Bunter Outcrop



- Bunter Sandstone greater subcrop covers an area of 5 km^2
- Interpreted exposed outcropping Bunter covers an 1.4km^2 area (28% of the greater area)

4.2.4.5 Hydraulic Properties

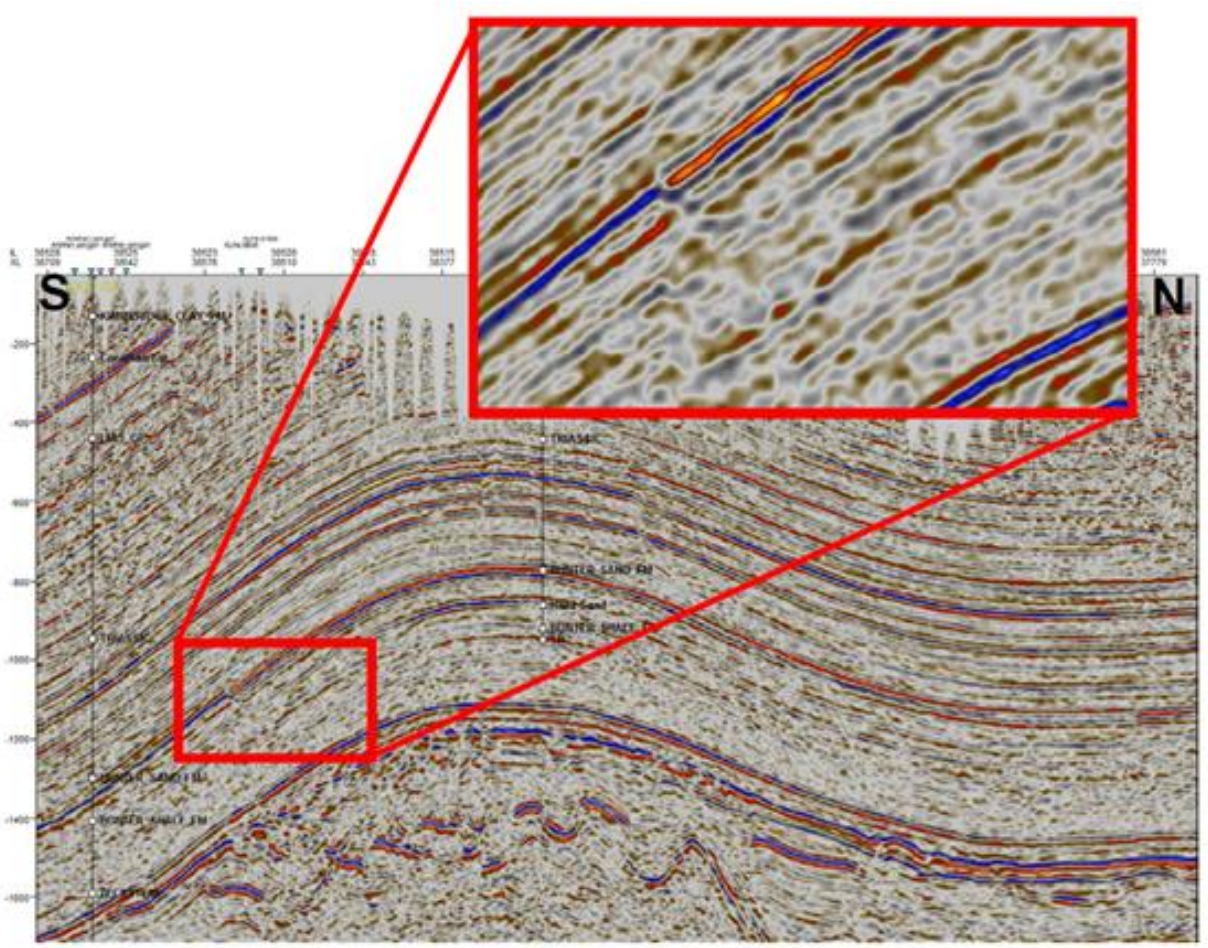
Bunter Sandstone

The Bunter sandstone is dominantly coarse grain alluvial or aeolian sandstone and in other areas of the southern North Sea has a significant proportion of halite cement, which blocks the pore space reducing the quality of the reservoir. In wells drilled in the Endurance structure (wells 42/25d-3 and 42/25-1), there is much less halite cement than at other locations in the southern North Sea. In well 42/25d-3, the amount of halite is around 1.5% compared to 2.7% dolomite and 2.2% anhydrite, although different measurement techniques do give different results.

In exploration seismology, negative polarity is a term that describes the convention of displaying an increase in velocity, such as from slow velocity shale to a high velocity dolomite, as a trough and travel from a high velocity rock to a slower velocity rock as a positive peak.

The top Bunter sandstone reflector within the Endurance structure has an inverse (negative) seismic polarity as compared with shallower reflectors (Figure 4.16). The polarity of this seismic reflector changes at the flanks of the Endurance structure and is positive outside of the Endurance structure. This reversal of seismic polarity within the Endurance structure is interpreted as delineating the area in which there is little halite cement within the Bunter sandstone, resulting in a lower seismic velocity than overlying rocks, which causes a phase reversal. The boundary of the phase reversal indicates there is little halite cement from the Endurance structure to the seabed outcrop of the Bunter sandstone.

Figure 4.16 Endurance Seismic Data Showing the Phase Reversal in the Top Bunter Sandstone Reflector



The lack of halite cement within the Bunter sandstone in the Endurance storage site means that the reservoir quality is very high, in contrast to the poor reservoir quality outside the phase reversal boundary (Figure 4.9). The porosity of the Bunter sandstone is high, with an average of 22% and some samples exceeding 30%, compared to typical values in Triassic sandstone with similar burial depth of around 18%. The explanation for this relatively high porosity is that the Bunter sandstone was cemented by halite at the time of burial, which prevented compaction and that the cement has dissolved away at a later stage. A model based on thermohaline convection has been proposed to explain the late stage dissolution of halite cement, with the discharge location of the thermohaline convection system being the seabed outcrop. Note that thermohaline convection occurs in the ocean when warm salted layers sit on top of cool and less salted ones, then the salted water rapidly diffuses downwards even in the presence of stabilising temperature gradients, due to double diffusion between the falling blobs and their surroundings.

The reservoir quality in the Endurance structure is generally very good, although there is a slight decrease in quality with depth as the average grain size decreases and there is an increase in the proportion of mudstone beds. The average permeability of the Bunter sandstone is around 270mD ($2.7x10^{-13}m^2$) measured in a well test at well 42/25d-3. Porosity logs through the Bunter show a decrease in porosity from 22.3% in L3 to 20.5% in L2 and 15.5% in L1 which results in permeability estimates (based on porosity) of 425mD in L3, 178mD in L2 and 32mD in L1.

There is no evidence from seismic data for any major structural features within the Bunter sandstone and the injection test showed no evidence of any lateral boundaries within a 1.2km radius of the well. There is evidence from logging and petrography of some horizontal features that could affect vertical flow. These features include thin mudstone layers and a calcitic ooilitic layer, note that oolite is a sedimentary rock formed from ooids, spherical grains, usually composed of calcium carbonate, composed of concentric layers. The ooilitic layer is thought to be the most continuous as it has been observed in both well 42/25d-3 and in a crestal legacy well (42/25-1); however it is thought that this layer may provide a baffle rather than a barrier to fluid flow.

Röt Clay

The Röt clay is a silty claystone, with a porosity of 3%. There is the possibility that a small amount of CO_2 may move into the Röt clay through diffusion or sub-seismic fractures although it is a proven seal in the Esmond, Forbes and Gordon gas fields to the north of the Endurance structure; see Figure 4.3. Normalised gamma ray logs for the Röt clay from boreholes in and adjacent to the Endurance structure and the Esmond gas field have been compared and are very similar, suggesting the shale quality is consistent across the region. Permeability in the Röt clay is extremely low (around 0.001mD, $1x10^{-18}m^2$) such that flow through the Röt clay would be more likely to occur by fracturing than by porous flow.

To test the sealing capacities of the Röt clay, a mini-frac test was carried out in well 42/25d-3 which found that the fracture closure pressure (the fluid pressure required to open a fracture) is 264bar. Evidence of the strength of the Röt clay has also been obtained from the Esmond gas field which was at an initial pressure of 2280psi, but the abandonment pressure was 150psi. The pressure in the Bunter sandstone recovered to 1750psi in 13 years, while the pressure in a layer of sandstone within the Röt clay has remained at 150psi. Note that this sandstone inter-layer is not present in the Röt clay at the Endurance structure.

This indicates that the sandstone layer is isolated from the Bunter sandstone by the Röt clay, which is 6m thick at this location and the Röt clay is able to hold back a differential pressure of 160psi (110bar).

Röt Halite

The Röt halite is around 100m thick and is expected to have an extremely low porosity and permeability such that fluid flow through this unit would only occur through fracturing. In addition, fractures in salt deposits are known to heal, so are unlikely to be long lasting features.

4.2.4.6 Formation Water

The pore water in the Bunter sandstone at the Endurance structure is very saline with a range of approximately 252,000mg/kg to approximately 262,000mg/kg NaCl compared to seawater at 35,000mg/kg; however this level of salinity is below the saturation concentration for sodium and chloride, which at the reservoir conditions would be around 350,000mg/kg, based on a simple geochemical calculation. There are three measurement points for salinity, two near the base of the Bunter and one at the top. The measurement point at the top of the Bunter sandstone has a slightly lower salinity than at the base of the Bunter sandstone, but given the small number of data points and the error involved in the measurements, it is not clear whether this represents a trend or noise in the measurements.

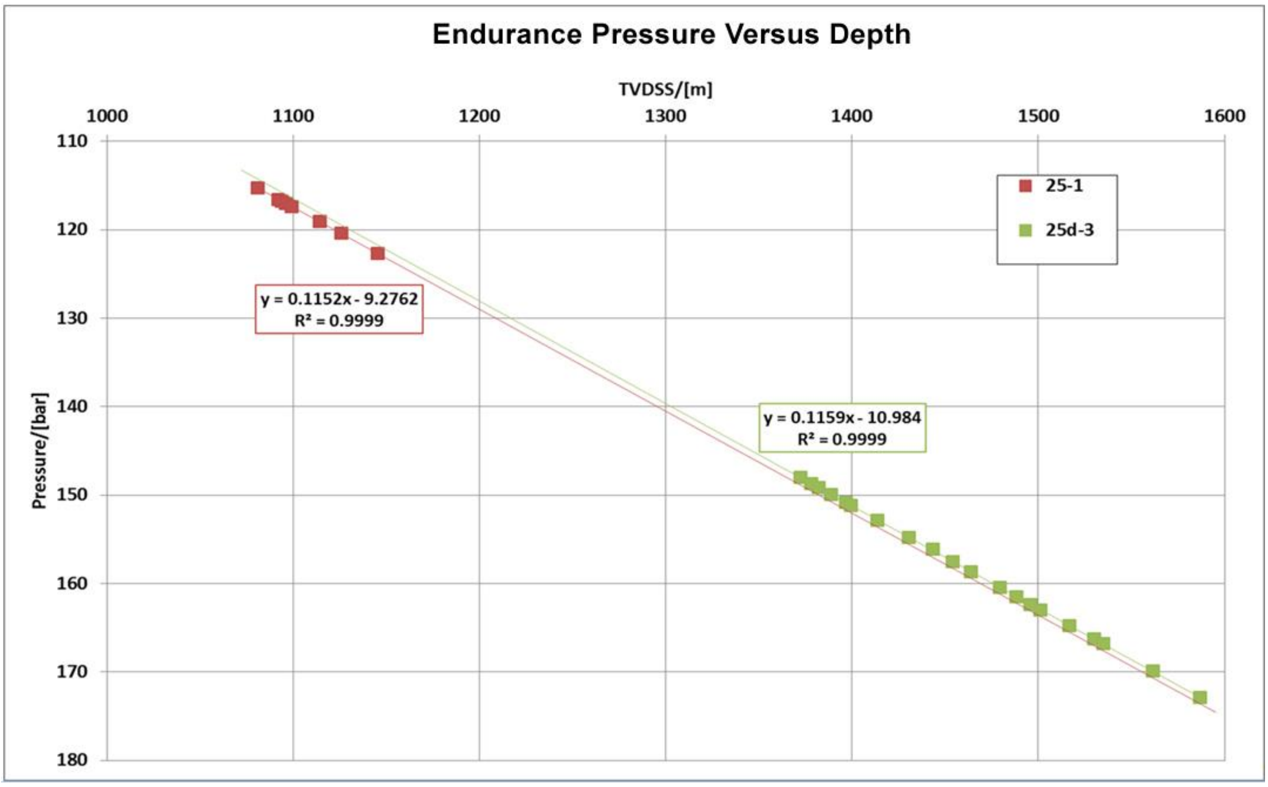
The pressure gradient measured in wells 42/25-1 and 42/25d-3 can be used to calculate the density of brine in the reservoir. The two wells have slightly different pressure gradients, resulting in density estimates of 1174kg/m^3 and 1181kg/m^3. The pressure and temperature of the reservoir is 152bar at 1405m TVDSS and 61°C. At the seabed, the pressure is approximately 6.5bar, so if there is a hydrostatic pressure gradient between the seabed and the reservoir, due to hydraulic connection between the anticline and the seabed outcrop for example, the average density of the brine must be around 1107kg/m^3. This implies that the salinity of the water decreases between the reservoir and the seabed.

There is no conclusive evidence about the age of the water within the formation and the degree of any past meteoric water invasion. Strontium and oxygen isotope data have been interpreted as inconclusive as to the degree of any mixing with meteoric water. Evidence from the dissolution of feldspar (a group of rock-forming minerals) on the other hand indicates that meteoric water has reached the reservoir. The loss of halite cement and the salinity gradient also suggest that salt has been able to move out of the Bunter sandstone. The evidence supports some degree of past mixing of meteoric water, although the timing of such mixing is unknown. The most likely source of this water is the present seabed outcrop, which will have been sub-aerially exposed during time intervals within the Quaternary period when sea level was much lower than at the present day. The area has also been glaciated during the Quaternary period, which opens the possibility that sub-glacial water may have been able to recharge the deeper Bunter sandstone.

In other areas of the southern North Sea, the Bunter sandstone is a proven gas reservoir. However over most of the Southern North Sea, gas is trapped below the Zechstein halite. At the Endurance structure there is no evidence of thinning of the Zechstein halite and therefore it is unlikely that gas could have migrated through the salt. There is also no evidence of hydrocarbons in drill cuttings from the Bunter sandstone, nor was any evidence of hydrocarbons detected in the formation water analysis.
The Bunter sandstone in the Endurance structure reservoir is hydraulically connected to the Bunter sandstone across a wider area. The pressure in the Endurance structure measured in well 42/25-1 in 1990 is around 0.7bar higher than pressure measured in 2013 in well 42/25d-3, see Figure 4.17.

This is interpreted to be due to the cessation of production at the Esmond gas field and flow of water into the Bunter sandstone at Esmond from the underlying water bearing sandstone. Based on the geometry of the geological structure and the observed pressure communication, it is estimated that the Bunter sandstone is hydraulically connected over an area of 20,000km^2.

Figure 4.17 Pressure Gradients Measured in 1990 (42/25-1) and 2013 (42/25d-3)



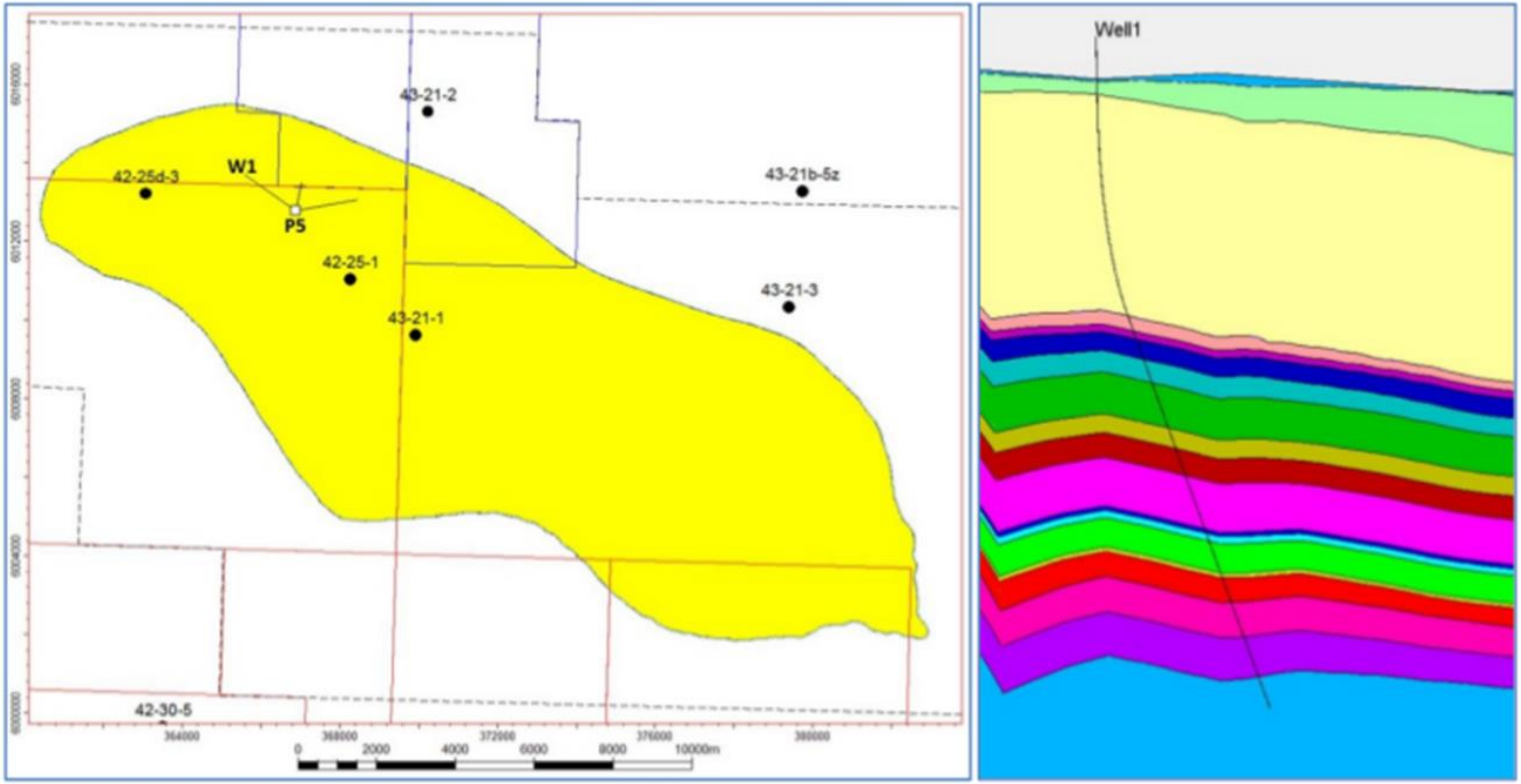
4.2.4.7 Storage Plans

The CO_2 volumes will be a maximum of 2.68MTPA over a period of 20 years. The target system availability is 99%. The pipeline and injection infrastructure have a design life of 40 years. The CO_2 will be injected into the reservoir from three wells drilled from a single off-shore platform. These wells will provide the necessary operational flexibility in terms of varying injection rates and allowing one well to be shut down for maintenance when required. The potential location of the platform towards the western end of the Endurance structure and the three wells which could radiate in northwest, north and northeast directions, are shown in Figure 4.18.

The location was chosen so as not to coincide with the potential wind farm at the south and east of the Endurance structure. It also avoids areas with large seabed sand waves and faults in the overburden. The injection wells are down-dip of the two old appraisal wells (42/25-1 and 43/21-1), but up-dip of the new appraisal well (42/25d-3).

The well design has been kept simple so as to facilitate secure permanent abandonment. Dry trees (well head at or above the sea surface) will be used and well inclination will be limited to 60°, which will allow sufficient bottom hole well spacing to prevent significant injection interactions, whilst still allowing wireline entry. The deepest that injection will occur is approximately 30m above the containment spill point, whilst the shallowest injection depth has not been fixed.

Figure 4.18 Injection Platform (P5) and Well Head Locations



The perforating strategy has considered various factors:

- the required injection rate;
- CO_2 pressure, temperature and phase control;
- controlling near borehole effects;
- maintaining sufficient separation from the borehole seals, primary seal and secondary seals to prevent risk of pressure, or more significantly, thermally induced fracturing;
- maintaining sufficient separation from the borehole seals, primary seal and secondary seals to prevent risk of chemical alteration if water washing is required to periodically remove halite precipitates;
- maximising exposure of CO_2 to formation water to maximise residual trapping and dissolution; and
- the general increase in permeability from the base of the reservoir upwards.

The advantages of injecting deeper within the Bunter sandstone include maximising the distance between the injection wells and the crest of the anticline. This will maximise residual trapping and dissolution. Deep injection will also reduce the risk of local pressure increase and temperature decrease at the injection site affecting the integrity of the well seals, primary seal and secondary seal assumes that the perforated sections of the injection wells will extend to the middle of the Bunter sandstone L2 horizon.

The materials used in the well (metals in the casing, cement, elastomers in the plugs) will be chosen to be resistant to corrosion, which may be particularly important when CO_2 and water are both in the well at the same time during and following water washing. The casing will be designed to be strong enough for the loads that it is likely to experience. Cements required for the operating well need to be sufficiently resistant to the prevailing chemical environment for 30 years to 50 years and cements that contribute to the integrity of the storage site need to resist the chemical environment for around 10,000 years.

There may be significant daily variations in the supply of CO_2 depending on operation of the power station that produces the CO_2 in response to demand for electricity. There may also be periods when the power plant is shut down, causing emissions from the plant to be zero. The injection system design and operation is being optimised to accommodate variations in the pressure and rate of CO_2 supply, as well as accounting for periods of no injection in a given well. A number of factors are being taken into consideration to maintain well seal integrity and injectivity.

Factors that potentially can affect well seal integrity are:

- stresses will change due to pressure and temperature changes in response to variations in power generation and hence CO_2 injection rates;
- CO_2 phase changes with depth in wells could increase stresses; the wells have therefore been designed and operating procedures devised, to minimise the likelihood of two-phase operating conditions occurring in the well-bore; two of the wells are of 5.5 inch diameter and one is of 4.5 inch diameter, which will handle injection under different rates of CO_2 supply; mitigation measures such as N_2 injection at start-up may be used to prevent phase changes while the system attains operational conditions; owing to these measures, two-phase flow can occur only at the top of the tubing and will not affect integrity; and
- there is expected to be some thermal fracturing immediately adjacent to the perforated sections of the injection wells the perforated sections will be located sufficiently far from the well seals to prevent risk of damage to the seals by thermal fracturing.

Factors that can potentially affect injectivity are:

- cycles of near-well pore space drying out during injection and subsequent re-wetting during pressure shut-in, in response to variations in power generation and hence CO_2 supply, can lead to build-up of halite precipitates and loss of injectivity; mitigation of loss of injectivity can be achieved by extra and repeat perforating, the risks of which would be assessed should the need arise;
- periodic water washing will likely be used to remove halite precipitates; this process could lead to hydrate precipitation, which itself could cause loss of injectivity; an inhibitor such as Monoethylene Glycol (MEG) can be used to prevent hydrate precipitation; and
- pressure cycles and thermal fracturing immediately adjacent to the well can lead to sand generation and well clogging; the wells are designed to minimise the risk of sand clogging and it will also be possible to remove sand during well maintenance; hydrate and calcite cements do not bind the Bunter sandstone, so washing is not likely to lead to cement loss and sand generation.

Well abandonment is being optimised for CO_2 storage. This includes both the choice of cement that will be used to plug the wells, but may also involve casing removal. The casing may be removed by milling to allow the plugs to be placed in direct contact with the rock. This removes the risk of an open annulus between the casing and plug. If the plug is in direct contact with the Röt halite, creep of the halite against the plug will act to maintain a good seal. The casing might also be removed in a section of the Röt halite without plugging, thereby allowing the halite to fully creep and close the hole.

4.2.5 Hazards and Receptor Classes

4.2.5.1 Key Hazards

The hazards of interest from the perspective of the risk assessment include:

- the CO_2 itself, the potential for loss of containment and the potential for impacts on receptors, for example as a result of seawater acidification;
- saline formation water displaced as a result of CO_2 storage and the potential for impacts on receptors at the seabed or within the water column as a result of changes in salinity or heavy metal concentrations; and
- physical deformation of the seabed due to storage, with the potential for damage to seabed infrastructure.

Environmental receptors that need to be considered to assess the potential impacts that might arise from the above hazards can be categorised in three broad areas:

- direct impacts to humans;
- ecological receptors; and
- non-biological receptors.

These are detailed in the following three sections.

4.2.5.2 Direct Impacts to Humans

As the Endurance structure storage site is located offshore, there are no permanent human populations that could be impacted directly by any of the hazards identified in Section 4.2.5.1. Human activities within the area are connected with the oil and gas industry, shipping, fishing and maintenance of offshore wind resources. So, any potential human receptor carrying out these activities would be present within the area only transiently. It is implausible that the CO_2 itself or displaced formation waters could impact upon these human receptors. However, impacts due to induced seismicity and surface deformation need to be covered by the assessment. Furthermore, possible indirect impacts to humans caused by impacts upon the receptors described below also need to be considered.

4.2.5.3 Ecological Receptors

Appendix A describes the marine receptors of relevance to the assessment. These can be summarised as comprising marine organisms that inhabit the benthic and pelagic zones in the region of the storage system.

Receptors of relevance include:

- plankton and other simple life forms;
- algae, noting that the presence of algae will be limited at depth;
- benthic dwelling creatures such as catworms, sea urchins and amphipods to assemblages of larger, more mobile species characterised by brown shrimp, hermit crab, flying crab, common starfish and brittlestars;
- fish and shellfish in the pelagic zone; the part of the open sea that is not near the coast or sea floor;
- marine mammals; and
- seabirds.

The assessment takes the cautious approach of identifying risk on the basis of whether it is plausible that observable impacts could occur to one of the above classes of receptor. This means that it is not necessary to assess impacts on all receptors, just those that are likely to be most sensitive to changes in conditions and for which it is possible impacts could be detected by monitoring.

4.2.5.4 Non-biological Receptors

Other receptors that need to be considered are:

- Infrastructure, both fixed and transitory such as ships and rigs, including:
  - Infrastructure connected with CO_2 storage; and
  - Infrastructure connected with offshore wind exploitation; and
- Adjacent oil and gas resources.

Infrastructure could be affected by surface uplift or similar effects and this is an important consideration for the assessment. Harmful interactions (lateral or vertical) with other hydrocarbon resources also need to be avoided.

4.3 Scenarios

4.3.1 Overview

The risk assessment is structured according to scenarios for the future evolution of the storage system. It is analysis of these scenarios that forms the central element of the assessment. The scenarios are described in this section and then assessed in Section 4.5.

4.3.2 Nature of Scenarios

The term ‘scenario’ here means:

a plausible description of the potential evolution of a system according to the nature of the features, events and processes that might act within and upon it.

A scenario is not a prediction of the future behaviour of a CO_2 storage site, but a representation of the status of a system under a given assumed set of circumstances. The purpose of the scenarios can be summarised as forming a basis for analysing CO_2 storage system behaviour and for communicating the results of the analysis.

Scenarios for risk assessments for the long-term performance of systems that involve both man-made and natural components typically include:

- a best estimate or Expected Evolution Scenario (EES), describing the as-designed performance of the system and its evolution with time, corresponding to the planned performance of the system;
- lower probability Alternative Evolution Scenario (AES) exploring deviations from the expected evolution.

Within each category of scenarios, further scenario ‘cases’ or ‘variants’ are often defined which explore specific uncertainties or issues within the context of that scenario.

Demonstrating that the performance of the system will be acceptable then involves:

- Providing evidence confirming that performance of the system for the EES will match intended performance requirements and will not involve unacceptable impacts to receptors; and
- Showing that the AES are very unlikely to occur and/or would also not lead to unacceptable impacts.

It is important to note therefore that the identification of an AES does not indicate it is considered likely to happen. Rather, best practice in risk assessment is to identify a suitably comprehensive (but not overly complicated) set of scenarios that could plausibly occur, to show to regulators and other stakeholders that all plausible issues of concern have been identified and assessed. Not all scenarios will need the same level of effort in the assessment; for many less likely scenarios, qualitative arguments on logic and probability alone may be sufficient.

4.3.3 Timeframes for Scenarios

For each scenario, analyses are undertaken to determine the performance of the system to determine its consequences for receptors, including humans, ecosystems and natural resources, providing confidence that performance measures will be met. Those consequences, the ‘risk’, will be a function both of the likelihood of an impact occurring and of the extent of that impact.

A set of scenarios is required, such that the analyses collectively:

- provide arguments supporting the expected performance of the system;
- explore all plausible adverse consequences of CO_2 storage; and
- demonstrate understanding of the mechanisms by which leaks could lead to adverse environmental impacts.

Analysis of these scenarios and arguments on their probability of occurrence, including noting possible mitigation measures, then forms the basis of the risk assessment.

A generic set of overall timeframes for the assessment is set out in Section 4.1.2. However, for the assessment scenarios it is helpful to develop the generic timeframes into time periods of relevance to the assessment, on the basis of key features and processes. Therefore, the generic timeframes are here developed into scenario-relevant times for the assessment. Each scenario represents three timescales:

- **Operational Phase:** This is the period during which CO_2 is injected into the reservoir, which will last for about 20 years (for phase 1);
- **Short Term Post Closure Phase:** This is the post-closure/pre-transfer phase defined in 2009/31/EC CCS Directive, during which the storage system will be monitored. The time is imprecisely defined, but will last until the competent authority, DECC, is satisfied that the stored CO_2 is evolving in line with expectations and moving towards a state of greater stability (risks, initially very low anyway, are continuing to decrease). Well plugging and abandonment will occur within this period; and
- **Long Term Post Closure Phase:** This is the post-transfer of responsibility phase defined in 2009/31/EC CCS Directive. The time period is imprecisely defined, but will be several thousands of years.

4.3.4 Derivation of Scenarios

Scenarios can be defined in a number of ways. However it is helpful that all scenarios are identified and developed using the same framework, to provide confidence to assessors and stakeholders that the approach is systematic and covers all risks. Over recent years, experience in a number of industries has led to the development of a ‘top down’ structured approach. The specific approach adopted in the risk assessment for the Project is described below.

A scenario is essentially a structured collection of Features Events and Processes (FEPs). A feature represents a component of a storage system, whereas a process is an interaction between the system components, or between the surrounding environment and the system components. An event is a process that operates over a timescale that is very short compared to the timeframe of the assessment, but there is no precise distinction between events and processes. In the context of CO_2 storage, CO_2 interactions would be considered a process because they will occur over the entire timescale considered by a risk assessment. In contrast, typically the drilling of a new borehole into a CO_2 storage reservoir would be considered an event since it occurs over a very small proportion of the entire assessment timescale.

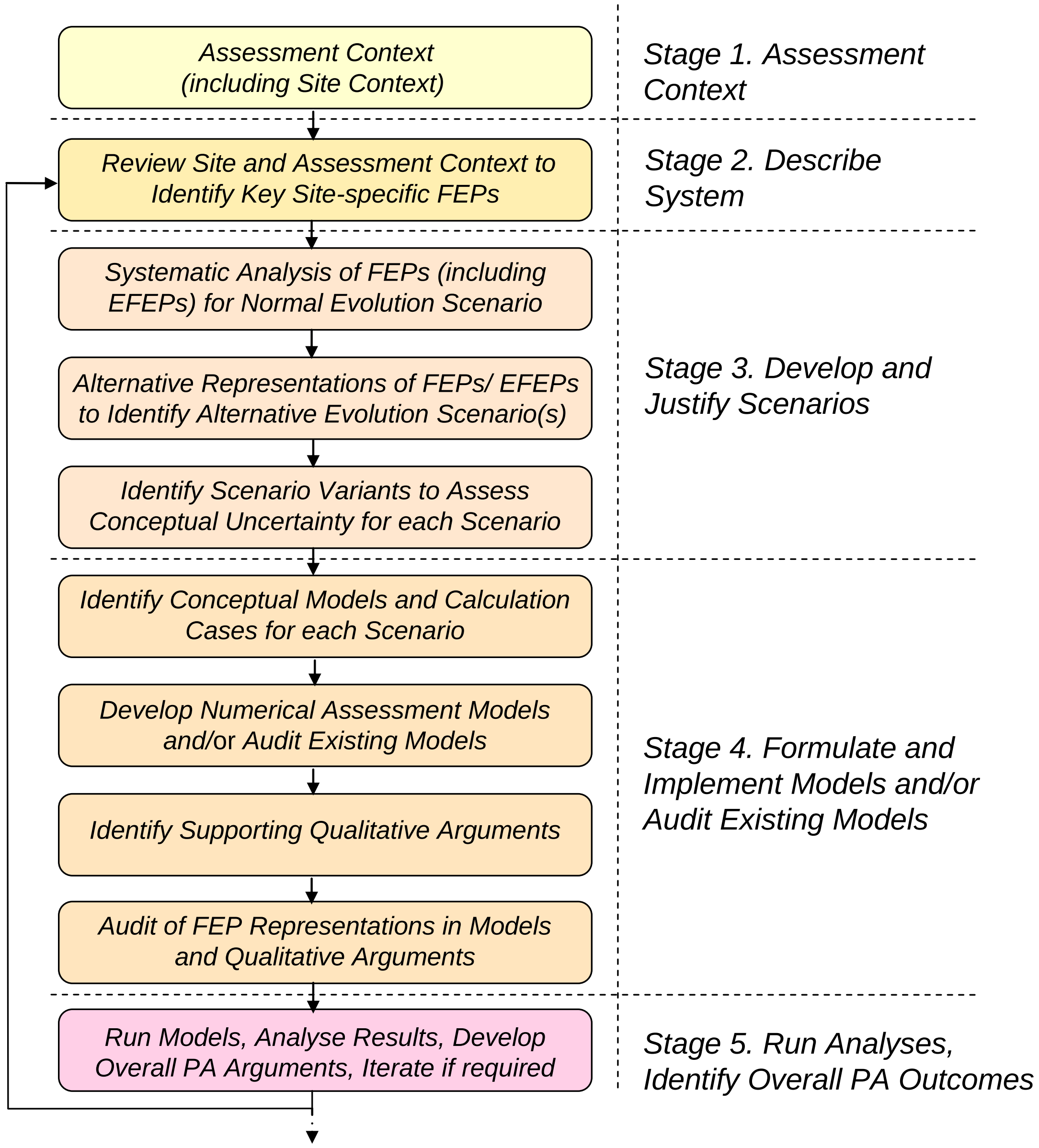
A distinction can be made between internal FEPs that lie within the boundaries of a storage system and external FEPs (EFEPs) that are part of the global system but external to the storage system; the EFEPs may however act upon the system to alter its evolution, for example seismic effects. Together, the FEPs of the system describe conceptual models that may be related to scenarios for system evolution.

The top down FEP approach involves identifying the main features, events and processes that are important to system evolution, at a high level, to avoid unnecessary complication, and potential hazards and risks and linking those with the expected evolution of the system. In other words, the FEPs are based on the system description and it is shown that they are all represented in a way that demonstrates suitable coverage and helps inform risk assessors how to represent them in conceptual and numerical models, or to assess them using logical arguments.

Then, plausible alternative assumptions for the evolution of the system (linked to key FEPs, including recognising the potential for external factors/EFEPs to change the system evolution) are recognised to derive AES.

A schematic diagram showing the typical use of scenarios in a risk assessment process is shown in Figure 4.19.

Figure 4.19 Schematic of a Typical Risk Assessment Process



Databases of detailed FEPs for geological storage of CO_2 have been compiled, such databases are used to audit the scenarios generated using the high level top down approach, thereby helping to demonstrate that they sufficiently cover the key issues and uncertainties, see Appendix D.

4.3.5 Performance Measures

It is important that scenarios for risk assessment are defined so that they can be assessed against key performance measures. The key performance measures include:

1. providing confidence that the basic performance measures will be met under the expected evolution of the system; the required volume of CO_2 will be successfully injected and stored within the defined storage complex for the required periods of time; and
2. showing that risks to receptors will be low, due to low impacts and/or low probability of occurrence.

Measure 1, above, requires the provision of arguments and underpinning evidence that the evolution of the system will be as designed. Measure 2 requires the consideration of all plausible risk factors, which need to be linked with hazards and potential consequences.

The hazards to be considered concern the stored CO_2 and the features of the storage system that could potentially cause harm as a consequence of the behaviour of the CO_2 when stored.

The scenarios need to explore:

- all the factors that could cause control over the CO_2 to be lost;
- the likelihood of these factors being realised;
- the consequences of the loss of control over the $CO_{2;}$
- all hazards within the CO_2 storage system and its surroundings that could cause harm as a result of the behaviour of the CO_2 when in storage;
- the likelihood of such harm occurring; and
- the nature of that harm.

The consequences of loss of control over the stored CO_2, or the action of some other hazard as a consequence of the behaviour of the CO_2 when in storage include:

- impacts on biological receptors and ecological receptors, as described in Section 4.2.5; and
- impacts on other receptors such as adjacent hydrocarbon resources.

Assessments for the scenarios need to demonstrate that performance measures relevant to each potential impact have been met. In general this will involve showing that risks are sufficiently low as to be of no concern to regulators or other stakeholders and/or that they can be mitigated cost-effectively if they are realised.

4.3.6 Features Events and Processes

At a very high level, the Endurance CO_2 storage site and its environs can be described by the FEPs listed in Table 4.1. This list is based upon key features of the site from the systems description, but has also been informed by FEP lists compiled for several other facilities, for example, generic North Sea storage locations considered by the RISCS EC project (Research into Impacts and Safety in CO_2 Storage; RISCS, 2014) and Krechba.

Table 4.1 Initial Key FEP List

FEPs

Storage Complex

SC1 - Storage System

- Reservoir rock
    - Heterogeneity
    - Reservoir geometry
    - Reservoir faulting
    - Reservoir pressure
    - Reservoir compressibility
    - Vertical connectivity
    - Strength
    - Compartmentalisation
- Storage volume
- Injectivity
- Induced seismicity
- Injected CO_2
    - Fluid
    - Impurities
    - Temperature
    - Migration
    - Volume
    - Pressure
    - Physical properties
- Formation fluids
    - Fluid
    - Salinity
    - Temperature
    - Migration
    - Pressure
    - Physical properties
- Physico-chemical processes
    - CO_2 Dissolution
    - Mineral precipitation/dissolution
    - pH
    - Hydrate formation
    - Sand generation
- Accidental over-filling

SC2 - Primary Seal

- Faults and fractures
- Formation waters
- Chemistry

SC3 - Overburden

SC4 - Underburden

Wells

W1 - Wells

- Active injection wells
- Older wells
- Well cement and seals
- Casings and corrosion
- Well monitoring
- Well seal degradation
- Fluids injected into wells other than CO_2

Other System FEPs

O1 - Seawater column

O2 - Hydrocarbon resources

O3 - Humans

O4 - Seabed

O5 - Marine biota

O6 – Pressure kicks

O7 - Regional stress field

O8 - Marine sand dunes

External Factors (EFEPs)

E1 - Seismicity

E2 – Ocean currents

E3 - Accidental damage of well heads by human activities

E4 - Exploration

E5 - Resource exploitation activities elsewhere

E6 - Fishing

E7 - Sabotage

4.3.7 Identification of Scenarios

The EES reflects the expected current and future evolution of the system given the present understanding of the above FEPs. A summary of the EES follows to highlight key assumptions that differentiate it from other evolution scenarios; it is described in detail in Section 4.3.9 and in Appendix A.1.

Figure 4.20 Expected Evolution Scenario, Condensed Description

CO_2 will be injected into the storage reservoir (Bunter sandstone) in line with current site operator plans at a variable rate dependent on the supply of CO_2 from the power station, up to a maximum rate of 2.68MT/yr. Reservoir pressure will be monitored and injection will be managed to prevent pressures that could risk the integrity of the Röt clay, the primary seal which overlies the reservoir, from being attained. If required, sufficient injectivity for CO_2 to be stored at the required rate will be maintained by measures such as water washing to prevent salt precipitation and use of MEG to prevent hydrate formation. The CO_2 will spread laterally and vertically from the injection well(s), but will remain within the Endurance structure, beneath the primary seal, which will provide a tight seal for the system against vertical transport. Within the storage system CO_2 will migrate as a free phase and dissolve in formation water. Migration of CO_2 through the reservoir will be heterogeneous, with some occurring through the rock matrix and some potentially occurring within any sub seismic faults and fractures that occur (providing increased opportunity for spreading and dissolution). The permeability of the primary seals and overlying secondary seals will remain as at the present. The wells and well seals will behave as designed and the wells will not act as conduits for leakage of CO_2 or migration of formation water; the well seals will slowly evolve chemically and physically, but this will not adversely affect their long-term barrier function. There will be continual monitoring of the storage site and wider storage complex. Any future evolution of the biosphere will be caused by factors other than CO_2 storage.

By considering the main FEP groups in turn and identifying key alternative assumptions, making sure the key hazards are covered, the AES can be identified; see Table 4.2.

Table 4.2 Alternative Evolution Scenarios

Identifier	Title	Main Variants	Notes
AE1	Reduced injectivity due to chemical changes/ reactivity	Chemical precipitation reduces porosity Physical changes due to chemical reactions results in loss of injectivity	Principally exploring: 1. Potential consequences of salt precipitation and hydrate formation. Includes recognising impurities in the injected gas stream 2. Potential consequences of physical changes to the formation owing to dissolution of minerals, such as reduced porosity/permeability, strength loss and fracturing, sand generation clogging of injection wells The two variants are not distinguished as separate scenarios because their analysis is the same
AE2	Reservoir pressurisation due to unexpected compartmentalisation	-	Reservoir pressurisation/compartmentalisation differs from expectations
AE3	Leakage through the primary seal and secondary seals	AE3.a: Via faults/ fractures AE3.b: Diffusive leakage	AE3.b includes diffusion of dissolved CO_2 and diffuse leakage of CO_2. Assessment considers the possibility of interactions with marine receptors
AE4	Increased displacement of high salinity formation	-	This considers displacement of high salinity waters beyond that assumed for the EES, assessing the potential for impacts at the seabed, caused by either

Identifier	Title	Main Variants	Notes
	waters		discharge via fractures or discharge via the seabed outcrop
AE5	Well failure	AE5.a: Injection wells AE5.b: Other wells	Considers the possibility of a leakage pathway via poorly performing or absent/destroyed well seal(s). Includes the potential for damage to well-heads for example as a result of trawling activities
AE6	Lateral interaction with other hydrocarbon resources	-	Addresses whether it is plausible that the CO_2 could migrate laterally, sufficient to interfere with other hydrocarbon resources
AE7	Resource exploitation elsewhere affects CO_2 storage system	-	Considers the potential for exploitation of other resources to affect conditions within the storage system for example as a result of pressure changes
AE8	Seabed uplift/tilting	-	Assessing whether it is plausible that impacts to the seabed (such as in the area of the wind farm) could arise due to seabed uplift/tilting beyond the EES
AE9	Human intrusion	-	Exploring the potential for inadvertent human intrusion, for example as a result of exploration activities in the future. In this case, intrusion would be unexpected and hence likely to pose risks that were unforeseen. Does not include intentional human intrusion, because in this case the organisation undertaking the intrusion is assumed to be aware of the risks and would be responsible for managing risks and ensuring safety
AE10	Leakage as a result of seismic events	AE10.a : Induced seismicity AE10.b : Natural seismicity	The induced seismicity variant explores the potential for overpressures to build up allowing (for example) some fracture widening near injection boreholes, or compromising well seals (see also AE5). The natural seismic variant explores whether natural seismic events could influence storage system evolution
AE11	Sabotage	-	Damage to well heads or seals as a result of sabotage. Note links with other scenarios such as AE5 and AE9.
AE12	Accidental over-filling	-	The margin of the CO_2 plume moves more rapidly and/or further from the injection point than planned. This could be due to more CO_2 being injected than planned initially (while in principle this could be accidental, in reality it is almost certainly something that will be due to modified injection planning). Other causes of over-filling in this sense are smaller storage capacity than predicted and/or more highly permeable conduits (such as fractures) than have been recognised prior to injection

Possible actions of other EFEPs and alternative evolutions of many of the other FEPs not explicitly mentioned in the above scenario titles are addressed by analysing the above scenarios. This approach is possible because any plausible additional AES, which could be constructed using the set of FEPs and EFEPs, which are included the AES listed in Table 4.2, would be similar to one or more of these above listed AES. Any other FEPs and EFEPs that are not represented explicitly in the above scenarios are sufficiently implausible not to be worthy of further assessment.

Intentional human intrusion within legal frameworks is typically regarded as out-of-scope of long-term risk assessments. Such intrusion implies that the CO_2 storage system is known about by whoever is undertaking the intrusive actions. In such a case it will be the responsibility of the intruding organisation to ensure safety and performance. Therefore arrangements to ensure future generations are aware of the presence and dimensions of the system militate against such scenarios. However, sabotage (intrusion to damage performance outside legal frameworks) requires explicit discussion within the set of scenarios. In addition, sabotage to prevent injection operations is considered to be associated with operational activities outside of the storage system, hence out-of-scope of this risk assessment; sabotage scenarios here therefore focus on damage of well heads after operations are complete.

4.3.8 Scenario Description Overview

The EES and AES identified in the previous section are described in summary form in the following sections. More detailed descriptions are provided in Appendix A.

4.3.9 Expected Evolution Scenario

Table 4.3 provides the same information presented in Figure 4.20, but in bullet point form. Subsequent scenario descriptions are provided in a similar form to highlight differences.

Table 4.3 EES Condensed Description

CO_2 Injection	• Operations will be in line with current site operator plans • Bunter sandstone reservoir pressure monitored to preserve integrity of the Röt clay primary seal, which overlies the reservoir • Injectivity will be maintained by taking appropriate measures, such as water washes with meg; • Will be at a rate determined by the supply of CO_2, with a maximum rate of 2.68MT/yr
CO_2 Migration	• Lateral extent of the CO_2 will remain within the storage site • Will occur as a free phase and dissolved in water within the storage site • Heterogeneous petrophysical properties, for example due to the presence of sub-seismic faults and fractures, or lithological variations (such as sandier and more clay rich beds) will increase dissolution and diffusion into rock matrix (compared with a homogeneous medium)
Primary Seal and Secondary Seals	• Will provide a tight seal against vertical migration, with permeability as currently estimated
Well Seals	• Will behave ‘as designed’ • Will evolve chemically and physically, but slowly over the long term and in such a way that their performance does not deteriorate
Monitoring	• Wells will be monitored in the operational and short term post closure phases • There will be continuing monitoring of the storage complex
The Biosphere	• Will not evolve significantly as a consequence of CO_2 storage, but will likely evolve as a result of other factors, such as climate change

4.3.10 Alternative Evolution Scenarios

4.3.10.1 Overview

In the following subsections, each of the scenarios identified in Table 4.2 are described in turn, focusing on the key changes from the EES.

4.3.10.2 AE1 Reduced Injectivity

The Reduced Injectivity Scenario (AE1) is illustrated schematically in Figure 4.21, in which only the rock formations surrounding the storage reservoir (Bunter sandstone) are shown. Changes from the EES are summarised in Table 4.4

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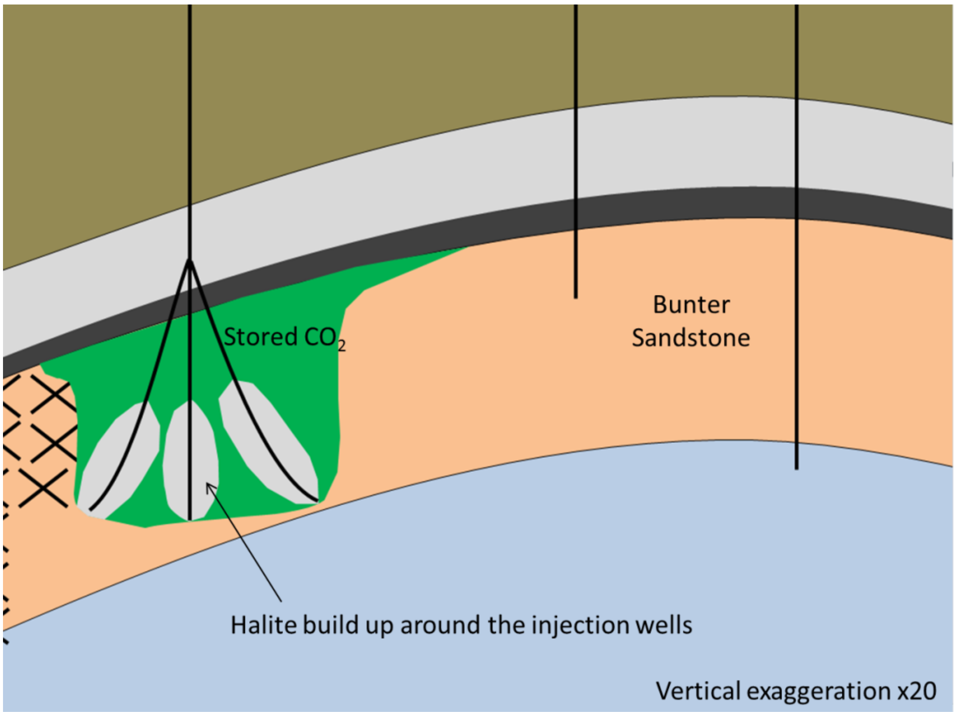
Figure 4.21 Reduced Injectivity Scenario (AE1)



The rock formations surrounding the storage reservoir (Bunter sandstone) only are shown.

Table 4.4 AE1 Reduced Injectivity due to Chemical Changes/Reactivity – Changes from Expected Evolution

CO_2 Injection	• Washes with filtered seawater including a hydrate inhibitor (such as MEG) will not be sufficient to retain injectivity • Sand generation results in clogging of the injection wells • Will be at a rate influenced by the supply of CO_2 reduced by precipitation of minerals or hydrates at or near the point of injection and sand clogging of the injection wells

4.3.10.3 AE2 Reservoir Pressurisation

The Reservoir Pressurisation Scenario (AE2) is illustrated schematically in Figure 4.22, in which only rock formations surrounding the storage reservoir (Bunter sandstone) are shown. Changes from the EES are summarised in Table 4.5.

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Figure 4.22 Reservoir Pressurisation Scenario (AE2)

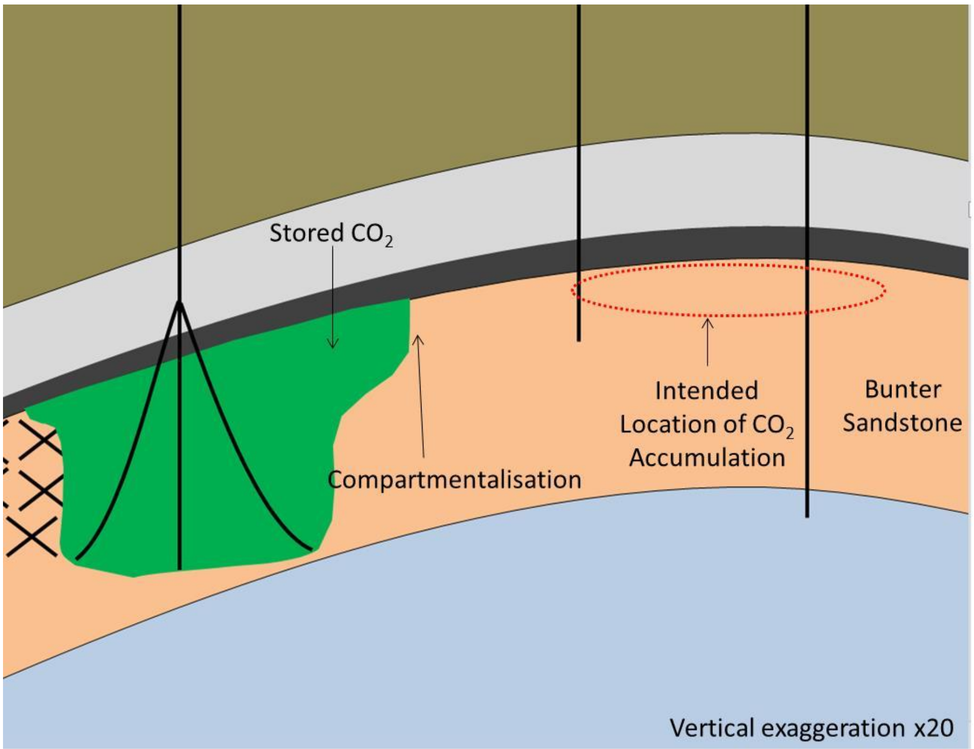


Table 4.5 AE2 Reservoir Pressurisation Due to Unexpected Compartmentalisation – Changes from Expected Evolution

CO_2 Injection	- Will be at a rate influenced by the supply of CO_2, but pressurisation within the system will reduce injectivity
CO_2 Migration	- Lateral extent of the CO_2 will remain closer to the injection point than expected, due to compartmentalisation

Note It is possible that impurities in the injected CO_2 stream could lead to changes to pressure behaviour, but the effects are captured within this scenario also.

4.3.10.4 AE3 Leakage through the Primary Seal and Secondary Seals

AE3.a via Faults/Fractures

The Leakage through the Primary Seal and Secondary Seals via Faults/Fractures Scenario (AE3.a) is illustrated schematically in Figure 4.23, in whcih. Changes from the EES are summarised in Table 4.6.

Figure 4.23 Leakage through Primary and Secondary Seals via Faults/Fractures Scenario (AE3.a)

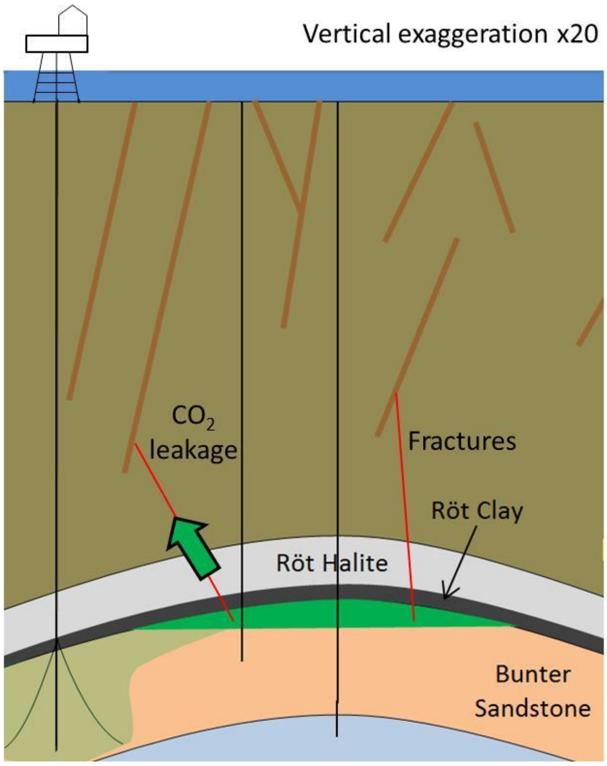


Table 4.6 AE3.a Leakage through Primary and Secondary Seals via Faults/Fractures – Changes from Expected Evolution

Primary Seal and Secondary Seals	- Will provide a tight system against vertical migration, with permeability as currently estimated except that faults/fractures within the zone occupied by the CO_2 provide a conductive pathway through the primary seal and secondary seals; this may be either as a result of a pre-existing pathway or as a result of fault/fracture widening

AE3.b Diffusion

The leakage through the primary seal and secondary seals by diffusion scenario (AE3.b) is illustrated schematically in Figure 4.24. Changes from the EES are summarised in Table 4.7.

Figure 4.24 Leakage through Primary and Secondary Seals by Diffusion Scenario (AE3.b)

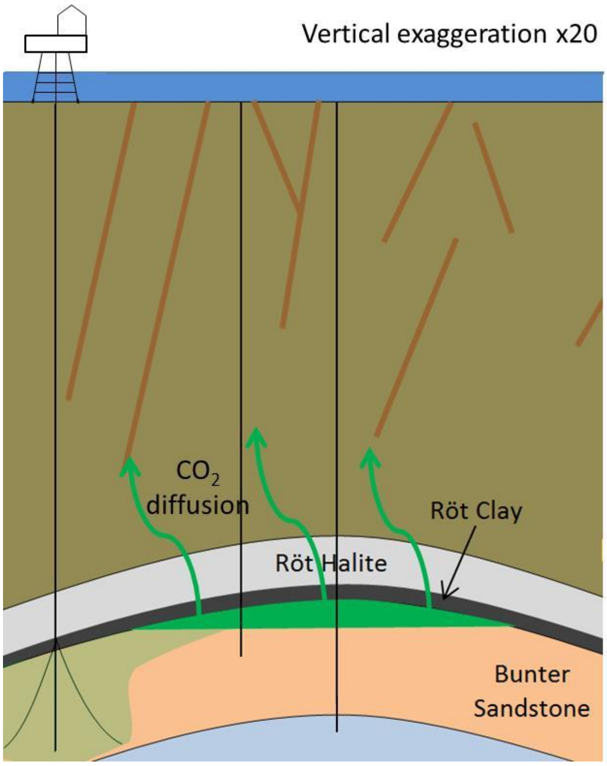


Table 4.7 AE3.b Leakage through Primary and Secondary Seals by Diffusion – Changes from Expected Evolution

Primary Seal and Secondary Seals	- Will provide a barrier against vertical migration, except that its diffusivity will be considerably higher than current estimates* or the primary seal is significantly thinner than expected

*: Including the potential for increased 'effective diffusivity' through microfractures.

4.3.10.5 AE4 Increased Displacement of High Salinity Formation Waters

The Increased Displacement of High Salinity Formation Waters Scenario (AE4) is illustrated schematically in Figure 4.25 and Figure 4.26. Changes from the EES are summarised in Table 4.8. This scenario considers that the amount of formation water discharged to the seabed is greater than expected (AE4.a) or the salinity is higher than expected (AE4.b). Discharge to the seabed may occur via fractures (Figure 4.25) or at outcrop (Figure 4.26), although discharge via fractures is unlikely – see AE3.a.

Figure 4.25 Increased Displacement of High Salinity Formation Waters via Fractures Scenario (AE4)

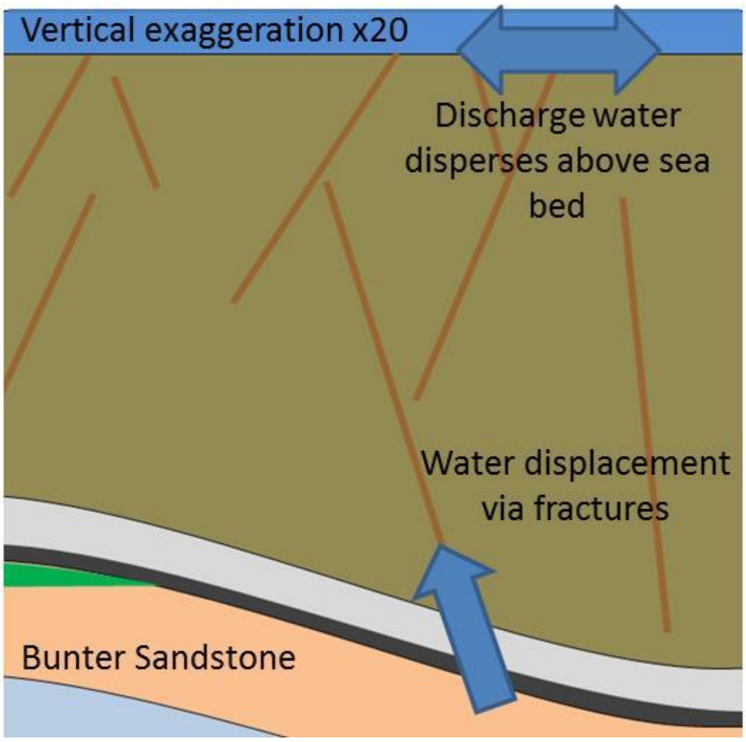
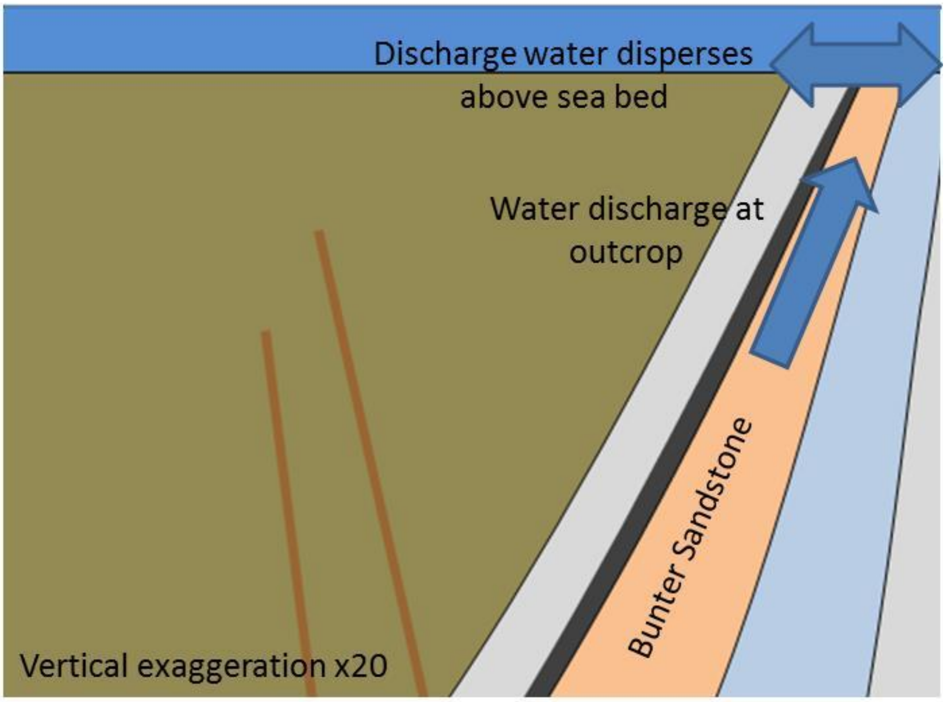


Table 4.8 AE4 Increased Displacement of High Salinity Formation Waters – Changes from Expected Evolution

CO_2 Injection	- Variants consider situations whereby injection leads to either discharge of increased volumes of formation waters to the seabed and water column (Variant AE4.a) or the formation waters have greater salinity (Variant AE4.b)
The Biosphere	- Will be subject to a local increase in salinity in the seabed near the water column interface, followed by dispersion of the increased salinity water within the seawaters

Figure 4.26 Increased Displacement of High Salinity Formation Waters via Outcrop Scenario (AE4)



4.3.10.6 AE5 Well Failure

AE5.a Injection Wells

The Well Failure: Injection Wells Scenario (AE5.a) is illustrated schematically in Figure 4.27, in which only lower part of injection well shown. Changes from the EES are summarised in Table 4.9.

Figure 4.27 Well Failure Injection Wells Scenario (AE5.a)

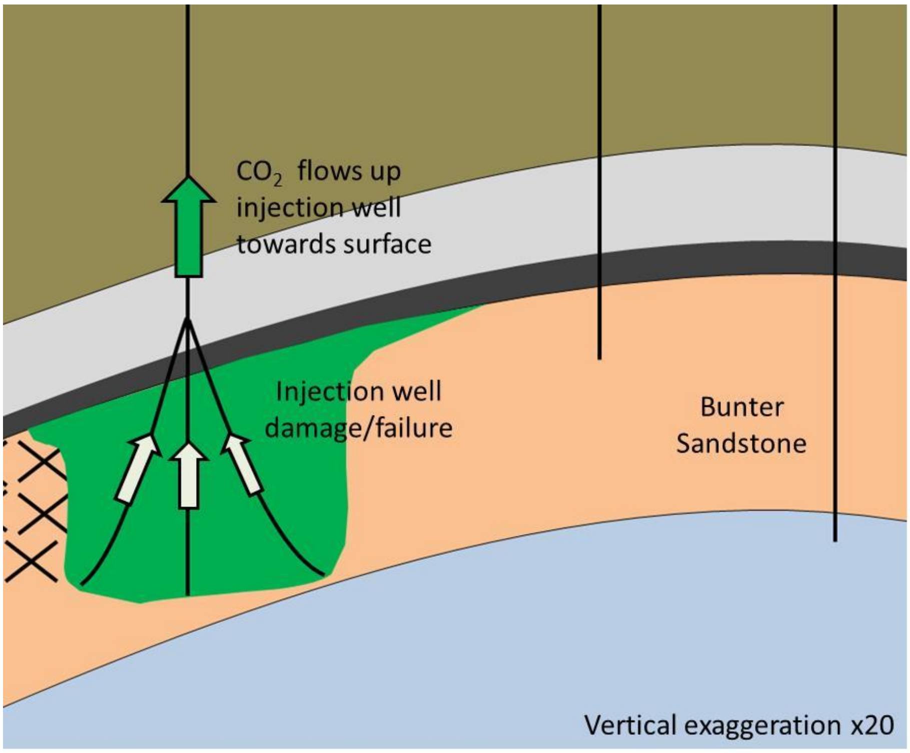


Table 4.9 AE5.a Well Failure Injection Wells – Changes from Expected Evolution

Well Seals	• One of the wells used for injection will subsequently suffer early well seal failure or significant accidental damage to the seabed exposure of the abandoned well, for example, as a result of trawling activities post-abandonment. Variants explore: Failure/damage during injection (AE5.a.1) Failure/damage on injection cessation (AE5.a.2) Failure/damage a few hundred years after injection cessation (AE5.a.3) These variants consider failure to either be: complete (open pathway to water column) or partial (increased conductivity pathway to surface)

AE5.b Other Wells

The Well Failure: Other Wells Scenario (AE5.b) is illustrated schematically in Figure 4.28. Changes from the EES are summarised in Table 4.10.

Figure 4.28 Well Failure Other Wells Scenario (AE5.b)

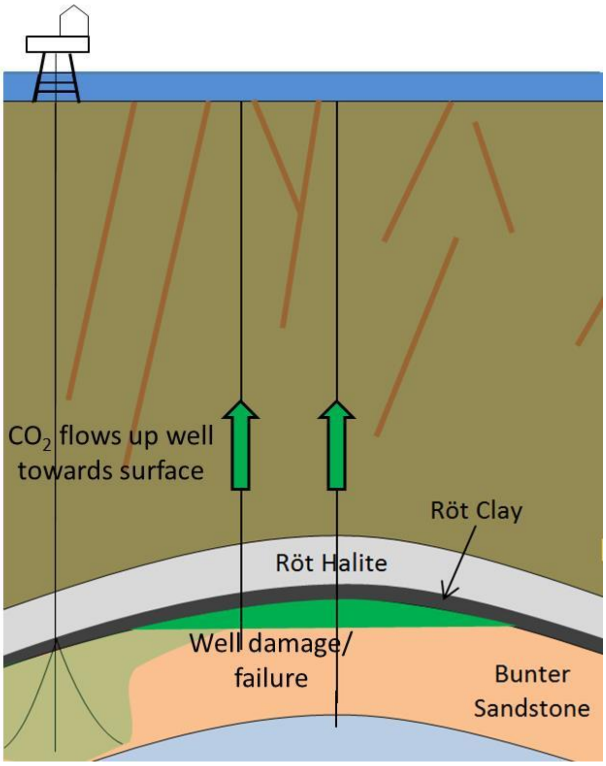


Table 4.10 AE5.b Well Failure: Other Wells – Changes from Expected Evolution

Well Seals	• One of the existing abandoned exploration wells situated some distance from the injection area will subsequently suffer early well seal failure. Variants explore: Failure during injection (AE5.b.1) Failure on injection cessation (AE5.b.2) Failure a few hundred years after injection cessation (AE5.b.3) These variants consider failure to either be: Complete (open pathway to water column) or partial (increased conductivity pathway to surface)

4.3.10.7 AE6 Lateral Interaction with Other Hydrocarbon Resources

The Lateral Interaction with Other Hydrocarbon Resources Scenario (AE6) is included for completeness. However, although the pressure changes in the Endurance structure may impact on other reservoirs in the Bunter sandstone, the potential pressure changes at the nearest gas fields due to CO_2 injection into the Endurance structure are negligible compared with the pressure changes due to gas production, or if these fields were subsequently used for CO_2 storage following their depletion of gas. Therefore, no schematic illustration of this scenario is provided. Changes from the EES are summarised in Table 4.11.

Table 4.11 AE6 Lateral Interaction with Other Hydrocarbon Resources – Changes from Expected Evolution

CO_2 Migration	• Lateral extent of the CO_2 will be significantly greater than is currently expected, with the potential for interaction with other hydrocarbon resources

4.3.10.8 AE7 Resource Exploitation Elsewhere Affects CO_2 Storage System

The Resource Exploitation Elsewhere Affects CO_2 Storage System Scenario (AE7) is illustrated schematically in Figure 4.29, in which only rock formations around stored CO_2 plume shown. Changes from the EES are summarised in Table 4.12.

Figure 4.29 Resource Exploitation Elsewhere Affects CO_2 Storage System Scenario (AE7)

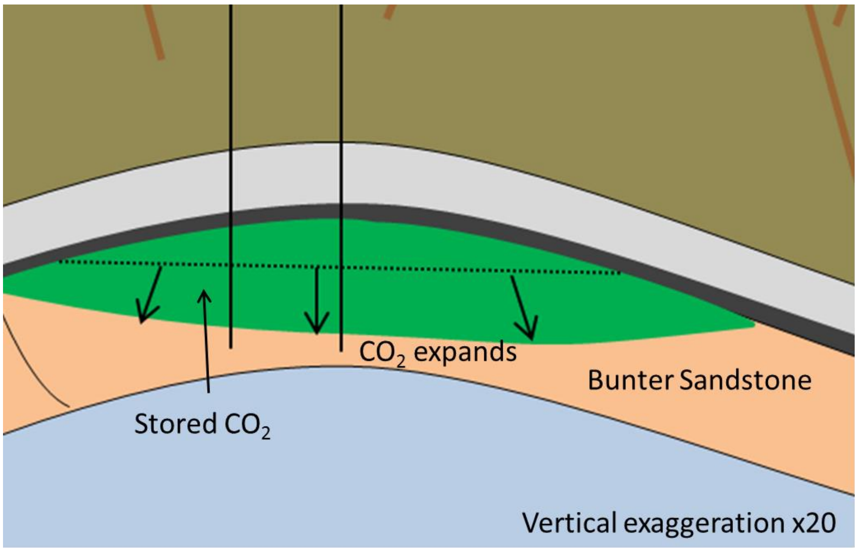


Table 4.12 AE7 Resource Exploitation Elsewhere Affects CO_2 Storage System – Changes from Expected Evolution

CO_2 Injection	• Will be at a rate influenced by the supply of CO_2, but pressure changes will influence injectivity
CO_2 Migration	• Lateral extent of the CO_2 will be more or less than 'expected' due to resource exploitation elsewhere, leading to an increase or reduction in pressure in the storage site

4.3.10.9 *AE8 Seabed Uplift/Tilting*

The Seabed Uplift/Tilting Scenario (AE8) is illustrated schematically in Figure 4.30, in which only the region of the seabed shown. Changes from the EES are summarised in Table 4.13.

Figure 4.30 Seabed Uplift/Tilting Scenario (AE8)

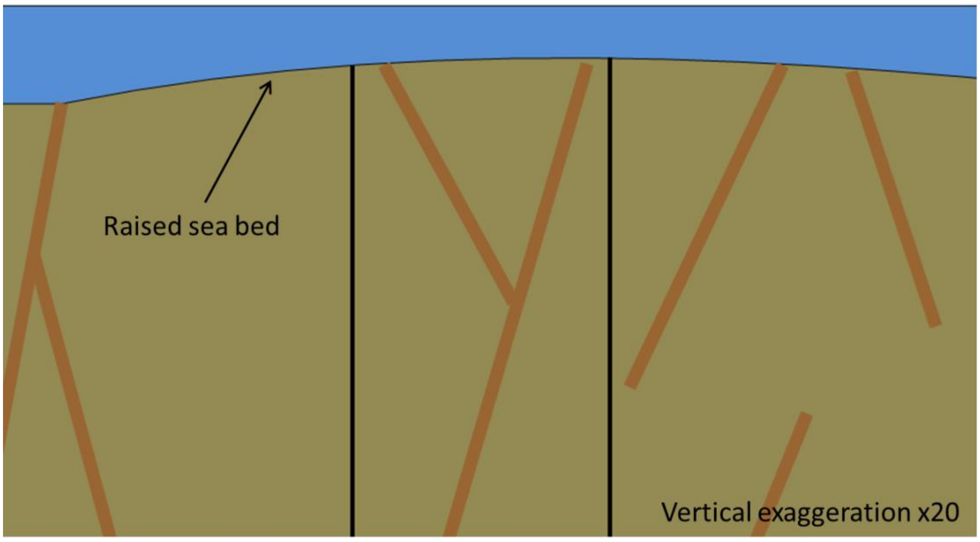


Table 4.13 AE8 Seabed Uplift/Tilting – Changes from Expected Evolution

CO_2 Injection	• Will be at a rate influenced by the supply of CO_2, but will lead to reservoir pressurisation beyond the EES, leading to potentially seabed uplift and/or tilting
CO_2 Migration	• Reduced residual trapping and dissolution during migration leads to increased pressures
Primary Seal and Secondary Seals	• Movement on faults in the primary seal and overburden results in locally increased uplift

4.3.10.10 AE9 Human Intrusion

The Human Intrusion Scenario (AE9) is illustrated schematically in Figure 4.31, in which only sea and geosphere immediately below the seabed are shown. Changes from the EES are summarised in

Table 4.14.

Figure 4.31 Human Intrusion Scenario (AE9)

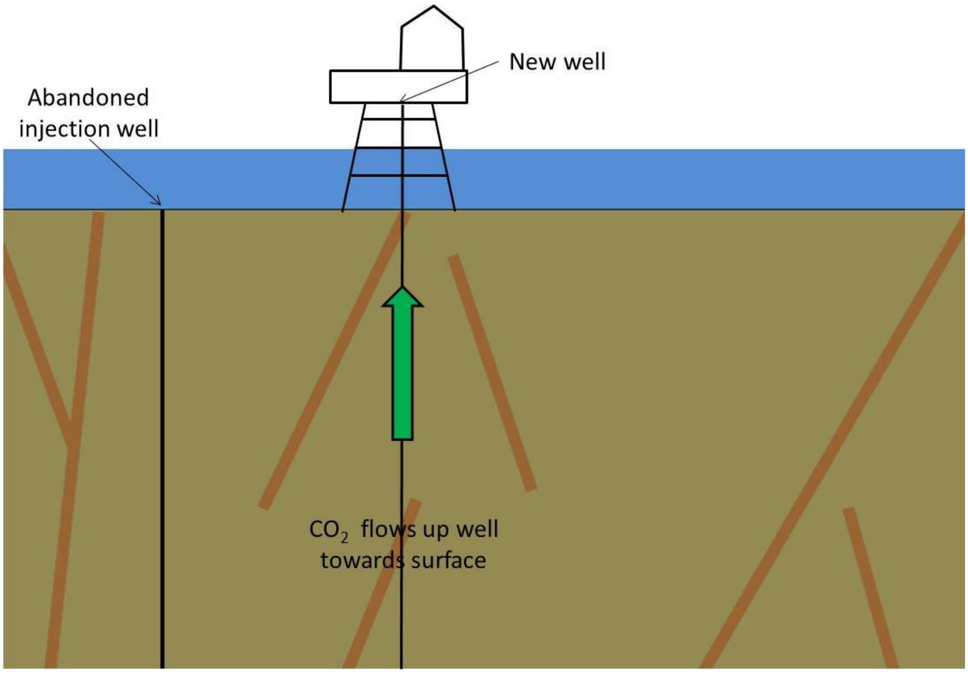


Table 4.14 AE9 Human Intrusion – Changes from Expected Evolution

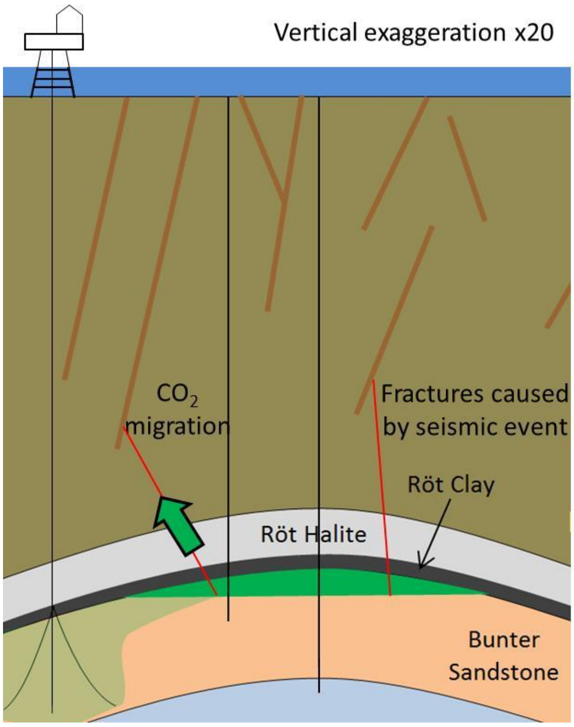
Well Seals	• A new well will be drilled into the storage system in this scenario, by people who do not know of the existence of the system, leading to a temporary new well pathway to the surface until blocked/remediated • The well is poorly abandoned, results in a chronic leakage pathway to the seabed

4.3.10.11 AE10 Leakage as a Result of Seismic Events

Overview of Leakage as a Result of Seismic Events

The Leakage as a Result of Seismic Events Scenario (AE10) explores the leakage of CO_2 via faults or fractures that are either created or opened by seismicity, whether induced or natural. These situations are illustrated schematically in Figure 4.32.

Figure 4.32 Leakage as Result of Seismic Events Scenario (AE10)



AE10.a Induced Seismicity

In the Induced Seismicity variant of the Leakage as Result of Seismic Events Scenario (AE10.a), fractures or faults are either created or opened as a consequence of seismicity due to CO_2 injection, or activities in other hydrocarbon fields in the area. Changes from the EES are summarised in Table 4.15.

Table 4.15 AE10.a Induced Seismicity – Changes from Expected Evolution

CO_2 Injection	• Reservoir pressure monitoring in this scenario proves insufficient to preserve primary seal integrity and induced seismicity occurs*
Primary Seal and Secondary Seals	• Will provide a tight system against vertical migration, with permeability as currently estimated except that faults/fractures within the zone occupied by the CO_2 plume provide a conductive pathway through the primary seal as a result of fault/fracture dilation through induced seismicity (AE10.a.1)
Well Seals	• A further variant considers that one of the wells used for injection will suffer early well seal failure as a result of induced seismicity during injection (AE10.a.2)

* Also covers the potential for induced seismicity due to operations in adjacent fields

AE10.b Natural Seismicity

In the Natural Seismicity variant of the Leakage as Result of Seismic Events Scenario (AE10.b), fractures or faults are either created or opened as a consequence of natural seismicity. Changes from the EES are summarised in Table 4.16.

Table 4.16 AE10.b Natural Seismicity – Changes from Expected Evolution

Primary Seal and Secondary Seals	• Will provide a tight system against vertical migration, with permeability as currently estimated except that faults/fractures within the zone occupied by the CO_2 provide a conductive pathway through the primary seal; in this variant as a result of fault/fracture shifts or widening as a result of a significant seismic event

4.3.10.12 AE11 Sabotage

The Sabotage Scenario (AE11) involves humans deliberately and maliciously causing damage to seabed installations, such that well seals in the upper part of one or more abandoned wells are damaged. Changes from the EES are summarised in Table 4.17.

Table 4.17 AE11 Sabotage – Changes from Expected Evolution

Well Seals	• The seabed exposures of the abandoned wells will be damaged as a result of intentional sabotage, leading to partial failure of the upper components of well seals (see also AE5)

4.3.10.13 AE12 Accidental Over-filling

The Accidental Over-filling Scenario (AE12) is illustrated schematically in Figure 4.33. Changes from the EES are summarised in Table 4.18.

Figure 4.33 Accidental Overfilling Scenario (AE12)

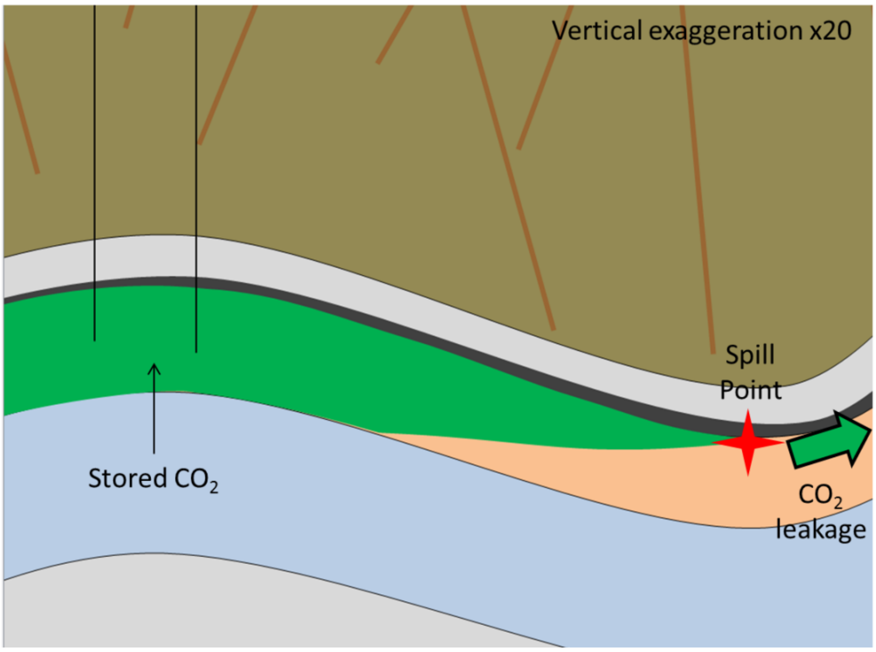


Table 4.18 AE12 Accidental Over-filling – Changes from Expected Evolution

CO_2 Injection	• Operations will be in line with current site operator plans except that a significant amount of CO_2 will be injected that is additional to current plans
CO_2 Migration	• Lateral extent of the CO_2 may be increased compared to the Expected Evolution Scenario due to CO_2 volumes being greater than initially planned and/or the storage capacity being less than initially predicted and/or there being localised, more permeable conduits through the reservoir than recognised initially

4.4 Analysis of Key Risks Associated with Scenarios

4.4.1 Overview

The assessment of risks presented in Section 4.5 and summarised in Section 4.6 is underpinned by a wide range of evidence sources. These range from site data, interpretation of data, detailed modelling outputs and simpler scoping calculations to bound and assess specific risks.

This section provides an assessment of a range of key risks associated with the scenarios identified in previous sections. The focus is on key aspects for which specific risk analyses were identified as being required in order to complement existing work. These analyses include logical arguments and scoping calculations to further characterise and bound risks.

Each aspect of the analysis presented below considers a specific aspect of the system that is relevant to estimating risk. These aspects may be relevant to more than one scenario. For example, discharge of higher salinity waters to the seabed and seawater column will occur for the EES and for various AES scenarios. Therefore, as common data and arguments can inform on the risk outcomes for more than one scenario, they are assessed together.

Key risks not addressed in this section (for example the implications of seabed uplift) are assessed directly on the basis of evidence that is already directly relevant in Section 4.5.

4.4.2 Discharge of Higher Salinity Waters

For the EES, it is anticipated that injection of CO_2 into Endurance will result in discharge of water at the seabed outcrop of the Bunter sandstone, located approximately 25km to the southeast of the crest of Endurance. The water in Endurance is highly saline, but the water that will discharge at the outcrop is expected to be more similar to seawater. A scoping calculation was undertaken to assess:

- the potential salinity of the water that will be discharged to the seabed; and
- the potential environmental impacts.

4.4.2.1 Description of the Discharge Zone

Geography and Geology

The outcropping Bunter sandstone and shale form a circular feature on the seabed which is approximately 10m high, see Figure 4.14. The slightly lower topography inside and outside the circular feature is associated with the outcropping Zechstein halite, Bunter shale and the Röt clay and Röt halite, see Figure 4.14 and Figure 4.15. The outcrop area is covered by Holocene sands, which form dunes above the Endurance structure. Across approximately 70% of the Bunter sandstone outcrop see Figure 4.15, the Holocene sands are underlain by Quaternary clayey sand (Markham's hole formation) or stiff sandy clay (Swarte bank formation). Seismic data indicate that the total thickness of Quaternary and Holocene deposits is up to 15m.

There is some uncertainty as to the thickness of the Quaternary sediments. Cuttings from well 43/28a-3, see Figure 4.14, indicate that the Quaternary may be as much as 90m thick. Reasons for this apparent discrepancy are discussed by AGR (2015b). At present, the explanation considered to be most likely is that dissolution of soluble salts such as anhydrite within the Röt clay and evaporite bearing portions of the Bunter sandstone has resulted in collapse structures that contain greater thicknesses of Quaternary deposits. Well 43/28a-3 may have intercepted one of these features. However, this uncertainty is not particularly important in the context of the potential impacts of discharge of saline water at outcrop.

The Quaternary sediments are thought to be significantly less permeable than the Bunter sandstone and the Holocene cover sands. Therefore, discharge of water at the outcrop may be focussed through the areas where the Quaternary sediments are absent.

Flora and Fauna

Two studies have sampled the fauna in the general area of the Endurance structure and the seabed outcrop, however no data has been found from directly over the seabed outcrop.

The offshore environmental impact assessment for the project reports data from the northwest and southeast of the Endurance structure (locations P1 and P2). Each survey had eight sample stations. The benthic communities made up of organisms that live in (infauna) and on (epifauna) the seabed at the two locations were quite similar. Sediment was classified as sand to slightly gravelly sand. The infauna was dominated by echinoderms and polychaetes, with the most abundant taxa (group of one or more populations of an organism), the small urchin Echinocyamus pusillus and juvenile Ophiuroid brittlestars accounting for 39% of individuals sampled at the P1 site and 36% at the P2 site. The five most abundant taxa at P1 were completed by the annelid worms Grania sp. and S. armiger and the bivalve Cochlodesma praetenue.

Data on the benthic fauna is also available from the smart wind project. The closest data point is around 600m south of the outcrop and the three most common taxa at this sample point were Ophiuroid brittlestars Amphiura filiformis, polychaetes Lumbrineris gracilis and bivalves Mysella bidentate.

It is uncertain whether the observed species are representative of the species that live at the seabed outcrop of the Bunter sandstone. There is a possibility that the characteristics of the outcrop and the proximity to the Zechstein halite could alter the conditions enough for a different community of organisms to develop.

Salinity Profile in the Bunter Sandstone

Using the pressure gradient between the seabed (depth 65m, pressure 6.5bar) and the reservoir (depth 1405m below sea level, pressure 152bar), the average density of the fluid in the Bunter sandstone between the seabed outcrop and the reservoir can be calculated, assuming a hydrostatic pressure gradient, which is 1107kg/m^3.

The pressure gradient measured in wells 42/25-1 and 42/25d-3 can also be used to calculate the density of brine in the reservoir. The two wells have slightly different pressure gradients, resulting in density estimates of 1174kg/m^3 and 1181kg/m^3.

Taking the reservoir brine density of 1181kg/m^3 and a seawater density of 1027kg/m^3 at 10°C the average of these densities is 1103kg/m^3, which is similar to the average density calculated from the pressure gradient (1107kg/m^3). This is evidence that a linear density variation of brine/saline water from the reservoir to the seabed is a plausible approximation. There is likely to be some non-linearity due to temperature gradients and near seabed effects, but as a broad trend, a linear model seems reasonable.

4.4.2.2 Discharges and Salinity

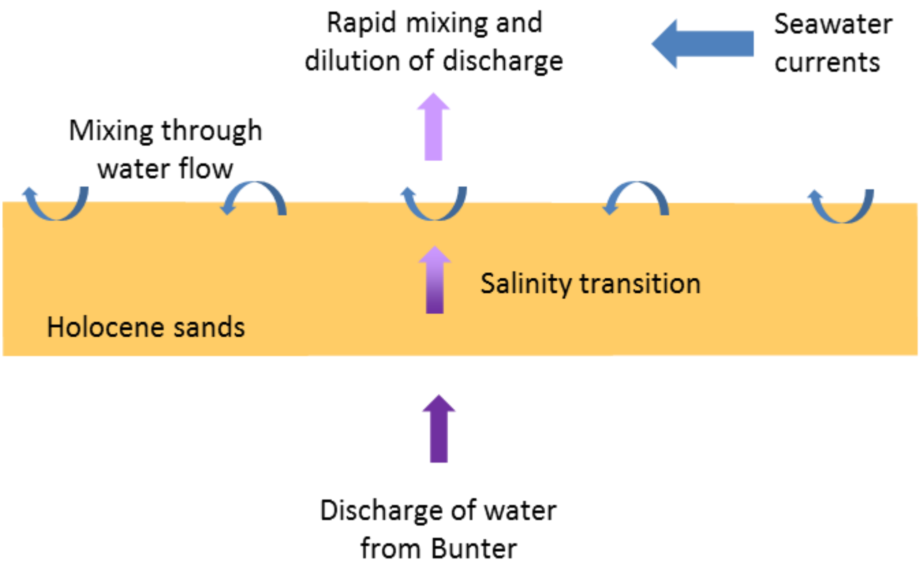
The maximum rate of CO_2 injection is 2.68MT/yr and injection will continue for c. 20 years. These values, together with an assumed CO_2 density of 700kg/m^3 in the reservoir, mean that the stored CO_2 volume is <3.48 x 10^{8}m^3. This volume is also an upper limit on the volume of water that could be discharged from the outcrop. Taking an outcrop area of 5km^2 and a typical sandstone porosity of 22%, the top 70m of water will be discharged from the sandstone.

The seawater is assumed to have a typical salinity of 35% and has an average temperature of 10°C, which gives a density of 1027kg/m^3. Assuming a linear density gradient, at a depth of 70m below the seabed, the density is 1035kg/m^3. At a temperature of 10°C, this is a salinity of 45%.

4.4.2.3 Mixing and Dilution of the Discharges

Figure 4.34 shows the conceptual model of mixing and dilution of discharges from the Bunter sandstone. Water discharged from the Bunter sandstone would flow up through the overlying Holocene sands. The best estimate discharge flux (rate of volume flow across a unit area) from the outcrop is 3000m^3/d. The discharge velocity will depend on whether discharge occurs over the entire outcrop, or only the fraction of the outcrop that is not covered by Quaternary deposits, but will be of the order 0.6 to 2mm/day. There may be some mixing and dilution with seawater towards the top of the Holocene sands Figure 4.34. There will be much more rapid dilution and mixing in the water column.

Figure 4.34 Conceptual Model of Mixing and Dilution of Discharges from the Bunter Sandstone



The amount of seawater the discharge mixes with will depend on the bottom current velocities. NGCL's offshore environmental impact assessment scoping describes the bottom currents above the storage complex:

'In this part of the southern North Sea the outer margins of a southwards flowing coastal current are deflected offshore from Flamborough Head along the northern flank of the Dogger Bank. The position of this eastwards flowing current is known to fluctuate throughout the year and therefore may influence conditions at the storage site and along some of the pipeline route.

One of the primary features of the developed Flamborough Front is an associated near-geostrophic jet running parallel to the front, with speeds in the order of 0.15m/s in the core. The front is primarily a bottom feature with a weak surface signature and is most prevalent during late spring through to late autumn. As the wind increases and convective mixing is introduced in autumn, the front (and its corresponding current) migrates northwards across the shelf away from the proposed storage site and pipeline location'.

Taking the width of the Bunter sandstone outcrop perpendicular to the bottom currents as 1000m and the current velocity as 0.15m/s, it is possible to make a very simple estimate of the amount of mixing immediately above the seabed. This is a very rough calculation because it neglects factors such as the topography and roughness of the seabed which will promote additional mixing. The current velocity is near the lower end of the range used in calculations of dispersion around a borehole from which discharge takes place (range 0.1m/s to 0.5m/s).

The volume of seawater the discharge will mix with, immediately above the discharge area, is:

1000m x 2mm x 0.15m/s = 25,920m^3/d.

This gives a dilution factor of 8.6 (25,920m^3/d/3000m^3/d), although the amount of dilution immediately adjacent to the discharge location may be lower at certain times of the year when the currents are weaker. There will be significantly greater dilution with increasing distance from the discharge area.

4.4.2.4 Assessment of Environmental Impacts

During a number of different projects unconnected with CO_2 storage, saline waters are deliberately discharged to the sea. For example, brine generated through the development of gas storage caverns at Aldborough and Preesall has been discharged to the sea via diffusers on the seabed. The discharge volumes are much larger than the potential discharge from the outcrop of the Bunter sandstone (17,000m^3/d and 80,000m^3/d respectively compared with 3000m^3/d). They are also much more localised and the discharge is of brine rather than water that may have slightly elevated salinity. The Aldborough and Preesall discharge consents are based on limiting salinity of the seawater to 40% at distances of 50 to 250m from the diffuser. A salinity of 40% is around the tolerable upper limit for a number of species.

The scoping calculations above indicate that the salinity of the water discharging to the seabed could increase to up to 45%. This is above the tolerable limit for some species. However, the majority of biota is expected to be found in the top few centimetres of the sediment, in which there may be mixing and dilution with seawater. At most 50:50 mixing with seawater is required to decrease the salinity to 40%. This degree of mixing is plausible, especially noting that the discharge fluxes will not be constant with time. The discharge fluxes will increase as CO_2 is injected into the reservoir, peak immediately following injection and then gradually decrease to zero. Discharges above 40% salinity are associated with the second half of the discharge period, with the highest salinities associated with small volumetric discharge fluxes towards the end of the discharge period. Therefore there is potential for significant dilution of these final, highest salinity discharges. Immediately above the seabed the salinity would be reduced to close to ambient and there would be no significant perturbation of the salinity of the water column.

The Environmental Impact Assessments (EIAs) for the Aldborough and Preesall developments provide further confidence that seabed discharges with slightly elevated salinity will not significantly impact benthic fauna. These EIAs note there is the potential for some (recoverable) impacts to benthic communities. To help mitigate these potential impacts, diffusers are typically located at least 1m above the seabed. Nevertheless, relatively dense saline water around the diffusers could plausibly locally pond and interact with the seabed and the fauna that occupy the top few centimetres of the sediment. The EIAs consider ponding will not lead to significant impacts to the seabed. Although this is partially due to the discharge height of at least 1m and its influence on mixing, it also suggests that, in the opinion of those assessors, even large, sustained high salinity fluxes to the near seabed environment are unlikely to lead to significant impacts to benthic fauna.

4.4.2.5 Conclusions Regarding Brine Discharge

Injection of CO_2 into Endurance is expected to result in discharge of water at the seabed outcrop of the Bunter sandstone. Water is expected to be of similar salinity to seawater. In the second half of the discharge period it is conceivable that the salinity of the waters discharging could rise slightly above the tolerable upper limit for many organisms. However, the volumetric discharge fluxes are sufficiently low that mixing and dilution with seawater is likely to prevent significant impacts to benthic fauna. There is not expected to be any significant perturbation of the salinity of the water column.

4.4.3 Contaminant Discharge

In accordance with guidance on lifecycle risk assessment for CO_2 storage projects it is necessary to assess whether any brine discharges that may occur from the seabed, either at wells or at the Bunter sandstone outcrop, could transport sufficient contaminants to cause significant impacts to receptors.

The chemistry of formation water in the Bunter sandstone formation of the Endurance structure has been evaluated. The only available analyses of Bunter sandstone formation water in this structure were obtained from well 42/25d-3. These analyses are tabulated in Table 4.19. While analyses of drilling fluid tracers employed in the drilling of the borehole indicate insignificant drilling fluid contamination, it is impossible to sample deep formation without perturbing their compositions to some degree. Other processes that typically cause chemical perturbations include mixing between chemically distinct formation waters, corrosion of metal drilling equipment, degassing during depressurisation and microbial activity during borehole drilling and sampling. Many such perturbations will usually affect trace constituents (especially redox sensitive ones like heavy metals) to a much greater degree than major constituents. The degree to which such processes have operated in 42/25d-3 are presently uncertain.

Formation water dispersion above the seabed around brine production wells, in the event that these should be required for pressure management (which is not expected or planned during injection of the CO_2 volumes), was modelled. The conclusion from this modelling was that brine discharge at the seabed would produce a dense water plume with a higher salinity than seawater, which would disperse relatively slowly. Potentially large sand waves present on the seabed above much of the Endurance structure could hinder this dispersion. However, under mean flow conditions a horizontal discharge only a few metres above the seabed was predicted to result in salinity of 62% on the seabed below the discharge point and 46% at a distance of 500m. For vertical discharge at a height of 4m above the seabed the salinity on the seabed at a distance of 500m was calculated to be 40%. Thus, by suitably managing the discharge location maximum salinity increases could be limited to values comparable in magnitude to those caused by brine discharges to seawater that have been permitted elsewhere in other projects.

The composition of the Bunter sandstone formation water in the Endurance structure was compared with a number of natural water compositions from other locations and a variety of water quality standards and guidelines. It was found that concentrations of various heavy metals and other elements of concern in the marine environment are elevated in the formation water from the Bunter sandstone. However, these elevated concentrations would not necessarily prevent discharges being permitted, provided a risk based assessment shows that:

- risks are acceptable, taking into account exposure resulting from discharge of the produced water and the sensitivity of the receiving environment to this exposure, such that Predicted Environmental Concentration (PEC) < Predicted No Effect Concentration (PNEC); and
- if the risk is not acceptable, by taking appropriate measures based on Best Available Technology (BAT) and Best Environmental Practice (BEP) to avoid or minimise exposure levels above the PNEC.

Table 4.19 Formation Water Composition in Well 42/25d-3

Formation water compared with compositions of marine water, North Sea background concentrations, PNEC values and WHO drinking water guideline values.

Sampling Point/ Depth		5167.5ft depth	4722ft depth	4634ft depth	Separator water line	4589.37ft depth	Estimated maximum contribution by formation water to formation water - seawater-mixture	Estimated maximum concentration in most saline formation water - seawater-mixture	Surface seawater composition mg/l	Ranges of background concentrations of dissolved trace metals in the southern North Sea mg/kg	Ranges of background concentrations of dissolved trace metals in the northern North Sea mg/kg	PNEC values for substances in seawater mg/l	WHO drinking water guideline values and indicative upper limits before water would be impotable mg/l
Chloride	mg/kg	154146	148780	148164	155600	155405	16100	33500	19400	NR	NR	NR	300#
Fluoride	mg/kg	0.15	0.12	0.1	0.13	0.14	0.0156	1.186	1.3	NR	NR	NR	1.5
Sulphate	mg/kg	296	359	385	360	364	39.9	2470	2711	NR	NR	NR	None
Bromide	mg/kg	473	460	444	438	470	49.1	109	67.3	NR	NR	NR	None
Nitrate	mg/kg	<4	<4	<4	<4	<4	<4	N.C.	2.2	NR	NR	NR	50
Iodide	mg/kg	<4	<4	<4	<4	<4	<4	N.C.	0.06	NR	NR	NR	None
Phosphate	mg/kg	<20	<20	<20	<20	<20	<20	N.C.	0.184	NR	NR	NR	
Total Carbonate (as Bicarbonate) Immediate	mg/kg	38	37	43	NR	39	4.46	131	142.24	NR	NR	NR	None
Formate	mg/kg	<2	<2	<2	<2	<2	<2	N.C.	NR	NR	NR	NR	None
Acetate	mg/kg	<2	<2	<2	<2	<2	<2	N.C.	NR	NR	NR	NR	None
Propionate	mg/kg	<3	<3	<3	<3	<3	<3	N.C.	NR	NR	NR	NR	None
Butyrate	mg/kg	<4	<4	<4	<4	<4	<4	N.C.	NR	NR	NR	NR	None
Iso-valerate	mg/kg	<4	<4	<4	<4	<4	<4	N.C.	NR	NR	NR	NR	None
Lithium	mg/kg	7.9	8	7.6	8.4	8.5	0.882	1.04	0.18	NR	NR	NR	None
Barium	mg/kg	2	1	1	1	1	0.207	0.219	0.013	NR	NR	NR	0.7
Strontium	mg/kg	108	111	103	117	116	12.1	19.18	7.9	NR	NR	NR	None
Calcium	mg/kg	8858	8610	8037	8985	9129	947	1316	412	NR	NR	NR	300#
Magnesium	mg/kg	2543	3014	3192	3138	3103	331	1491	1290	NR	NR	NR	
Sodium	mg/kg	85512	79664	79953	83763	84792	8870	18550	10800	NR	NR	NR	300#
Potassium	mg/kg	1400	1469	1483	1553	1525	161	519	399	NR	NR	NR	300#
Iron	mg/kg	<1	<1	<1	2	1	0.207	0.209	0.002	NR	0.0002 - 0.0006	NR	0.3ł
Copper	mg/kg	3.9	1.7	1.3	1	1.7	0.405	0.405	0.00025	0.00014 - 0.00036	0.00005 - 0.00009	0.0026	2
Zinc	mg/kg	7.8	8.5	7.9	8.9	8.8	0.923	0.927	0.0049	0.00017 - 0.00028	0.00025 - 0.00045	0.0034 above background	None
Manganese	mg/kg	2.6	1.6	1.5	1.7	1.7	0.270	0.270	0.0002	NR	0.00006 - 0.00015	NR	None
Aluminium	mg/kg	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6	N.C.	0.002	NR	NR	NR	0.9*
Ammonium	mg/kg	<10	<10	<10	<10	<10	<10	N.C.	NR	NR	NR	NR	35$
Lead	mg/kg	1.1	1.3	1.4	1.4	1.5	0.156	0.156	0.00003	0.00001 - 0.000017	0.00001 - 0.00002	0.0013	0.01
Chromium	mg/kg	0.3	0.4	0.4	0.7	0.7	0.0726	0.073	0.0003	NR	NR	0.0006 above background	0.05
Nickel	mg/kg	<0.2	1.8	1.6	<0.2	0.4	0.187	0.188	0.00056	0.00018 - 0.00026	0.0002 - 0.00025	0.0086 above background	0.07
Cadmium	mg/kg	0.2	0.2	0.2	0.1	0.2	0.0207	0.021	0.00011	0.000009 -.000012	0.0000080 - 000025	0.0002 above background	0.003
Cobalt	mg/kg	0.15	0.16	0.16	0.09	0.08	0.0166	0.017	0.00002	0.0000060 - 000024	NR	NR	None
Silver	mg/kg	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	N.C.	0.00004	NR	NR	NR	None
Vanadium	mg/kg	0.07	0.07	0.08	0.07	0.06	0.0083	0.011	0.0025	0.00009 - 0.00105	0.00125 - 0.00145	NR	None

Sampling Point/ Depth		5167.5ft depth	4722ft depth	4634ft depth	Separator water line	4589.37ft depth	Estimated maximum contribution by formation water to formation water - seawater-mixture	Estimated maximum concentration in most saline formation water - seawater-mixture	Surface seawater composition mg/l	Ranges of background concentrations of dissolved trace metals in the southern North Sea mg/kg	Ranges of background concentrations of dissolved trace metals in the northern North Sea mg/kg	PNEC values for substances in seawater mg/l	WHO drinking water guideline values and indicative upper limits before water would be impotable mg/l
Arsenic	mg/kg	1.2	1.3	1.5	2.1	2.4	0.249	0.252	0.0037	NR	NR	0.0006 above background	0.01
Boron	mg/kg	9	10	9	10	10	1.04	5.02	4.44	NR	NR	NR	2.4
Phosphorus	mg/kg	<6	<6	<6	<6	<6	<6	N.C.	0.06	NR	NR	NR	None
Silicon	mg/kg	3	3	3	4	4	0.415	2.385	2.2	NR	NR	NR	None
Sulphur	mg/kg	84	104	112	107	106	11.6	822.6	905	NR	NR	NR	None
Total Barium	mg/kg	2	2	1	2	1	0.207	0.219	0.013	NR	NR	NR	0.7
Total Iron	mg/kg	<1	1	<1	3	1	0.311	0.313	0.002	NR	NR	NR	0.3ƚ
Soluble Mercury	mg/kg	0.0004	0.0002	0.0002	0.0003	<0.0002	0.0000415	6.84 x 10^{-5}	0.00003	NR	0.0000002 - 0.0000005	0.00005 above background	0.006

Notes:
N.C. Not calculated
NR Not reported in the specified literature source.
*This concentration is stated as a health-based value; no guideline value is specified.
$ This is a concentration at which ammonium would be tasted, but it would not cause health problems at such a low concentration; no guideline value is specified.
#This is the upper limit of the taste threshold for the chloride in drinking water (taste thresholds for NaCl, KCl and CaCl2 are in the range 200mg/l to 300 mg/l depending upon the individual undertaking the tasting); no health-based guideline is specified.
ƚThis is the level at which discolouration is observed; no guideline value is specified.
WHO is the World Health Organisation

While deliberate discharges of formation water from wells are not planned during the Project and discharges from sealed wells are not expected to occur, discharges of formation water are predicted to take place from the seabed outcrop of the Bunter sandstone, as discussed in Section 4.4.2. However, there is no information available about the chemistry of the formation water within the Bunter sandstone beneath the outcrop. Appraisal well 42/25-d3, which yielded the water for which analyses are reported, is located more than 25km from the outcrop. Furthermore, the area around the outcrop has been glaciated during the Pleistocene and intermittently emergent above sea level during interglacial periods. It is likely that during these periods of glaciation and emergence, fresh water would have recharged the subsurface beneath the outcrop. It is well established that near coastal areas of the present North Sea, formation waters may contain components of such recharge waters at depths of up to several hundred metres. Taking these factors into account, the relevance of the water chemical data from 42/25-d3 for deducing the levels of contaminants that might be discharged from the outcrop is questionable.

In the absence of other information, some insights into the plausible hazard that might be posed by the formation waters in the Bunter sandstone of well 42/25-d3 can be gained by comparing the concentrations of the solutes in these waters with the composition of seawater, background concentrations in the North Sea, PNEC values and WHO drinking water guideline values (Table 4.19). These latter values are used for comparison, even though clearly the discharged brine would never be considered for drinking by humans, because they include values for certain constituents for which other relevant standards are not available. A potential contaminant having a concentration lower than that of a WHO guideline value, which is based on a conservative assessment of potential health impacts, is a good reason for not being concerned about that potential contaminant. For example, no PNEC value is specified for iron, but there is a WHO drinking water guideline value of 0.3mg/l.

Those constituents for which a PNEC value has not been quoted and for which there is also no WHO drinking water guideline value are not generally considered to be of primary environmental concern individually.

If the water in the Bunter sandstone beneath the outcrop were to be chemically similar to the water sampled in well 42/25-d3, then after dilution during discharge to a salinity of 45% (the maximum post-dilution salinity calculated Section 5.2.3 based on conservative estimates of fluxes and also similar to the diluted well discharges calculated by Hartley Anderson 2014a), the only heavy metals that would have concentrations in excess of PNEC values and drinking water guideline levels are lead, chromium, nickel, cadmium, zinc and arsenic. Additionally, copper concentrations would be in excess of the PNEC concentration given by OSPAR (2014), but does not exceed the WHO drinking water guideline value. Although the boron concentration is calculated to be higher than the WHO guideline value, it is only 13% higher than the seawater value.

Of course as noted in Section 4.4.4.4, if formation water discharge from the outcrop resulted in seawater salinity rising to >40%, there would be adverse environmental impacts due to the salinity, quite apart from the toxic effects of heavy metals and other contaminants. However, this calculation is based on very conservative assumptions. As explained in Section 4.4.2, during the Project only the formation water occupying pore space to a depth of about 70m below the seabed would be discharged at the seabed. Furthermore, consideration of the formation water pressures in Section 4.4.2.2 suggests that the maximum formation water salinity at a depth of 70m below the seabed would be about 45%. Assuming that this water represents a mixture between brine like that sampled from the Bunter sandstone in well 42/25-d3 and seawater implies that the maximum concentrations of the contaminants in the water that could be discharged from the seabed during the Project would be around 17% of the values given in Table 4.19. This would imply that among the contaminants for which PNEC and/or WHO drinking water guidelines have been specified, only arsenic, lead and zinc could be of concern.

In summary, there are good reasons to believe that the chemistry of formation water that could plausibly be discharged at the seabed outcrop of the Bunter sandstone would be different from the composition of the deep formation water sampled from the Bunter sandstone in well 42/25-d3. If, however, the water within the Bunter sandstone beneath the outcrop is in fact a mixture between present seawater and brine like that sampled from the Bunter sandstone in well 42/25-d3, then it is plausible that the concentrations of certain contaminants, notably certain heavy metals, could rise to levels in water discharging from the outcrop as to be of concern from an environmental impact perspective. However, under more realistic (though still pessimistic) assumptions, only arsenic, lead and zinc would potentially be of concern. It is noteworthy that, even under these assumptions, the levels of heavy metals would not be of concern throughout the entire period of discharge (as salinity levels would rise from seawater levels initially, to the levels of a brine-seawater mixture presently at c. 70m depth below the seabed). The only way to resolve outstanding uncertainties about the chemistry of formation water beneath the outcrop would be to obtain and analyse water samples from boreholes drilled there.

4.4.4 Diffuse Releases

According to the EES there will be no significant leakage of CO_2 from the storage site. Alternative evolution scenario AE3.b considers the possibility that there is some diffuse leakage through the primary seal. The following scoping calculations estimate the potential leakage of CO_2 for the EES and AE3.b.

4.4.4.1 Primary Seal, Secondary Seals and Overburden

The stratigraphy at the Endurance structure is shown in Figure 4.10. The scoping calculations focus on the sealing properties of the Röt clay and Röt halite. The overlying formations are not considered. This is very cautious because the overlying rocks also act as secondary seals.

4.4.4.2 Processes

The two key processes are Darcy flow of CO_2 and diffusion of CO_2 dissolved in brine.

Darcy Flow of CO_2

The flux of CO_2 through the Röt clay and Röt halite is calculated assuming Darcy flow. The scoping calculation assumes that the formations are fully gas saturated, so there is a continuous gas pathway. In reality a gas pathway is unlikely to form because the gas pressure in the reservoir is likely to be below the gas entry pressure of the overlying claystone and halite. For example, the Queenston shale is one of the sealing formations for the Nuclear Waste Management Organisation’s (NWMO’s) proposed deep geologic repository for low and intermediate level radioactive waste. The properties of the Queenston shale may be similar to the Röt clay. It has a gas entry pressure of ~100bar. This is significantly higher than the expected 40bar pressure increase at crest of the Endurance structure and under these conditions CO_2 would not significantly enter the Röt clay.

Even if CO_2 was able to enter the Röt clay, migrate across it and thereafter enter the halite, as the volume of the gas increases the pressure would decrease. This would limit further penetration of the gas and would act to prevent formation of a continuous gas pathway from the Bunter sandstone to the seabed.

In the event that a gas pathway forms, the gas flow rate is equal to:

$$Q = A\frac{k\rho g}{\mu}i$$

Where:

Q is the gas flow rate (m^3/s)
A is the area for gas flow (m^2)
k is the permeability (m^2)
ρ is the gas density (kg/m^3)
g is gravitational acceleration (m/s^2)
μ is the viscosity (Pa s)
i is the hydraulic gradient (-).

Diffusion of Dissolved CO_2

The free CO_2 phase will be trapped at the crest of the anticline and brine will only be present at the residual saturation. CO_2 will dissolve in the residual brine until the brine becomes CO_2-saturated. The dissolved gas then migrates by diffusion. It is assumed that the free CO_2 does not enter the Röt clay or halite, so the clay and halite are fully saturated with brine. The top of halite is assumed to be a zero concentration boundary. Two metrics are calculated:

- the flux of dissolved gas out of the top of the halite; and
- the concentration of dissolved CO_2 at the top of the halite.

The calculations were undertaken using a 1-D Fickian transport model. The model was configured using seven compartments. The first compartment is the reservoir rock, in which a fixed concentration of dissolved CO_2 is specified. The next five compartments represent the combined Röt clay and Röt halite. These two formations were not differentiated in the model and therefore were assigned the same parameter values. The final compartment has a very large volume and acts as a zero concentration boundary.

4.4.4.3 Parameter Values

Area of CO_2 Phase

Free CO_2 phase will migrate to the top of the anticline where it will be structurally trapped. The scoping calculations assume vertical migration of CO_2. The plan area of the free CO_2 phase has been estimated by assuming the shape of the volume of trapped gas can be approximated by an inverted cone.

The total mass of CO_2 injected is 2.68MT/yr for 20 years = 53.6MT.

The density of the gas is assumed to be 700kg/m^3, the reservoir porosity is assumed to be 22% and the residual saturation of brine is assumed to be 0.15. The volume of the gas ‘cone’ is 5.47 x 10^{8}m^3.

The volume of the cone is equal to:

$$V_c = \frac{\pi r^2 h}{3}$$

Vc is the volume of the cone (m^3)

r is the radius of the base of the cone (m)

h is the height of the cone (m).

The height of the cone is equal to r.tanθ, where θ is the slope of the side of the cone.

Assuming the slope of the anticline is an average of 2 to 7 degrees (4.5 degrees), r is equal to 1.76 x 10^{3}m. The plan area of the base of the (circular) cone is 9.75 x 10^{6}m^2. The height of the cone is 139m.

Parameters for Darcy Flow Calculations

Parameter values used in the Darcy flow calculations are given in Table 4.20.

Table 4.20 Parameter Values for Darcy Flow Calculations

Parameter	Value	Units
Permeability of Röt clay (EES)	1 x 10^{-20}	m^2
Permeability of Röt halite (EES)	1 x 10^{-21}	m^2
Thickness of Röt clay	11	m
Thickness of Röt halite	106	m
Harmonic mean permeability	1.09 x 10^{-21}	m^2
Over pressure of CO_2 phase	40	Bar
Viscosity CO_2 (at a temperature of 48°C)	1.61 x 10^{-5}	Pa s

Parameters for Diffusion Calculations

Parameter values used in the diffusion calculations are given in Table 4.21.

Table 4.21 Parameter Values for Diffusion Calculations

Parameter	Value	Units	Notes
Gas pressure	150	bar	Crestal depth 1025m Average density of overlying water column 1107kg/m^3 Gas overpressure 40bar
Henry's constant	4.5 x 10^{-4}	Mol fraction	Extrapolated to the gas pressure above Note this value is for fresh water, so it will overestimate CO_2 dissolution in brine, therefore it is cautious
Effective diffusivity Bunter sandstone	3.3 x 10-^{11}	m^2/s	Assumed – free water diffusivity of 1 x 10^{-9}m^2/s multiplied by porosity multiplied by residual brine saturation of 0.15
Effective diffusivity Röt clay and halite (EES)	5 x 10^{-13}	m^2/s	An estimate for Röt clay based on shales at the Bruce site Assume halite is similar, but it may be lower
Effective diffusivity Röt clay and halite (AE3.b)	1 x 10^{-11}	m^2/s	Free water diffusivity of 1 x 10^{-9}m^2/s multiplied by an assumed micro-fracture porosity of 1%
Porosity Bunter sandstone	0.22	-	
Porosity Röt clay and halite (EES)	0.03	-	
Porosity Röt clay and halite (AE3.b)	0.01	-	Consistent with effective diffusivity
Tortuosity Röt clay and halite (EES)	0.0167	-	Effective diffusivity is the product of free water diffusivity of 1 x 10^{-9}m^2/s, porosity and tortuosity

4.4.4.4 Fluxes for the Expected Evolution Scenario and Alternative Evolution Scenarios

Darcy Flow of Free CO_2 Phase

For the EES the flux of the free CO_2 phase is 713m^3/yr. At a density of 700kg/m^3 this is 5.0 x 10^5kg/yr. This compares with an annual injection rate of 2.68MTPA, or 2.68E9kg/yr. So the loss rate is 0.02% of the injection rate. This is a very cautious value because, for example, it neglects the sealing formations overlying the Röt halite and therefore significantly overestimates the hydraulic gradient. More significantly, the gas pressure in the reservoir is likely to be below the gas entry pressure for the Röt clay and Halite, so there is not likely to be significant penetration of gas into these sealing formations and a gas pathway is unlikely to form.

Some diffuse leakage through the sealing formations may be possible if hydraulically connected sub seismic micro-fractures are present (AE3.b). It is very unlikely that such fractures will be present in the halite, so this is a very cautious assumption. Where the micro-fractures connect to form a continuous pathway to the seabed or an open fault, the initially diffuse migrating CO_2 would become progressively focussed, so that any CO_2 emissions at the seabed would tend to be at a number of localised points across a wider area.

The fracture gas entry pressure would be low, so this increases the potential for a gas pathway to form compared with the EES. The micro-fractures would also increase the formation permeabilities. The potential gas flux increases proportionally with the permeability. So if the harmonic mean permeability of the Röt clay and halite was one or two orders of magnitude higher than assumed in the EES, the calculated diffuse gas flux for AE3.b, would be 5.0 x 10^6kg/yr (1.4t/d) or 5.0 x 10^7kg/yr (14t/d) respectively.

Diffusion of Dissolved CO_2

Figure 4.35 and Figure 4.36 show the concentration of dissolved CO_2 at the top of the Röt halite and the flux of dissolved CO_2 out the top of the halite. For both the EES and AE3.b the steady state fluxes of dissolved CO_2 are negligible. For the EES, it takes ~160,000yr for the dissolved concentration at the top of the halite to reach 1% of the dissolved concentration in the reservoir. For AE3.b this is reduced to ~30,000yr.

Figure 4.35 Concentration of Dissolved CO_2 at the Top of the Röt Halite

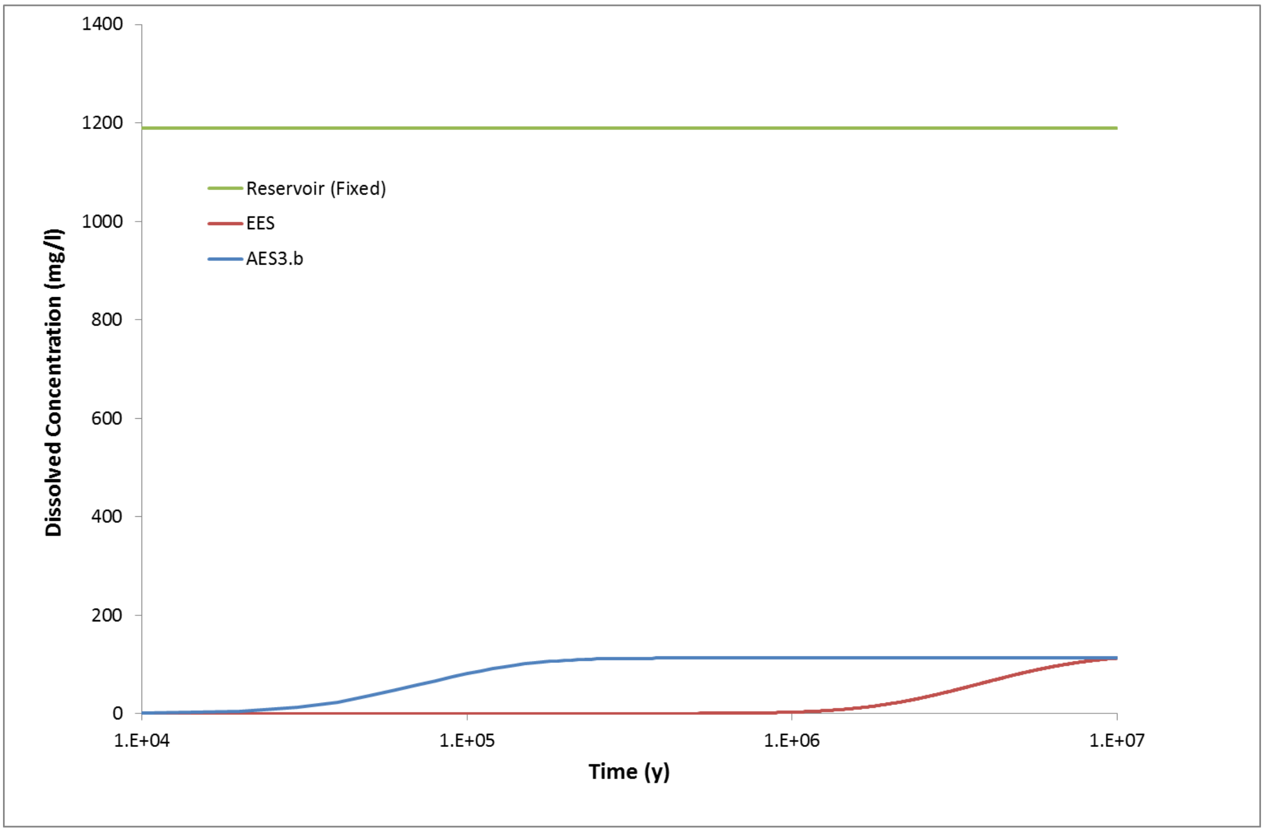
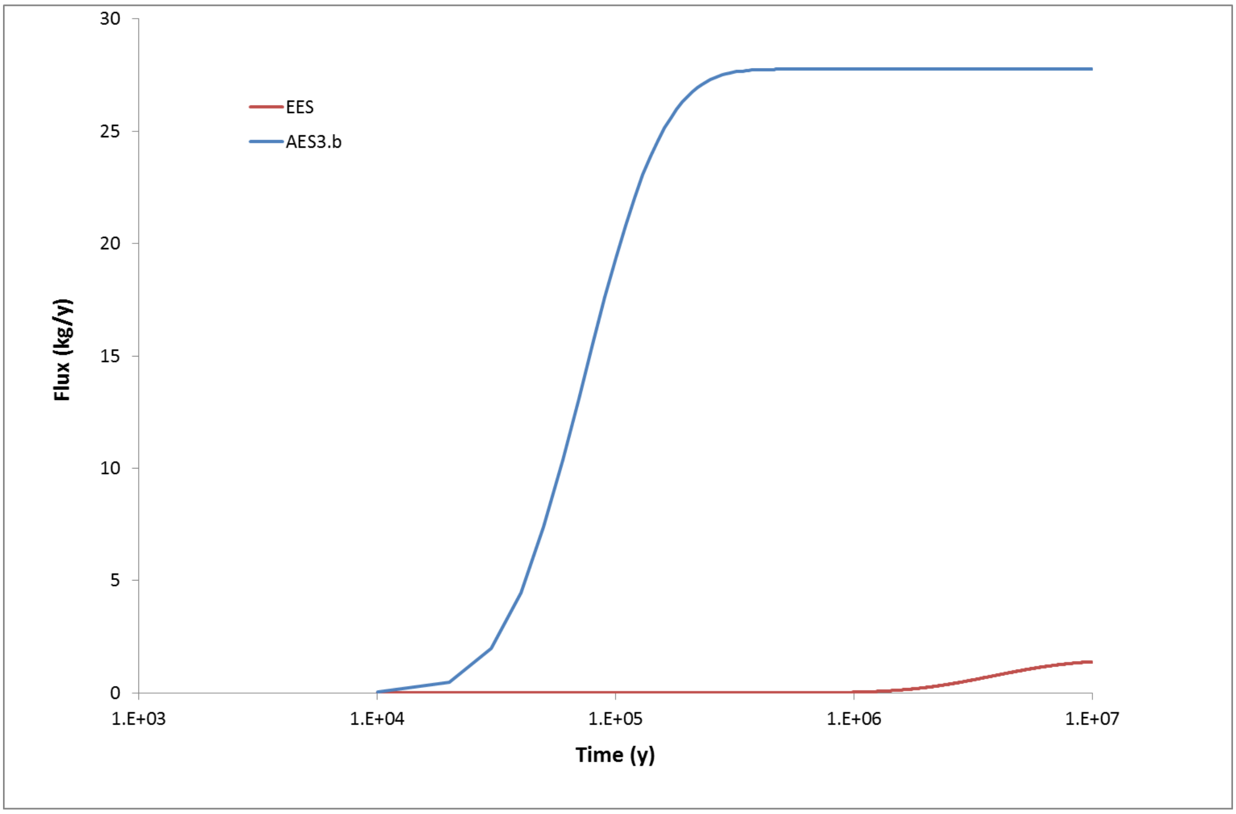


Figure 4.36 **Flux of Dissolved CO_2 at the Top of the Röt Halite**



4.4.4.5 Assessment of Environmental Impacts

The potential fluxes of dissolved CO_2 are negligible. They are not considered further as they will not be detectible and will not lead to measurable impacts.

If realised, AE3.b could plausibly produce a disperse leakage of the order 5.0 x 10^6kg/yr (1.4t/d) to 5.0 x 10^7kg/yr (14t/d), assuming micro-fracturing increases the permeability of the Röt clay and halite by one or two orders of magnitude respectively and the overlying formations are not seals. This is a flux of 3.6mol/s to 36mol/s over an area of 9.75 x 10^6m^2. The flux is therefore 0.37 x 10^{-6}mol/s/m^2 to 3.7 x 10^{-6}mol/s/m^2. This is consistent with the illustrative baseline natural flux of 2.5 x 10^{-6}mol/s/m^2.

The potential leakage fluxes are considerably higher than the illustrative baseline natural flux for marine environments of 1 x 10^{-8}mol/s/m^2, which is the minimum baseline flux for the southern North Sea. However, they are similar to the illustrative leakage fluxes for marine environments over a wide area of 1 x 10^{-6}mol/s/m^2. Therefore, the potential leakage fluxes estimated by the scoping calculations are of the order expected for a diffuse leakage scenario.

The primary mechanism by which CO_2 leakage impacts marine biota (organisms) is by changes in pH (decrease, acidification). The free CO_2 phase dissolves rapidly in seawater and bubbles of CO_2 rising from the seabed are expected to dissolve within the first ~10m of the water column. Dissolution of CO_2 increases the water density, so in systems with low current velocities and stratification where the CO_2 rich water is not rapidly diluted and dispersed, CO_2 rich water may 'pond' above the seabed. Given this potential ponding behaviour and that nektonic organisms can avoid the plume of CO_2 rich water, it is benthic organisms and to a lesser extent deep pelagic organisms that are most likely to be affected by leakage of CO_2. Above the storage complex, significant bottom currents (Section 4.4.2.3) will likely lead to rapid dilution and dispersion of any leaking CO_2, although it is noted that weak seasonal stratification can develop during late summer and this may slightly increase the potential impacts of CO_2 leakage compared with other times of the year.

Over an annual cycle the acidity in seawater will vary by 0.2 to 1.0pH units, although a smaller range of 0.3 to 0.4pH units is more typical for shelf seas such as the southern North Sea. The natural pH variation can also be significant over relatively small spatial and temporal scales and in some cases diurnal signals can approach the magnitude of seasonal variability. The impacts on organisms vary from species to species. Most species exhibit tolerance to small pH changes of the order 0.3pH units, but prolonged exposure can affect reproduction and lead to reductions in population health and numbers. The sensitivity is affected by a range of other environmental stressors including temperature changes and pollution.

Overall, the potential impacts of leakage are dependent on the leak rate and leak area; currents and water mixing, leading to dilution and dispersion; the individual species and lifecycle stage; the duration of exposure; and other environmental factors. Although it is difficult to quantify the impacts on biota, it is useful to examine the area in which the impacts might be significant.

Models of a range of different leak scenarios have been developed, to examine the development of plumes of CO_2 rich water, at current velocities typical of offshore North Sea conditions. For a scenario involving leakage from a point source at a rate of 4t/d, it was found that significant pH change would only be seen within a few metres of the source. Scenario AE3.b examines a similar leakage rate, but spread over an area of ~1 x $10^7 m^2$. The leak is spread over such a large area that it is not expected to have any significant impacts on benthic fauna.

4.4.4.6 Conclusions Regarding Diffuse Releases

Dissolved CO_2 is not likely to diffuse out of the storage complex within the timescales of interest (10,000+yr). Even if dissolved CO_2 eventually diffuses to the top of the storage complex, the flux will be so low that it will not be detectible and it will not have any environmental impacts.

It is unlikely that there will be diffuse leakage of a free CO_2 phase from the storage complex. Assuming there is micro-fracturing in the Röt clay and halite and very conservatively ignoring the additional overlying sealing formations, the diffuse flux of CO_2 to the seabed would be sufficiently small that it would not lead to any environmental impacts.

4.4.5 CO_2 Flux up a Leaky Well

In the EES it is assumed that none of the sealed and abandoned wells will leak. This includes the injection wells and existing abandoned wells. Alternative evolution scenario AE5 assumes that one of these wells is not fully sealed, enabling leakage of a free CO_2 phase to the seabed. The following scoping calculations estimate the potential leakage of a free CO_2 phase and the associated impacts for AE5.

4.4.5.1 Processes

The key process is Darcy flow of a free CO_2 phase, as described in Section 4.4.4.2. It is conservatively assumed there is an open annular fracture throughout the full length of the abandoned well. Calculations for injection wells are undertaken for the time when injection has just ceased, when the pressures are greatest and therefore the potential leakage flux is highest.

4.4.5.2 Parameter Values

Parameter values for the injection wells and crestal wells are given in Table 4.22 and Table 4.23 following.

Table 4.22 Parameter Values for Injection Wells

Parameter	Value	Units	Notes
Fracture aperture (a)	1×10^{-4}	m	Typical values Note the fracture transmissivity is equal to $a^3/12$ (m^3)
Fracture length	0.44	m	5.5inch diameter injection well
Measured Depth (MD)	1920	m	Estimated for a TVDSS of 1325m
Over pressure of free CO_2 phase	90	Bar	Typical maximum bottom hole pressure
Density of free CO_2 phase	700	kg/m^3	Appropriate for reservoir conditions The density may be higher at the peak injection pressure, but this is neglected, as are any density changes with depth up the leak pathway
Viscosity of CO_2	1.46×10^{-5}	Pa s	Calculated using the Sutherland formula at an injection temperature of 15°C

Table 4.23 Parameter Values for Crestal Wells

Parameter	Value	Units	Reference
Fracture aperture (a)	1×10^{-4}	m	Typical value based Note the fracture transmissivity is equal to $a^3/12$ (m^3).
Fracture length	0.98	m	12.25inch diameter well
Measured Depth (MD)	1025	m	Vertical well, so as TVDSS
Over pressure of free CO_2 phase	40	Bar	Crestal overpressure
Density of free CO_2 phase	700	kg/m^3	Appropriate for reservoir conditions. Density changes with depth up the leak pathway are neglected
Viscosity CO_2	1.61×10^{-5}	Pa s	Calculated using the Sutherland formula at an injection temperature of 48°C

4.4.5.3 Results

The potential leakage fluxes are given in Table 4.24.

Table 4.24 Calculated Potential Leakage Fluxes for Leaking Wells (AE5)

Well	Flux (kg/yr) and (t/d)	Flux ($mol/s/m^2$)	Percentage leakage compared with injection of 2.68MT/yr
Injection	2.6×10^5 (0.71)	1.2×10^1	0.01%
Crestal	4.4×10^5 (1.2)	4.1	0.02%

4.4.5.4 Assessment of Environmental Impacts

These leakage fluxes per unit area ($mol/s/m^2$) are up to an order of magnitude greater than those considered as a result of leaking wells in terrestrial environments, once the different leak areas are accounted for. They are many (~4+) orders of magnitude lower than the fluxes associated with a well blowout from a natural CO_2 accumulation at Sheep Mountain and the limiting flux for marine discharge from an open borehole. Therefore, the potential leakage fluxes estimated by the scoping calculations are of the order expected for a leaky well scenario.

Section 4.4.4.5 discusses the environmental impacts of CO_2 leakage. Overall, it was concluded that benthic organisms are most at risk, with the primary mechanism for harm being a decrease in pH (acidity of an aqueous solution). The potential impacts are dependent on the leak rate and leak area; currents and water mixing, leading to dilution and dispersion; the individual species and lifecycle stage; the duration of exposure; and other environmental factors. Although it is difficult to quantify the impacts on biota, it is useful to examine the area in which the impacts might be significant.

For a scenario involving leakage from a point source at a rate of 4t/d, it was found that significant pH change would only been seen within a few metres of the source. This leakage rate is of the same order of the results of the scoping calculations (Table 4.24). It is therefore expected that a leaky well would not lead to significant environmental impacts on benthic fauna. The area impacted might be slightly greater when combined with the weak stratification of the water column that occurs in late summer. However, evidence from natural submarine CO_2 seeps near Panarea, southern Italy, indicates that under stratified conditions the area impacted would still be small. For example, at Panarea elevated CO_2 concentrations were found to be limited to within 100m to 300m of the natural seep when seasonal stratification was most well-developed.

4.4.5.5 Conclusions Regarding Flux up a Leaky Well

Leakage from either the injection or crestal wells could potentially have an impact on benthic biota. However, the impacts would be localised to within a few metres of the well and would therefore be small.

4.4.6 Potential for Leakage from Crestal Wells to Occur

4.4.6.1 Introduction

The abandoned exploration and injection wells will age over time in response to Thermo-Hydro-Mechanical-Chemical (THMC) processes. For the Project it is assumed that there are no brine production wells. These ageing processes can be beneficial, with the abandoned wells evolving to a state where they continue to provide long-term sealing. Alternatively, they can be detrimental and might result in a reduction in sealing performance. Depending on the relative rates of these processes, a combination of effects may be observed resulting in an initial decrease in sealing performance followed by an increase, or vice-versa. An assessment of the risks of leakage of cement plugs in these crestal wells shows that the two crestal wells are ‘Category 2’, namely that they have adequate proven cement quality for one barrier. It was concluded that the risk based on the engineered barriers was of ‘medium’ criticality. However, these assessments did not consider the natural barrier and in particular the ability of salt to creep and thereby seal open sections of borehole. This process significantly enhances confidence that long-term integrity of the seals will be maintained.

This section identifies the key well ageing processes that can affect long-term sealing performance and develops alternative conceptual models for well ageing. These are mapped to the assessment scenarios.

The wells of greatest concern are the two old exploration wells at the crest of the anticline: 42/25-1 and 43/21-1 (Figure 4.18), for which information is available. These two abandoned wells are particularly important because they are expected to be in permanent contact with the injected CO_2 during the post-closure period, once the CO_2 has migrated to the top of the Endurance anticline. Abandonment was not undertaken with long-term CO_2 storage in mind and therefore has not been optimised for this purpose. Also the quality of the abandonment work is less certain than for a well abandoned more recently with direct information on methodology adopted from the operator that undertook the abandonment. The abandonment design for the injection wells will be different to those of these old wells and will be optimised for long-term CO_2 storage. As CO_2 migrates to the top of the anticline it will migrate away from the abandoned injection wells, so they will not be subjected to long-term exposure to significant amounts of free CO_2 gas. Therefore the two crestal wells are the focus of this section.

It should be noted that the amount of CO_2 that will be injected is small compared with the size of the Endurance structure. During this it is planned to store a maximum of 53.6MT of CO_2, which would have a volume of around $8 \times 10^7 m^3$ under reservoir conditions. This volume is approximately two orders of magnitude smaller than the most likely volume of pore space available within the Endurance structure, which is around $5 \times 10^9 m^3$.

CO_2 will be trapped by dissolution as it migrates through the reservoir to the top of the structural trap. There will also be localised structural trapping due to secondary topography (small crests and troughs) in the top surface of the reservoir. Therefore some of the CO_2 gas will probably not actually reach the crestal wells. AGR (2015c) noted that relative permeability data suggest that residual hydrodynamic trapping may only be minor.

4.4.6.2 Description of the Crestal Wells

Of all the existing wells within and adjacent to the Endurance structure, the more recent of the two crestal wells are reproduced in Figure 4.6, so there may be more confidence in the quality of abandonment of well 42/25-1. This well will be exposed to CO_2 earlier than well 43/21-1, which is located approximately 2.5km further away from the planned injection point. Eventually both wells will be permanently exposed to CO_2 gas.

4.4.6.3 FEPs Analysis

The abandoned wells will age chemically and physically over time in response to THMC processes. In this section the key well ageing processes are identified using an interaction matrix approach, see Table 4.25. The main system features are identified and form the leading diagonal of the matrix. The events and process that result in interactions between the features are then described in the off-diagonal elements. If no interaction is ever possible the off-diagonal elements are greyed out. Interactions that are not possible initially, but may become possible as the well ages are identified. This is a useful approach to identify the key FEPs and ensure that all possible interactions have been considered. However, it should be noted that this approach does not describe process couplings explicitly. Couplings need to be considered when using the results of the FEPs analysis.

Table 4.25 FEP Interaction Matrix

Feature 1	Processes by which Feature 1 affects Feature 2	No direct interaction between these features so ‘greyed out’
Processes by which Feature 2 affects Feature 1	**Feature 2**	Processes by which Feature 2 affects Feature 3
No direct interaction between these features so ‘greyed out’	Processes by which Feature 3 affects Feature 2	**Feature 3**

This analysis approach was applied to well 42/25-1 since the information is slightly more complete than for well 43/21-1. However, the key features of the wells are sufficiently similar that the results of the analysis are relevant to both wells. The main difference is that the inter-plug fluid in well 43/21-1 is unknown and while well 43/21-1 uses class B cement, well 42/25-1 uses class G (see note below). This might lead to differences in the key cement ageing process and hence the long-term sealing performance. The interaction matrix for well 42/25-1 is shown in Table 4.26.

Class B and G cements differ in compositional requirements in that class B cement has no minimum requirement for Tricalcium Silicate (Alite) which can form up to 65% of a class G cement. Nor does class B require Tricalcium Aluminate (up to 3% in class G). The use of Alite in cement is to allow for rapid reaction with water and the early development of the cement strength; a key factor in the costly construction of wells.

Table 4.26 FEP Interaction Matrix for Ageing of Well 42/25-1 (- Indicates no Key Well Ageing Processes Identified; Grey Fields Indicate no Direct Interaction).

Seawater	-	Corrosion	Corrosion	Corrosion	-	Lighter than Oil-Based Mud (OBM) so will float	Chemical alteration – cracking, strength change, armouring, porosity reduction	Dissolution	-	-	Dilution	Dissolution
-	**Overburden**	-	-	-	-	-	-	Confinement			-	-
-	-	**Conductor**		-		Expansive corrosion pressurisation	Expansive corrosion stresses				-	-
-	-		**Casing**	-		Expansive corrosion pressurisation	Expansive corrosion stresses				-	-
-	-	Mechanical support and alignment	Mechanical support and alignment	**Casing Shoe**		Expansive corrosion pressurisation	Expansive corrosion stresses				-	-
-	-				**Open Hole**	-	-	-	-	-	-	-
Contaminates if casing/seal/ /plug failure allows to come into contact	Penetrates surrounding rock formations if not confined by casing/seals/plugs	-	Fills and stabilises	-	Fills and stabilises	**Drilling Fluid**	-	Resists creep while seals/plugs retain	-	Flow into sandstone if no longer retained by seals/plugs	Denser than brine, sinks if no longer retained by seals/plugs	Dissolution if seal/plug failure allows to come into contact
Hydraulic sealing	-	Corrosion protection (high pH)	Corrosion protection (high pH)	Corrosion protection (high pH)	Fills, stabilises & seals	-	**Cement Around Casing/Plug/Seal**	Resists creep loads	Mechanical stabilisation & hydraulic sealing	Mechanical stabilisation & hydraulic sealing	Hydraulic sealing	Hydraulic sealing
Salinisation	-				Creeps into open hole	Creep pressurisation	Creep loads Reaction between Cl in the halite and cement	**Röt** **Halite**	-	-	-	-
-					-	-	-	-	**Röt** **Clay**	-	-	-
Permeable reservoir					-	Permeable reservoir	-	-	-	**Bunter** **Sandstone**	-	Permeable reservoir
Salinisation	-	Corrosion	Corrosion	Corrosion	-	Lighter than OBM so will float	Chemical alteration – cracking, strength change, armouring, porosity reduction	-	-	-	**Reservoir** **Brine**	Dissolution
Acidification	-	Corrosion	Corrosion	Corrosion		-	Chemical alteration – carbonation	-	-	-	Acidification	**CO_2**

The key FEPs identified in the FEP matrix can be grouped as follows:

- processes leading to reduction in the permeability/porosity of cement seals/plugs:
    - reaction with CO_2 leading to precipitation of calcite/siderite (iron from metal components), porosity and permeability decrease (armouring), interface sealing, strength increase; and
    - reaction with formation water leading to precipitation of high specific volume phases such as ettringite (hydrous calcium aluminium sulphate mineral);
- processes leading to weakening and cracking of cement around casing/plugs/seals:
    - sulphate attack;
    - chloride attack;
    - expansive stresses from corrosion of steel components; and
    - creep loads from the halite;
- processes leading to closing of open hole:
    - creep of the halite; and
- other FEPs that have the potential to affect the ageing behaviour of the wells, such as:
    - corrosion of metallic components of the completion system; and
    - penetration of drilling mud into the surrounding rock formation.

4.4.6.4 Well Ageing Conceptual Models

Based on the FEP groups identified above, a number of different conceptual models of well ageing can be envisaged, depending on the relative rates of the different key processes. Each conceptual model is described as an ageing pathway. The ageing pathways are mapped to the assessment scenarios. Future scoping calculations could be used to estimate the rates of the various processes and thereby rule out certain potential ageing pathways, or ascribe qualitative probabilities, such as expected, unlikely and so on. The ageing pathways are summarised and mapped to the assessment scenarios in Table 4.27.

It should be noted that all these ageing pathways assume there is CO_2 gas at the crest of the anticline, such that there is a source of CO_2 gas to potentially leak.

Table 4.27 Well Ageing Pathways and Mappings to Assessment Scenarios

Ageing Pathway	Description	Assessment Scenario
AP1	Improvements in overall sealing through plug armouring (carbonation by reaction with CO_2)	EES
AP2	Closure of open hole in the Röt Halite by salt creep	EES
AP3	Multiple barrier failure. Poor sealing and open interfaces allow rapid degradation of plugs and seals, in combination with wall collapse in open hole and/or slow halite creep rates	Borehole leakage

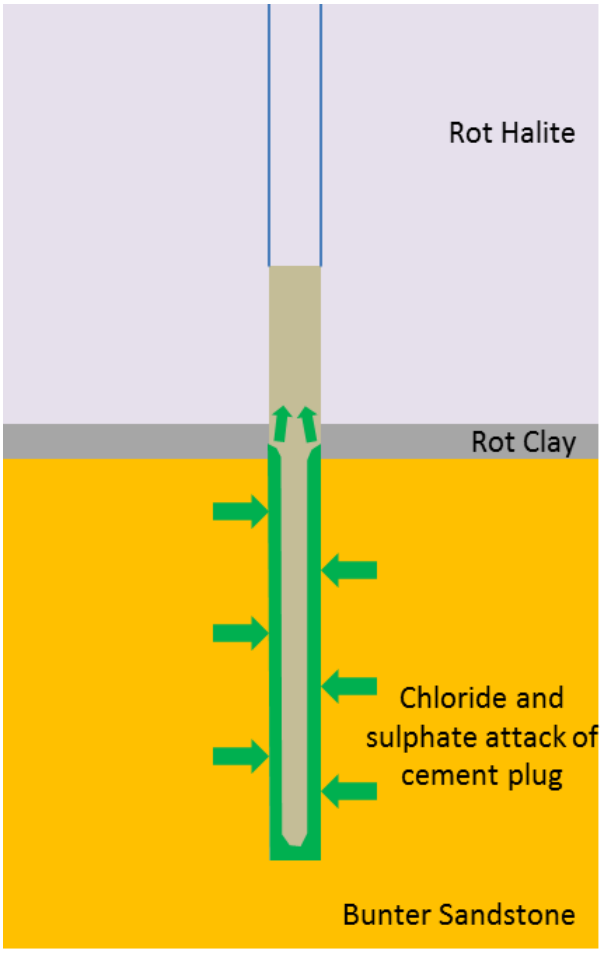
4.4.6.5 Ageing Pathway 1

It is assumed that the well has been successfully sealed and abandoned. There may be some open interfaces and other weaknesses, but these are not connected and there is not an open connection between the seabed and the reservoir. There is little information about reactions between CO_2 charged water and the Class B and G cements used in the plugs of the two historical boreholes. However, based on observations reported on other kinds of cement, a number of ageing processes are expected.

Initially the basal plug will be in contact with brine in the reservoir and cracking and weakening may occur through chloride and sulphate attack. However, these processes need to be balanced against the reduction in porosity and permeability that will accompany the formation of solid phases, such as ettringite. The entire surface of the plug will be open to attack in the Bunter sandstone, Röt clay and Röt halite. In the permeable Bunter sandstone mass transport between the formation and the cement plug will be relatively rapid, leading to relatively rapid rates of alteration. However in contrast the very low permeability of the Röt clay and Röt halite is expected to restrict mass transport between the cement and the formation and thereby lead to a slow rate of cement alteration.

In the presence of CO_2 charged water an alteration front will move upwards through the plug from the top of the Bunter. If the cement is unfractured and well bonded to the walls of the borehole, the interactions with CO_2 charged water will cause uniform alteration across the width of the plug. There is little direct evidence for the very long-term behaviour (longer than a few tens of years) of cementitious well plugs in deep subsurface environments. However, based on available laboratory experiments and observations in abandoned and operational wells some inferences can be made.

Figure 4.37 Basal Plug Chemical Alteration Fronts



Due to the significant vertical thickness of the plug and the absence of any vertical flow through the abandoned well, it is believed that it will take many thousands or tens of thousands of years for the alteration front to move uniformly through the full thickness of the plug. Such movement of an alteration front would be necessary to potentially generate a leakage pathway. However, it should be noted that even at the time of breakthrough of an alteration front, the cement plug may still retain its integrity and act to substantially retard CO_2 migration.

From observations made on cement sampled from a borehole the SACROC field of Texas that has been exposed to CO_2 rich brine during Enhanced Oil Recovery (EOR) operations for over 30 years, at a temperature of c.50°C, it was reported that an alteration depth in the cement ranged from 1 to 10mm, implying a rate of up to 0.33mm/yr. The particular circumstances under which this alteration occurred are dissimilar to those in the Endurance legacy wells structure. Notably, unlike in the lower sections of these legacy wells, in the SACROC well there was a casing present and the composition of the cement sampled was thought to be API Class A. However, there are some reasons to suppose that long-term rates of chemical alteration within the cement plugs at the bottom of the Endurance legacy wells would, if anything, be slower than these rates. Notably the halite-saturated brine would minimise the CO_2 solubility, which would tend to lower the rate of reaction. Additionally, the rate of migration of any reaction front by diffusion would tend to diminish as the chemical gradient in the vicinity of the front decreases. As an illustration, if the cement plug that in the bottom of 42/25-1 were to alter at the rate deduced from the SACROC observations, it would take about 225,000 years to completely alter the 75m of the plug that extend above the Bunter sandstone. A similar illustrative calculation for the cement plug in the bottom of 43/21-1 gives 155,000 years to alter completely the 52m length of the plug that lies above the Bunter sandstone.

Long before the plug is degraded throughout its entire thickness, the stored CO_2 accumulates at the top of the anticline. The water (brine) saturation is reduced to residual levels, such that the supply of chloride and sulphate to the cement is significantly reduced.

Reaction of CO_2 with the cement results in the initial replacement of CSH phases in the cement by calcite. This clogs the pores in the cement, reducing the porosity and permeability and increasing the strength. Any open interfaces, or fractures arising from chloride/sulphate attack are filled with precipitates and are sealed. An armouring front may continue to develop up the basal plug, from the top of the Bunter upwards. Behind the front, there will be a zone of carbonation, behind which there will be a zone of decarbonation. Within this decarbonated zone the initially formed calcite will have dissolved, resulting in residual cement material with higher porosity and permeability and lower strength than the unaltered cement.

Even if the basal plug would be degraded sufficiently to allow CO_2 to pass through it, the CO_2 would need to then traverse two further cement plugs before leaving the storage complex. That is, for leakage to occur, three cement plugs would need to degrade to the extent necessary to allow CO_2 to pass through them. If chemical alteration is uniform across the width of each plug as described above for the basal plug, then each one could potentially take many thousands of years to degrade sufficiently to allow CO_2 to pass through them.

The well will also be degrading from the seabed downwards due to interaction with seawater. If seawater is able to breach the upper plug, the high density Oil Based Mud (OBM) will prevent the seawater from reaching the top of the basal plug. It is very unlikely that the basal plug would leak during the timeframe considered.

4.4.6.6 Ageing Pathway 2

It is assumed that the well has been successfully sealed and abandoned. There may be some open interfaces and other weaknesses, but these are not connected and there is not an open connection between the seabed and the reservoir.

The Röt halite is expected to creep and the high overpulls observed during drilling of 42/25-1 are evidence of this process. Note that overpull is the amount of force exerted on a tubular, such as the drill string in the well, that is greater than the tubular in the well. OBM is trapped in the open hole in the Röt halite. Creep of the halite increases the pressure in the OBM filling the open hole. As the underlying plug and/or overlying seals age and crack, the OBM is able to flow up/down the well and the halite can creep into the open hole. This process continues until all the OBM has been squeezed out hole and the open hole fully closed and permanently sealed.

4.4.6.7 Ageing Pathway 3

In order for leakage to occur multiple barriers have to fail. This is most likely to occur if well abandonment was done poorly such that there are open interfaces present in the well and in particular if there are connected open interfaces from the seabed to the reservoir. This allows OBM to begin to sink into the Bunter sandstone immediately following abandonment and increased concrete attack by chloride and sulphate throughout the well. Exposure of the metal components to seawater and brine causes them to corrode and the resultant expansive stresses generate further cracks in the cements.

It is assumed that the OBM sinks rapidly into the Bunter so it does not resist creep of the halite into the open hole. Creep of the halite is sufficiently fast that the strain limit of the halite is exceeded and it collapses into the open hole forming a zone of collapsed rock. This collapse zone may resist creep of the halite and may provide an open pathway until it is eventually closed by further creep of the halite. Alternatively the halite may creep much more slowly than expected, resulting in an open pathway for an extended period of time.

As CO_2 is injected into the Bunter the reservoir pressure increases. This drives brine up through the well, increasing the supply of chloride and sulphate, resulting in further cement cracking, strength loss and enhancement of the leakage pathway. Eventually CO_2 gas reaches the crest of the anticline and leakage can occur.

Leakage may stop as creep of the halite eventually closes the pathway and/or in response to armouring processes.

4.5 Key Risks

4.5.1 Introduction

Risk characterisation concerns bringing together the understanding of system performance and associated impacts for the relevant scenarios in order to understand the key arguments for containment and safety and to highlight and describe any remaining risks.

The approach to risk characterisation used for this assessment involves:

- the utilisation of Evidence Support Logic (ESL) to represent and integrate all the key lines of reasoning and underpinning evidence for containment and safety, see Section 4.5.2;
- representing and describing remaining risks using a risk matrix, see Section 4.5.3; and
- using the Bow-Tie approach to highlight remaining risks and to indicate plausible mitigations, see Section 4.5.4.

4.5.2 Application of Evidence Support Logic

4.5.2.1 Overview of Evidence Support Logic

ESL involves systematically breaking down a hypothesis under consideration into a logical hypothesis model (a ‘decision tree’), the elements of which expose basic judgments and opinions about the quality of evidence associated with a particular interpretation or proposition. A tree structure is constructed that connects some key hypothesis of interest to supporting hypotheses that can be tested as easily as possible using direct observations of relevant phenomena or model outputs. In practice, intermediate hypotheses will usually occur within the tree, between the readily testable hypotheses at the lowest level and the top-level hypothesis of interest.

Numerical representations of confidence for and against the truth of each hypothesis at the lowest level of the tree are input by users. These representations of confidence are then combined and propagated through the tree to the top-level hypothesis. The propagation is controlled by numerical sufficiencies (effectively weights) and logical operators that are specified when the tree is constructed. Once a tree is constructed, it may be used to identify what hypotheses are most significant for decision making at any particular stage of a project. This identification can then be used to prioritise subsequent information gathering and analysis activities. Furthermore, the tree provides a record of the developing decision making process throughout a project.

A key feature of ESL is its basis on ‘three value’ logic, which allows for a measure of uncertainty as well, recognising that belief in a proposition may be only partial and that some level of belief concerning the meaning of the evidence may be assigned to an uncommitted state. Uncertainties are handled as ‘intervals’ that enable the admission of a general level of uncertainty providing a recognition that information may be incomplete and possibly inconsistent (judgment on evidence for + judgment on evidence against + uncertainty due to overconfidence or uncommitted belief = 1).

The ESL approach has been implemented within the TESLA software, which provides:

- an interface for constructing and displaying a tree;
- functionality to embed supporting explanations, documents; and web page links within the tree; and
- tools to analyse a tree.

Further details of the methodology are provided in Appendix C.

4.5.2.2 Overview of Decision Trees

The integration work undertaken has focussed on the development of the structure and parameterisation of three trees that cover the main arguments at the heart of the risk assessment. These trees cover:

1. containment of CO_2. This first tree aims to assess the level of confidence on the basis of available evidence that ‘The CO_2 volume planned to be stored will be completely and permanently contained’; utilising the wording required by 2009/31/EC CCS Directive. This tree uses a structure that represents the requirements of 2009/31/EC CCS Directive, then linking to project-specific evidence sources. While the primary focus is on containment, consistent with 2009/31/EC CCS Directive risks to human health and the environment are also assessed associated with potential low likelihood leakage scenarios;
2. displacement of formation fluids. This tree complements the ‘containment’ tree by examining the evidence for the potential displacement of formation fluids (including potential higher salinity waters) and the potential for impacts on receptors; and
3. physical effects (seabed deformation). This tree further complements the above trees by structuring arguments associated with the potential for seabed deformation for example, uplift, that may arise due to CO_2 storage, including assessing the potential impacts on other structures on the seabed.

In each case, the outcomes suggest there is substantial confidence in performance for each of these aspects. There is some remaining uncertainty (that may in part be an indication of risk) associated with some of the trees, especially that for containment, but it is anticipated that the outcomes of the current ongoing modelling work (detailed and scoping models) will reduce at least some of this uncertainty.

In Sections 4.5.2.3 to 4.5.2.5, a number of TESLA plots summarising the outcomes, including sources of confidence and areas of remaining uncertainty, are highlighted. Full details are recorded within the tree files themselves and can be viewed either using the TESLA tool or via reports generated by the TESLA tool. Relevant tree titles and version numbers are provided in Appendix C. These can be accessed through TESLA by 'clicking' on specific hypotheses. Alternatively, the tree reports provided in Appendix D summarise the evidence that provides confidence for and against each leaf hypothesis at the lowest level of each decision tree and the basis for the confidence value assigned to each of these hypotheses.

4.5.2.3 Containment Tree

The diagrams shown in Figure 4.38 to Figure 4.41 ('tree plots' in ESL terminology) summarise the outcomes for the containment tree. Here, confidence for safe containment (green space) dominates at the top level. This reflects the multiple lines of reasoning that:

- the storage reservoir will have sufficient capacity to take the volume of CO_2 planned to be stored and that chemical and physical effects will not prevent that capacity being accessed at the required rate;
- there is strong evidence that the storage site will evolve towards long-term stability and that the expected evolution will be consistent with ensuring containment; and
- there are no 'what if' scenarios that could plausibly challenge containment or lead to significant impacts to receptors.

There is a small amount of red space (effectively, representing risk) related primarily to the small possibility that chemical effects could challenge injectivity beyond current expectations. There is also some 'white space' or residual uncertainty, indicative of missing information that may at least in part turn green (resolve into confidence for performance) once remaining models and performance data become available.

The confidence entries for the lines of reasoning associated with Hypothesis 2 are blank. This is because the generic tree was identified to be used both before and during/after CO_2 injection. The elements assessed by Hypothesis 2 and children correspond to 2009/31/EC CCS Directive requirements post-injection. They have been retained here for consistency with the original published generic tree but evidence values are necessarily absent. The plots presented do not show the child hypotheses that support Hypothesis 2 for that reason.

There are several hypotheses which are associated with notable amounts of confidence against performance, but which do not have an overall influence on the outcomes. These include:

- Hypothesis 3.2.3.1.1; here the red (40% confidence) reflects the potential that there might be economic resources underlying the storage complex; however this does not have an impact on its parent as its sibling hypothesis (3.2.3.1.2) identifies high confidence that people who might seek to access those resources in the future would be able to recognise the existence of the stored CO_2 and take measures to avoid leakage (in any case, 'deliberate' intrusion with knowledge is out of scope of the assessment). This means that the potential presence of an economic resource is immaterial as the risk is small in any case and the logic in the tree (confidence against both, or all, siblings being required for confidence against the parent) reflects this;
- similarly, although models indicate that if there is inadvertent human intrusion into the storage complex leakage of CO_2 out of it could result, the models also show that this leakage would be very small and the impacts on receptors would be very small. Combined with the arguments above that inadvertent intrusion is not likely, again the confidence against does not propagate up the tree; and

- Finally Hypothesis 3.2.6.1 notes that resource exploitation elsewhere could cause observable/monitorable interactions (for example pressure changes) within the storage complex, but this does not present a risk because, as represented by its sibling hypothesis 3.2.6.2, the effects of such interactions would be insignificant and would not challenge containment or lead to observable impacts on receptors.

Figure 4.38 Tree Plot - Containment (All Except Hypothesis 2 to Hypothesis 3.2 Expanded)

- 0.88 0.06 0.06 / 0 — The CO2 volume planned to be stored will be completely and "permanently" contained
  - 1 / 0 — 0.6 0.38 0.02 / 0 — 1 The storage reservoir has sufficient accessible capacity to take the volume of CO2 planned to be stored at the required injection rate
    - 1 / ALL — 1 0 0 — 1.1 The total expected connected pore volume of the storage reservoir is sufficient for the planned CO2 volume
    - 1 / ALL — 0.6 0.38 0.02 / 0 — 1.2 Chemical effects will not prevent the required storage capacity being accessed at the required injection rate
      - 1 / ALL — 0.6 0.38 0.02 / 0 — 1.2.1 Chemical effects near the point of injection will not prevent the required storage capacity being accessed at the required injection rate
        - 1 / 0.9 — 0.6 0.38 0.02 — 1.2.1.1 Halite and hydrate precipitation will not prevent the required storage capacity being accessed at the required injection rate
        - 1 / 0.2 — 0.7 0.3 0 — 1.2.1.2 Other precipitates will not prevent the required storage capacity being accessed at the required injection rate
      - 1 / ALL — 0.85 0.15 0 — 1.2.2 Chemical effects away from the point of injection will not prevent the required storage capacity being accessed at the required injection rate
    - 1 / ALL — 0.75 0.25 0 / 0 — 1.3 Physical effects will not prevent the required storage capacity being accessed at the required injection rate
      - 1 / 0.75 — 0.9 0.1 0 — 1.3.1 Physical features will not prevent the required storage capacity being accessed at the required injection rate
      - 1 / 0.4 — 0.6 0.4 0 — 1.3.2 Physical alteration due to physico-chemical processes will not prevent the required storage capacity being accessed at the required injection rate
  - 0.9 / 0.8 — 0 1 0 / 0 — 2 The observed behaviour (migration, spatial distribution, partitioning between phases) of CO2 conforms with predictions and supports containment
  - 0.9 / 0.95 — 0.93 0.02 0.05 — 3 The storage site will evolve towards long-term (containment) stability following closure
    - ANY / ALL — 0.98 0.02 0 / 0 — 3.1 The expected system evolution is towards long-term stability following closure
      - 0.3 / 0.8 — 0.8 0.2 0 / 0 — 3.1.1 The storage complex contains no plausible leakage pathways by which CO2 could return to the surface or near-surface environments
        - 0.6 / ALL — 0.8 0.2 0 — 3.1.1.1 Wells / boreholes will not provide leakage paths
        - 0.6 / ALL — 0.85 0.15 0 — 3.1.1.2 Structures (faults, fracture zones etc) will not provide leakage paths
        - 0.6 / ALL — 0.9 0.1 0 — 3.1.1.3 Confining rock (primary seal, secondary seal and overburden to ultimate seal) has sufficient integrity
      - 0.6 / 0.6 — 0.9 0.1 0 / 0 — 3.1.2 The CO2 will not migrate laterally beyond the defined storage complex
        - 1 / ALL — 0.99 0.01 0 — 3.1.2.1 Free CO2 will not migrate laterally beyond the defined storage complex
        - 1 / ALL — 0.9 0.1 0 — 3.1.2.2 Dissolved CO2 will not migrate laterally beyond the defined storage complex
      - 0.9 / 0.8 — 0.96 0.04 0 / 0 — 3.1.3 Predictions of post-closure behaviour of the containment complex predict evolution towards long-term stability for any plausible boundary conditions
        - 0.9 / 0.7 — 0.9 0.1 0 — 3.1.3.1 Multi-phase flow models predict evolution towards no flow of free and dissolved CO2
        - 0.9 / 0.7 — 0.9 0.1 0 — 3.1.3.2 Geomechanical models predict evolution towards no deformation due to CO2 in the long term
        - 0.9 / 0.8 — 0.9 0.1 0 — 3.1.3.3 Geochemical models predict evolution towards long-term chemical stability
      - 0.6 / 0.5 — 0.9 0.1 0 — 3.1.4 Analogues support evolution towards long-term stability
    - ANY / ALL — 0.93 0.02 0.05 / 0 — 3.2 There will be no "high-impact, low-probability" events that could significantly disturb system following closure

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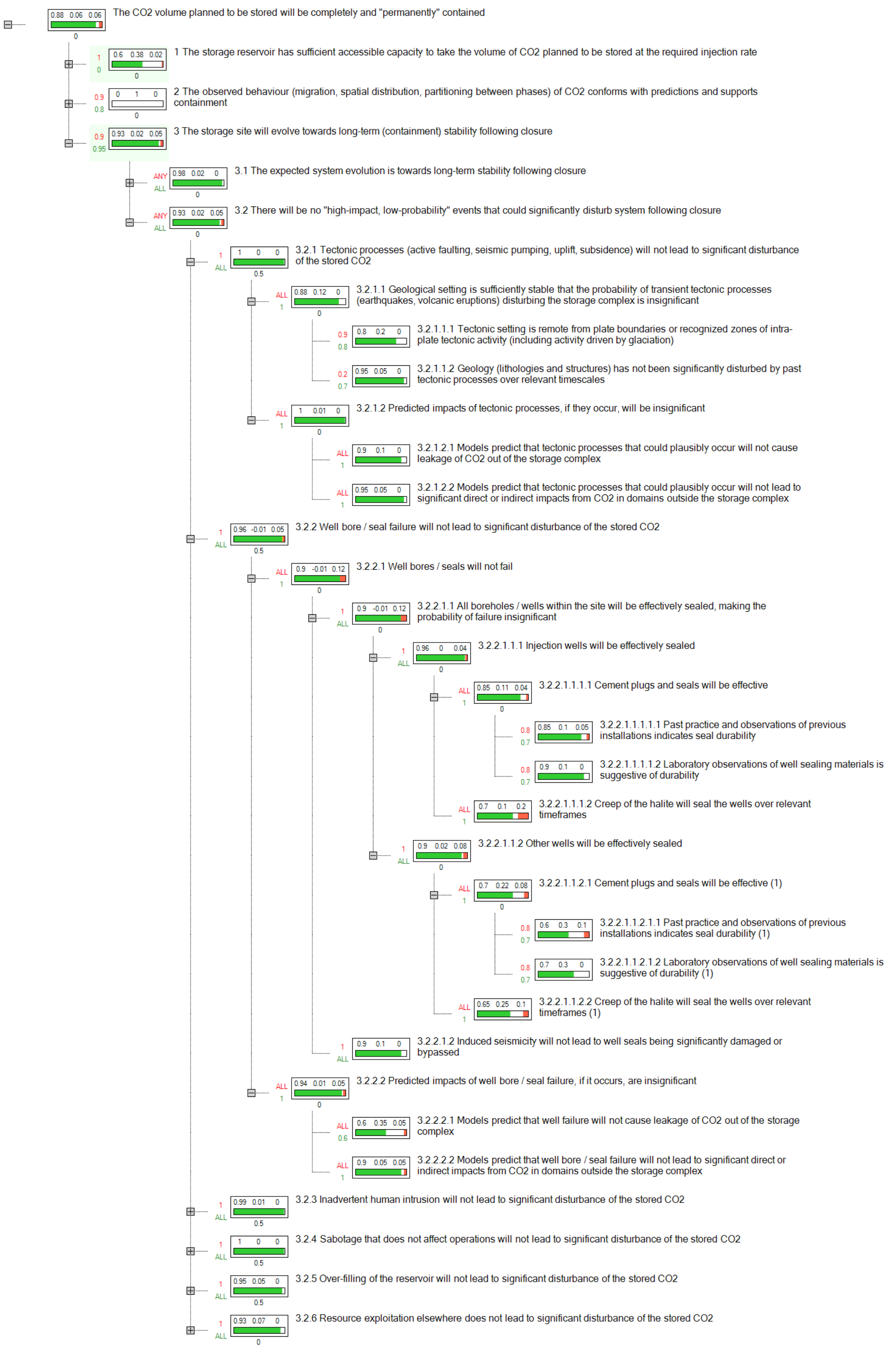
Figure 4.39 Tree Plot - Containment (Only Hypotheses 3.2 Expanded)



- The CO2 volume planned to be stored will be completely and "permanently" contained
  - 1 The storage reservoir has sufficient accessible capacity to take the volume of CO2 planned to be stored at the required injection rate
  - 2 The observed behaviour (migration, spatial distribution, partitioning between phases) of CO2 conforms with predictions and supports containment
  - 3 The storage site will evolve towards long-term (containment) stability following closure
    - 3.1 The expected system evolution is towards long-term stability following closure
    - 3.2 There will be no "high-impact, low-probability" events that could significantly disturb system following closure
      - 3.2.1 Tectonic processes (active faulting, seismic pumping, uplift, subsidence) will not lead to significant disturbance of the stored CO2
        - 3.2.1.1 Geological setting is sufficiently stable that the probability of transient tectonic processes (earthquakes, volcanic eruptions) disturbing the storage complex is insignificant
          - 3.2.1.1.1 Tectonic setting is remote from plate boundaries or recognized zones of intra-plate tectonic activity (including activity driven by glaciation)
          - 3.2.1.1.2 Geology (lithologies and structures) has not been significantly disturbed by past tectonic processes over relevant timescales
        - 3.2.1.2 Predicted impacts of tectonic processes, if they occur, will be insignificant
          - 3.2.1.2.1 Models predict that tectonic processes that could plausibly occur will not cause leakage of CO2 out of the storage complex
          - 3.2.1.2.2 Models predict that tectonic processes that could plausibly occur will not lead to significant direct or indirect impacts from CO2 in domains outside the storage complex
      - 3.2.2 Well bore / seal failure will not lead to significant disturbance of the stored CO2
        - 3.2.2.1 Well bores / seals will not fail
          - 3.2.2.1.1 All boreholes / wells within the site will be effectively sealed, making the probability of failure insignificant
            - 3.2.2.1.1.1 Injection wells will be effectively sealed
              - 3.2.2.1.1.1.1 Cement plugs and seals will be effective
                - 3.2.2.1.1.1.1.1 Past practice and observations of previous installations indicates seal durability
                - 3.2.2.1.1.1.1.2 Laboratory observations of well sealing materials is suggestive of durability
              - 3.2.2.1.1.1.2 Creep of the halite will seal the wells over relevant timeframes
            - 3.2.2.1.1.2 Other wells will be effectively sealed
              - 3.2.2.1.1.2.1 Cement plugs and seals will be effective (1)
                - 3.2.2.1.1.2.1.1 Past practice and observations of previous installations indicates seal durability (1)
                - 3.2.2.1.1.2.1.2 Laboratory observations of well sealing materials is suggestive of durability (1)
              - 3.2.2.1.1.2.2 Creep of the halite will seal the wells over relevant timeframes (1)
          - 3.2.2.1.2 Induced seismicity will not lead to well seals being significantly damaged or bypassed
        - 3.2.2.2 Predicted impacts of well bore / seal failure, if it occurs, are insignificant
          - 3.2.2.2.1 Models predict that well failure will not cause leakage of CO2 out of the storage complex
          - 3.2.2.2.2 Models predict that well bore / seal failure will not lead to significant direct or indirect impacts from CO2 in domains outside the storage complex
      - 3.2.3 Inadvertent human intrusion will not lead to significant disturbance of the stored CO2
      - 3.2.4 Sabotage that does not affect operations will not lead to significant disturbance of the stored CO2
      - 3.2.5 Over-filling of the reservoir will not lead to significant disturbance of the stored CO2
      - 3.2.6 Resource exploitation elsewhere does not lead to significant disturbance of the stored CO2

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Figure 4.40 Tree Plot - Containment (Hypotheses 3.2.3 to 3.2.4, Remainder Not Expanded)


The CO2 volume planned to be stored will be completely and "permanently" contained

1 The storage reservoir has sufficient accessible capacity to take the volume of CO2 planned to be stored at the required injection rate

2 The observed behaviour (migration, spatial distribution, partitioning between phases) of CO2 conforms with predictions and supports containment

3 The storage site will evolve towards long-term (containment) stability following closure

3.1 The expected system evolution is towards long-term stability following closure

3.2 There will be no "high-impact, low-probability" events that could significantly disturb system following closure

3.2.1 Tectonic processes (active faulting, seismic pumping, uplift, subsidence) will not lead to significant disturbance of the stored CO2

3.2.2 Well bore / seal failure will not lead to significant disturbance of the stored CO2

3.2.3 Inadvertent human intrusion will not lead to significant disturbance of the stored CO2

3.2.3.1 There is insignificant likelihood of inadvertent human intrusion

3.2.3.1.1 There are no economic resources that would cause intrusive activities to penetrate the storage complex

3.2.3.1.2 People with the technical capability to intrude into the storage complex would be able to recognize the existence of CO2 and take appropriate measures

3.2.3.2 Predicted impacts of human intrusion, if it occurs, due to the stored CO2 are insignificant

3.2.3.2.1 Future human groups responsible for any unintentional intrusion would implement mitigating actions sufficient to ensure mitigating impacts

3.2.3.2.2 Impacts associated with any unmitigated intrusion events would be insignificant

3.2.3.2.2.1 Models predict that any plausible human intrusion will not cause leakage of CO2 out of the storage complex

3.2.3.2.2.2 Models predict that any plausible human intrusion will not lead to significant direct or indirect impacts from CO2 in domains outside the storage complex

3.2.4 Sabotage that does not affect operations will not lead to significant disturbance of the stored CO2

3.2.4.1 There is insignificant likelihood of sabotage

3.2.4.2 Predicted impacts of any sabotage, if it occurs, are insignificant

3.2.4.2.1 Models predict that any plausible sabotage events will not cause leakage of CO2 out of the storage complex

3.2.4.2.2 Models predict that any plausible sabotage events will not lead to significant direct or indirect impacts from CO2 in domains outside the storage complex

3.2.5 Over-filling of the reservoir will not lead to significant disturbance of the stored CO2

3.2.6 Resource exploitation elsewhere does not lead to significant disturbance of the stored CO2

Evaluation of CO2 storage volumes and containment risks v21 31/03/2015

Figure 4.41 Tree Plot - Containment (Hypotheses 3.2.5 to 3.2.6, Remainder Not Expanded)

The CO2 volume planned to be stored will be completely and "permanently" contained

1 The storage reservoir has sufficient accessible capacity to take the volume of CO2 planned to be stored at the required injection rate

2 The observed behaviour (migration, spatial distribution, partitioning between phases) of CO2 conforms with predictions and supports containment

3 The storage site will evolve towards long-term (containment) stability following closure

3.1 The expected system evolution is towards long-term stability following closure

3.2 There will be no "high-impact, low-probability" events that could significantly disturb system following closure

3.2.1 Tectonic processes (active faulting, seismic pumping, uplift, subsidence) will not lead to significant disturbance of the stored CO2

3.2.2 Well bore / seal failure will not lead to significant disturbance of the stored CO2

3.2.3 Inadvertent human intrusion will not lead to significant disturbance of the stored CO2

3.2.4 Sabotage that does not affect operations will not lead to significant disturbance of the stored CO2

3.2.5 Over-filling of the reservoir will not lead to significant disturbance of the stored CO2

3.2.5.1 There is insignificant likelihood of over-filling

3.2.5.1.1 The capacity is known and accessibility of the capacity is known

3.2.5.1.2 The injected CO2 volumes can be adequately managed so as not to exceed known accessible capacity

3.2.5.2 Predicted impacts of over-filling, if it occurs, are insignificant

3.2.5.2.1 Models predict that over-filling will not cause leakage of CO2 out of the storage complex

3.2.5.2.1.1 Free CO2 will not migrate laterally beyond the defined storage complex due to over-filling

3.2.5.2.1.2 Dissolved CO2 will not migrate laterally beyond the defined storage complex due to over-filling

3.2.5.2.2 Models predict that over-filling will not lead to significant direct or indirect impacts from CO2 in domains outside the storage complex

3.2.6 Resource exploitation elsewhere does not lead to significant disturbance of the stored CO2

3.2.6.1 There is insignificant likelihood of obervable additional interactions

3.2.6.2 Predicted impacts of significant additional interactions, if they occur, are insignificant

3.2.6.2.1 Models predict that additional interactions due to resource exploitation elsewhere will not cause leakage of CO2 out of the storage complex as a consequence of CO2 storage

3.2.6.2.1.1 Free CO2 will not migrate laterally beyond the defined storage complex as a consequence of resource exploitation

3.2.6.2.1.2 Dissolved CO2 will not migrate laterally beyond the defined storage complex as a consequence of resource exploitation

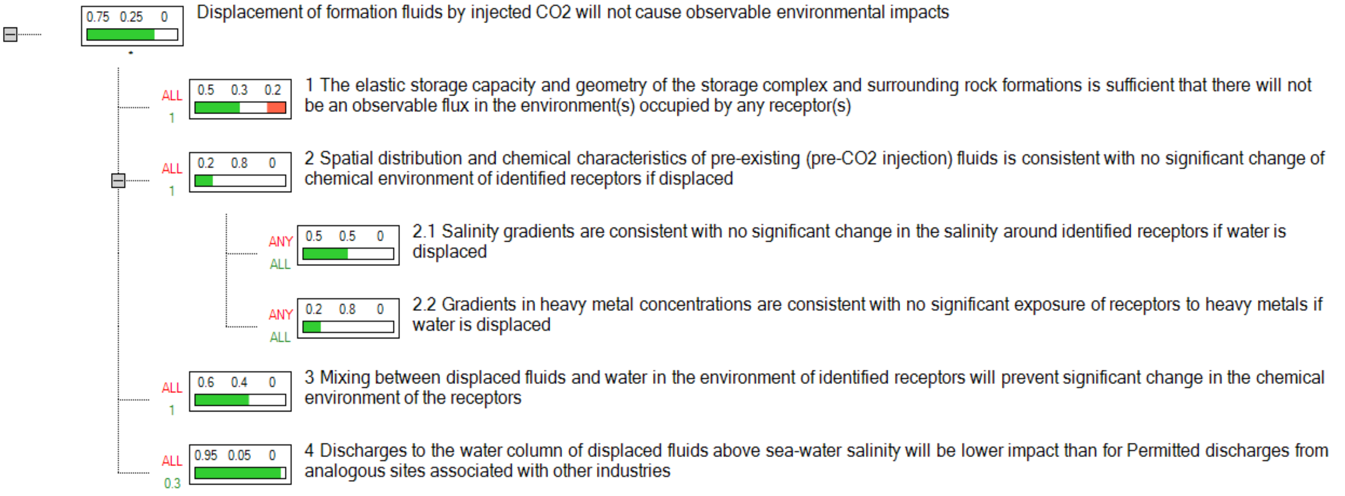
3.2.6.2.2 Models predict that resource exploitation elsewhere will not lead to significant direct or indirect impacts from CO2 in domains outside the storage complex

Evaluation of CO2 storage volumes and containment risks v21 31/03/2015

4.5.2.4 Displacement of Formation Fluids Tree

The tree plot shown in Figure 4.42 summarises the outcomes for displacement of formation fluids (including the potential for displacement of higher salinity waters, or even brines and impacts on seabed or water column dwelling receptors). Here, confidence that there will not be observable impacts is high with moderate residual uncertainty, based upon analyses of available information, including scoping calculations.

Figure 4.42 Tree Plot – Displacement of Formation Fluids



Displacement of formation fluids by injected CO2 will not cause observable environmental impacts

1 The elastic storage capacity and geometry of the storage complex and surrounding rock formations is sufficient that there will not be an observable flux in the environment(s) occupied by any receptor(s)

2 Spatial distribution and chemical characteristics of pre-existing (pre-CO2 injection) fluids is consistent with no significant change of chemical environment of identified receptors if displaced

2.1 Salinity gradients are consistent with no significant change in the salinity around identified receptors if water is displaced

2.2 Gradients in heavy metal concentrations are consistent with no significant exposure of receptors to heavy metals if water is displaced

3 Mixing between displaced fluids and water in the environment of identified receptors will prevent significant change in the chemical environment of the receptors

4 Discharges to the water column of displaced fluids above sea-water salinity will be lower impact than for Permitted discharges from analogous sites associated with other industries

Higher salinity formation waters evaluation v15 (27/04/2015)

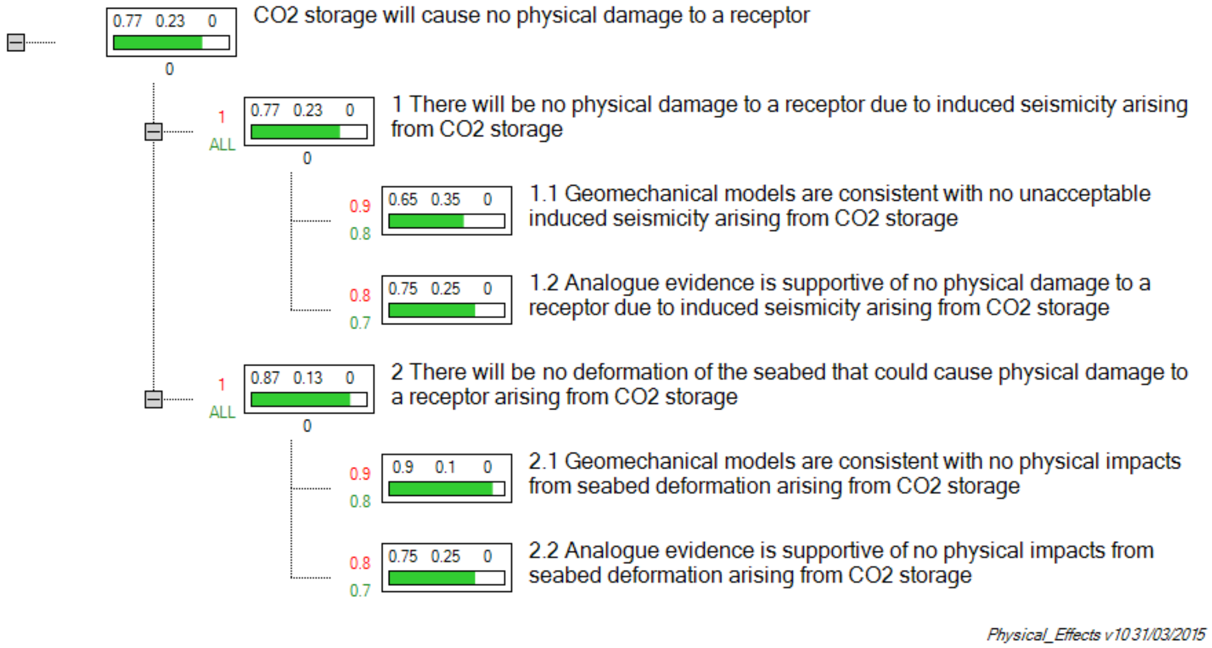
The greatest contributor to uncertainty at the top level of the tree is lacking information about chemical gradients within the formation water of the Bunter sandstone immediately below the seabed outcrop. There is less uncertainty about salinity gradients than there is about gradients in the chemical constituents of the formation water. Deductions about salinity gradients can be made from measured reservoir pressures and knowledge about the sources of salinity in the geological sequence (presence of halite down-dip, presence of seawater at the seabed), but the nearest compositions of formation water from the Bunter sandstone come from appraisal well 42/25-d3, which is located more than 25km from the outcrop.

However, the water immediately beneath the outcrop is likely to be seawater, the composition of which is known and this gives a small degree of confidence in Hypothesis 2.2, that gradients in heavy metal concentrations won’t lead to significant exposure of receptors to heavy metals if the formation water is displaced (Figure 4.42). It should be noted, however, that the lack of information leads to a large white space in the representation of this hypothesis and it cannot be excluded that heavy metal concentrations could be high enough to result in significant impacts.

4.5.2.5 Physical Effects Tree

The outcomes for the assessment of physical effects (including impacts on other receptors as a result of changes to the seabed) are presented in Figure 4.43. Confidence in the outcomes is again high.

Figure 4.43 Tree Plot – Physical Effects



4.5.3 Assessment of Risk

4.5.3.1 Risk Matrix

The assessed risks are presented in the risk matrix in Table 4.28. The rows of the matrix represent the probability that a particular phenomenon will occur, one with greater likelihood being placed in a higher row of the matrix than one with lower likelihood. The probabilities are expressed using a linguistic scale, in recognition of the fact that they are expert judgments, albeit ones that are conditioned by evaluating a combination of quantitative and qualitative evidence. The scale is as follows:

- Very high - Almost certain to occur
- High - Clearly more likely to occur than not to occur
- Medium - As likely to occur as not to occur
- Low - Clearly less likely to occur than not to occur
- Very low - Almost certain not to occur

Table 4.28 Risk Matrix

		Worst Plausible Consequence During the Assessment Time Frame				
		Very low	**Low**	**Medium**	**High**	**Very high**
Probability	**Very high**	• Physical uplift of seabed • Lateral migration of dissolved CO_2 out of storage complex • Induced seismicity • Natural seismicity	• Displacement of higher salinity waters and interaction with benthic or pelagic biota (effect of higher salinity and contaminants)			
	High	• Reduced injectivity due to chemical changes/reactivity				
	Medium	• Resource exploitation elsewhere disturbs CO_2 • Interaction of CO_2 storage with other resources				
	Low		• Physical/chemical conditions prevent required capacity being accessed			
	Very low	• Tectonic processes disturb CO_2 • Sabotage (of well heads) • Leakage through primary seals/secondary seals • Lateral migration of free CO_2 out of the storage complex	• Over-filling	• Reservoir pressurisation/compartmentalisation • Failure of historical well seals • Failure of injection well seals • Inadvertent human intrusion leads to leakage		

It should be noted that this scheme does not divide probability space equally. It is designed to highlight phenomena that are clearly not expected to happen (probability 'Very low') and those that are clearly expected to happen (probability 'Very high').

The columns of the matrix represent the worst plausible consequences of each phenomenon, should it occur, during the assessment time frame. This is a cautious bounding approach. The reason for this approach is that mitigation planning should consider the worst plausible result of any phenomenon happening. For example, reservoir pressurisation due to compartmentalisation could plausibly attain any value between the pressure prior to CO_2 injection and some maximum pressure. For the purposes of mitigation planning it is the maximum consequence that is of concern.

Like the probabilities, consequences are represented on a linguistic scale, a phenomenon with a lower worst-case consequence being listed to the left of a phenomenon with a higher worst-case consequence. However, whereas probability categories can be defined objectively (even though a judgment as to the actual probability of a given phenomenon occurring is inevitably subjective), consequence categories are themselves subjective; whether a consequence is considered severe or not depends upon a value judgment. One person may regard a 'severe consequence' to have a particular set of characteristics whereas another person might regard the same characteristics to indicate a 'mild consequence'. For this reason, the approach taken here is to classify consequences as to whether or not they are 'observably detrimental', using the following scale:

- Very high - a consequence is of sufficient magnitude that it definitely would be observed and is clearly detrimental to one or more receptors (engineered structures, natural resources, organisms) over a wide area (>10m^2) or would call into question the effectiveness of CO_2 storage as a contributor to mitigating climate change;
- High - a consequence is of sufficient magnitude that it probably would be observed and is clearly detrimental to one or more receptors (engineered structures, natural resources, organisms) over a small area (<10m^2) or would call into question the effectiveness of CO_2 storage as a contributor to mitigating climate change;
- Medium - a consequence would be of sufficient magnitude that probably it would be observed and could be detrimental to one or more receptors (engineered structures, natural resources, organisms), but would not call into question the effectiveness of CO_2 storage as a contributor to mitigating climate change;
- Low - a consequence would be sufficiently small that probably it would not be observed and would not call into question the effectiveness of CO_2 storage as a contributor to mitigating climate change, but nevertheless could be detrimental to any receptors (engineered structures, natural resources, organisms); and
- Very low - a consequence would not be detrimental to one or more receptors (engineered structures, natural resources, organisms) and would not call into question the effectiveness of CO_2 storage as a contributor to mitigating climate change.

Here the term 'detrimental' implies a tendency towards weakening structures (moving them towards the limits of their design envelopes or exceeding their design envelopes), impairing resource quality, or impairing the health of organisms. However, it should be noted that this scheme does not deal with how detrimental a particular consequence is perceived to be by stakeholders (regulators, legislators, NGOs, the general public and so on). For example, leakage of CO_2 that caused the observable impairment of health of organisms, such as, stunted growth that could not be attributed to causes other than CO_2 leakage over a wide area; this would be seen by all stakeholders as 'detrimental' and therefore would be placed in the 'Very high' consequence category. However, the scheme does not distinguish whether these detrimental consequences might be regarded as tolerable.

The risks illustrated in the matrix can be mapped to the various scenarios presented in Section 4.3 and Appendix A. Each risk corresponds to one of the scenarios. Judgments of probability and worst plausible consequence are supported by the judgments on evidence represented in the decision trees presented in Section 4.5.2.2 and Appendix C. The support given by these trees to the assessment of risks shown in the risk matrix is explained in the next section.

4.5.3.2 Relationship between Risk Matrix and Evidence Support Logic Trees

Justifications for the risks summarised in the risk matrix (Table 4.28) are shown in Table 4.29. This table also summarises relationships between the judgments of the probability of occurrence and potential consequences of each phenomena represented in the risk matrix and the judgments represented in the ESL trees. More details of the trees are provided in Section 4.5.2.2 and Appendix C.

The risk matrix does not indicate the levels of confidence that may be placed in the consequences of phenomena occurring. In contrast, the sizes of the green or red fields in an ESL tree indicate the levels of confidence that may be assigned to a particular judgment as to whether or not an impact is significant. Thus, to gain a full picture of both the risk judgments and the confidence that may be placed in them, both the risk matrix and the ESL trees need to be consulted.

There is an important distinction between the judgments of impacts represented in the ESL trees and the consequences represented in the risk matrix. The ESL trees simply represent judgments as to whether or not the impact of a phenomenon, if the phenomenon occurs, is ‘significant’. In contrast, the risk matrix aims to give a general indication of how significant may be the consequence of a phenomenon occurring. The judgments represented in the ESL trees considered an impact to be ‘significant’ if it can be observed and calls into question the safety and/or effectiveness of CO_2 storage. If an ESL tree indicates that an impact is judged to be ‘insignificant’, then in the risk matrix it could be classified as having consequences that are ‘very low’ or ‘low’. In contrast, if an ESL tree indicates that an impact is judged to be ‘significant’, then in the risk matrix it could be classified as having consequences that are ‘medium’, ‘high’ or ‘very high’

Table 4.29 Explanation of the Risks Represented in the Risk Matrix Shown in Table 4.28

Phenomenon	Reason for Probability	Reason for Consequences	Summary of Supporting Confidence from ESL – (‘Significant’ here is something that is observed and calls into question the safety and/or effectiveness of CO_2 storage)
Physical uplift of seabed	Very high: Geomechanical models indicate that there will be a small degree of uplift of the seabed	Very low: Geomechanical models indicate that the maximum degree of uplift will be only 9cm – 15cm and gradients will be extremely low, in the order of 10-5	‘Physical Effects’ Tree, high to very high degrees of confidence (>0.7) in the truth of the hypotheses: 2. There will be no deformation of the seabed that could cause physical damage to a receptor arising from CO_2 storage 2.1 Geomechanical models are consistent with no physical impacts from seabed deformation arising from CO_2 storage 2.2 Analogue evidence is supportive of no physical impacts from seabed deformation arising from CO_2 storage
Lateral migration of dissolved CO_2 out of storage complex	Very high: Conceptual models of fluid flow indicate dense CO_2-charged water will migrate laterally and downwards out of the storage complex; CO_2-charged formation water will be more dense than the formation water prior to interaction with CO_2. It was calculated that around 10% of the CO_2 would dissolve in the formation water over a timescale of c. 500 years	Very low: Dense CO_2-charged formation water will tend to sink towards structural lows. Seismic data indicate that these structural lows are well away from receptors and the near-surface. Additionally, any migration would be very slow	‘Containment’ Tree, very high degrees of confidence (>0.9) in the truth of the hypotheses: 3.1.2.2 Dissolved CO_2 will not migrate laterally beyond the defined storage complex Note: This judgment relies on the validity of the assumption that the lateral boundaries of the storage complex can be placed sufficiently far away from the crest of the Endurance structure No evidence exists that there will be significant adverse effects of lateral migration of dissolved CO_2 out of the storage complex
Induced seismicity	Very high: Induced seismicity will occur to some degree – microseismic events will accompany pressure changes and/or temperature contrast in the reservoir (IEAGHG, 2013)	Very low: The magnitude of induced seismicity will be very small and there is abundant evidence from geomechanical models and analogue studies that the magnitude of induced seismic events will be too small to compromise storage complex integrity. Simplified geomechanical models show that there is strain of the Röt clay and halite. Injection rates and pressures will be carefully monitored and controlled to ensure they remain well below fracture closure pressures and so they are unlikely to induce fracturing or movement on existing fractures	‘Physical Effects’ Tree, high degree of confidence (0.77) in the truth of the hypothesis: 1. There will be no physical damage to a receptor due to induced seismicity arising from CO_2 storage Supported by moderately high to high confidence (>0.5) in the child hypotheses: 1.1 Geomechanical models are consistent with no unacceptable induced seismicity arising from CO_2 storage 1.2 Analogue evidence is supportive of no physical damage to a receptor due to induced seismicity arising from CO_2 storage No evidence exists that there will be significantly adverse physical effects of induced seismicity.

Phenomenon	Reason for Probability	Reason for Consequences	Summary of Supporting Confidence from ESL – (‘Significant’ here is something that is observed and calls into question the safety and/or effectiveness of CO_2 storage)
Natural seismicity	Very high: No area of the world is completely aseismic; small earthquakes are regularly recorded in the SNS. The largest recorded earthquake in the vicinity of the UK (M6.1) occurred in the Dogger Bank in 1931, around 50km from the Endurance structure	Very low: The magnitude of natural seismicity will be too small to compromise the integrity of deep subsurface reservoirs. The fact that hydrocarbon reservoirs have remained in the SNS over geologically significant time periods indicates that natural seismicity in this area is not of a scale and nature that is able to compromise storage complex integrity	‘Containment’ Tree, very high degree of confidence (0.99) in the truth of the hypothesis: 3.2.1 Tectonic processes (active faulting, seismic pumping, uplift, subsidence) will not lead to significant disturbance of the stored CO_2 Supported by high degree of confidence (0.88) in the hypothesis: 3.2.1.1 Geological setting is sufficiently stable that the probability of transient tectonic processes (earthquakes, volcanic eruptions) disturbing the storage complex is insignificant and very high degree of confidence (0.99) in the hypothesis: 3.2.1.2 Predicted impacts of tectonic processes, if they occur, will be insignificant 3.2.1.1 is supported by high degree of confidence (0.8) in hypothesis: 3.2.1.1.1 Tectonic setting is remote from plate boundaries or recognised zones of intra-plate tectonic activity (including activity driven by glaciation) and very high degree of confidence (0.95) in hypothesis: 3.2.1.1.2 Geology (lithologies and structures) has not been significantly disturbed by past tectonic processes over relevant timescales 3.2.1.2 is supported by very high degrees of confidence (>0.9) in hypotheses: 3.2.1.2.1 Models predict that tectonic processes that could plausibly occur will not cause leakage of CO_2 out of the storage complex 3.2.1.2.2 Models predict that tectonic processes that could plausibly occur will not lead to significant direct or indirect impacts from CO_2 in domains outside the storage complex No evidence exists that there will be significantly adverse physical effects of natural seismicity

Phenomenon	Reason for Probability	Reason for Consequences	Summary of Supporting Confidence from ESL – (‘Significant’ here is something that is observed and calls into question the safety and/or effectiveness of CO_2 storage)
Reduced injectivity due to chemical changes/ reactivity	High: Models indicate that depending upon the injection regime, chemical changes (such as halite precipitation) are likely to occur near to the injection well. In extremis this could prevent injection of the planned volume of CO_2. Otherwise injection pressures could increase or the timeframes for injection could be extended.	Very low: There are well-established mitigation methods (such as seawater flushing, use of MEG) that will prevent adverse consequences	‘Containment’ Tree, moderate degree of confidence (0.6) in the truth of the hypothesis: 1.2 Chemical effects will not prevent the required storage capacity being accessed at the required injection rate supported by moderate degree of confidence (0.6) in the truth of the hypothesis: 1.2.1 Chemical effects near the point of injection will not prevent the required storage capacity being accessed at the required injection rate and a high degree of confidence (0.85) in the truth of the hypothesis: 1.2.2 Chemical effects away from the point of injection will not prevent the required storage capacity being accessed at the required injection rate 1.2.1 is supported by moderately high (>0.5) degrees of confidence in the truth of the hypotheses: 1.2.1.1 Halite and hydrate precipitation will not prevent the required storage capacity being accessed at the required injection rate 1.2.1.2 Other precipitates will not prevent the required storage capacity being accessed at the required injection rate ‘Containment’ Tree, high degree of confidence (0.75) in the truth of the hypothesis: 1.3 Physical effects will not prevent the required storage capacity being accessed at the required injection rate Supported by very high confidence (0.9) in truth of the hypothesis: 1.3.1 Physical features will not prevent the required storage capacity being accessed at the required injection rate and moderate confidence (0.6) in the truth of the hypothesis: 1.3.2 Physical alteration due to physico-chemical processes will not prevent the required storage capacity being accessed at the required injection rate There is a very small amount of evidence that halite and/or hydrate precipitation near the injection well may prevent the required porosity being accessed at the required rate – but this is derived from model results and only occurs under specific conditions that should be avoided.

Phenomenon	Reason for Probability	Reason for Consequences	Summary of Supporting Confidence from ESL – (‘Significant’ here is something that is observed and calls into question the safety and/or effectiveness of CO_2 storage)
Resource exploitation elsewhere disturbs CO_2	Medium: All proven resources in the Bunter sandstone are a considerable distance (10’s of km) from the Endurance storage reservoir. However, there is good evidence from pressure data that the Bunter sandstone is well connected across a wide area of this part of the SNS. Hence, resource exploitation in this formation (including CO_2 injection into the Bunter sandstone in other structures) is quite likely to have some observable impact upon the Bunter sandstone in the Endurance structure. Within the same region deeper hydrocarbon resources also exist, but these are separated from the Bunter sandstone by impermeable thick Zechstein salt-bearing strata. There are no resources shallower than the Bunter sandstone in the Endurance structure.	Very low: Pressure data indicating hydraulic connection between the Endurance reservoir and hydrocarbon reservoirs to the northeast show that impacts on CO_2 storage would be very small (AGR, 2014i).	‘Containment’ Tree, very high degree of confidence (0.93) in the truth of the hypothesis: 3.2.6 Resource exploitation elsewhere does not lead to significant disturbance of the stored CO_2 3.2.6 is supported by a very high degree of confidence (0.93) in the truth of the hypothesis: 3.2.6.2 Predicted impacts of significant additional interactions, if they occur, are insignificant which is supported by very high degrees of confidence (>0.9) in the truth of the hypotheses: 3.2.6.2.1 Models predict that additional interactions due to resource exploitation elsewhere will not cause leakage of CO_2 out of the storage complex as a consequence of CO_2 storage 3.2.6.2.1.1 Free CO_2 will not migrate laterally beyond the defined storage complex as a consequence of resource exploitation 3.2.6.2.1.2 Dissolved CO_2 will not migrate laterally beyond the defined storage complex as a consequence of resource exploitation 3.2.6.2.2 Models predict that resource exploitation elsewhere will not lead to significant direct or indirect impacts from CO_2 in domains outside the storage complex No evidence exists that there will be significantly adverse effects of resource exploitation, were it to occur. There is some confidence (0.4) in the falsehood of the hypothesis: 3.2.3.1.1 There are no economic resources that would cause intrusive activities to penetrate the storage complex

Phenomenon	Reason for Probability	Reason for Consequences	Summary of Supporting Confidence from ESL – (‘Significant’ here is something that is observed and calls into question the safety and/or effectiveness of CO_2 storage)
Interaction of CO_2 storage with other resources	Medium: All proven resources in the Bunter sandstone are some distance (10’s of km) from the Endurance storage reservoir. However, there is good evidence from pressure data that the Bunter sandstone is well connected across a wide area of this part of the SNS. Hence, CO_2 injection into the Bunter sandstone in the Endurance structure is quite likely to have some observable impact upon the Bunter sandstone in other structures. Within the same region deeper hydrocarbon resources also exist, but these are separated from the Bunter sandstone by impermeable thick Zechstein salt-bearing strata. There are no resources shallower than the Bunter sandstone in the Endurance structure.	Very low: Pressure data indicating hydraulic connection between the Bunter sandstone reservoir in the Endurance structure and hydrocarbon reservoirs to the northeast show that impacts of CO_2 storage would be very small	‘Containment’ Tree, hypotheses: As for ‘Resource exploitation elsewhere disturbs CO_2’

Phenomenon	Reason for Probability	Reason for Consequences	Summary of Supporting Confidence from ESL – (‘Significant’ here is something that is observed and calls into question the safety and/or effectiveness of CO_2 storage)
Tectonic processes disturb CO_2	Very low: The SNS is in a tectonically stable region of the world. There are no recognised active faults within the Endurance structure	Very low: Any tectonic processes that occurred (uplift/subsidence) would not compromise the integrity of the primary seal (BGS, 2013). Evidence for this comes from the preservation of hydrocarbon resources in the Bunter sandstone reservoir elsewhere in the SNS for geologically significant periods of time	‘Containment’ Tree, very high degree of confidence (1.0) in the truth of the hypothesis: 3.2.1 Tectonic processes (active faulting, seismic pumping, uplift, subsidence) will not lead to significant disturbance of the stored CO_2 Supported by high degree of confidence (0.88) in the truth of the hypothesis: 3.2.1.1 Geological setting is sufficiently stable that the probability of transient tectonic processes (earthquakes, volcanic eruptions) disturbing the storage complex is insignificant which is supported in turn by a high degree of confidence (0.8) in the truth of the hypothesis: 3.2.1.1.1 Tectonic setting is remote from plate boundaries or recognised zones of intra-plate tectonic activity (including activity driven by glaciation) And a very high degree of confidence (0.95) in the hypothesis: 3.2.1.1.2 Geology (lithologies and structures) has not been significantly disturbed by past tectonic processes over relevant timescales 3.2.1 supported by very high degrees of confidence (>0.9) in the hypotheses: 3.2.1.2 Predicted impacts of tectonic processes, if they occur, will be insignificant 3.2.1.2.1 Models predict that tectonic processes that could plausibly occur will not cause leakage of CO_2 out of the storage complex 3.2.1.2.2 Models predict that tectonic processes that could plausibly occur will not lead to significant direct or indirect impacts from CO_2 in domains outside the storage complex No evidence exists that there will be significantly adverse effects of tectonic processes in this area, were they do occur
Sabotage (of well heads)	Very low: The wells are all located offshore and therefore inherently difficult for unauthorised people to gain access to. Security arrangements that are commonly employed by North Sea hydrocarbon field operators will further limit the ability for sabotage to take place	Very low: If well heads are damaged during the operational phase, then they are likely to be repaired rapidly. Post-operations there will be plugs/seals in the wells and therefore damage to well heads will not result in adverse consequences	‘Containment’ Tree, very high degrees of confidence (>0.9) in the hypotheses: 3.2.4 Sabotage that does not affect operations will not lead to significant disturbance of the stored CO_2 3.2.4.1 There is insignificant likelihood of sabotage 3.2.4.2 Predicted impacts of any sabotage, if it occurs, are insignificant 3.2.4.2.1 Models predict that any conceivable sabotage events will not cause leakage of CO_2 out of the storage complex 3.2.4.2.2 Models predict that sabotage events will not lead to significant direct or indirect impacts from CO_2 in domains outside the storage complex No evidence exists that there will be significantly adverse effects of sabotage in the deep subsurface, were it to occur.

Phenomenon	Reason for Probability	Reason for Consequences	Summary of Supporting Confidence from ESL – (‘Significant’ here is something that is observed and calls into question the safety and/or effectiveness of CO_2 storage)
Leakage through primary seal/secondary seals	Very low: The primary seal consists of the Röt clay and the deepest secondary seal is the Röt halite, both of which have inherently good sealing qualities. There is no evidence for any structures (faults) that extend through these formations in the vicinity of the Endurance storage complex	Very low: Even if leakage were to occur through the primary seal and secondary seals it would be at a very low rate since diffusion would be the primary driving mechanism; any fractures or unidentified faults in the Röt halite would not form fluid flow pathways owing to the self-healing characteristics of halite. Above the Röt halite there is a thick sequence of largely low permeability Jurassic sedimentary rocks which would also provide additional secondary sealing	‘Containment’ Tree, high degree of confidence (0.85) in the truth of the hypothesis: 3.1.1.2 Structures (faults, fracture zones etc.) will not provide leakage paths Very high degrees of confidence (>0.9) in the hypotheses: 3.1.1.3 Confining rock (primary seal and secondary seal, overburden to ultimate seal) has sufficient integrity 3.1.3 Predictions of post-closure behaviour of the storage complex predict evolution towards long-term stability for any plausible boundary conditions 3.1.3.1 Multi-phase flow models predict evolution towards no flow of free and dissolved CO_2 3.1.3.2 Geomechanical models predict evolution towards no deformation due to CO_2 in the long term 3.1.3.3 Geochemical models predict evolution towards long-term chemical stability No evidence exists that there will be significantly adverse effects of primary seal/secondary seal failure, were it to occur
Lateral migration of free CO_2 out of the Storage complex	Very low: The storage capacity of the Bunter sandstone reservoir within the storage site, as presently defined, is very large compared with the Project CO_2 volume. There is no evidence for heterogeneities (such as relatively permeable structures within the Bunter sandstone reservoir) that could result in the margin of the plume migrating more rapidly than predicted. Additionally, the Endurance structure has a 4-way closure, such that buoyant migration of the CO_2 up-dip will naturally take the CO_2 away from the margins of the structure	Very low: Even if some free CO_2 were to migrate laterally out of the presently defined storage complex, the vast majority would remain within the Endurance structure. Trapping in irregularities along the top of the Bunter sandstone, hydrodynamic trapping (which is thought likely to account for only a very small proportion of the CO_2) and dissolution would mean that not all the CO_2 that did spill would rise towards the surface. That is, it is inconceivable that any more than a small proportion of the CO_2 could rise to the near-surface or come into contact with any of the defined receptors	‘Containment’ Tree, very high degrees of confidence (>0.9) in the truth of the hypotheses: 3.1.2 The CO_2 will not migrate laterally beyond the defined storage complex 3.1.2.1 Free CO_2 will not migrate laterally beyond the defined storage complex No evidence exists that there will be significantly adverse effects of lateral migration of CO_2 out of the storage complex, were it to occur

Phenomenon	Reason for Probability	Reason for Consequences	Summary of Supporting Confidence from ESL – (‘Significant’ here is something that is observed and calls into question the safety and/or effectiveness of CO_2 storage)
Displacement of higher salinity waters and interaction with benthic or pelagic biota (effect of higher salinity and contaminants)	Very high: A range of models (reservoir simulations and simple scoping calculations) show that higher salinity waters will be displaced towards the seabed in the vicinity of the outcrop of the Bunter sandstone c. 25 km to the southeast of the Endurance storage complex	Low: Models indicate that the flux of displaced water to the seabed is likely to be too small to observe. While it cannot be ruled out that there would be some detrimental impacts on organisms within/near the seabed, it seems unlikely that such impacts would be observed. Note also that there is uncertainty whether the discharged fluids would be of significantly higher salinity than seawater. Similar arguments can be applied to heavy metal contaminants. However, there is very little evidence available with which to judge possible concentration of these constituents in the discharging water	‘Formation Water Displacement’ Tree, high degree of confidence (0.75 in the truth of the root hypothesis: Displacement of formation fluids by injected CO_2 will not cause observable environmental impacts Reflecting a very high degree of confidence (0.95) in the truth of the hypothesis: 4. Discharges to the water column of displaced fluids above seawater salinity will be lower impact than for Permitted discharges from analogous sites associated with other industries and a moderate degree of confidence (0.6) in the truth of the hypothesis: 3. Mixing between displaced fluids and water in the environment of identified receptors will prevent significant change in the chemical environment of the receptors There is no evidence that displacement of higher salinity waters would lead to significant impacts. Some confidence (0.2) that heavy metal contaminants would not cause significant impacts is provided by the hypothesis: 2.2 Gradients in heavy metal concentrations are consistent with no significant exposure of receptors to heavy metals if water is displaced
Over-filling	Very low: The CO_2-accessible pore volume of the CO_2 storage reservoir within the Endurance storage complex is thought to be many times larger than the Project CO_2 volume. Injection will be well-controlled to prevent over-filling. There is no evidence for heterogeneous permeability/distribution of pore space that could result in the margins of the Project CO_2 volume extending beyond the spill point of the Endurance structure	Low: Even if free CO_2 were to migrate laterally out of the presently defined storage complex, it is inconceivable that any more than a small proportion of the CO_2 could rise to the near-surface or come into contact with any of the defined receptors. Trapping in irregularities along the top of the Bunter sandstone, hydrodynamic trapping (which is thought likely to account for only a very small proportion of the CO_2) and dissolution would mean that not all the CO_2 that did spill would rise towards the surface	‘Containment’ Tree, very high degree of confidence (>0.90) in the truth of the hypotheses: 3.2.5 Over-filling of the reservoir will not lead to significant disturbance of the stored CO_2 3.2.5.1 There is insignificant likelihood of over-filling 3.2.5.1.1 The capacity is known and accessibility of the capacity is known 3.2.5.1.2 The injected CO_2 volumes can be adequately managed so as not to exceed known accessible capacity 3.2.5.2.1.1 Free CO_2 will not migrate laterally beyond the defined storage complex due to over-filling There is a high degree of confidence (0.8) in the truth of the hypothesis: 3.2.5.2.2 Models predict that over-filling will not lead to significant direct or indirect impacts from CO_2 in domains outside the storage complex No evidence exists that any plausible overfilling would lead to significant impacts

Phenomenon	Reason for Probability	Reason for Consequences	Summary of Supporting Confidence from ESL – (‘Significant’ here is something that is observed and calls into question the safety and/or effectiveness of CO_2 storage)
Physical/ chemical conditions prevent required capacity being accessed	Low: Geochemical models indicate that porosity and permeability will not be changed significantly as a consequence of chemical reactions within the reservoir. The storage capacity of the Bunter sandstone reservoir within the storage site, as presently defined, is very large compared with the Project CO_2 volume.	Low: If the required storage capacity could not be reached, there would be a need to stop injection which would call into question the value of the project as a contributor to mitigating climate change. However, additional wells could be drilled to access the storage capacity more effectively.	‘Containment’ Tree, moderate degrees of confidence (>0.5) in the truth of the hypotheses: 1.2 Chemical effects will not prevent the required storage capacity being accessed at the required injection rate 1.2.1 Chemical effects near the point of injection will not prevent the required storage capacity being accessed at the required injection rate 1.2.1.1 Halite and hydrate precipitation will not prevent the required storage capacity being accessed at the required injection rate High degrees of confidence (>0.7) in the truth of the hypotheses: 1.2.1.2 Other precipitates will not prevent the required storage capacity being accessed at the required injection rate 1.2.2 Chemical effects away from the point of injection will not prevent the required storage capacity being accessed at the required injection rate 1.3 Physical effects will not prevent the required storage capacity being accessed at the required injection rate Hypothesis 1.3 is supported by very high confidence (0.9) in the truth of the hypothesis: 1.3.1 Physical features will not prevent the required storage capacity being accessed at the required injection rate And moderate confidence (0.6) in the truth of the hypothesis: 1.3.2 Physical alteration due to physico-chemical processes will not prevent the required storage capacity being accessed at the required injection rate No evidence exists that there would be significant impacts from physical/chemical conditions preventing required capacity being accessed
Reservoir pressurisation/compartmentalisation	Very low: There is no evidence for compartmentalisation of the Bunter sandstone reservoir (AGR, 2014g). Pressure data indicate good connectivity over long distances for example, pressure interaction with the Esmond gas field	Medium: If the required storage capacity could not be reached, there would be a need to stop injection which would call into question the value of the project as a contributor to mitigating climate change. However, additional boreholes could be drilled to access the storage capacity more effectively	‘Containment’ Tree, high confidence (0.75) in the truth of the hypothesis: 1.3 Physical effects will not prevent the required storage capacity being accessed at the required injection rate supported by very high confidence (0.9) in the truth of the hypothesis: 1.3.1 Physical features will not prevent the required storage capacity being accessed at the required injection rate and moderate confidence (0.6) in the truth of the hypothesis 1.3.2 Physical alteration due to physico-chemical processes will not prevent the required storage capacity being accessed at the required injection rate

Phenomenon	Reason for Probability	Reason for Consequences	Summary of Supporting Confidence from ESL – (‘Significant’ here is something that is observed and calls into question the safety and/or effectiveness of CO_2 storage)
Failure of historical well seals	Very low: Relates to overall well sealing failure for wells that each have several seals. There are multiple barriers: cement plugs, Röt halite which will tend to creep into the borehole if residual drilling fluid is lost; which will make it very unlikely that seals will fail	Medium: If the seals were to fail, there could be localised release of CO_2 to the seabed. This release could interact detrimentally with organisms, but these impacts would be localised. Leakage of CO_2 in this way may call into question the effectiveness of the CO_2 storage project as a contributor to mitigating climate change	‘Containment’ Tree, high degree of confidence (0.96) in the truth of the hypothesis: 3.2.2 Well bore/seal failure will not lead to significant disturbance of the stored CO_2 and very high degree of confidence (0.94) in the truth of the hypothesis: 3.2.2.2 Predicted impacts of well bore/seal failure, if it occurs, are insignificant There is a low degree of confidence (0.05) in the falsehood of the hypothesis: 3.2.2 Well bore/seal failure will not lead to significant disturbance of the stored CO_2 arising from very low to low degrees of confidence (>0.05) in the falsehood of the hypotheses: 3.2.2.1 Models predict that well failure will not cause leakage of CO_2 out of the storage complex 3.2.2.2 Models predict that well bore/seal failure will not lead to significant direct or indirect impacts from CO_2 in domains outside the storage complex
Failure of injection well seals	Very low: Relates to overall well sealing failure for wells including several seals. There are multiple barriers: cement plugs, Röt halite which will tend to creep into the borehole if residual drilling fluid is lost; which will make it very unlikely that seals will fail. Injection wells will be completed/sealed to an even higher standard than the historical wells	Medium: If the seals were to fail, there could be localised release of CO_2 to the seabed. This release could interact detrimentally with organisms, but these impacts would be localised. Leakage of CO_2 in this way would call into question the effectiveness of the CO_2 storage project as a contributor to mitigating climate change	‘Containment’ Tree, hypotheses: As for failure of historical well seals
Inadvertent human intrusion leads to leakage	Very low: The storage reservoir is offshore at a depth of c.1000m to c. 1500m below the seabed. Intrusion into this reservoir will require highly developed technology and it is highly likely that any organisation possessing such technology would be able to recognise the existence of stored CO_2	Medium: The impact of inadvertent human intrusion would likely be similar to well seals failing – except that the process could be managed, such that impacts would be minimised	‘Containment’ Tree, very high degree of confidence (0.99) in the hypothesis: 3.2.3 Inadvertent human intrusion will not lead to significant disturbance of the stored CO_2 Supported by high confidence (0.76) in the truth of the hypothesis: 3.2.3.1 There is insignificant likelihood of inadvertent human intrusion and very high confidence (0.99) in the truth of the hypothesis: 3.2.3.2 Predicted impacts of human intrusion, if it occurs, due to the stored CO_2 are insignificant However, there is a very low degree of confidence (0.05) in the falsehood of the hypothesis: 3.2.3.2.2 Impacts associated with any unmitigated intrusion events would be insignificant

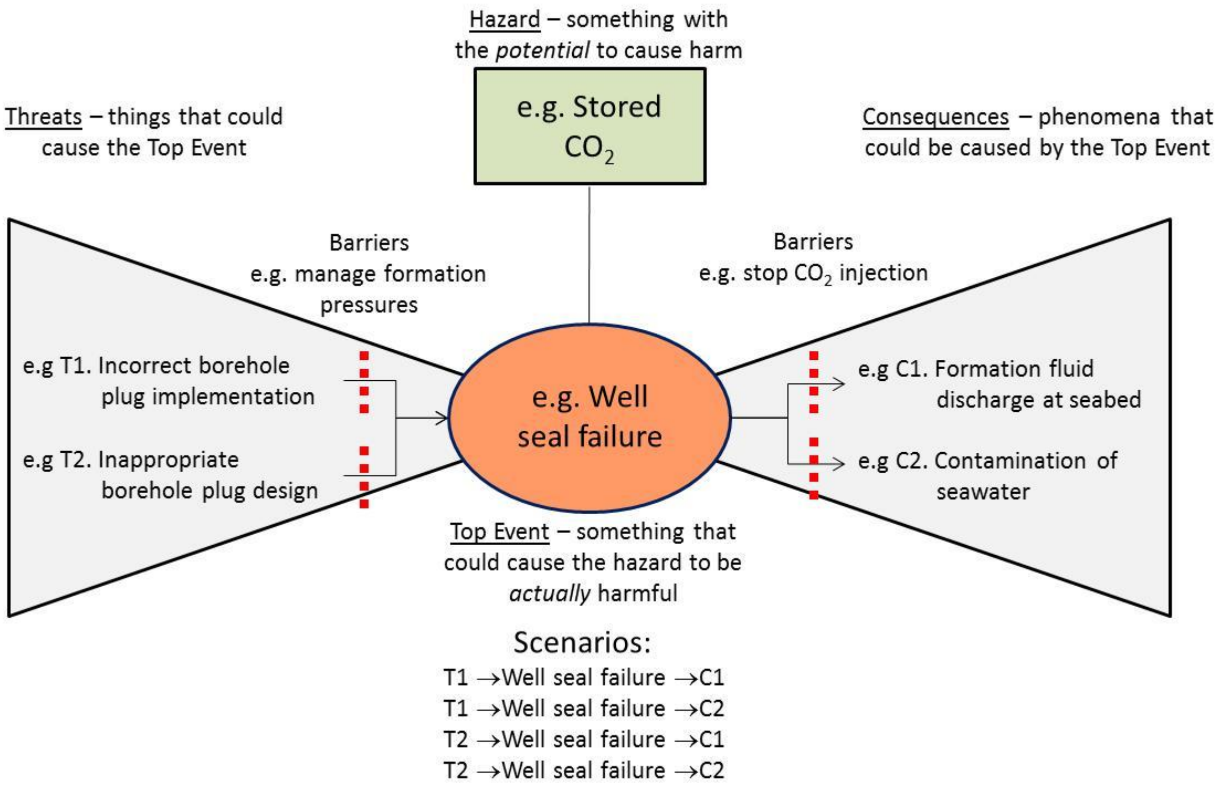
4.5.4 Risk Communication

4.5.4.1 The Bow Tie Method

This section presents a general introduction to the bow tie method. Subsequent sections describe the application of the bow tie analysis in the current study.

Bow tie analysis is a structured methodology for visualising and communicating risks and the steps taken to manage them (Figure 4.44). The bow tie method is particularly successful in representing and communicating the main risks and their implications.

Figure 4.44 Bow Tie Analysis



When applied to any system of interest, the main steps in a bow tie analysis are:

1. identification of hazards, which are features of a system that have potential to cause harm;
2. identification of ‘top events’ that could cause each hazard to be actually harmful;
3. identification of the threats, which are phenomena that could lead to each ‘top event’;
4. identification of the consequences should each ‘top event’ occur;
5. identification of barriers that could prevent each threat (control barriers) and consequence (recovery barriers);
6. identification of ‘escalation factors’, which are phenomena that could prevent each barrier from working; and
7. identification of ‘escalation factor barriers’, which are actions and/or system components that are designed to ensure that each ‘escalation factor’ does not occur.

Corresponding to a single ‘top event’ there are usually multiple threats and multiple consequences, giving rise to the bow tie appearance of the visualisation (Figure 4.44). Pathways through the bow tie structure, which connect threats to consequences via ‘top events’, correspond to scenarios that need to be analysed.

The bow tie method is particularly helpful in communicating key risks in a complimentary manner to the ESL approach (Section 4.5.2.2 and Appendix C). However, ESL can offer particular benefits where a case needs to be made for a particular course of action, where the impacts of risks and uncertainties need to be clearly identified, understood and communicated.

In order to carry out a bow tie analysis decisions need to be made concerning:

- the hazards that exist (what system components constitute hazards that are actually of concern?);
- the ‘top event’ (what events could really cause a hazard to be harmful?);
- the threats (what plausible threats could lead to a ‘top event’?);
- the consequences (what consequences of a ‘top event’ are really of concern?);
- the control and/or recovery barriers (what barriers could be employed practicably and effectively?); and
- ‘Escalation factors’ and ‘escalation factor barriers’ (what ‘escalation factors’ are plausible and what corresponding ‘escalation factor barriers’ could be employed practicably and effectively?).

Furthermore, an audit trail is needed to document all these decisions and the reasons for them transparently. By appropriately structuring a tree, ESL can be used to support the above decisions and thus provide an audit trail to the bow tie analysis.

4.5.4.2 Application of the Bow Tie Method

The bow tie analysis presented for the Project is intended to complement the ESL analysis and the associated risk matrices, by providing separate schematics of the main risks, the threats/events that could cause them and how they might be mitigated. Whereas the ESL tree and the risk matrices present the assessment outcomes, taking into account the likelihood and consequences of different risks including mitigation plans in the underpinning analysis, the bow tie approach focuses on showing the main risks and the passive and active measures taken to address them. This format is particularly useful in that it explicitly shows the main measures that need to be considered in monitoring and mitigation plans. However, it does not show the likelihood of success of those measures, or whether the risks they address are of significance. The bow tie can therefore provide an important contribution to financial project planning by representing the active measures that may need to be taken in the future, thus helping to communicate the rationale for financial provisions. However, as the approach aims to provide a comprehensive list of risks and measures, but does not address likelihood or consequence of risks with or without the measures, the final list of provisions used for financial planning may justifiably differ from the basic list in the bow tie.

Three main ‘hazards’ have been identified in the risk assessment work:

- CO_2 leakage, including the potential for loss of containment and the possibility of impacts on receptors associated with leakage;
- displacement of formation waters and the potential for formation waters of higher salinity or with higher heavy metal concentrations than seawater to interact with receptors in the benthic or pelagic zones as a result; and
- pressure-related physical deformation effects such as seabed uplift and the potential for impacts on receptors such as seabed structures associated with other facilities.

As discussed earlier, risks associated with each of these hazards and associated scenarios are considered to be very low. However, it is important that future monitoring work is undertaken to confirm the validity of assumptions underpinning that assessment and that provision is made for the mitigation of any risks, however unlikely it is that they will mature and lead to significant impacts. The bow ties presented in subsequent sections are intended to support the link between the risk assessment outcomes and the mitigation and monitoring plans.

However, bow tie diagrams have only been developed for leakage and for formation water displacement hazards. On the basis of the risk assessment outcomes it is considered that the likelihood of pressure-related physical impacts of significance on seabed structures other than those associated with the current CO_2 storage scheme is so low that the bow tie would effectively be meaningless.

On that basis, the following sections provide details of bow tie analyses undertaken for the other two hazards.

4.5.4.3 Outcomes of the Bow Tie Analysis

Containment Bow Tie

A containment bow tie was developed to represent threats that could lead to leakage and approaches to mitigating impacts.

Formation Water Displacement Bow Tie

A formation water displacement bow tie was developed to represent threats that could lead to displacement of higher salinity and/or higher heavy metal concentration waters and approaches to mitigating impacts to receptors.

4.6 Risk Statement

4.6.1 Summary

The main outcomes of the risk assessment, as recorded in the ESL tree and risk matrix presented in Section 4.5, can be summarised as follows:

The risk assessment provides a high level of confidence that long-term containment of the CO_2 planned to be stored will be achieved and the system will evolve to long-term stability. Risks to human health or environmental receptors associated with loss of containment (in the unlikely event it occurs), displacement of brine and deformation are either low or very low.

A more detailed summary description of the outcomes of the three main areas of assessment is provided below.

4.6.1.1 Containment

The risk assessment provides a high level of confidence that:

- the capacity required for the CO_2 planned to be stored will be accessible, as the capacity of the reservoir is very large compared to the required volume and chemical effects can be managed;
- the expected evolution of the system is towards long-term stability; and

- loss of containment is very unlikely to occur and impacts associated with any plausible low likelihood leakage scenarios would be low in any case.

The most important risks identified relate to the potential for chemical effects to challenge injectivity if the fluid washing approach to control precipitation of salt or hydrate is not as effective as planned and the potential for leakage via wells. The assessment, however, provides confidence that:

- the planned approach to fluid washing during injection will be sufficient to prevent significant challenges to injectivity, especially noting the flexibility of the washing approach and the significant capacity of the system compared to the CO_2 volume planned to be injected;
- leakage through the injection wells after they are sealed is very unlikely, noting they will include multiple seals which will be designed to resist CO_2 migration;
- leakage through existing historic wells is also unlikely, as less is known about these wells and consequently this assessment is subject to greater uncertainty. Nevertheless these historic wells have multiple seals and contain drilling mud which will resist CO_2 migration; even if the seals fail and the drilling mud is forced out of the boreholes, the surrounding halite will tend to creep and re-seal the well; and
- in the unlikely event that well seals fail and creep is insufficient to prevent formation of a pathway for CO_2 migration to the seabed, there is confidence that the potential impacts to receptors would be very low and not significant.

4.6.1.2 Displacement of Formation Fluids

The risk assessment also provides a high level of confidence that, whilst some formation fluids will be displaced to the seabed and water column as a result of CO_2 storage, impacts to receptors from salinity perturbations will be very low. This is because:

- some or all of the volume of displaced fluids may not be of much higher salinity than seawater; and
- even if higher salinity waters are discharged, mixing with seawater within the seabed and in particular within the seawater column will be sufficient to ensure impacts to receptors remain low.

There remains a high degree of uncertainty about the potential impacts of perturbed water chemistry (as opposed to levels of salinity) over the region where discharge could occur. However, similar arguments to those made for salinity above would also apply here. It is considered plausible that dilution both below the seabed and in the water column above could reduce the concentrations of all chemical constituents to levels that are not of concern. However, the uncertainties will be specifically addressed by appropriate measurement, monitoring and verification plans.

4.6.1.3 Physical Effects

Finally the assessment provides high confidence that although there will be some displacement of the seabed due to pressurisation within the CO_2 storage complex, the effect will be very small and the risk of impact to receptors will be very low.

4.6.2 Risks and Mitigation Planning

Bow ties have been used to assess how risks can be mitigated.

The context for mitigation planning is provided by those assessment outcomes, which were identified as risks, but which were in turn assessed as being low or very low. Approaches to mitigating risks are presented using bow tie methodology in Section 4.5.4.

As is appropriate for a subsurface CO_2 storage system that is expected to provide containment over a long timeframe, many of the key mitigating factors are the passive controls offered by the natural system and components of the engineered design. The containment properties of the primary seal and secondary seals, the multiple seals within the existing and future boreholes upon completion, creep of the halite and the effects of mixing of any displaced fluids within the seabed and seawater column are examples of important factors recognised in the assessment.

Active controls (those that rely upon human operations) include managing injectivity, which may involve washing to control chemical effects near the injection point and ensuring that over-pressurisation and over-filling are avoided. These requirements are already recognised and addressed in detail in operational planning for the storage system. These plans underpin relevant aspects of the risk assessment and contribute to the high level of assessed confidence in performance. No additional risks have been identified that are not adequately addressed by existing plans.

A further active mitigation control reflects the possibility that leaking wells could be drilled out and resealed. However, the assessment provides confidence that the multiple seals in the existing and future wells, the presence of drilling mud in the boreholes and the creep properties of the halite mean that risks associated with historical well failure are low and this mitigation action is unlikely to be necessary.

4.6.3 Comparison between Assessed Risks and Regulatory Requirements

The assessment has been framed to directly address key regulatory requirements. Indeed the ESL tree utilised to integrate the assessment outcomes (Section 4.5) is structured specifically to reflect the requirements of 2009/31/EC CCS Directive. The risk statement above is also structured to respond to those requirements. It shows that there is high confidence that the performance of the system will be consistent with UK regulatory requirements, demonstrating confidence in capacity, containment and long-term stability, assessing that environmental and human health risks will be low and identifying remaining risks and mitigation actions of relevance to the scope of the assessment.

A detailed breakdown of regulatory requirements arising from implementation of 2009/31/EC CCS Directive and OSPAR guidelines (OSPAR, 2007) is presented in Appendix C. This document provides an audit showing how all the requirements and indeed those from best practice such as the CO_2QUALSTORE guideline (DNV, 2010) and other public domain assessments, have been addressed by the scenarios considered in the risk assessment. This provides a more detailed demonstration that the assessment has addressed all relevant regulatory requirements.

5 Monitoring, Measurement and Verification Plan

5.1 Introduction

The Monitoring, Measurement and Verification (MMV) plan, based on the characterisation of the storage site and storage complex and on the independent storage complex risk assessment, has been developed in accordance with National Grid’s environmental policy in order to protect and enhance the environment. In addition, the proposed MMV plan has been designed to adhere to environmental legislation; specifically, the requirements in the extracts from Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 (2010 No. 2221) located in Appendix E.

The MMV plan will be subject to annual reporting but will also require updates which will be presented at least annually during the operational phase. The purpose of updating the MMV plan is to ensure that the most recent developments in methodology, data interpretation and technology are used whenever appropriate to ensure conformance and containment. The review and update process requires the plan to be continuously challenged and amended whenever necessary. Updates will be provided not only during the period of active injection but also during the post-injection and post closure periods. The MMV plan will be reviewed, revised and issued for the start of the operational phase once the pre-injection baseline surveys have been recorded and the three injection wells drilled and evaluated. After site closure and the permanent removal of the injection facilities, the ownership of the storage site will pass to the competent authority in the UK. In line with current regulations, this transfer of ownership is accompanied by a financial contribution from the storage operator to the competent authority to fund the monitoring activities for at least 30 years. The monitoring activities after transfer will reflect the monitoring technologies used and the data obtained up to this time and the monitoring activities of the competent authority will proportionately decrease throughout these 30 years.

5.2 Containment

The Endurance storage complex is designed for the permanent secure containment of CO_2. The risk assessment considers and analyses the risks to containment and their potential consequences. These risks to containment are a major consideration for the MMV plan to ensure that any significant irregularity can be detected as early as possible and the associated corrective measure determined. To ensure that all the threats to containment have been identified, the risk assessment details the various databases of features, events and processes have been interrogated and both expected and alternative evolution scenarios that arise have been audited against these carbon capture and sequestration databases.

The overall conclusion of the risk assessment process is that it provides a high level of confidence that permanent containment of the CO_2 planned to be stored will be achieved and the system will evolve to long term stability. Risks to human health or environmental receptors associated with loss of containment (in the unlikely event it occurs), displacement of brine and deformation, are either low or very low.

Containment focuses on the fact that the injected CO_2 should remain in the Bunter sandstone formation and within the storage complex for long term storage. Containment is a safety critical risk and therefore as a key part of the risk assessment, a containment Bow Tie has been developed and is fully reported therein. With it, the potential risks to CO_2 containment (lack of containment of the volumes planned to be stored) are identified and these, along with their escalating factors, are:

- leakage through existing boreholes (legacy wells) and new wells (injectors). Escalation factors are:
    - induced seismicity damages/bypasses plugs and seals; and

  - sabotage to wellheads;
- leakage through caprocks/seals with escalation factor:
  - induced seismicity created new faults/fractures;
- leakage due to unintentional human intrusion;
- lateral leakage of free or dissolved CO_{2}:
  - accidental overfilling; and
  - pressure changes due to nearby resource exploitation; and
- required injectivity (planned volumes) cannot be injected due to physical or geochemical change; the potential consequences are:
  - observable/significant loss of containment;
  - observable/significant impact on environmental receptors in the seabed and/or the seawater column;
  - observable/significant impact on hydrocarbon resources; and
  - required capacity cannot be accessed.

5.3 Conformance

During the operations phase, under normal operation conditions, containment is assured and the focus of the MMV programme is to prove conformance. Conformance means that the storage complex is behaving in a predictable manner and is fully consistent with the subsurface model.

In case of any inconsistencies, or if any significant discrepancy exists between the model based assumptions, the response of the storage complex or the observed migration of the CO_2 plume, these inconsistencies will require explanation and possible revision, including history matching, of the subsurface models.

The potential consequences associated with the loss of conformance are:

- the containment risk changes;
- changes to the duration of post injection and post closure phases;
- changes to conditions for transfer of the storage complex to the competent authority; and
- changes to the storage efficiency and capacity of the storage complex.

In each case, the consequences may be positive or negative with regard to the operation of the storage complex and hence the importance of the frequent and regular review and updates to the MMV plan. The potential threats towards demonstrating conformance are either because the original modelling is not correctly predicting the performance of the storage complex or that there are errors from the monitoring. These monitoring errors can arise due to bias in the acquisition or systematic processing or interpretation errors.

In summary, conformance is to verify storage performance by confirming that the storage site is responding to the injection and migration of CO_2 in a predictable manner and to calibrate and revise performance predictions provided by subsurface modelling on the basis of measured parameters.

5.4 Monitoring, Measurement and Verification Plan Design Framework

The framework for the preparation of the MMV plan is the relevant UK legislation and the Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 (2010 No. 2221). It also considers 2009/31/EC CCS Directive.

The key design parameters influencing the MMV plan are as follows:

1. the need to mitigate risks identified by the risk assessment;
2. the monitoring area extends laterally beyond the boundaries of the storage complex and includes the area of the Bunter sandstone formations seabed outcrop to the southeast of the Endurance structure, which is expected to see some limited production of formation brine;
3. the monitoring and measurement programme comprises both:
    - The base case activities that generally follow a planned schedule either in time or according to injected volumes; and
    - Contingent activities that are to be scheduled in response to the recognition or detection of an irregularity;
4. the monitoring and measurement programme will be adapted via the annual update and review process according to the performance of the storage complex, revised forecasts and the possible introduction of new technologies, data acquisition and interpretation;
5. the verification process combines the data acquired with the storage complex characterisation; and
6. the duration of post injection and post closure periods will be determined according to the evidence and interpretation of the monitoring data.

The design principles for the MMV plan adhere to the following order of precedence:

1. protection of human health and safety;
2. protection of ecosystems and the environment;
3. protection of physical assets;
4. reputation and confidence in greenhouse gas sequestration; and
5. facilitation of cost effective and cost beneficial systems.

They also will apply the following principles:

- comply with the latest regulatory standards and prevailing industry best practise;
- establish thresholds, trigger points and actions for the detection of and the response to irregularities;
- select monitoring and measurement components that will mitigate risk to As Low As Reasonably Practicable (ALARP); and
- select monitoring and measurement components intended to manage aspects that are not critical to health, safety and the environment on the basis of technical feasibility and the economic value of data acquisition.

5.5 Monitoring, Measurement and Verification Plan Methodology

The MMV plan covers all of the instrumentation and equipment for the measurement and monitoring of the storage complex, the operation of the wells and the composition of the injected fluids. The plan reflects the characterisation of the storage site and storage complex and the results of the quantitative risk assessment. The risk assessment was prepared by independent scientific and mathematical consultants.

The scope of the monitoring programme is grouped into four elements and the timing of the plan into four phases. The four elements and four phases, as specified in the guidance to 2009/31/EC CCS Directive are:

- Operational – concerns injection well control, rate and composition of CO_2 and pressures and temperatures both at surface and down hole;
- Plume – forecasts and measures the migration of the CO_2 from the injection wells through the storage site to the crest of the structure. Calibration and verification of the suite of simulation models of the storage site and storage complex for static, dynamic, geochemical and geomechanical behaviour are at the heart of this element;

- Pathways – monitors seals, faults and fractures and wells for possible migration of CO_2 out of the storage site and through the storage complex; and
- Environmental (leakage) – detection and quantification of leakage and its impact on emissions and on safety and environmental factors.

The MMV plan implementation is divided in to four distinct phases and for each, the requirements and the capabilities of the technology are very different. The four phases are:

1. Injection

This is the active operational storage phase when CO_2 is being injected into the storage complex. The average pressure rises during the injection phase which therefore corresponds to the period of highest risk for the integrity of the store and when the surveillance effort for the effect of the injection on the storage complex is at its maximum.

Monitoring the migration of the plume over the area between the injection wells and the crest of the structure is a key indicator of storage site response and its behaviour. In addition to reservoir modelling based on the pressure response to injection volumes, time lapse seismic is the main technology capable of demonstrating this conformance.

2. Post Injection

Once injection ceases, the average pressure of the storage complex will start to decline and the risk profile for store integrity will reduce accordingly. With the relatively high permeability of the storage site, pressure is anticipated to decline rapidly and once the trajectory of the pressure response has been established, the monitoring and measurement effort can be reduced and the optimum timing for the permanent sealing of the wells and the removal of the surface infrastructure will be decided.

The plume will continue to migrate after injection ceases and time lapse seismic will provide confirmation.

3. Post Closure

After the wells are sealed and the infrastructure has been removed, the ability to monitor the storage complex is limited to short term pressure measurement within the site, checking for evidence of leakage of CO_2 at the seabed and time lapse seismic to confirm the migration of the CO_2 plume. If the behaviour of the storage complex is shown to be evolving towards a state of permanent storage as expected, arrangements will be made for the transfer of the responsibility for the CO_2 store from the operator to the competent authority.

4. After Transfer

After the competent authority accepts responsibility for the store, it is anticipated that monitoring and measurement tasks continue for 30 years to confirm the evolution of the system to long term stability in accordance with 2009/31/EC CCS Directive.

Prior to the commencement of injection, for some of the MMV technologies, baseline surveys are required. For technologies where baseline surveys are required, their requirements and the recommended duration for monitoring is specified in Section 5.8.

5.6 Legislative Context and Definitions

Under the current legislation the following definitions have been proposed. They are illustrated in Figure 5.1.

5.6.1 Storage Site

A defined volume within a geological formation used for CO_2 storage and associated injection wells and infrastructure.

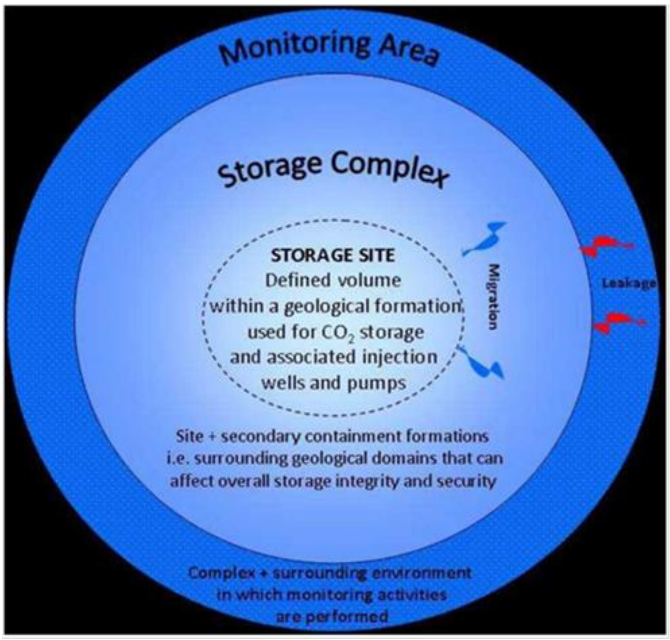
5.6.2 Storage Complex

The storage complex consists of the storage site plus secondary formations; surrounding geological domains that can affect overall storage integrity and security.

The identification and definition of storage complex is critical as leakage is defined as the release of CO_2 from the storage complex whereas movement of CO_2 within the storage complex is defined as migration.

It is expected that stored carbon dioxide will be retained permanently within the storage site and any migration outside the storage site may represent a significant irregularity in which case the operator will be required to institute corrective measures. Where migration does imply a risk of leakage outside the complex or an increase in environmental or public health risk, then it will represent a significant irregularity.

Figure 5.1: CO_2 Storage Definitions



5.6.3 Migration

The movement of CO_2 within the storage complex is defined as migration.

5.6.4 Leakage

Leakage means any release of CO_2 from the storage complex.

5.6.5 Storage Permit

The storage permit, issued by the competent authority, authorises the geological storage of CO_2 in a storage site by the operator and specifying the conditions under which it may take place.

5.6.6 Substantial Change

A substantial change refers to any change which is not provided for in the storage permit. In order to address the various changes which may occur and for which accountability may be made in the storage permit, Section 5.9 summarises the normal and alternative evolution scenarios that may arise from injecting CO_2 in the storage site and which are fully reported in the risk assessment.

5.6.7 CO_2 Plume

The CO_2 plume is the location and volume of the dispersing mass of CO_2 in the geological formations.

5.6.8 Significant Irregularity

A significant irregularity in injection or storage operations, or in the condition of the storage complex itself; which implies the risk of a leakage, or risk to the environment, or risk to human health.

5.6.9 Significant Risk

This addresses the combination of a probability of occurrence of damage and a magnitude of damage that cannot be disregarded without calling into question the purpose of 2009/31/EC CCS Directive for the storage site concerned.

5.6.10 Corrective Measures

Any actions taken to correct significant irregularities or close leakages; in order to prevent or stop the release of CO_2 from the storage complex.

5.6.11 Closure

This is the definitive cessation of CO_2 injection into the storage site.

5.6.12 Post Closure

Post closure is the period after the closure of a storage site and includes the period after transfer back to the competent authority.

5.7 Endurance Site Specific Definitions

The Endurance storage complex is a four way dip closure at top Bunter straddling quadrants 42 and 43 of the UK Sector of the southern North Sea. The structure is a saline aquifer, approximately 22km long, 7km wide and over 200m thick. The development will use a platform with six wells slots through which three injection wells slots are to be drilled.

5.7.1 Endurance Storage Site

The bunter sandstone formation of the Endurance storage site is comprised of three layers of the Bunter sandstone formation.

The vertical extent of the storage site is shown in Figure 5.2 and Figure 5.3.

The areal dimensions of the storage site are taken from the most likely top Bunter depth map which closes at 1460m TVDSS as shown in Figure 5.4.

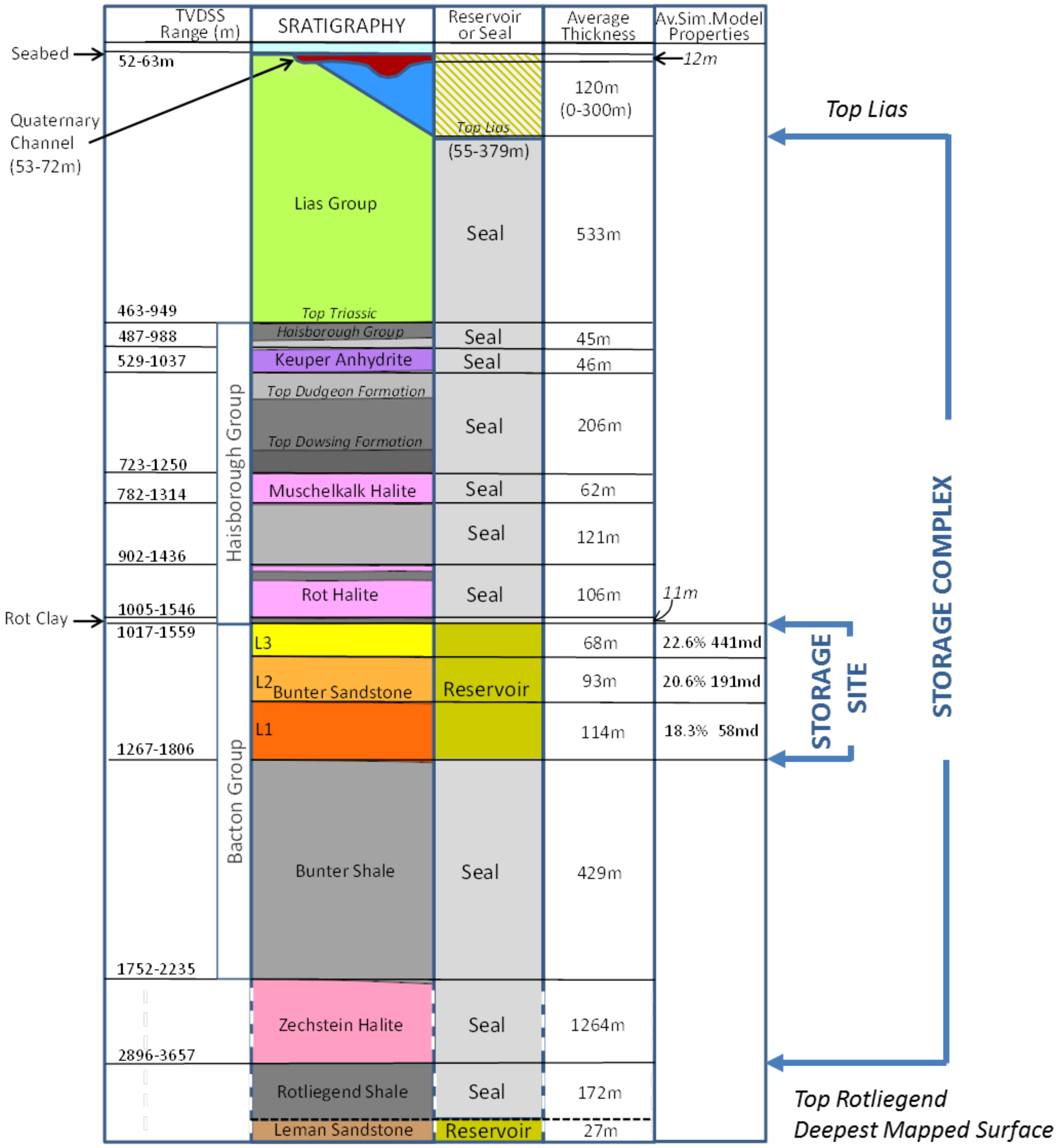
5.7.2 Endurance Storage Complex

The storage complex is defined from the top Rotliegend (c. 2896m to 3657m) to the top of the Lias formation (c 52m to 63m) and entirely encompasses the storage site.

The upper Rotliegend is likely to provide a further seal. However, the base of the formation and the top of the underlying Leman sandstone reservoir cannot be mapped seismically with any confidence and consequently the base of the storage complex has been placed at the deepest confident mapable horizon, namely the top Rotliegend.

The areal definition for the storage complex for the Endurance structure is taken as the closure of the high case (deeper on flanks) top Bunter sandstone depth map at -1554m TVDSS. It includes all the overburden geological formations directly above the Röt clay seal up to the top of the Lias, the shallowest formation that is anticipated to be a sealing interval.

Figure 5.2: Vertical Limits of the Storage Site and Complex



5.7.3 Endurance Monitoring Area

The monitoring area will extend beyond the storage site and storage complex; both vertically and areally. The areal extent also includes the seabed outcrop of the Bunter formation to the east and south of the main Endurance structure. This additional area is included as it is expected that formation brine will be expelled from the outcrop as a result of the increased pressure caused by CO_2 emplacement within the Endurance structure. Due to the structural configuration and particularly as the injection point is shallower than the structural closure, it is considered impossible that any CO_2 will be present at the outcrop.

Vertically the monitoring area includes stratigraphy out with the storage complex. This includes the Middle Jurassic to Cretaceous strata which outcrop the seabed on the margins of the Endurance anticline. It also includes quaternary channels of unknown lithology which locally erode older stratigraphy.

The requirements for monitoring the outcrop are predominantly environmental and relate only to the quantities of dissolved solids in the formation brine at that location.

Refer to Figure 5.4 for the line of section A-A'.

Figure 5.3: Section Illustrating Key Wells and Limits of Storage Site, Complex and Monitoring Area

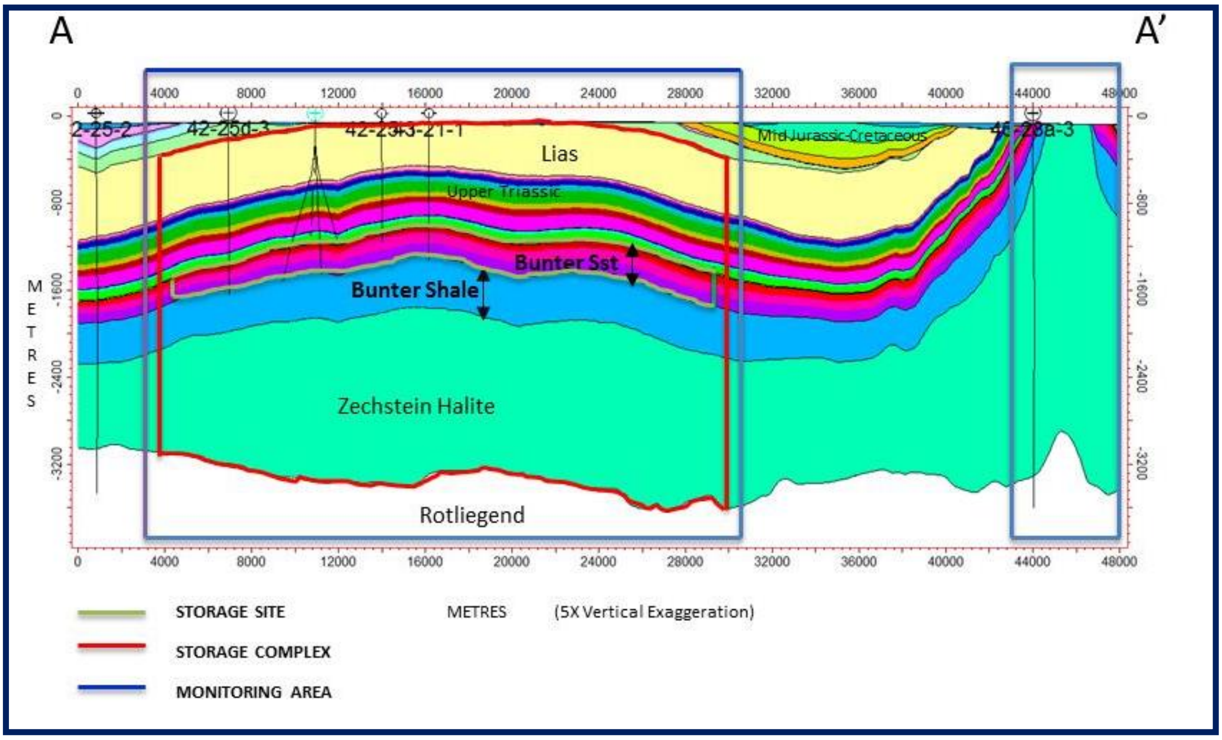
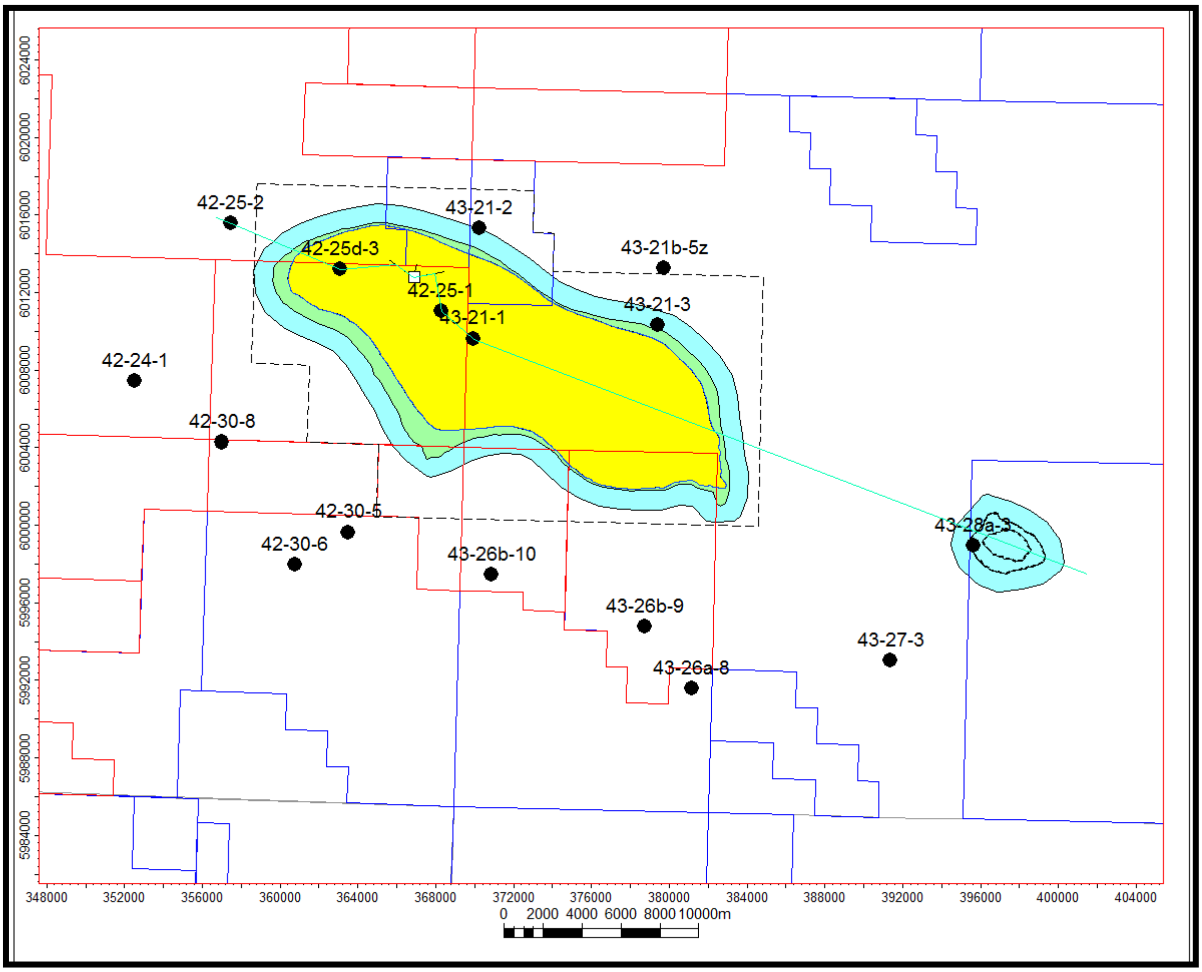


Figure 5.4: Areal View Illustrating the Storage Site, Complex and Monitoring Area



The extent of monitoring to be carried out is intended to balance the requirements laid out in legislation with economic considerations regarding type and frequency of monitoring with particular reference to plume migration.

As a result, the northwest of the CCS license area, including appraisal and crestal wells (in addition to the injection wells) will be subject to more stringent and regular monitoring than the south and east of the structure and the Bunter outcrop until such times as plume migration or other events occur such that the types, extent and frequency of monitoring needs to be modified.

5.8 Assessment of Monitoring Technologies

The guidance associated with the 2009/31/EC CCS Directive contains a list of technologies that are recommended to be assessed for their appropriateness for a site specific MMV plan. For each of these technologies that are appropriate for use in subsea storage reservoirs, the preliminary analysis for the site specific plan is based on the following broad concepts:

- technical measurement;
- methodology;
- cost/benefit;
- resolution;

- reliability, accuracy and repeatability;
- coverage and location;
- frequency of surveys;
- maturity of technology (track record);
- logistics; and
- experience from other CO_2 projects.

Table 5.1 shows a list of those technologies, which although appropriate for offshore use, are considered unsuitable or inappropriate for the project.

5.8.1 First Level Excluded Technologies

Endurance subsurface input into MMV provides the detailed rationale for these exceptions; while Sections 5.8.1.1 to 5.8.1.9 summarises the reasons why they are excluded.

Although they are not specifically mentioned in the guidance, the reasons why monitoring wells are not proposed or required are outlined in Section 5.8.1.9 below.

Table 5.1 First Level Excluded Technologies

Category	Monitoring Method
Well logging	Sonic logging
	Cement bond logging
	Pulsed neutron logging
	Density logging
	Gamma ray logging
	Resistivity logging
Well CO_2 sampling	Sampling and chemical analysis
Seismic	4D seismic array
	Vertical seismic profile
	Cross-hole seismic
High resolution geophysics	Multi-beam echo sounding
	Shallow 2D seismic
	Boomer/sparker profile
	High resolution acoustic imaging
	GPR
Gravity survey	Time lapse gravimetry
	In well gravimetry
Electrical and electromagnetic	Electromagnetic resistance
	Seabottom electromagnetic
	Permanent borehole electromagnetic
	Cross-hole electromagnetic
	Cross-hole electrical tomography
Water sampling and geochemistry	Downhole fluid chemistry
	Long term borehole monitoring of pH
Atmospheric CO_2 flux and concentration monitoring	Airborne laser
Monitoring wells	

5.8.1.1 Well Logging

Sonic, density, gamma ray and resistivity logging are not included in the MMV plan as they will be used during the drilling of the three injection wells prior to the commencement of the MMV plan programme. These logs will be extensively used for the petrophysical interpretation and its input into the site characterisation.

The cement bond logs are also used at the time of the well drilling for the evaluation of the quality of the cementation of the casings and to confirm hydraulic isolation or whether any repair of the primary cementation is required.

With regard to pulsed neutron logging, the applicability of this technique is more appropriate to oil and gas reservoirs in order to detect subtle changes in saturation close to the perforations under water flood or water encroachment situations. It will not be particularly useful in deviated CO_2 injection wells where saturations in the near perforation part of the formations will be dependent on recent injection history and readily measured by standard production logs.

5.8.1.2 Well Sampling of CO_2

Well sampling of CO_2 for chemical analysis is not appropriate. Sampling and analysis will take place at surface (category – operational measurement) and for well operations particularly with regard to corrosion and hydrate formation, backflow of injection well will not be allowed and neither are platform facilities provided for this purpose.

5.8.1.3 Seismic

For the various reasons discussed below, 4D array seismic, vertical seismic profiling and cross well seismic are not proposed for use in the Endurance MMV plan.

4D array seismic refers to either an ocean bottom cable or seismic nodes permanently or semi-permanently installed on the seabed. These techniques provide multi-component data by recording shear wave data in addition to the standard P-wave information.

The separation interval of the nodes or cables is determined by the depth of the geological objective. For the nodal systems, the multi-component geophone sensor is housed in a ruggedised container which is placed directly on the seabed with no physical (wired) connection to the acquisition system. The node is retrieved and the data downloaded from flash memory after the survey has been completed. An ocean bottom acquisition operation typically involved the use of two vessels, one for deployment of the receiver system and one that acts as the source deployment/shooting vessel. Ocean bottom acquisition methods, utilising geophones, have some attractive properties over more conventional towed streamer methods particularly the acquisition of shear wave data. Logistically the technique allows for greater operational flexibility where surface obstructions such as platforms and wind farms preclude the use of vessels towing many kilometres of hydrophone cables. In addition to operational advantages, ocean bottom surveys typically have greater fold (number of shot receiver combinations that record reflected energy from a given point in the subsurface) and a wider range of recorded azimuths associated with the survey geometry which can have a demonstrable uplift on data quality, especially in areas of geological complexity. These benefits though are weighed against the substantially higher costs and on this basis taking into account that the data provides only confirmation of conformance and does not relate to containment or potential threats to containment, this technology is not proposed for use.

Permanent installations are not only very expensive but also are not suitable for this area where extensive fishing activity takes place as cabling and nodes would need to be buried and the area is also populated with quite severe sand waves. The area of the network would be much more extensive than that proposed for the microseismic network. Further, the use of the network would only be occasional and would not be used for the vast majority of the time.

A Vertical Seismic Profile (VSP) is acquired using a surface seismic source and vertical array of geophones run on wireline or permanently installed with the well completion, these surveys can provide time lapse seismic images near the borehole and image changes of impedance in a similar fashion to time lapse surface 2D and 3D survey (though at higher resolution). Using a series of offset source positions (walk away mode), images can be obtained a few 100m from the borehole. These surveys might detect near wellbore gaseous CO_2 build-up in the shallower overburden (<800m). However, as there are not any porous beds in the shallow overburden and as the injector wells are located well away from where the plume will migrate to the crest of the structure, no evaluation of the plume is therefore practical from the information that might be derived from VSP data and therefore VSP is not proposed.

Cross hole seismic, involve a high bandwidth seismic survey conducted between pairs of wells, providing a tomogram of seismic velocity in time lapse mode together with changes in reflected amplitudes from above or below source and receiver depths. The high resolution information can be inverted for saturation and pressure. Similarly to the VSP above, this acquisition will not provide useful data again because of the relative position of the injection wells and the eventual destination of the stored CO_2 in the crest of the structure and is not proposed.

5.8.1.4 High Resolution Geophysics

Multi-beam echo sounding, although high resolution, only provides seabed profiling and therefore is not proposed.

Shallow 2D seismic provides imaging in the overburden and primarily would be used to identify shallow to moderate depth horizons charged with migrating CO_2 but in the Endurance storage complex there are no beds in the shallow to moderate depth formations that have porosity and therefore could become charged with migrating or leaking CO_2.

Boomer/Sparker surveys and high resolution acoustic surveys provide imaging in the very shallow formation but as with the shallow 2D seismic, in the Endurance storage complex and as with shallow 2D, in the overburden there are no porous beds within the target depth ranges that could become charged with CO_2 and so these methods are not appropriate.

Ground penetrating radar does not function in salt water environments.

5.8.1.5 Gravity Surveys

Time lapse gravity surveying will detect differences in the densities of the formations under investigation. Assessment of these anomalies can give an indication of the depth, size and shape of the volume of difference. The method provides an alternative geophysical measurement of reservoir contents compared to seismic (velocity, acoustic impedance) and electromagnetic (resistivity).

A feasibility study modelling the use of borehole gravimetric sensors and seabed deployment of gravity meters has shown that the method has relatively low spatial and vertical resolution. Borehole gravimeters and the inversion of borehole time lapse gravity signals to density changes in 3D space are immature technologies. The use of seabed time lapse gravimetric surveys for reservoir monitoring is currently limited to field experiments by Statoil in Norway.

For these reasons, gravity surveying is not considered a core monitoring technology for the Endurance CCS project, but seabed gravity surveying is maintained as a potential technology should the technology mature and in the event that future seismic access over the monitoring area is limited by additional infrastructure such as wind farms that are already licensed in the immediate vicinity.

Areal gravity surveys do not provide sufficient resolution to be able to adequately define the free CO_2 in the crestal location and the in well gravimetry, because of their location away from the crest would not be able to detect the free CO_2 cap.

5.8.1.6 Electromagnetic Surveys

Controlled Source Electromagnetic (CSEM) imaging uses a high power variable frequency electrical source towed from a vessel in conjunction with seabed deployed receivers to measure the earth’s resistivity. They are able to measure a physical quantity (resistivity) which is independent of seismic effects and theoretically have higher sensitivity to saturation at high CO_2 concentrations in brine than seismic velocity.

The electrical resistivity of reservoir rocks is highly sensitive to changes in water saturation as demonstrated by Archie’s Law which relates in-situ electrical conductivity of a sedimentary rock to its porosity and brine saturation. Carbon dioxide is electrically resistive and therefore in the context of super critical CO_2 displacing highly saline in-situ pore fluid waters, a resistivity contrast should be observable through the utilisation of electromagnetic acquisition techniques. However, resistivity is not as sensitive to low concentrations of CO_2 compared to seismic velocity. The technique would suffer from a limited skin depth of penetration due to the conductive nature of the Bunter and the overburden and also there are problems with CSEM application in shallow water (<100m) due to airwave interference. These problems collectively make the technology unsuitable for plume monitoring for Endurance.

Electromagnetic surveys including CSEM do not provide sufficient resolution in order to adequately image the CO_2 cap and even more so are incapable of showing the migration of the plume where brine and CO_2 saturations are at intermediate levels. They are also costly to perform as a full field survey.

Magneto-telluric surveys measure spatial variations in the Earth’s resistivity using natural electromagnetic sources and provide low resolution information about deep Earth structure. The technique requires simultaneous acquisition of data at an array of receivers positioned to cover the geographical area of the storage complex. These would necessarily be on the seabed and such an extensive array would be very expensive. The data acquired would not be of suitable resolution to address the scenarios defined and so this technique is not considered applicable to the project.

5.8.1.7 Water Sampling and Geochemistry

Neither downhole fluid chemistry nor long term borehole monitoring of pH from the injection wells will be useful as mentioned above, as no backflow of wells is planned or envisaged for operational reasons.

5.8.1.8 Atmospheric CO_2 Flux and Concentration Monitoring

Differential flow measurement will indicate any leakage or venting to air before concentrations will be sufficiently high for airborne laser detection which in any case would require the deployment of a specialist aircraft to the platform location.

5.8.1.9 Monitoring Wells

Monitoring wells are not proposed for the Endurance MMV plan. There are three main considerations for this:

- the data, which they can provide, is in practice limited to pressure and temperature since sampling to provide CO_2 saturation information or reservoir fluid would be prohibitively expensive. Saturation information or fluid samples would require the use of subsea logging and a flow-back or a production system and these would in turn require the deployment of a well service vessel or drilling rig. Pressure information can be readily and continuously interpreted from the bottom-hole gauge data that would be obtained from all the injection wells and temperature data can be modelled to an acceptable level of accuracy;
- wells are considered to be the biggest threat to long term secure containment and, although the probability of a leak is very low and the worst plausible consequence is medium, the benefit of monitoring wells is very limited against this possible risk; and
- the cost of establishing monitoring wells and the additional cost of their eventual abandonment, given their limited benefit is disproportionate.

5.8.2 Technologies Proposed for Endurance Monitoring, Measurement and Verification Plan

This section discusses the technologies currently proposed for the Endurance MMV plan. Compared to the guidance some additional items (for example, tiltmeters, tubing and casing condition logs) have been added and are highlighted. There is also some consolidation and rearrangement (for example, operational measurement of wellhead flow and composition and well CO_2 sampling and analysis have been combined to Wellhead flow and composition; side scan sonar is combined with sonar bubble stream detection; environmental monitoring encompasses water sampling and geochemistry, soil/sediment sampling/atmospheric CO_2 flux and ecosystem monitoring).

Table 5.2 Proposed Technologies for Endurance MMV Plan

Category	Monitoring Method
Operational measurement	Wellhead pressure and temperature
	Wellhead flow and composition
	Downhole pressure and temperature
	Inert and isotope tracers
	Casing annulus pressures
Well Logging	Production logging
	Optical logging
	Casing condition logging
	Downhole sensor replacement
Reflection seismic	2D seismic
	3D seismic
High resolution geophysics	Microseismic network
	Tiltmeter network

Category	Monitoring Method
	Global Positioning System (GPS)
	Bubblestream detection (sonar)
Environmental monitoring	Seawater chemistry
	Ground water monitoring
	Seabed sampling and gas analysis
	Infrared gas analysis and acoustic leak detection
	Ecosystem monitoring

5.8.2.1 Operational Measurements

Operational measurements generally refer to data acquired and samples obtained on the injection platform. There is a wide range and availability of technologies that can be used for the project for recording and transmitting temperatures, pressures and flow rates. The function of operational measurements is primarily operational to ensure that each well is managed within their operational targets and envelope in conjunction with the remainder of the surface and subsea facilities. Sampling refers to occasional physical samples obtained from the well streams and returned to the shore for laboratory analysis. Samples are only rarely required as the composition of the CO_2 is continuously monitored at the inlet to the onshore pipeline.

Surface Temperature Pressure and Flow Rates

Each injection well shall be provided with equipment for the continuous recording and transmittal of pressure, temperature and flow rate. This data is high priority and will be transmitted to shore for real time assessment of operating conditions. Flow meters for each well will be used for well allocation, reservoir engineering and the recognition of failures or leakage across the system.

These are primary measurements and not subject to a baseline survey.

Downhole Temperature and Pressure

Downhole pressure and temperature measurements are considered to be key data as they are applicable to a number of different monitoring programme elements. One of their primary functions is to provide feedback on well operation with respect to its operating envelope (maximum pressure and flow rate), integrity (loss of integrity in wellbore architecture) and can provide early warning of potential significant changes in operating regime or changes in injectivity.

Downhole pressure and temperature measurements are also used to validate and calibrate dynamic reservoir modelling designed to predict and forecast the CO_2 plume migration and development in the reservoir.

In the event of a downhole instrumentation failure, data history may adequately enable models to be used to track downhole pressures and temperature although replacement of failed sensors would be considered a priority.

The requirement is for semi-continuous measurement of the pressure and temperature at the bottom of each injection well.

A variety of downhole measurement and sensor technologies is available for pressure and temperature measurement. There are also different configurations for the gauges and various methods for transmitting data back to the surface.

Detail design will be tasked to choose the most appropriate type of gauge and the various factors that need to be included in these decisions relate to accuracy, reliability, redundancy, ease of replacement and cost.

The location of the gauges is important for optimum well integrity and it is proposed that the gauges are located above the tubing packer and therefore over 150m from the injection point. This would avoid the presence of feed through wire which could create a leak path. For this reason also, the use of distributed temperature and distributed acoustic sensors on fibre optic cable is not considered practical or useful. The power and communication cable will be removed during well abandonment along with the tubing string and consequently will not pose any risk to abandoned well integrity.

Specialist gauges can be deployed, at the time of the abandonment of the wells and removal of the platform, that continue to monitor reservoir pressure data. Currently this technology allows data transmission for up to five years after deployment. The data are transmitted via a low frequency electromagnetic link (without the need for a cable connection) and is collated by a remote subsea station. These data will provide assurance that the storage site is evolving as predicted.

These are primary measurements and not subject to a baseline survey.

Well Stream Sampling

There is limited requirement for well stream sampling as the composition of the CO_2 input into the pipeline is continuously monitored by gas chromatography at the power plant location. Occasional samples may be used to check whether any contamination from pipeline corrosion is present but as the requirement is for the water content of the CO_2 to be less than 50ppm it is unlikely. In any case, these samples should then be taken upstream of the platform filters (5 micron).

Tracers (Inert and Isotopic)

If the baseline sea bottom survey and baseline environmental sampling all confirm the absence of native CO_2 or of any artefacts that could indicate that CO_2 has recently emanated from the overburden, tracers to identify the origin of any future CO_2 at the seabed are probably not required. If there is evidence of recent emissions, then it is recommended that tracers would be used. Tracers would be injected into the CO_2 stream at the power plant location.

The preference is to use isotopes of carbon as the other commonly introduced tracers, krypton or sulphur hexafluoride have been shown to transit porous media at a significantly different rate than that of CO_2.

Sampling and analysis for tracers are contingent measurements dependent on the detection of leakage at seabed.

Casing Annulus Pressures and Temperatures

The annulus pressures and temperatures on each well will be measured and transmitted continuously. The objective is to detect any indication of leakage of CO_2 outside the production tubing and production packer. The pressure and temperature will vary depending on the injection rates and the arrival temperature of CO_2.

These are primary measurements and not subject to a baseline survey.

5.8.2.2 Logging

Logging operations would require the mobilisation of a significant amount of equipment including wireline winch, pressure control equipment, tools and personnel. Logging operations will take, depending on the services to be run, from one or two days up to 10 days per well. Consequently, logging operations will only be scheduled if there is cause for concern regarding the operation of the well, potential tubing or packer leakage or a decline in injectivity that requires investigation or failure of a downhole sensor. However, once a logging package has been mobilised, the opportunity will be taken to run additional services to check such things as tubing condition, injectivity and temperature profiles.

The main choices are electric line surface readout equipment or slickline memory tools. The main difference is in the pressure control equipment that is substantially more complicated for electric line work.

All logging operations are contingent upon the detection of an irregularity.

Production Logging

Mainly used to define the injectivity profile of the formations that are perforated. Production logging will also provide limited information regarding the plume development in the near wellbore region of the Bunter sandstone formation.

If repeat perforating or the adding of an additional perforation interval is required, production logging equipment will be used.

Optical Logging

Restricted to visual inspection of the well and usually used in the event of damage or a blockage in the well bore as indicated by increased surface pressure.

Casing Condition Logging

Various eddy current, magnetic and multi-finger callipers can be used to determine the condition of the tubing and detect the presence of corrosion or scale. Neither corrosion nor scale is expected to occur in the injection wells due to the proposed use of full duplex stainless steel tubulars, the limits of the composition of the CO_2 and the filtration that will be installed on the platform and hence will be reserved for use in a contingency.

Downhole Sensor Replacement

The selection of downhole sensors, vendors and type would be made during detailed design. If wireline replaceable sensors are chosen, these can be conveniently retrieved and replaced using slickline tools in the event of failure.

5.8.2.3 Reflection Seismic

Time lapse seismic monitoring of the CO_2 injection process forms a critical component of the development scheme and, as part of the subsurface development of a monitoring strategy. Two prime monitoring objectives are:

a. The development of the CO_2 plume; and
b. The assessment of the store and well integrity.

Seismic has the advantage of imaging the whole local earth volume including the reservoir, overburden and surroundings. It will be sensitive to CO_2 replacing brine (or vice versa) and to substantial changes in pore pressure. This makes the technique useful for storage site integrity and reservoir management. Petro-acoustic modelling can be carried out to further investigate sensitivity and allow the results to be interpreted in a quantitative fashion although preliminary studies, which have already been made, indicate that results will have good sensitivity. These sensitivity thresholds have already been investigated through a time lapse synthetic seismic modelling study.

The image produced by a seismic survey depends on contrasts in the physical properties of the rocks and pore fluids. The strength of a seismic reflection depends on contrasts in P-wave velocity (Vp), S-wave velocity (Vs) and density of the rock layers. Time lapse imaging is based on changes of these properties over the monitoring period caused by changes of fluid fill and/or pore pressure and/or inflation/compaction of the reservoir and overburden. Time lapse imaging involves repeating the survey and comparing the differences.

The proven track record of time lapse surface reflection seismic methods to track plume migration in high profile CO_2 sequestration projects makes reflection seismology an obvious choice for monitoring CO_2 injection over the Endurance geological storage site. Time lapse reflection seismic involves repeating an acquisition geometry over time, with a baseline survey; prior to CO_2 injection, followed by monitor surveys over the duration of the CO_2 injection and potentially continuation of monitoring post CO_2 injection. A fundamental requirement for time lapse success is ensuring survey parameters (source receiver x, y, z locations, acquisition geometries, source parameters and so on) between successive shoots are repeated as closely as is technologically feasible. On a very simplistic level, the difference between the repeat surveys should theoretically be a function of fluid changes (saturation and pressure) in the reservoir assuming no survey parameter differences, geomechanical or geochemical changes have physically altered the integrity of the host rock and overburden.

Marine reflection seismic data can be acquired in numerous ways; however, towed streamer is most pertinent to the Endurance geological storage site (as opposed to ocean bottom cables or nodes).

Towed streamer acquisition involves specifically equipped vessels towing anything from one to sixteen hydrophone cables (streamers) containing many data channels of variable length that is dependent on the depth of the subsurface target to be imaged. The streamers are towed at a fixed depth below the sea surface and with a cable separation that again is predetermined by the depth of the imaging objective. An impulsive seismic source, typically an array of airguns are also towed at a predetermined depth and positioned between the vessel and the streamer cable. The deployment depth of the airgun source has a fundamental impact on the acoustic characteristic of the source that is generated; amplitude and frequency content.

Towed streamer reflection seismic surveying is a mature technology in the hydrocarbon exploitation business with several acquisition and processing suppliers. The cost of these surveys can be quite high, dependent on acquisition specifications; these will be defined during detailed design for a fit for purpose survey and to provide accurate estimates of these costs.

3D Acquisition Geometries

3D seismic is recommended as the preferred technology for monitoring plume development and the development of the free CO_2 cap at the crestal location of the Endurance structure.

A preliminary seismic contractor engagement exercise was undertaken by a subsurface team in 2012 which provides an overview of contractor capabilities and also provides high level costs relevant to acquiring 3D data over the Endurance structure. It should be noted that the costs are not indicative of the eventual survey costs that could be incurred and a detailed survey evaluation and design exercise needs to be conducted for more accurate cost estimates.

Time Lapse Feasibility Studies: Rock Physics

In order for a time lapse seismic acquisition programme to be able to successfully image reservoir fluid replacement and rock mechanical change mechanisms, there needs to be favourable rock physics conditions and repeatable seismic acquisition.

Rock physics looks at the relationship between reservoir properties (porosity/lithology/pore fluid/temperature/pressure and so on) and seismic response to elastic properties (compressional velocity, shear velocity, density). In a time lapse sense, the changes in reservoir and elastic properties and their expression in the seismic domain are the focus. In particular, the impact of fluid saturation and pore pressure changes are studied, with other changes such as compaction being of importance only in unconsolidated sands or high pressure settings. The strongest time lapse seismic signals are generally found to be due to saturation changes, especially if one of the fluids is gas because of the sensitivity of seismic compressional velocity to even low gas saturations. High porosity reservoirs with lower incompressibility will have greater time lapse sensitivity than tighter (low porosity) systems. Sensitivity to pressure change is generally much weaker except where pressuring up of a local compartment occurs without pressure bleed off.

Time Lapse Feasibility Studies: Seismic Acquisition

A valid time lapse response should be due to the effect of changes in reservoir properties and therefore the associated seismic properties. The causes of time lapse noise must therefore be negated as much as possible. Most of the causes of time lapse noise and by extension, most of the effort in tackling them are concerned with the data acquisition and processing stages of a time lapse monitoring project. The following is a brief, but by no means comprehensive list of potential sources of time lapse noise in chronological order:

1. Seismic source and receiver positioning (x, y, z) variability;
2. Seismic survey geometry variability;
3. Seismic source characteristic variability;
4. Recording equipment characteristics variability;
5. Ambient noise variability;
6. Environmental changes;
7. Tidal and temperature variations; and
8. Processing parameter and software/algorithm variability.

A common way to measure non-repeatable noise in time lapse seismic data sets is to difference the two migrated stacks and compute the energy of the difference compared to the average energy in each of the individual data sets. This measure of noise is termed the value Normalised Root Mean Square (NRMS). In a perfectly repeatable world the NRMS would equal zero. With the current best practice time lapse acquisition and processing techniques for streamer data NRMS values of around 20% are considered good. Ocean bottom acquisition can achieve NRMS values of 10% and less. Most of the main seismic contractors offer technologies that are designed to alleviate the source and receiver repeatability issue in towed streamer configurations. Dynamically controlled fins or hydroplanes can be positioned along the streamer cable to enable lateral steering in addition to the more conventional depth control afforded by streamer birds. The ability to steer the cable laterally allows control of streamer separation and cable feathering and thus potentially improves receiver positioning repeatability from survey to survey. The maximum feather tolerance achievable with this steerable streamer technology is in the region of ±3 . The same dynamic positioning is also achievable for the source array as well as hardware that ensures the source output characteristics are stable for the duration of the shoot.

The Polarcus 3D (2013) seismic data will be used as the baseline. It will be reprocessed and some additional acquisition will be required before injection commences to ensure repeatable coverage is possible around the platform location once the platform has been installed. This additional acquisition will require two boat phantom undershoots.

In summary, a successful time lapse project can only be achieved with reservoir properties that satisfy basic rock physics prerequisites and with data acquisition and processing techniques that are repeatable within predetermined thresholds.

3D Seismic Time Lapse Acquisition

The baseline survey was acquired using very high energy air gun arrays so that the seismic could provide high resolution imaging below 4,000m. For the Endurance storage complex, imaging down to only 1,500m is required and in order to minimise environmental impact air gun arrays with much lower peak energy output will be used. The choice of optimum gun configuration and streamer geometry will be based on modelling to be finalised after the reprocessing of the baseline survey.

The development of the plume and the migration of the injected CO_2 to its crestal location is not critical for the operation of the injection wells. As it will not affect either the rate or volumes of CO_2 injected, it is proposed to minimise the frequency of the 3D surveys and to constrain the area of the surveys to the injection wells and the crest of the structure where the migration footprint will be present.

The first survey should be undertaken approximately four years after injection commences so as to be sure that enough CO_2 will have accumulated in the free CO_2 cap to be clearly imaged. After that and after calibration of the dynamic reservoir model with the first survey results, further surveys will be proposed. The recommended timing based on the current version of the model would be 12 years, 18 years after injection commenced and three years after injection has ceased given the anticipated injection period of 20 years and a total volume of 54MT.

5.8.2.4 High Resolution Geophysics

Microseismic Network

There is no requirement for a passive microseismic network for the project but as it will be required in the event of any potential future expansion of the Endurance store capacity it is recommended for installation before any injection commences (similarly to the other expansion considerations such as the 24in pipeline, additional capacity at the beach pumping station and the provision of spare injection wells slots). The installation before injection start-up is essential for the acquisition of a baseline survey.

The basis for the operation of the microseismic network is that changes in the stress state of the subsurface rocks caused by pressure changes can cause small scale shear slippage and generate low amplitude seismic events (micro earthquakes) which the network is designed to detect. The location of these events can be indicative of planned re-pressurisation or unplanned pressure build up, or failure of seals, faults or well bore cement. The microseismic events are detected on arrays of permanent geophones in sensor nodes placed on the seabed.

A microseismic monitoring project would have three objectives:

- to determine/understand the baseline (background) seismicity of the area prior to CO_2 injection;
- to monitor the injection process for cap rock integrity assurance and possibly geomechanical model history matching; and
- detection of near wellbore events as part of the well integrity monitoring systems.

A feasibility study has assessed the capabilities of subsea and downhole monitoring networks in terms of sensitivity (minimum magnitude) and location accuracy and recommends deploying a subsea network (minimum 31 nodes), for a homogeneous coverage of the cap rock integrity together with a shallow downhole array, for the monitoring of the fracture opening (microseismic events with low energy) in the vicinity of the injection zone.

Microseismic recording is a primary measurement and will require a baseline survey of at least six months.

Tiltmeter network

As with the microseismic network, there is no requirement for tiltmeters for the project. However, as with the microseismic network it must be in place before any injection takes place as environmental disturbance is minimised and as it is also considerably cheaper to install the tiltmeter network at the same time, it is recommended for installation before injection commences. It also can then be active for the project and will provide an additional layer of safety regarding the monitoring of the deformation of the storage complex.

The tiltmeters primarily confirm the predictions of overburden deformation made by the geomechanical modelling but also provide independent evaluation of fracturing and faulting events.

The co-located microseismic and tiltmeter networks will be established in the area of the platform over the injection wells and from there up over the area of the crest of the Endurance structure.

Each of the planned 31 nodes will be established in short 6inch diameter and 1.828m (6 foot) long conductor pipes set into the seabed (grouted or piled) and the interconnecting cabling will be installed using a seabed plough. The distance between the nodes is planned to be 1,200m and the total cable length (25mm diameter; specific gravity 1.8) will be less than 50km. The conductor and cable network will then be protected from the nets of fishing trawlers by burial up to 1m deep. Cable installation will be by jet trencher in areas with sand waves and may require a tracked cutter dredge in areas of harder seabed.

The network will be connected back to the platform where the data will be recorded but pre-processed and filtered before being transmitted to the control room.

Although the microseismic and tiltmeter network is not required for the project, once it has been installed the additional cost to run it is relatively small and will provide information on natural seismicity and possibly on thermal fracturing when injection is being established.

Tiltmeters are a primary measurement and no pre-injection baseline survey is required.

Global Positioning System (GPS)

GPS receivers will be installed on the platform to independently confirm vertical movements caused by seabed deformation. The accuracy and resolution of these systems is better than 1mm and can, cost effectively confirm seabed deformation which is expected to be a maximum of approximately 100mm during the project.

GPS is a primary measurement and no baseline survey is required.

Bubble Stream Detection

Sonar devices have been developed to detect subsea leakages of gas by identifying streams of bubbles. The bubble streams vary greatly depending on the flux of the leakage and the pressure and temperature of the water. In the case of low flux CO_2 leakage the gas is rapidly adsorbed into the water and the bubble stream disappears as it gets shallower. These various effects have been well described and the algorithms associated with the sonar detectors are able to determine to a high degree of accuracy the flux of a detected leak.

Sonar devices can be installed on stationary landers that monitor an area with a radius of approximately 1km or can be installed on an AUV that can be deployed to follow a coverage pattern across the entire area of the store.

For the Endurance storage complex, given the very low probability of a leakage, it is recommended that an AUV is deployed annually and that it would additionally carry other sensors monitoring pH, salinity across the area of the storage complex and the nearby Bunter sandstone formation subsea outcrop. Permanent stationary landers are not recommended as they do not provide any substantial benefit over the AUV survey but do pose a significant difficulty due to fishing operations in the area.

Bubble stream sonar is a primary measurement.

A baseline survey will need to be acquired prior to injection commencing and a number of surveys will be included in order to record seasonal variations in the recorded parameters.

5.8.2.5 Environmental Monitoring

A comprehensive environmental monitoring baseline has been acquired at the storage site and the outcrop for the purposes of the offshore environmental statement however it is proposed that further environmental monitoring take place prior to injection to develop an MMV baseline. Once a baseline environmental programme is complete, ongoing environmental monitoring is designed to recognise environmental effects that may be caused by the operation of the storage complex.

The scope of the environment programme covers the water column, the sediment and atmospheric (fugitive) emissions associated with leakage from the platform. In addition, to the leakage of CO_2, the environmental monitoring programme will look to identify impacts caused by emission of formation water from the subsea outcrop of the Bunter sandstone formation some 20km east southeast of the injection platform. Although brine discharge from the outcrop is assessed to be highly likely to occur, dispersion studies (undertaken as part of the Environmental Impact Assessment) indicate that the worst plausible consequences are ‘low’ or ‘sufficiently small that probably it would not be observed but could, nevertheless, be detrimental to one or more receptors'. These dispersion studies which considered the maximum possible emission rates modelled both as a point source and as a distributed system similar in area to the outcrop also used worst case concentrations of formation water constituents.

Seawater chemistry

The monitoring of seawater chemistry will be by both the acquisition of physical samples during seabed sampling and from the annual AUV surveys. Conductivity (as a measure of salinity) and water column temperature profiles will be recorded. Of most importance is the possible and likely displacement of formation water in the vicinity of the subsea outcrop of the Bunter sandstone Formation.

Seawater chemistry is a primary measurement and a baseline survey is required.

Ground Water Monitoring

Only of relevance at the subsea outcrop, ground water monitoring will only be by grab sample deployment in the event of the detection of significant changes in seawater chemistry.

It is a contingent measurement and a baseline survey is required.

Seabed Sampling and Gas Analysis

Seabed and vadose zone grab samples will be analysed for changes in soil and potential contaminants. Specialist samples for gas analysis may also be obtained.

Grab and core samples are a primary measurement but soil samples for gas analysis are contingent, a baseline survey is required. Samples will be taken periodically from a number of stations arranged over the storage site foot print as well as from stations extending beyond for use as reference points. Samples will be analysed (in line with OSPAR guidance where relevant) for sediment composition, heavy and trace metals, hydrocarbons, fauna as well as for CO_2 and pH in pore water. Contemporaneously, seabed condition and larger visible fauna will be documented by photography.

For the important Bunter sandstone outcrop, the presence of bedrock at the seabed surface makes sampling difficult but stations surrounding the area where sampling is possible will be used and over the outcrop area conductivity, temperature profiles and photographic documentation will be recorded.

Infrared Gas Analysis and Acoustic Leak Detection

The platform will be equipped with both infrared gas and acoustic leak detectors for fugitive emissions from the platform.

These are primary measurements and a baseline survey is not required.

Ecosystem Monitoring

Marine and sediment biota will be monitored for significant changes in numbers, species and tissue concentrations and if changes are detected, investigative procedures to ascertain the reasons for changes will be put in place.

These are primary samples and baseline sampling is required.

5.9 Storage Complex Risk Assessment Results

The risk assessment identifies a number of potential risks to the system. They are summarised in the risk matrix presented in Table 5.3. It is these risks that the MMV plan addresses although there are some exceptions. The exceptions that are not monitored by elements of the MMV plan are the risks of sabotage and of inadvertent human intrusion and interactions with other resources and resource exploitation.

Table 5.3 Risk Matrix of the Worst Plausible Consequences

	Worst Plausible Consequence during the Assessment Time Frame				
Probability	**Very Low**	**Low**	**Medium**	**High**	**Very High**
Very high	Physical uplift of seabed Lateral migration of dissolved CO_2 out of storage complex Induced seismicity Natural seismicity	Displacement of higher salinity waters and interaction with benthic or pelagic biota			
High	Reduced injectivity due to chemical changes/reactivity				
Medium	Resource exploitation elsewhere disturbs CO_2 Interaction of CO_2 storage with other resources				
Low		Physical/chemical conditions prevent required capacity being accessed			
Very low	Tectonic processes disturb CO_2 Sabotage (of well heads) Leakage through caprock/seals Lateral migration of free CO_2 out of the storage complex	Over-filling	Reservoir pressurisation/ compartmentalisation Failure of historical well seals Failure of injection well seals Inadvertent human intrusion leads to leakage		

The rows of the matrix represent the probability that a particular phenomenon will occur, one with greater likelihood being placed in a higher row of the matrix than one with lower likelihood. The probabilities are expressed using a linguistic scale, in recognition of the fact that they are expert judgements, albeit judgements that are conditioned by evaluating a combination of quantitative and qualitative evidence.

The scale is as follows:

- Very High - Almost certain to occur;
- High - Clearly more likely to occur than not to occur;
- Medium - As likely to occur as not to occur;
- Low - Clearly less likely to occur than not to occur; and
- Very Low - Almost certain not to occur.

This scheme does not divide probability space equally and is designed to highlight phenomena that are clearly not expected to happen (probability very low) and those that are clearly expected to happen (probability very high).

The columns of the matrix represent the worst plausible consequences of each phenomenon, should it occur, during the assessment time frame. This is a cautious bounding approach exploring the most significant consequences that are plausible. The reason for this approach is that mitigation planning should consider the worst plausible result of any phenomenon happening. For example, reservoir pressurisation due to compartmentalisation could conceivably attain any value between 0bar and some maximum pressure. For the purposes of mitigation planning it is the maximum consequence that is of concern.

Like the probabilities, consequences are represented on a linguistic scale, a phenomenon with a lower worst case consequence being listed to the left of a phenomenon with a higher worst case consequence. However, whereas probability categories can be defined objectively (even though a judgment as to the actual probability of a given phenomenon occurring is inevitably subjective), consequence categories are themselves subjective; whether a consequence is considered severe or not depends upon a value judgment. One person may regard a ‘severe consequence’ to have a particular set of characteristics whereas another person might regard the same characteristics to indicate a ‘mild consequence’. For this reason, the approach taken here is to classify consequences as to whether or not they are ‘observably detrimental’, using the following scale:

- Very High - a consequence is of sufficient magnitude that it would definitely be observed and is clearly detrimental to one or more receptors (engineered structures, natural resources, organisms) over a wide area ($>10m^2$) or would call into question the effectiveness of CO_2 storage as a contributor to mitigating climate change;
- High - a consequence is of sufficient magnitude that it would probably be observed and is clearly detrimental to one or more receptors (engineered structures, natural resources, organisms) over a small area ($<10m^2$) or would call into question the effectiveness of CO_2 storage as a contributor to mitigating climate change;
- Medium - a consequence would be of sufficient magnitude that probably it would be observed and could be detrimental to one or more receptors (engineered structures, natural resources, organisms), but would not call into question the effectiveness of CO_2 storage as a contributor to mitigating climate change;
- Low - a consequence would be sufficiently small that probably it would not be observed and would not call into question the effectiveness of CO_2 storage as a contributor to mitigating climate change, but could nevertheless be detrimental to one or more receptors (engineered structures, natural resources, organisms); and
- Very Low - a consequence would not be detrimental to one or more receptors (engineered structures, natural resources, organisms) and would not call into question the effectiveness of CO_2 storage as a contributor to mitigating climate change.

Here the term ‘detrimental’ implies a tendency towards weakening structures (moving them towards the limits of their design envelopes or exceeding their design envelopes), impairing resource quality, or impairing the health of organisms. However, it should be noted that this scheme does not deal with how detrimental a particular consequence is perceived to be by stakeholders (regulators, legislators, non-governmental organisations, the general public and so on). For example, leakage of CO_2 that caused the observable impairment of health of organisms (for example, stunted growth that could not be attributed to causes other than CO_2 leakage) over a wide area would be seen by all stakeholders as detrimental and therefore would be placed in the Very high consequence category. However, the scheme does not distinguish whether these detrimental consequences might be regarded as tolerable.

5.9.1 Storage Complex Evolution Scenarios

The risks have been identified and quantified by a rigorous top down process that uses the system description to identify site specific and generic Features, Events and Processes (FEPs). From the FEPs, normal and alternative evolution scenarios are identified and explored. These are fully described in the risk assessment and summarised in Table 5.4 along with the appropriate element of MMV plan technology with which the risk can be monitored.

Table 5.4 Summary of the Risk Assessment

Alternative Evolutionary Scenario	Scenario	Main Variants	Notes	MMV Plan Technology Section 5.10
AE1	Reduced injectivity due to chemical changes/reactivity	AE1: Chemical precipitation reduces porosity AE1: Physical changes due to chemical reactions results in loss of injectivity	Principally exploring: Potential consequences of salt precipitation and hydrate formation. Includes recognising impurities in the injected gas stream. Potential consequences of physical changes to the formation owing to dissolution of minerals, for example, reduced porosity/permeability, strength loss and fracturing, sand generation clogging of injection wells	Downhole Pressure and Temperature Measurement
AE2	Reservoir pressurisation due to unexpected compartmentalisation	-	Reservoir pressurisation/compartmentalisation differs from expectations	Downhole Pressure and Temperature Measurement
AE3	Leakage through the primary seal and secondary seals	AE3: Via faults/fractures AE3: Diffusive leakage	AE3.b includes diffusion of dissolved CO_2 and diffuse leakage of CO_2 gas. Assessment considers the possibility of interactions with marine receptors	AUV Leak Detection Sonar
AE4	Increased displacement of high salinity formation waters	-	This considers displacement of high salinity waters beyond that assumed for the EES, assessing the potential for impacts at the sea bed, caused by either discharge via fractures or discharge via the seabed outcrop	Environmental Sampling
AE5	Well failure	AE5: Injection wells AE5: Other wells	Considers the possibility of a leakage pathway via poorly performing or absent/destroyed well seal(s). Includes the potential for damage to wellheads for example, as a result of trawling activities	Surface Pressure and Temperature Measurement AUV Leak Detection Sonar

Alternative Evolutionary Scenario	Scenario	Main Variants	Notes	MMV Plan Technology Section 5.10
AE6	Lateral interaction with other hydrocarbon resources	-	Addresses whether it is plausible that the CO_2 could migrate laterally sufficient to interfere with other hydrocarbon resources	Not addressed by MMV Plan
AE7	Resource exploitation elsewhere affects CO_2 storage system	-	Considers the potential for exploitation of other resources to affect conditions within the storage system for example, as a result of pressure changes	Not addressed by MMV Plan
AE8	Seabed uplift/deformation	-	Assessing whether it is plausible that impacts to the seabed (for example, in the area of the wind farm) could arise due to seabed uplift/tilting beyond the EES	Tiltmeter Network/GPS
AE9	Human intrusion	-	Exploring the potential for inadvertent human intrusion for example, as a result of exploration activities in the future. In this case, intrusion would be unexpected and hence likely to pose risks that were unforeseen. Does not include intentional human intrusion, because in this case the organisation undertaking the intrusion is assumed to be aware of the risks and would be responsible for managing risks and ensuring safety	Addressed by operational procedures
AE10	Leakage as a result of seismic events	AE10: Induced seismicity AE10: Natural seismicity	The induced seismicity variant explores the potential for overpressures to build up allowing (for example) some fracture widening near injection boreholes, or compromising well seals (see also AE5). The natural seismic variant explores whether seismic events could influence storage system evolution	Microseismic Network
AE11	Sabotage	-	Damage to well heads or seals as a result of sabotage. Note links with other scenarios for example, AE5 and AE9	Addressed by operational procedures
AE12	Accidental overfilling	-	The margin of the CO_2 plume moves more rapidly and/or further from the injection point than planned. This could be due to more CO_2 being injected than planned initially (while in principle this could be accidental, in reality it is almost certainly something that will be due to modified injection planning). Other causes of over-filling in this sense are smaller storage capacity than predicted and/or more highly permeable conduits (for example, fractures) than have been recognised prior to injection	3D Time Lapse Seismic

5.10 Monitoring, Measurement and Verification Plan Technology Phases

A summary of the technologies is presented in Section 5.8 of this document. A detailed review of the available technologies has been carried out and the suitability, practicality, cost and benefit of each technology has been evaluated.

In Section 5.9 of this document, the available technologies have then been assessed against their respective performance and value for monitoring for the residual risks identified in the risk assessment. Table 5.5 shows when the recommended technology will be used with respect to the four phases of the project.

Table 5.5 Technology and Applicable Phase

Monitoring Method	Technology and Applicable Phase					
	Primary or Contingent	Baseline	Injection	Post-Injection	Post Closure	After-Transfer
Wellhead pressure and temperature	P					
Wellhead flow and composition	P					
Downhole pressure and temperature	P				1	
Inert and isotope tracers	C		2	2		
Casing annulus pressures	P					
Production logging	C					
Optical logging	C					
Casing condition logging	C					
Downhole sensor replacement	C					
3D seismic	P				3	3
Microseismic network	P			4		
Tiltmeter network	P			5		
Global Positioning System (GPS)	P					
Bubblestream detection (sonar)	P					
Seawater chemistry	P					
Ground water monitoring	P					
Seabed sampling and gas analysis	C					
Infrared gas analysis and acoustic leak detection	P					
Ecosystem monitoring	P					

Notes: Colours denote use of technology by phase, any requirement for a baseline survey and whether the technology is primary or contingent:

1. Available for approximately five years after closure
2. Only required if gas seeps are identified prior to injection
3. Only required if an irregularity is identified
4. Decommissioned approximately two years after injection ceases
5. Decommissioned with microseismic network.

5.10.1 Operational Phase

During the operational phase the principal objective of the MMV plan is to ensure conformance. This process is based on the calibration of the dynamic reservoir models. Once the three injection wells are drilled, have been evaluated and the injection intervals selected for perforation, the dynamic reservoir models will be revised with data from the wells and run for the prediction of storage site behaviour as injection commences.

As injection pressure and temperature data is acquired during the first few months, these models will be continually adjusted. Once the performance and forecast matches, no further intervention is required unless significant deviations occur.

In the absence of any significant deviations in storage site performance, the next significant input will be the acquisition of the 3D seismic after approximately four years of injection. The dynamic models will then be adjusted to reflect the information from the interpretation of this data.

Significant deviations are expected to arise only from salt precipitation in the near wellbore region and various mitigation measures including the provision of temporary water wash are in place if it is more severe than expected. These include increased water wash frequency and additional perforations. Production logging may be mobilised in order to assess the severity of the problem (Alternative Evolution Scenario – AE1).

5.10.2 Post Injection

The fully history matched simulation will be used to predict the rate of decay of the average reservoir pressure after injection ceases. If the pressure decay trajectory does not match the prediction it may be necessary to increase the post-injection duration before the decision is made to abandon the injection infrastructure. Further information is included in the provisional post-closure report.

5.10.3 Post Abandonment

If no significant deviations are experienced during the post injection period, it is unlikely that any will be detected during the post abandonment period as the pressure will continue to drop and the integrity of the storage site and storage complex will increase, not only from the decaying pressure but also from the permanent abandonment of the injection wells removing the possibility of well failure from the alternative evolution scenarios.

5.10.4 After Transfer

Similarly, to Section 5.6.12 Post Closure above, the continuation of the pressure decay will continue to improve the integrity of the storage site and storage complex.

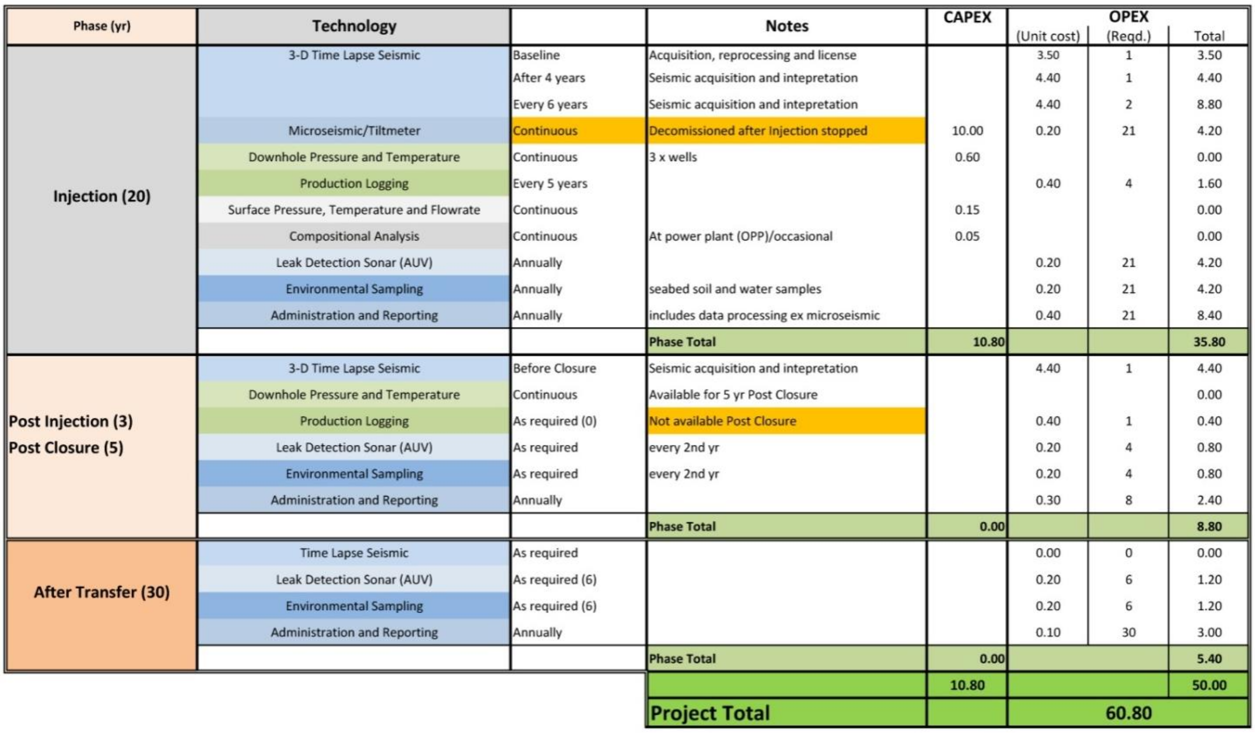
5.11 Monitoring, Measurement and Verification Plan Costs

The approximate costs of the MMV Plan are shown in Table 5.6. These include the costs to setup or establish the monitoring equipment and an annual administration, data processing and plan update estimate.

As some of the monitoring is done only contingently, an estimate of the likely frequency of deployment requirement is included. When equipment, such as a microseismic tiltmeter, needs to be decommissioned the cost is included in the establishment Capital Expenditure (CAPEX).

Baseline costs are included as an additional year's operating cost.

Table 5.6 MMV Plan Operational Frequency and Approximate Cost Estimates



Phase (yr)	Technology		Notes	CAPEX	OPEX		
					(Unit cost)	(Reqd.)	Total
Injection (20)	3-D Time Lapse Seismic	Baseline	Acquisition, reprocessing and license		3.50	1	3.50
		After 4 years	Seismic acquisition and intepretation		4.40	1	4.40
		Every 6 years	Seismic acquisition and intepretation		4.40	2	8.80
	Microseismic/Tiltmeter	Continuous	Decomissioned after Injection stopped	10.00	0.20	21	4.20
	Downhole Pressure and Temperature	Continuous	3 x wells	0.60			0.00
	Production Logging	Every 5 years			0.40	4	1.60
	Surface Pressure, Temperature and Flowrate	Continuous		0.15			0.00
	Compositional Analysis	Continuous	At power plant (OPP)/occasional	0.05			0.00
	Leak Detection Sonar (AUV)	Annually			0.20	21	4.20
	Environmental Sampling	Annually	seabed soil and water samples		0.20	21	4.20
	Administration and Reporting	Annually	includes data processing ex microseismic		0.40	21	8.40
			Phase Total	**10.80**			**35.80**
Post Injection (3) **Post Closure (5)**	3-D Time Lapse Seismic	Before Closure	Seismic acquisition and intepretation		4.40	1	4.40
	Downhole Pressure and Temperature	Continuous	Available for 5 yr Post Closure				0.00
	Production Logging	As required (0)	Not available Post Closure		0.40	1	0.40
	Leak Detection Sonar (AUV)	As required	every 2nd yr		0.20	4	0.80
	Environmental Sampling	As required	every 2nd yr		0.20	4	0.80
	Administration and Reporting	Annually			0.30	8	2.40
			Phase Total	**0.00**			**8.80**
After Transfer (30)	Time Lapse Seismic	As required			0.00	0	0.00
	Leak Detection Sonar (AUV)	As required (6)			0.20	6	1.20
	Environmental Sampling	As required (6)			0.20	6	1.20
	Administration and Reporting	Annually			0.10	30	3.00
			Phase Total	**0.00**			**5.40**
				10.80			**50.00**
			Project Total		**60.80**		

5.12 Conclusions

The MMV plan is based on the risk assessment and the evolution scenarios that quantify those risks. The equipment, technologies and the methodologies of the plan address these risks through the four phases of the project.

A number of technologies are proposed for inclusion within the MMV plan but, the most important aspect of the plan is its annual update, where new technologies might be introduced if they provide an improved definition of conformance or containment.

Although cost estimates are provided, the introduction of new or improved technology might result in significant changes through the life of the project and as some of the technology will be deployed on a contingent basis, this again could cause significant variation in cost.

The conformance of the storage complex is based on the dynamic and geomechanical modelling. Not only do these models have to be calibrated with data as it is received through the life of the project but the drilling and evaluation of the three injection wells will also provide substantial additional data that will drive a revision of the models and a review and possible update to the risk assessment.

Once the three injection wells were drilled, the detailed design would provide the exact specifications for the monitoring and measurement sensors and the equipment and when the baseline surveys are complete, the operational phase MMV plan would be finalised. Thereafter, MMV plan is subject to annual reporting and annual updates throughout the operational phase. The updates are to ensure that the most recent developments in methodology, data interpretation and technology are used to ensure conformance and containment.

After site closure and the permanent removal of the injection facilities, the ownership of the storage site will pass to the competent authority in the UK. The monitoring activities after transfer will reflect the monitoring technologies used and the data obtained up to this time and the monitoring activities of the competent authority will proportionately decrease throughout these 30 years.

6 Corrective Measures Plan

6.1 Introduction

Corrective measures are intended to ensure the safety and effectiveness of geological storage. Corrective measures are part of the overall risk management process that is intended to ensure the safety of geological storage and to manage the risks from leakage during the project life cycle.

The plan is site and complex specific; it is risk based and linked to identified risks from site characterisation, risk assessment and MMV plan and subject to the limitations of available technologies.

The priorities for the corrective measures plan are ranked in the following order:

1. prevention of risks to human health;
2. prevention of risks to the environment; and
3. prevention of leakage from the storage complex.

The definitions particularly relevant to the corrective measures plan are:

- Significant Irregularity – any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of a Leakage or risk to the environment or to human health;
- Leakage – any release of CO_2 from the storage complex; and
- Storage Complex – the storage site and surrounding geological domains that can affect overall storage integrity and security.

Further definitions and the site specific descriptions are included in Section 5.6.

6.2 Scope

The Quantitative Risk Assessment (QRA) considers, among others, the risk to containment of the stored CO_2 within the storage complex and, as such, it forms the basis of the corrective measures plan. The scope of the QRA considers the storage complex which includes the associated infrastructure (injection, appraisal and legacy wells) and also surrounding domains that might plausibly be impacted by any:

1. leaking $CO_{2;}$
2. displaced, natural formation fluid; or
3. physical disturbances to the solid geosphere caused by CO_2 injection; induced seismicity, surface displacements.

The system considered by the risk assessment, consists of:

- the storage site (the defined volume within a geological formation used for CO_2 storage and associated wells and pumps; in the project, the Bunter sandstone reservoir);
- the storage complex (the storage site, plus the surrounding geological domains that can affect overall CO_2 storage integrity and security; in the project, the domains between the top Rotliegend (c. 2900 to 3650m) to the top of the Lias formation (c 50 to 60m), including the storage site);
- the pre-existing formation fluid, which will be displaced by the injected CO_2 and which will interact with the CO_2 by:
  - dissolving in the dense CO_2 stream, leading to desiccation and possibly salt precipitation from the residual brine (most likely close to the injection wells); and

  - dissolving the CO_2
- injection boreholes and associated infrastructure;
- legacy boreholes that might plausibly be contacted by migrating or leaking CO_2;
- actual and potential economic assets adjacent to the storage complex that might plausibly be impacted by any CO_2 that unexpectedly leaks; and
- the ecosystems in the region surrounding the storage complex that might plausibly be affected by any CO_2 that unexpectedly leaks or pre-existing formation fluids that are caused to flow as a consequence of CO_2 injection.

More specifically the assessment addresses Article 18, Point 1 of 2009/31/EC CCS Directive by:

- providing evidence that the projected volumes of CO_2 to be injected will be stored safely and completely and permanently contained; and
- stating risks to complete and permanent containment (as a basis for developing monitoring and mitigation plans), including risks of exceeding any pressure limits and thereby threatening the maintenance of site integrity.

The assessment also contributes to addressing Article 19, Point 2 of 2009/31/EC CCS Directive by providing evidence that the storage site will evolve towards a situation of long term stability following the completion of CO_2 injection.

The risk assessment has identified a total of 18 risks to the operation of the injection and storage. These are listed below but complete descriptions, along with expected and alternative evolution scenarios, are fully documented in the QRA:

1. physical uplift of the seabed*;
2. lateral migration of dissolved CO_2 out of storage complex;
3. induced seismicity*;
4. Natural Seismicity,
5. reduced injectivity due to chemical changes/reactivity*;
6. resource exploitation elsewhere disturbs CO_2*;
7. interaction of CO_2 storage with other resources*;
8. sabotage of wellheads;
9. leakage through caprock/seals;
10. lateral migration of free CO_2 out of storage complex;
11. displacement of higher salinity waters and interaction with benthic or pelagic biota*;
12. physical/chemical conditions prevent required capacity being accessed*;
13. overfilling (attempted storage of substantially higher volumes than authorised);
14. reservoir pressurisation/compartmentalisation*;
15. failure of historical (legacy) well seals;
16. failure of injection well seals;
17. inadvertent human intrusion leads to leakage; and
18. tectonic processes disturb CO_2.

*Note: Risks identified, do not have the potential to cause leakage of CO_2 and therefore are not considered to contribute to or constitute a significant irregularity.

Risks that do not have the potential to cause leakage of CO_2 from the Endurance storage complex are not considered further and the remainder are classified below both according to their probability of occurrence and according to whether or not their consequence would be detrimental to one or more receptors and would not call into question the effectiveness of the Endurance CO_2 storage as a contributor to mitigating climate change:

6.2.1 Risk Classification

The categories are defined as follows:

- almost certain not to occur but with observable detrimental consequence:
  - failure of historical (legacy) well seals;
  - failure of injection well seals; and
  - inadvertent human intrusion;
- almost certain to not occur but with detrimental consequence that would not be observed:
  - overfilling;
- almost certain not to occur but with no detrimental consequence:
  - sabotage;
  - leakage through caprock/seals;
  - CO_2 disturbed by tectonic processes; and
  - lateral migration of free CO_2 out of the storage complex; and
- almost certain to occur but with no detrimental consequence:
  - lateral migration of dissolved CO_2 out of the storage complex.

In order to be included as significant irregularities, the consequence of the risk events need to be detected by MMV plan technologies. The latter two categories have consequences that are generally below the detection threshold of the MMV plan and therefore, even if they were to occur, with the exception of special case of sabotage, their consequences would not be detected. The consequence of sabotage, which in any event can only occur during the operational phase, would not cause leakage due to the reaction of the system to close the subsurface safety valves which are specified to be installed in all the injection wells.

Overfilling, which would be immediately detected by the MMV plan’s inventory measurement, would have to take place on a massive scale in order to cause any detrimental effect and become a significant irregularity as a result neither needs to be considered with respect to the corrective measures plan.

The corrective measures plan therefore addresses three significant irregularities:

- failure of historical (legacy) well seals;
- failure of injection well seals; and
- inadvertent human intrusion.

The corrective measures plan is not a static document. During detailed design, implementation and during annual updates that address the risk assessment and MMV plan, it will be challenged and amended as necessary.

6.3 Significant Irregularities

6.3.1 Failure of Historical (Legacy) Well Seals

The mechanisms and processes that would cause a failure of historical well seals are extensively discussed and modelled in the QRA. Of primary importance is the consideration that in order for a leakage to occur that multiple barriers have to fail and it is the presence of these multiple barriers that control the flux of a leakage to very low levels.

6.3.2 Corrective Measure

Should there be a leakage via the multiple seals that are associated with these wells that results in the detection of CO_2 at the seabed, the flux of the leak firstly needs to be quantified. Depending on this quantification; appropriate corrective measures will be proposed in consultation with the competent authority.

6.3.3 Failure of Injector Well Seals

The failure of injector well seals fall into three time frames:

- during the operational phase;
- during well abandonment; and
- after closure.

6.3.3.1 During the Operational Phase

In order for leakage to occur during the operational phase when injection is ongoing, multiple barriers need to be breached. The wells are designed with a minimum of two barriers both of which need to be breached before any leakage can occur. Once the first of two barriers are breached, the instrumentation deployed under the auspices of the MMV plan will detect the anomaly and the necessary remedial actions can be taken before the second barrier is compromised. Each of the barriers will be designed to be capable of containing the worst case leak and no possibility exists of an uncontrolled leakage. Affected wells will be shut in for investigation and determination of appropriate remedial actions.

No further corrective measure is required for injection wells during the operational phase.

6.3.3.2 During Well Abandonment

In order for a leakage to occur during well abandonment operations, a major breach of standard operating procedures must take place. At all times, a minimum of two barriers must be in place and the systems are designed so that any failure of a barrier is immediately detectable. Once a failure is detected, standard operating procedures will be implemented to remedy the failure.

No further corrective measure is required.

6.3.3.3 After Closure

Free CO_2 is only present for a limited time after closure as the injection wells are down a dip and the CO_2 cap will migrate to the crest of the structure. The injection wells will be constructed of CO_2 corrosion resistant materials and, as in the case of the crestal legacy wells, multiple seals must be breached in order for a leak to occur.

The corrective measure will require that a mudline suspension or similar device will allow the re-establishment of a pressure connection to the intermediate and production casing so that the well can be re-entered and any leak paths present can be sealed.

6.3.4 Inadvertent Human Intrusion

In order that inadvertent human intrusion occurs it is necessary to postulate that at some time in the future, all records of the Endurance store have been lost and that there is also an attempt to drill an exploration type well. It is further necessary to assume that the well intercepts the free CO_2 trapped at the top of the anticline which could result in release of CO_2 gas to the atmosphere if preventative drilling practices are not adopted, or if there is some failure in equipment or operational procedures designed to prevent gas leakage. It is reasonable to assume that if the ‘explorers’ have the technology to drill into the storage complex then they would likely have the technology to successfully seal the well.

No corrective measure for this potential significant irregularity is planned.

7 Glossary

Abbreviations	Meaning
ALARP	As Low As Reasonably Practicable
AES	Alternative Evolution Scenarios
AUV	Autonomous Underwater Vehicle
barg	Bar Gauge
BAT	Best Available Technique
BEP	Best Environmental Practice
BHP	Bottom Hole Pressure
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
CPL	Capture Power Limited
CSEM	Controlled Source Electromagnetic
°C	Degrees Celsius
DECC	Department of Energy and Climate Change
EC	European Commission
EES	Expected Evolution Scenario
EFEPs	External Features Events and Processes
EIA	Environmental Impact Assessment
EOR	Enhanced Oil Recovery
ESL	Evidence Support Logic
ETS	Emissions Trading Scheme
FEED	Front End Engineering Design
FEPs	Features Events and Processes
GPS	Global Positioning System
HSE	Health and Safety Executive
kg/yr	kilogrammes per year
KSC	Contract made between CPL and NGC
MD	Measured Depth
MEG	Monoethylene Glycol
mm	Millimetres
MMV	Monitoring, Measurement and Verification
mol/s	mole (amount of substance) per second
MTPA	Million tonnes Per Annum
MW	Mega Watt
m^3/h	Cubic Metres per Hour
NGC	National Grid Carbon Limited
NGO	Non-Governmental Organisation
NRMS	Normalised Root Mean Square
NWMO	Nuclear Waste Management Organisation
OBM	Oil Based Mud
OPP	Oxy Power Plant
O_2	Oxygen
pH	Acidity of an aqueous solution

PEC	Predicted Environmental Concentration
PNEC	Predicted No Effect Concentration
ppm(v)	Parts Per Million (Volume)
QRA	Quantative Risk Assessment
RISCS	RISCS EC project (Research into Impacts and Safety in CO_2 Storage; RISCS, 2014)
T&S	Transportation and Storage
t/d	tonnes per day
THMC	Thermo-Hydro-Mechanical-Chemical
TVDSS	True Vertical Depth Subsea
UK	United Kingdom
VSP	Vertical Seismic Profile
WHO	World Health Organisation
WR	White Rose

Term	**Explanation**
Aeolian processes	Pertain to wind activity in the study of geology and weather and specifically to the wind's ability to shape the surface of the Earth (or other planets)
Anhydrite	A mineral—anhydrous calcium sulphate, $CaSO_4$
Anticlinal structures	A fold that is convex up and has its oldest beds at its core
Aseismic	A fault on which no earthquakes have been observed
Bathymetry	The study of underwater depth of lake or ocean floors. Bathymetric maps may also use a Digital Terrain Model and artificial illumination techniques to illustrate the depths being portrayed
Benthic community	Organisms that live in (infauna) and on (epifauna) the bottom of the ocean floor. These organisms are known as benthos. Benthos include worms, clams, crabs, lobsters, sponges, and other tiny organisms that live in the bottom sediments
Biota	The total collection of organisms of a geographic region or a time period, from local geographic scales and instantaneous temporal scales all the way up to whole-planet and whole-timescale spatiotemporal scales
Bunter sandstone	Sandstone deposits containing colourful rounded pebbles, a lithostratigraphic and allostratigraphic unit (a sequence of rock strata) in the subsurface of large parts of west and central Europe
Bow tie approach	A diagram that visualises risk as an overview of multiple plausible scenarios. It is shaped like a bow-tie, creating a clear differentiation between proactive and reactive risk management
Calcareous	Mostly or partly composed of calcium carbonate, in other words, containing lime or being chalky
Calcite cement	Occurs in meteoric realms (freshwater sources), the cement is produced by the dissolution of less stable aragonite and high-Mg calcite
Carboniferous	The Carboniferous Period lasted from about 359.2 to 299 million years ago* during the late Paleozoic Era. The term "Carboniferous" comes from England, in reference to the rich deposits of coal that occur there
Carbon capture	Collection of CO_2 from power station combustion process or other facilities and its process ready for transportation
Cretaceous	Derived from the Latin "creta" (chalk), geologic period and system from 145 ± 4 to 66 million years (Ma) ago
CCS Directive	European Union’s Directive on the Geological Storage of Carbon Dioxide (EC, 2009, 2011)

Darcy flow	The principle that governs how fluid moves in the subsurface is called Darcy's law. Darcy's law is an equation that defines the ability of a fluid to flow through a porous media such as rock. It relies on the fact that the amount of flow between two points is directly related to the difference in pressure between the points, the distance between the points, and the interconnectivity of flow pathways in the rock between the points. The measurement of interconnectivity is called permeability
Dense phase	The physical properties of CO_2 can vary according to temperature and pressure. It can be a gas, solid, liquid or can exist in a 'supercritical' state, where it behaves as a gas but has the viscosity of a liquid. The term 'dense phase' refers to CO_2 in either the supercritical or liquid stage
Epifauna	Also called epibenthos, are aquatic animals that live on the bottom substratum as opposed to within it, that is, the benthic fauna that live on top of the sediment surface at the seafloor
Ettringite	Hydrous calcium aluminium sulphate mineral
FEED contract	CPL have entered into an agreement with the UK Government's DECC pursuant to which it will carry out, among other things, the engineering, cost estimation and risk assessment required to specify the budget required to develop and operate the White Rose assets
Feldspars	($KAlSi_3O_8$ – $NaAlSi_3O_8$ – $CaAl_2Si_2O_8$) are a group of rock-forming tectosilicate minerals (with a structure composed of interconnected tetrahedrons) that make up as much as 60% of the Earth's crust
First load	The amount of CO_2 produced during the first year of the CO_2 transportation system
Fluvial	The processes associated with rivers and streams and the deposits and landforms created by them
Flux	The rate of volume flow across a unit area
Full chain	The complete process from the capture of the CO_2 at the emitter plant to its injection into the storage reservoir
Geosphere	The solid portion of the earth (distinguished from atmosphere, hydrosphere
Halite	Salt
Heterogeneous	A process involving substances in different phases (solid, liquid, or gaseous)
Infauna	Benthic organisms that live within the bottom substratum of a body of water, especially within the bottom-most oceanic sediments, rather than on its surface. Bacteria and microalgae may also live in the interstices of bottom sediments. In general, infaunal animals become progressively smaller and less abundant with increasing water depth and distance from shore, whereas bacteria show more constancy in abundance, tending toward one million cells per millilitre of interstitial seawater
Injection well	Deep subsurface rock formations identified for long-term storage
Joule-Thompson effect	Describes the temperature change of a gas or liquid when it is forced through a valve or porous plug while kept insulated so that no heat is exchanged with the environment
Jurassic	(from Jura Mountains) is a geologic period and system that extends from 201.3± 0.6 million years ago to 145± 4 million years ago; from the end of the Triassic to the beginning of the Cretaceous
Key Knowledge Deliverable	A series of reports Including this one) issued as public information to describe the flows and processes associated with the overall system. Also referred to as a KKD
Laminae	A thin layer, plate, or scale of sedimentary rock, organic tissue, or other material
Lias	A lithostratigraphic unit (a sequence of rock strata) found in a large area of western Europe, including the British Isles, the North Sea, the low countries and the north of Germany. It consists of marine limestones, shales, marls and clays
Liassic	The Lower Jurassic period of geologic time
Lithostatic stress	A pressure or stress imposed on a layer of soil or rock by the weight of overlying material
Marine biota	Marine biota can be classified broadly into those organisms living in either the pelagic environment (plankton and nekton) or the benthic environment (benthos)
Negative polarity	A term used in exploration seismology to describes the convention of displaying an increase in velocity, such as from a slow velocity shale to a high velocity dolomite, as a trough, and travel from a high velocity rock to a slower velocity rock as a positive peak

Neotectonics	The study of the motions and deformations of Earth's crust (geological and geomorphological processes) that are current or recent in geologic time
Oil-based mud	A mud where the base fluid is a petroleum product such as diesel fuel. Used for many reasons, including increased lubricity, enhanced shale inhibition, and greater cleaning abilities with less viscosity. Oil-based muds also withstand greater heat without breaking down
Ooids	Small (=2mm in diameter), spheroidal, "coated" (layered) sedimentary grains, usually composed of calcium carbonate, but sometimes made up of iron- or phosphate-based minerals
Oolite	Or egg stone is a sedimentary rock formed from ooids, spherical grains composed of concentric layers
Overpull	The amount of force exerted on a tubular, such as the drill string in the well, that is greater than the tubular in the well
Phase envelope	The behaviour of a gas at different phases represented as a function of pressure and temperature
Pelagic zone	The part of the open sea or ocean that is not near the coast or seafloor
Permian	A geologic period and system which extends from 298.9 to 252.17 million years ago. It is the last period of the Paleozoic, following the Carboniferous and preceding the Triassic of the Mesozoic
Playa lake	Dry lake
Quantum packer	A plug used to provide a seal between the outside of the production tubing and the inside of the casing, liner, or wellbore wall
Quaternary	A geologic period which spans from 2.588 ± 0.005 million years ago to the present
Receptors	Components of the environmental system, whether living or not, that could be subject to adverse (or positive) impacts as a result of CO_2 leakage or be impacted indirectly as a result of the presence or movement of CO_2 in the subsurface
Redox	A contraction of the name for chemical reduction-oxidation reaction. A reduction reaction always occurs with an oxidation reaction. Redox reactions include all chemical reactions in which atoms have their oxidation state changed; in general, redox reactions involve the transfer of electrons between chemical species
Rotliegend	Or Rotliegendes (German: the underlying red) is a lithostratigraphic unit (a sequence of rock strata) of latest Carboniferous to Guadalupian (middle Permian) age that is found in the subsurface of large areas in western and central Europe. The Rotliegend mainly consists of sandstone layers. It is usually covered by the Zechstein and lies on top of regionally different formations of late Carboniferous age
Salt diapirs	A type of structural dome formed when a thick bed of evaporite minerals (mainly salt, or halite) found at depth intrudes vertically into surrounding rock strata
Seismic two-way-time	Uses reflected energy from interfaces between subsurface layers, recorded as down and back up travel times, to determine their configuration
Stratigraphy	A is a branch of geology which studies rock layers and layering (stratification).
Taxa	Group of one or more populations of an organism
Tectonics	Is concerned with the processes which control the structure and properties of the Earth's crust, and its evolution through time
Thermally fracturing	Appears in the boundaries of mineral grains of rocks due to the different thermal expansion of different minerals while heating the rocks
Thermohaline convection	Occurs in the ocean when warm salted layers sit on top of cool and less salted ones, then the salted water rapidly diffuses downwards even in the presence of stabilising temperature gradients, due to double diffusion between the falling blobs and their surroundings
Triassic	A geologic period and system that extends from roughly 252.17 to 201.3 million years ago, an interval of 51.04 million years
Two-phase	A region with gas and liquid coexisting
Westphalian Coal Measures	The source rocks for gas found in the southern North Sea

White Rose Transport and Storage FEED Project	CPL and NGCL have entered into a key subcontract agreement where NGCL will perform this project which will meet that part of CPL’s obligations under the FEED Contract which are associated with the transport and storage assets
Zechstein	A unit of sedimentary rock layers of Middle to Late Permian (Guadalupian to Lopingian) age located in the European Permian Basin which stretches from the east coast of England to northern Poland

Appendices

Appendix A Detailed Scenario Descriptions

A.1 Expected Evolution Scenario

A.1.1 Introduction

The EES is a description of the expected behaviour of the system through time. By definition, this scenario assumes that all the main components of the system behave as expected or as designed, leading to the CO_2 being injected into the reservoir and completely contained within the storage complex in the long term.

Three timescales are considered in this description:

- the operational period of around 20 years (phase 1), during which CO_2 is injected into the reservoir;
- the short term post closure period of around 25 years, starting at the end of injection and ending when the majority of the CO_2 has stopped migrating; and
- the long term post closure period after final closure during which any changes within the storage system are very slow.

The key components of the storage system that are considered in the EES are:

Table A.1 Key Components of the Storage System Considered in the EES

Component	Description
Injected CO_2	The CO_2 stream is likely to include trace amounts of impurities such as N_2, O_2, H_2, Ar and H_2O, but the exact composition of the CO_2 stream is likely to vary with time to some degree. A limit on the amount of impurities that can enter the pipeline transportation system has been set, with at least 96% CO_2 in the CO_2 stream. Calculations such as reservoir simulations and geochemical models assume that the CO_2 is pure, given the uncertainty in the actual composition and a lack of data on the properties of CO_2 streams with a mixture of gases. The potential effects of impurities need to be considered when using model results to describe the expected evolution and are fully captured within the AES
Reservoir integrity	The Bunter sandstone is fully saturated with brine at a pressure of 152bar. The initial temperature of the formation is around 61°C and the strength of the rock from mini-frac tests has been measured as in excess of 250bar
Formation fluids	The fluid within the Bunter sandstone within the storage site is brine (salinity ranging from c.252,000mg/kg to c.262,000mg/kg)
Physico-chemical processes	There may be some thermal fracturing of the sandstone immediately adjacent to the injection well and dissolution/precipitation of minerals along the path of CO_2 migration. Physico-chemical processes will be most significant close to the injection wells and may include halite and hydrate precipitation and sand generation
Primary seal and secondary seal	The Röt clay is the primary seal. In the Esmond gas field, the Röt clay has been shown to hold a differential pressure of 110bar which is significantly greater than the pressure difference expected due to CO_2 injection at the Endurance of 40bar. The observations at Esmond are consistent with the results of a mini frac test on the Röt clay in well 42/25d-3. This test gave a fracture closure pressure of 3830psi, or 264bar. The deepest secondary seal in the Endurance structure is the Röt halite, which is a ~100m thick halite-dominated formation. However the CO_2 is unlikely to reach the Röt halite, being trapped beneath the Röt clay
Injection wells	The design of the injection system is still being optimised. However, the injection system is likely to include three sub-vertical injection wells radiating from a single platform. Injection is likely to be in the lower half of the Bunter sandstone to minimise risks to well, primary seal and secondary seal integrity. Well abandonment will be optimised for CO_2 storage

Component	Description
Appraisal wells	There are three appraisal wells penetrating the reservoir in structure Endurance. Wells 42/25-1 and 43/21-1 are located on the crest of the anticline and were drilled in 1990 and 1970 respectively. These wells have plugs in the Bunter sandstone, extending back through the Röt clay and into the Röt halite and at the shallower casing shoes. NGCL appraisal well 42/25d-3 is located on the flank of the anticline. It is cased to TD and has been plugged from just below the Röt clay to above the top of the Röt halite
Regional pressure effects	There is evidence that the Endurance reservoir is hydraulically connected to the Bunter sandstone across a wider area. Oil and gas production in the southern North Sea could affect the pressure in the Endurance structure; particularly gas production from reservoirs in the Bunter sandstone. Likewise, the injection of CO_2 into the Bunter sandstone at Endurance could change the pressure in gas reservoirs elsewhere in the southern North Sea. However, the gas reservoirs are located a long way from Endurance and consistent with pressure changes at Endurance ascribed to production from Esmond, the interactions are expected to be negligible
Seabed	It is anticipated there will be a small amount of uplift of the seabed above the ‘bubble’ of CO_2 trapped below the crest of the anticline. However, there is not expected to be any discernible differential movement on faults in the primary seal and overburden
Water column	The depth of the water column is ~60m. Bottom currents are up to 0.15m/s and are strongest in late spring to late autumn. Weak stratification may develop in late summer
Marine biota	Seabed dwelling organisms include echinoderms, polychaetes, annelid worms and bivalve molluscs

This list is based on the key FEPs identified in Section 4.3.6 of the main report, with FEPs that are not explicitly mentioned being covered implicitly (having a similar action to one of the explicitly mentioned FEPs, or having effects smaller than one of these FEPs). External FEPs such as sabotage are unlikely and therefore are not in the EES. In the following text, each of these components is described along with the evolution through time.

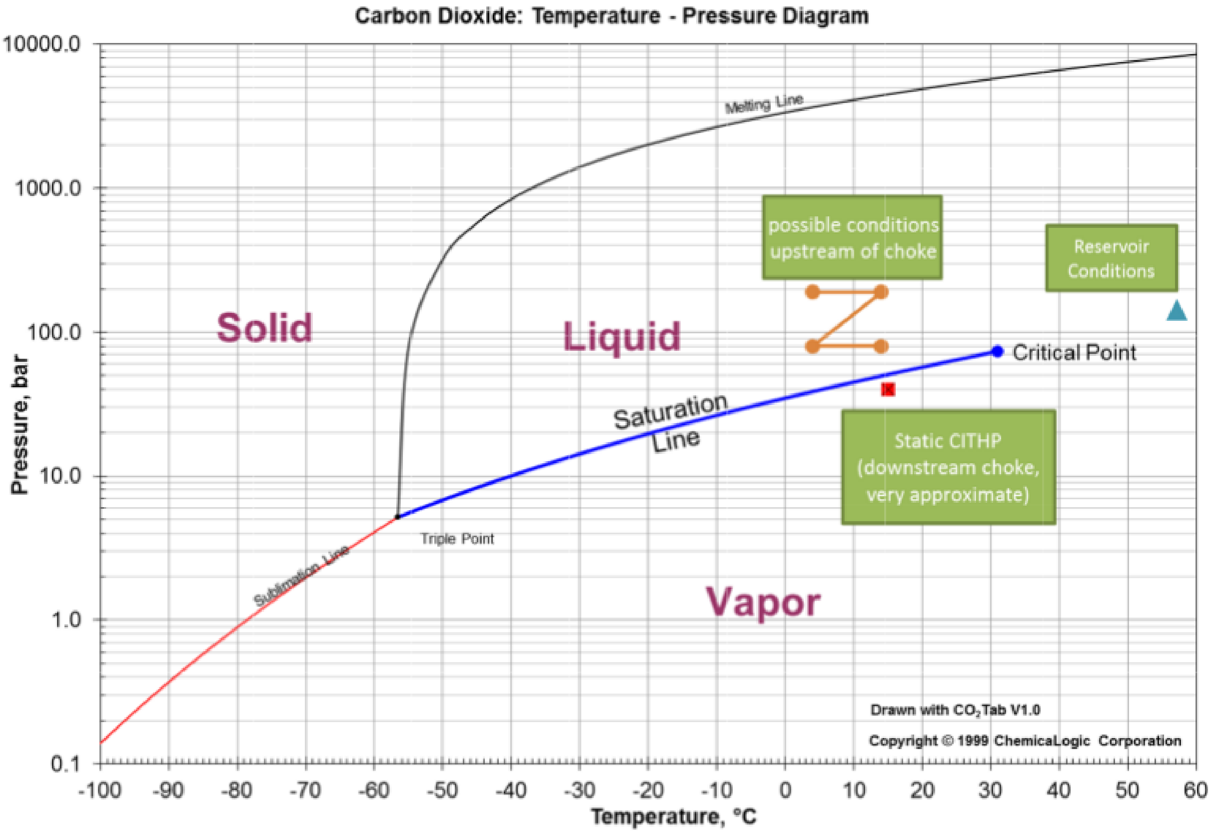
A.1.2 Injected CO_2

During the operational phase, CO_2 will be delivered to the injection well along a subsea pipeline. The rate of CO_2 supply from the power plant will vary between 2.68MT/y and 0.58MT/y, but could decrease to zero if the power plant goes offline for more than a day. When the CO_2 arrives at the injection wellhead, it will be at a temperature between -7°C to 24°C depending on the inputs and seabed temperature and a pressure between 90barg (bar gauge) and 182barg. Under these conditions, the CO_2 arriving at the well head will be in the liquid phase (Figure A.1).

The exact design of the injection wells has not been finalised, but it is the design intention to prevent phase transitions of the CO_2 in the well. Measures may be taken to avoid any phase transition of the CO_2 occurring within the wells, for example during injection start-up this might involve: heating the CO_2; controlling the pressure in the well, for example by a downhole choke; or injecting N_2.

Once the CO_2 has equilibrated to reservoir conditions of around 152bar and 61°C, the CO_2 will be a dense phase supercritical fluid (Figure A.1).

Figure A.1 Phase Diagram of CO_2



As the CO_2 enters the reservoir during the operational phase, it will displace the brine in the pore space, migrating laterally due to the pressure difference between the injection well and the reservoir and vertically due to buoyancy. The latest dynamic modelling work indicates that there will be little lateral spreading and the plume of CO_2 will rise vertically to the top of the Bunter sandstone. The CO_2 will then migrate laterally along the top of the reservoir. The time taken for the CO_2 to travel from the proposed injection wells to the crest will be between two and five years with a most likely value of three and a half years. After five years of injection, a free CO_2 phase is beginning to be trapped at the crest of the anticline. This migration behaviour will continue during the short term post closure phase.

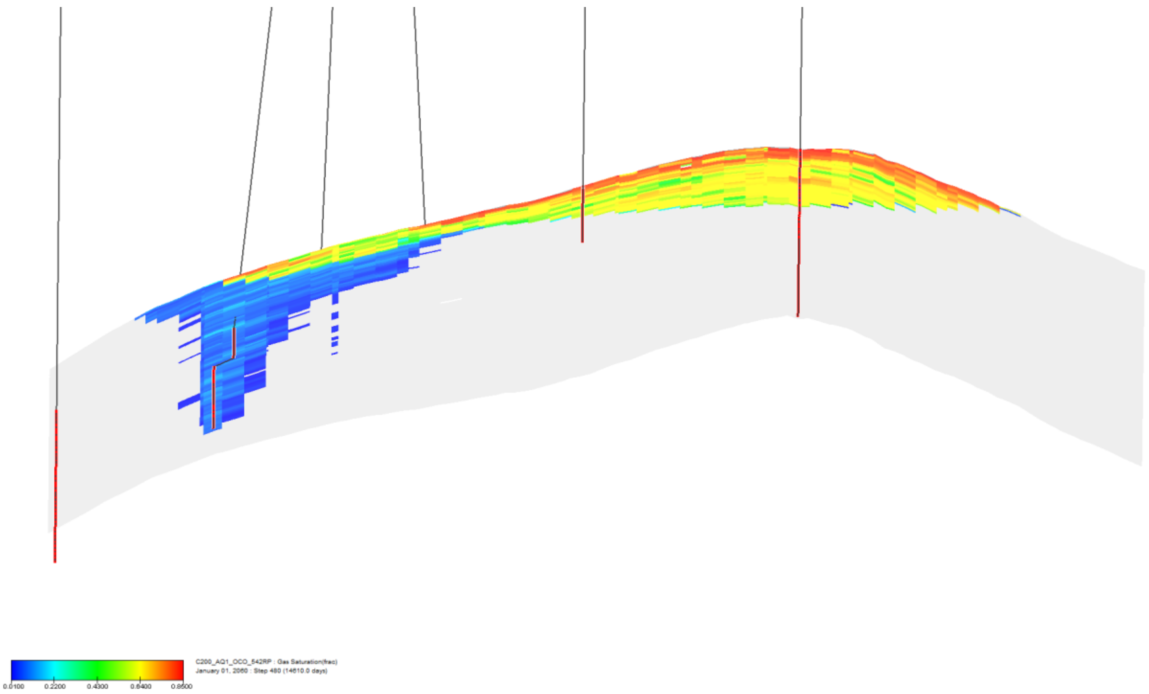
As a free CO_2 phase migrates through the reservoir there will be some dissolution in the brine. At the leading edge of the CO_2 plume, the CO_2 will be displacing brine and at the trailing edge, brine will be moving back into the pore space. As brine moves back into the pore space, a proportion of the CO_2 phase can be cut off from the migrating plume in a process known as residual trapping. However, relative permeability measurements on core taken from the 42/25d-3 appraisal well indicate that this could be a minor process in Endurance.

CO_2 will migrate vertically to the top of the Bunter sandstone so long as there are no low permeability barriers; a number of small lower permeability layers have been observed, but only one has been shown to have any lateral continuity. These lower permeability layers are likely to cause some sideways spreading of the CO_2, which will increase the volume of pore space through which CO_2 migrates and will increase dissolution, but will not stop vertical migration.

Vertical migration will cease at the top of the Bunter sandstone when the CO_2 reaches the base of the Röt clay, which is the primary seal. The CO_2 will then migrate laterally along the base of the Röt clay to the crest of the anticline. Again, some CO_2 will dissolve in the brine as it migrates to the crest.

In the long term post closure phase, it is assumed that gaseous CO_2 migration has ceased and except for a small amount of residual trapping and dissolution, all the CO_2 has migrated to the crest of the anticline. For example, Figure A.2 shows that migration is nearly complete following 20 years of shut-in. The risk of overfilling is negligible due to the small amount of CO_2 to be stored compared with the size of the structure.

Figure A.2 CO_2 Saturation After 20 Years of Shut in using Relative Permeability Data from Endurance



As described above, some CO_2 will have already dissolved in the brine as it migrated to the crest of the anticline. Dissolution will continue over long time scales, reducing the pressure in the reservoir. Dissolution is affected by the contact area between CO_2 and brine and this is increased by residual trapping and any lateral spreading of the CO_2. Brine with dissolved CO_2 is denser than the formation brine, so will sink, causing mixing of the formation waters and dilution of the dissolved CO_2. Dissolution and migration of dissolved CO_2 by convective and diffusive processes will continue, slowly reducing the amount of free gas.

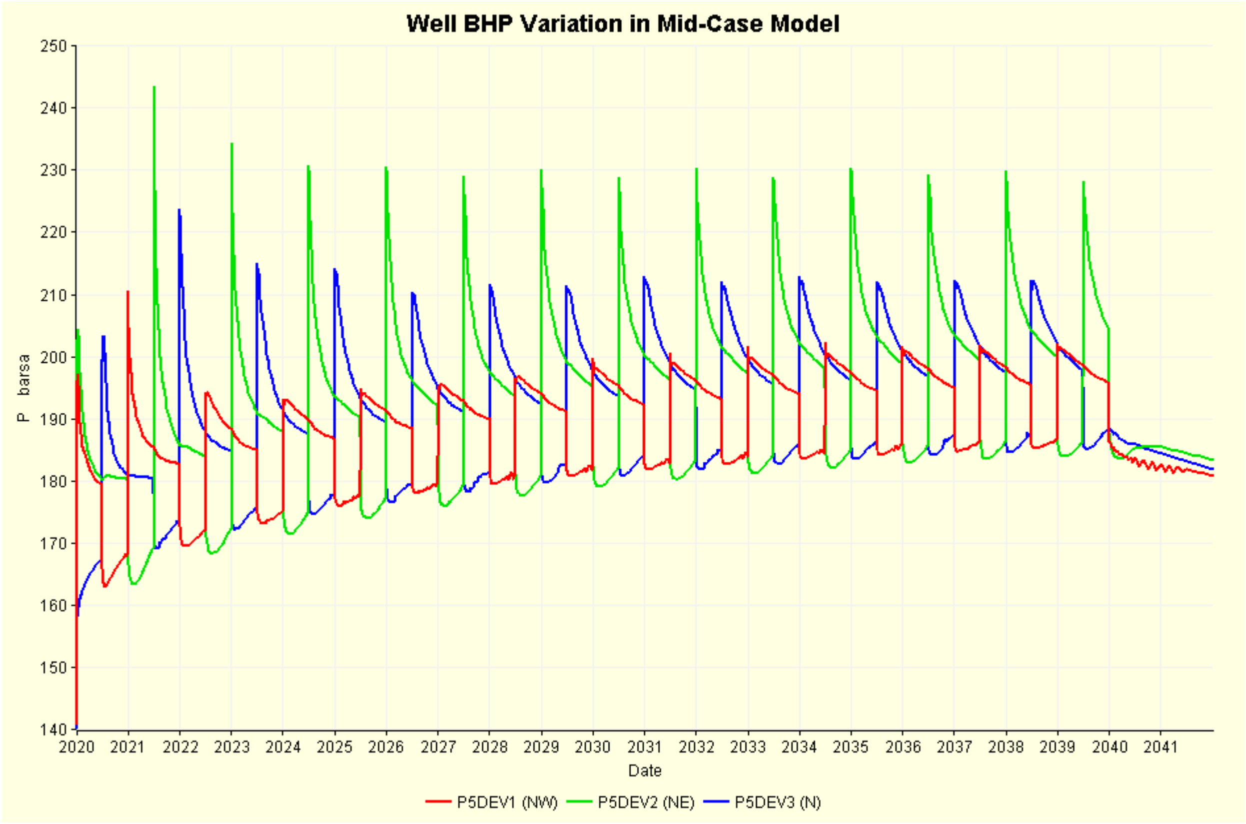
Eventually all the free CO_2 will dissolve. Convection and diffusion will result in a near uniform concentration of dissolved CO_2 in the formation. However, this will take very long timescales (tens of thousands to millions of years, depending upon reservoir geometry, heterogeneity and formation water salinity and circulation characteristics). The dissolved CO_2 could migrate outside the storage site, but the flux would be very small and it would be trapped in the topographic lows in the Bunter sandstone. Therefore it would not leak from the storage complex and would not reach any receptors.

For the EES, it is assumed that losses of dissolved CO_2 from the storage site over the timescales of interest (10,000 years) are negligible.

A.1.3 Reservoir Integrity

During the operational phase, there will be an increase in pressure around the injection well which will propagate away from the well. The Bottom Hole Pressure (BHP) will be highest at the start of an injection cycle, when the gas saturation around the well is low and hence the relative permeability for CO_2 is low (Figure A.3). As gas migrates into the reservoir and the gas saturation increases, the relative permeability for CO_2 will increase and the BHP needed to give the required injection rate will decrease. Once injection stops, there will be a period of shut-in, in which CO_2 migrates away from the well and brine flows back towards the well. There will then be another peak in BHP as injection restarts and brine is displaced from around the well. The different wells show different peaks in BHP with each cycle of injection, dependent on their location relative to the geometry of the reservoir, which affects migration of CO_2 away from the injection wells and inflow of brine during shut-in.

Figure A.3 Modelled BHP Variations for the Three Injection Wells with Injection Cycles



Mini-frac tests in the Bunter sandstone have shown that the fracture closure pressure is ~260bar, so there is a safety margin of ~20bar between the peak BHP and the fracture closure pressure of the Bunter sandstone. Therefore fracturing of the Bunter sandstone should not occur due to the injection pressure. However, the combination of the peak injection pressure and cooling of the reservoir by injection of relatively cold CO_2 may lead to some thermal fracturing immediately adjacent to the wells.

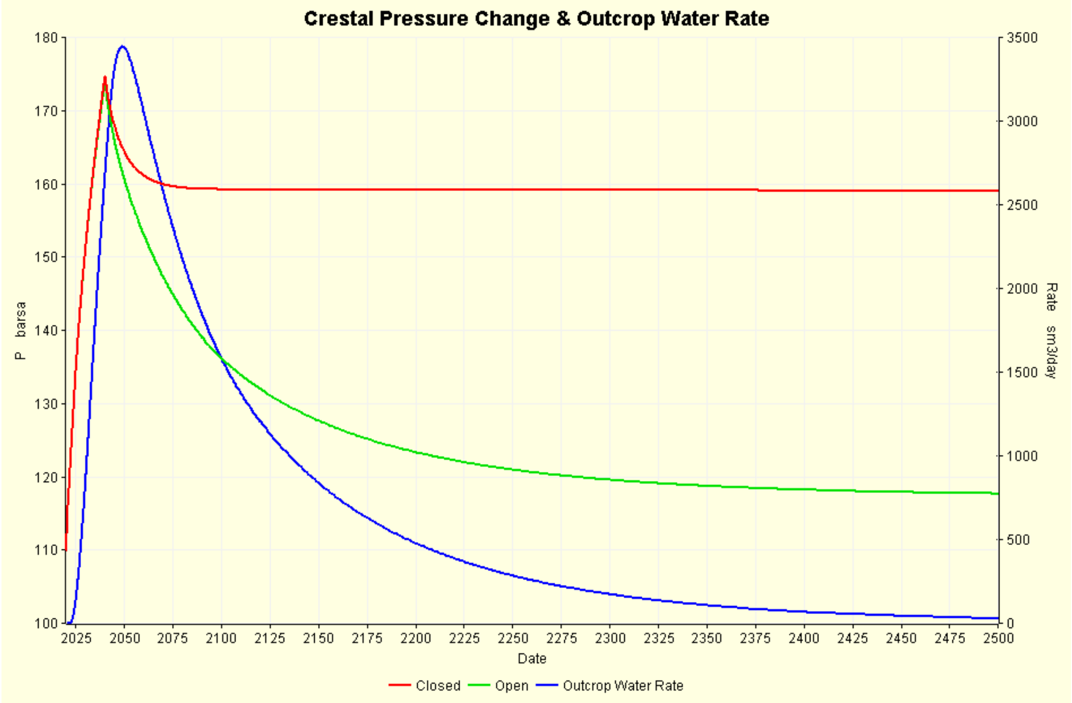
The injection pressure could be higher than predicted if there are presently unrecognised structures in the Bunter sandstone that reduce the permeability close to the well (skin effects), or compartmentalise the reservoir. If the peak injection pressures are higher than predicted due to skin effects, then there could be local pressure fracturing of the rock immediately adjacent to the wells. However, this would not have any significant impacts on the reservoir and would not be significantly different to the local thermal fracturing that is more likely to occur. In addition, local thermal fracturing will tend to overcome any skin effects, thereby reducing the peak BHPs and the likelihood of pressure fracturing. Further away from the injection wells, there is little evidence of any significant structures in the Bunter sandstone, so the injection pressures are expected to be similar to those of the reservoir simulations. Higher pressures will be considered in an AES.

When the CO_2 enters the reservoir, it is cold compared with the reservoir. Estimates of the temperature of the CO_2 at the injection well vary depending on assumptions in the well, but a minimum temperature could be as low as 15°C. As noted above, this is likely to cause some thermal fracturing of the reservoir rock. This is accounted for in the design of the wells, with the CO_2 injection intervals deep enough such that thermal fracturing does not reach the primary seal. There will be progressive cooling of the reservoir, primary seal and deepest secondary seal above the injection wells, but there will not be the rapid temperature changes that will occur immediately adjacent to the injection wells.

Once injection ceases, the pressure in the reservoir will drop (Figure A.4) in the short term post closure phase, as brine migrates out of the structure and the temperature around the injection well returns to the ambient temperature of the reservoir. The likelihood of fracturing the reservoir rock is greatly reduced during the post closure phase.

The final pressure in the reservoir in the long term post closure phase will depend on how large a volume of rock is in hydraulic connection with structure Endurance and also whether there is a hydraulic connection to the seabed at the outcrop. In the EES it is assumed that the reservoir does have a hydraulic connection to the seabed, because there is no evidence for any structures that could prevent this. Reservoir simulations show pressure returning towards pre-injection values when the reservoir is connected to the outcrop (Figure A.4).

Figure A.4 Pressure Change at Endurance Crest when the Outcrop is Closed/Open and Discharge of Water at the Seabed Outcrop



A.1.4 Formation Fluids

During the operational phase, the pressure gradient between the reservoir at the Endurance structure and the Bunter sandstone at the seabed outcrop will evolve from a hydrostatic gradient to a gradient that results in discharge of water at the outcrop. A water outflow rate of 3000m^3/d has been estimated at the outcrop, if it is fully open to Endurance during injection. This value assumes some connectivity to the wider Bunter. If there is no wider connection, the best estimate discharge rate is 3500m^3/d. The plan area of the Bunter seabed outcrop is 5km^2. Approximately 70% of the outcropping Bunter is covered by Quaternary deposits, that may be relatively impermeable and therefore may act to focus discharges through the exposed areas. There is some uncertainty as to the spatial extent, thickness and lithology of the Quaternary deposits. Nevertheless, the discharge area is expected to be sufficiently large that the flow rates and hence fluxes, are expected to be low (Section 4.4).

There are a number of lines of evidence that indicate the salinity in the Bunter sandstone decreases towards the outcrop (Section 4.4). Therefore the salinity of the water that will be discharged may be considerably lower than the salinity of the brine in the Endurance structure and may be more similar to seawater. Scoping calculations described in Section 4.4 of the main report assess the potential salinity of the water that is expected to be discharged and the potential impacts on the seabed and water column. The results of the scoping calculations indicate that the impacts are likely to be small.

A.1.5 Physico-chemical Processes

Relevant physico-chemical processes include:

- drying out during injection leading to halite precipitation, with coupled changes in porosity and permeability;
- reaction of CO_2 with brine and minerals in the reservoir, resulting in mineral precipitation and dissolution, with coupled changes in porosity, permeability and rock strength;
- phase changes in the injection wells; and
- sand generation due to chemical dissolution and physical stresses.

The near well physico-chemical processes and effects are different to those further away from the wells.

A.1.5.1 Near-well Effects

During the operational phase, physico-chemical processes within and near to the wells can potentially reduce injectivity through mineral precipitation and pore blocking, sand generation and well clogging; and could potentially affect the integrity of the well seals. It is anticipated that additional substances will need to be injected into the well and reservoir to remove mineral precipitates and potentially also to protect the integrity of well seals.

In the EES, it is assumed that any necessary substances are added to the CO_2 stream to maintain injectivity at the required rates. It is also assumed that the addition of these substances does not significantly change the physical or chemical properties of the CO_2 within the reservoir.

Salt Precipitation

Close to the injection well, a dry-out zone may develop in which the CO_2 displaces most of the formation water. However, a proportion of the water will remain trapped in the pore space. This immobile water will then evaporate, depositing solid salt into the pore space which could then impede flow. The volume of salt deposited from immobile water is likely to be a small percentage of the pore volume, but if repeated cycles of wetting and drying occur, for example due to periods of no injection at the well, the concentration of salt can build-up to significantly reduce the permeability of the formation.

The development of this dry-out zone depends on the rate of injection and the rates of vertical buoyancy driven migration of CO_2 compared with horizontal migration due to pressure gradients. If CO_2 is injected into a sufficiently high permeability formation at a sufficiently low rate, the CO_2 will migrate vertically and the dry out zone will be small. The rate of brine evaporation and salt precipitation will be low. For a given permeability formation, increasing the injection rate from a low value will cause the dry-out zone to expand and salt to be precipitated more rapidly near the well. As the injection rate continues to increase, the dry-out zone will get larger and the salt precipitation close to the well will be reduced. Thus there is a low, but not very low injection rate at which the reduction of permeability close to the well is greatest, leading to higher bottom hole pressures. This injection rate was found to be 1.2MT/yr which is a plausible rate for injection at a single well.

The rate of halite precipitation is significantly affected by the frequency of well shut-in, which leads to cycles of drying out and re-wetting; this was investigated. Based on these calculations it is expected that water washes will not be more frequent than every six months. However, the 2013 models were built prior to site specific hydraulic properties data being available; and the site specific data indicates that halite precipitation and the associated reduction in injectivity will occur more slowly than calculated.

Recent additional modelling work has identified that during continuous injection capillary suction of brine into the base of the CO_2 plume can also result in significant halite precipitation in this part of the plume.

Based on the evidence available to date, it seems likely that salt precipitation could be an important factor in the permeability near the well. The problems associated with salt precipitation reducing permeability can be mitigated by periodically injecting water (for example filtered seawater) before recommencing CO_2 injection so that any salt precipitated is dissolved out again.

The EES assumes that salt precipitation does occur close to the well, but that the effects are managed by using water washes at an appropriate frequency such that injectivity is maintained.

Hydrate Formation

Hydrate forms at high pressures and low temperatures and the presence of salt reduces hydrate stability. The pressures and temperatures that will occur in the reservoir under normal operation should be outside of the hydrate stability zone, especially given the high salinity of the water in the reservoir. However, at the start of injection following a water wash, there could be considerable cooling of the CO_2 at the wellhead choke due to the Joule-Thompson effect and there will be much less saline water close to the well bore in the reservoir. These two factors could lead to conditions being within the hydrate stability zone. As a solid phase, hydrate would block the pore space, leading to loss of injectivity.

The formation of hydrate can be inhibited by the presence of chemicals such as MEG and methanol, or by injecting N_2 at start-up to increase the pressure in the well bore prior to injection of CO_2 to reduce the amount of Joule-Thompson cooling.

The EES assumes that hydrate formation could occur but that it will be prevented by injection of chemicals such as MEG or methanol and that hydrate formation will not cause any loss of injectivity.

Sand Generation

A combination of factors could potentially lead to damage to the Bunter sandstone adjacent to the injection wells resulting in generation of sand:

- thermal fracturing;
- dissolution of residual halite cements during water washes to remove halite precipitates;
- dissolution of carbonate cements through reaction with CO_2; and
- stress changes associated with cycles of injection.

Sand could potentially enter and clog the injection wells, reducing injectivity. Design of the injection wells is taking this sand generation process into account and if required the sand can be removed through periodic well maintenance. Therefore, for the EES, it is assumed that sand generation does not affect injectivity or significantly impact on the system maintenance/availability.

Phase Changes and Well Seal Integrity

It may be necessary to avoid phase changes in the well because the associated stresses could increase the risk of damage to the well seals. Phase changes could occur at injection start up, including injection restart after temporary well shut-in. In addition to preventing hydrate formation, injection of N_2 at start-up could be used to prevent phase changes. Alternatively, the CO_2 stream could be heated at the well head, or phase changes could be controlled by the well design, potentially including use of a downhole choke.

A.1.5.2 Away From the Wells

As CO_2 migrates away from the injection wells, there will be drying out and potentially precipitation of halite. However, since the cycles of drying and wetting will be less extreme than near to the wells, the rate of halite precipitation will be lower. Capillary suction of brine into the base of the CO_2 plume may result in additional halite precipitation. However, the significance of this process will depend on the capillary properties of the sandstone and may vary spatially within the reservoir. These precipitates may not be removed by water washing.

CO_2 will react with brine forming carbonic acid, which will dissolve carbonate minerals in the reservoir. In turn, carbonate dissolution will result in some anhydrite precipitation. Mineral dissolution is not expected to significantly affect the strength and integrity of the Bunter sandstone, although it could potentially lead to some local physical disruption of the reservoir if there was significant dissolution of the calcarious ooid rich layer at the top of the L2 horizon (Section 4.4). This might reduce any baffle effect provided by the ooid layer.

Although mineral precipitation and dissolution might lead to changes in porosity and permeability away from the wells, the rate at which the physical properties evolve will be much slower than close to the wells. Even if significant pore blocking occurs, the free CO_2 phase would be able to migrate around the blockage, including multiple vertical baffles. Therefore, there are not expected to be any significant impacts on injectivity, or eventual migration of CO_2 to the crest of the anticline.

A.1.6 Primary Seal and Secondary Seals

The primary seal (Röt clay) and deepest secondary seal (Röt halite) will be sufficiently far away from the injection wells that near well pressure and thermal effects during the operational phase do not pose a risk to their integrity.

During the operational, short and long term post closure phases, the Röt clay will be in contact with a free CO_2 phase and will experience an increased pressure due to the trapped CO_2. The hydrostatic pressure plus the over-pressure due to the CO_2 (most likely to be around 40bar although a maximum of 65bar is possible) is likely to be significantly less than the fracture closure pressure of the Röt clay (around 264bar), so the presence of CO_2 is unlikely to cause fracturing in the Röt clay. Further evidence is provided by post-production pressure recovery in the Esmond gas field, where the Röt clay has held back a differential pressure of 110bar (Section 4.4).

There could be some diffusion of CO_2 into the Röt clay through the matrix or through any small scale structures (fractures, sub-seismic faults). The magnitude of this flux of CO_2 is expected to be extremely small. Dolomite pervades the matrix of the Röt clay, so diffusion of dissolved CO_2 into the clay could result in some dissolution, strength loss and mechanical movement/compaction. This is not included in the EES, but is captured by AES. In any case, the Röt halite would creep to accommodate any movements and would not react with the CO_2, so there is not expected to be any increased risk of primary seal failure or leakage. There may be some reaction of CO_2 with laminae and impurities present in the halite, but this is not expected to significantly alter the sealing properties of the halite.

A.1.7 Injection Wells

During the operational phase, injection of CO_2 will be managed to prevent damage to the wells and ensure the long term functioning as per the design. In particular, well operations will likely keep the CO_2 in a single phase in the well and the extent of water and CO_2 mixing in the well will be minimised to minimise corrosion of the well casing. There may be some fracturing of the reservoir rock around the injection well, but in the EES it is assumed that this fracturing does not interact with the well except in the injection zone. This AES considers the impacts of small scale fracturing of the reservoir interacting with the well seals or leakage.

Injection will cease at the start of the short term post closure phase, but the wells may not be plugged and abandoned until the end of this phase so they can be used for monitoring. The abandonment process will include installation of plugs designed to fulfil the long-term sealing requirements. CO_2 will rapidly migrate away from the injection wells, but some will have dissolved in the pore water close to the injection well. Therefore any plugs within the reservoir may encounter acidic conditions, but it is assumed that the materials chosen can withstand acidic conditions.

In the long term post closure phase, the well materials may start to degrade, but there is unlikely to be significant mobile free CO_2 close to the wells that could leak. The types of processes that could lead to degradation of the well seals are further described in Section 4.4. If the wells were to leak, there could be migration of brine up the well to the seabed, while there is an excess pressure in the reservoir (Figure A.4). However, this is not expected to occur in the EES and even if it was to occur, the flux would be small and is not expected to have any significant impacts.

A.1.8 Appraisal Wells

Well 42/25d-3 is located down dip of the likely injection location, so it may never be exposed to free CO_2. During the operational phase, there is likely to be a pressure increase, but this will be within the range that the well has been designed to withstand. As this is a new well, drilled in 2013, there is likely to be little degradation of the well, so that even if some CO_2 migrated to this well, it would be unlikely to leak.

Wells 42/25 1 and 43/21-1 are located on the crest of the anticline, between 2km and 5km south east of the injection well. The CO_2 is expected to travel as far as these appraisal wells during the operational phase. During the short term post closure phase, CO_2 will continue to migrate towards these crestal wells. They will be exposed to the CO_2 throughout the long term post closure phase.

The exposure of the well cement to CO_2 could increase the rate of degradation of the cement in the long term post closure phase. However, as the plugs extend 50 – 70m into the Röt halite and chemical alteration will only be possible from the base of the plug upwards where the plug is through a low permeability formation, degradation sufficient to allow CO_2 leakage would take a very long time. In addition, the Röt halite will creep in response to lithostatic and regional tectonic stresses and will tend to compress, close and seal the unplugged open hole sections of the wells through the Röt halite. These processes are further described in Section 4.4 of the main report. It is therefore assumed in the EES that there will be no leakage from the old appraisal wells.

A.1.9 Regional Pressure Effects

Evidence that the Endurance structure is hydraulically connected to hydrocarbon reservoirs comes from the pressure measured in well 42/25-1 in 1990 being around 0.7bar higher than pressure measured in 2013 in well 42/25d-3 (AGR, 2014i). It has been suggested that the drop in pressure between 1990 and 2013 is due to gas production at Esmond. During the operational phase, the pressure in the Bunter sandstone at the Endurance structure will be elevated due to the injection of CO_2 and this is likely to be of far greater magnitude than pressure changes due to operations in other reservoirs in the southern North Sea. The pressure changes in the Endurance structure may impact on other reservoirs in the Bunter sandstone, but the potential pressure changes at the gas fields due to CO_2 injection at Endurance are negligible compared with the pressure changes due to gas production, or if the depleted fields were subsequently used for CO_2 storage.

In the short term post closure phase, the effects of cessation of injection and ongoing discharge of water from the outcrop will be the main controls on pressure in structure Endurance. In the long term post closure phase, effects from other reservoirs may become relatively larger, although still small, as the pressure in Endurance decreases. The thick, very low permeability Bunter shale and Zechstein halite that underlie the Endurance structure will hydraulically isolate the Endurance structure from pressure changes associated with oil and gas production from the Zechstein, Rotliegend and Carboniferous fields at depth. This includes the immediately adjacent, but significantly deeper, Carboniferous Garrow gas field. The Forbes, Gordon and Caister gas reservoirs in the Bunter sandstone are located slightly further from the Endurance structure than Esmond, so pressure changes associated with gas production, post-production reservoir resaturation/repressurisation and any potential future CO_2 storage activities in these fields, should have similar or slightly smaller impacts to those associated with Esmond. Any changes in pressure would affect the volume of the free CO_2 phase trapped in the Endurance structure and hence the amount of gas that can be stored. However, only a small fraction of the storage capacity of Endurance is being used, so there is no risk that pressure changes could result in the volume of stored CO_2 expanding beyond the spill point, resulting in migration out of the storage site. Reservoir pressure changes could also affect injectivity, however pressure changes of a few bar would not be significant.

A.1.10 Seabed

Pressurisation of the Bunter sandstone in Endurance will cause a small amount of seabed uplift. The pressure distribution in the reservoir will change through the operational, short term post closure and long term post closure phases. The expected amount of uplift due to the ‘bubble’ of CO_2 below the crest of the anticline has been calculated. Assuming a CO_2 overpressure of 40bar, the best estimate uplift is 9cm at the Röt clay level, increasing to 0.15m if very weak faults are present. The uplift would be smaller at the seabed. This uplift would be spread over a significant area, so it would not result in significant tilting. Therefore it is not expected to have any significant impacts for development of the wind farm, or any other structures built on the seabed. Uplift will decrease over time as the pressure in the reservoir decreases (Figure A.4).

A.1.11 Water Column

In the EES, it is assumed there is no leakage of CO_2 from the storage complex, so the water column will not be affected by CO_2. There is expected to be discharge of formation waters that might be of higher salinity than seawater and possibly also higher potentially harmful contaminant content, at the outcrop, but this is likely to be rapidly diluted in the water column and so have no detrimental effect on the chemistry of the seawater above the seabed.

A.1.12 Marine Biota

In the EES, it is assumed there is no leakage of CO_2 from the storage complex; the CO_2 will not impact on marine biota. There is expected to be discharge of formation waters that might be of higher salinity than seawater at the outcrop and this could change the salinity of shallow sediments, affecting marine organisms that dwell in the sediment. Rapid dilution of the discharges in the water column means that there will be no impact on marine biota above the seabed.

A.2 Alternative Evolution Scenario AE1: Reduced Injectivity

Reduced injectivity describes a reduction in the rate at which CO_2 can be injected into the reservoir. Reduced injectivity (Figure A.5) can arise due to:

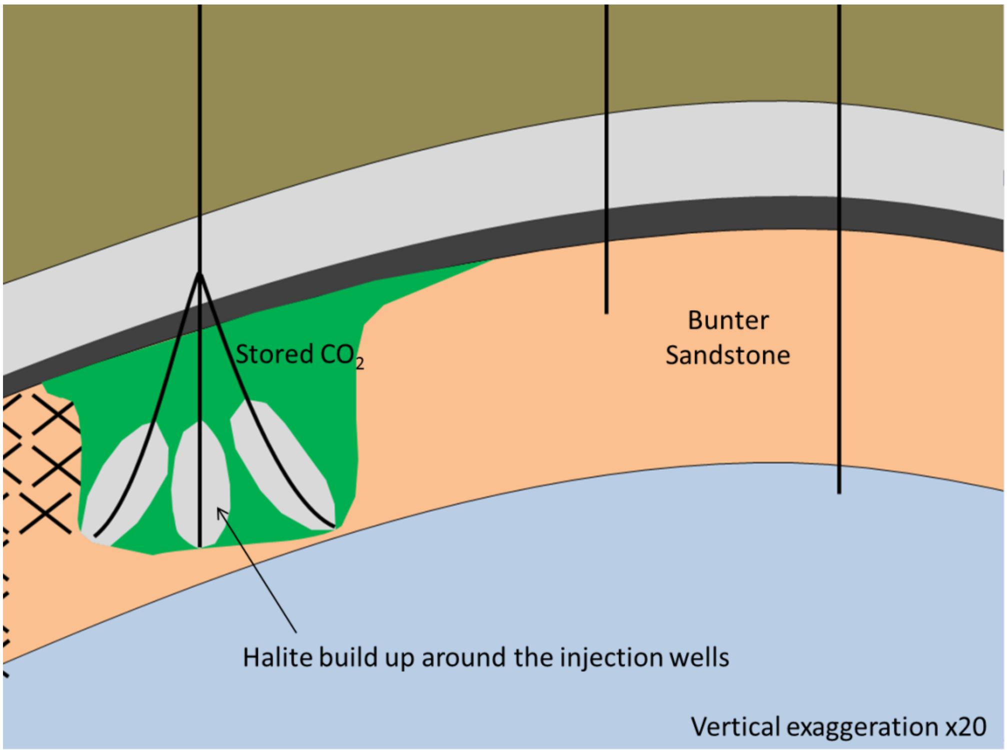
- reservoir compartmentalisation;
- halite precipitation;
- hydrate formation; and
- formation damage resulting in generation of loose sand and clogging of the injection well.

This scenario focuses on geochemical effects that could lead to reduced injectivity. (Reservoir compartmentalisation is considered separately as part of AE2.) Halite precipitation, hydrate formation and formation damage are all being taken into account in the injection system design and operation plan. The risk of reduced injectivity is controlled by a number of factors including the spare ‘capacity’ (redundancy) in the injection system design; optimisation of the design to minimise the need for mitigation actions to retain injectivity; and flexibility in the injection system design to allow for changes in model of operation. Mitigation actions that can be undertaken to recover injectivity are:

- Injection of less saline water (likely seawater) to dissolve halite precipitates;
- Incorporation of MEG or another inhibitor in the above, to prevent hydrate formation; and
- Well work over to remove any sand that has entered it, re-perforate the casing and replace clogged screens.

Figure A.5 Reduced Injectivity Scenario (AE1)

Rock formations surrounding the storage reservoir (Bunter sandstone) only are shown.



The risk of reduced injectivity is also affected by ‘defects and events’ outside the normal mode of operation, for example if:

- the system behaves differently from expectations due to the local properties of the rock at the injection location, for example a given amount of halite precipitation has a bigger impact on rock permeability than expected;
- part of the injection system degrades or fails over time, such that its mode of operation has to be changed; and
- there is a change in the operating regime of the power plant(s), which in turn affects the amount of CO_2 to be injected into the reservoir, including daily variations and shut-down periods.

Defects and events are being taken into consideration as part of the injection system design and optimisation process; and mitigation measures such as those described above are still available to recover injectivity. However, mitigation measures may be required with greater frequency than planned and there remains a residual risk of a permanent loss of injectivity.

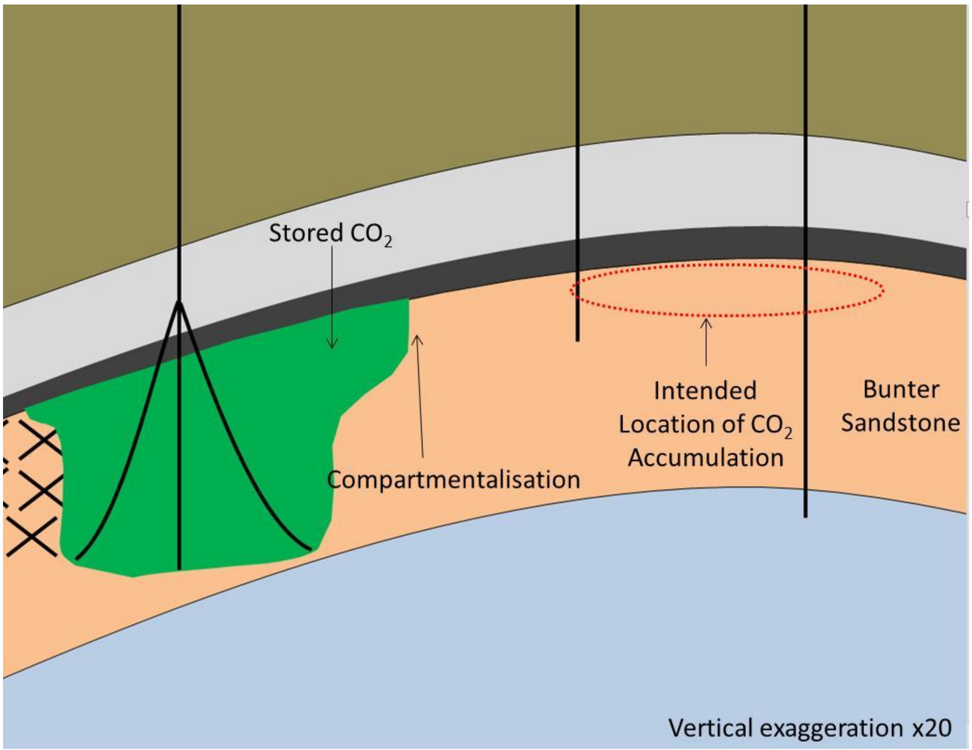
A.3 Alternative Evolution Scenario AE2: Reservoir Pressurisation

Compartmentalisation refers to the presence of low permeability structures in the reservoir, such as mineralised fault/fracture zones, which may significantly limit hydraulic connectivity within the reservoir. Unexpected compartmentalisation could lead to the injected CO_2 migrating away from the injection wells more slowly than expected, or even locally trap CO_2 (Figure A.6). This would lead to higher reservoir pressures around the injection wells, which in turn would reduce injectivity. In extreme cases it could significantly reduce the storage capacity of the reservoir, that is, if different areas of the Bunter sandstone were completely isolated from each other.

There is good evidence that there are no structures in the Bunter sandstone that would lead to compartmentalisation. This evidence comes from the wells that have been drilled into the Endurance structure, core logging and testing, in situ hydraulic tests, seismic data and the regional dataset that describes the extensive lateral continuity and predictability of the properties of the Bunter sandstone across the region. However, there is some residual uncertainty because only a very small volume of the Endurance structure has been subject to intrusive investigation and in-situ testing.

Figure A.6   Reservoir Pressurisation Scenario (AE2)

Rock formations surrounding the storage reservoir (Bunter sandstone) only are shown.



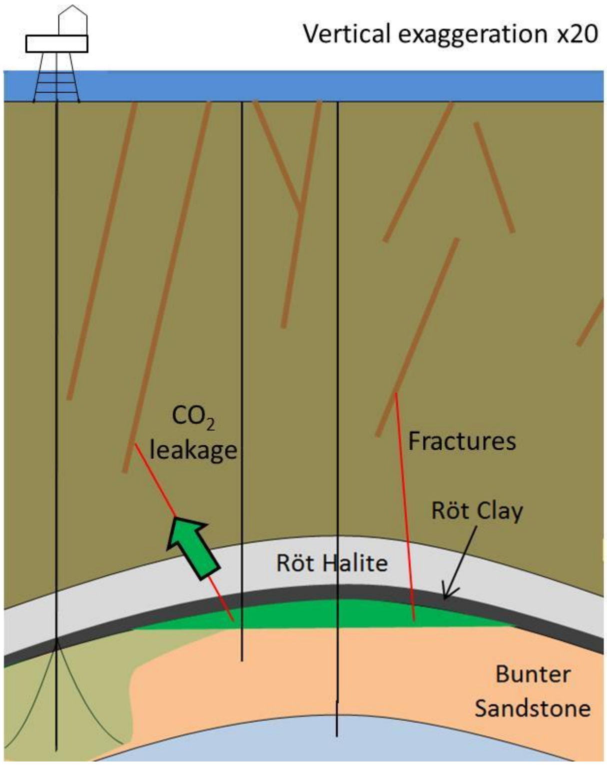
A.4 Alternative Evolution Scenario AE3: Reservoir Leakage through the Primary Seal and Secondary Seals

A.4.1 AE3.a via Faults/Fractures

The presence of faults above the Endurance structure has been interpreted from seismics (Section 4.2). The faults do not penetrate to the Bunter sandstone in the central part of the structure, but some faults penetrate close to the top of the Bunter sandstone on the south eastern flank of the anticline. However, this does not mean that the faults are open and in particular they are likely to be closed in the Röt halite, due to creep of the salt. Other lines of evidence that the faults are likely to be sealed include the lateral continuity and consistency of the Röt clay and Röt halite across the region and these formations form the seal of the southern North Sea gas fields in the Bunter sandstone.

Since the faults seen on the seismics do not extend through the deepest secondary seal and then through the primary seal into the reservoir, this scenario considers the possibility that there are existing sub-seismic fractures through the primary seal. If these fractures connect to a sufficient number of shallower sub-seismic fractures, or to the reservoir to shallower faults that are visible on the seismics (Figure A.7), a pathway for CO_2 leakage could be formed. In order for leakage outside of the storage complex to occur, these fractures must not have been closed by creep of the salt, the fractures are closed but not fully sealed due to the roughness of the fracture surfaces, or these existing fractures must be re-opened.

Figure A.7 Leakage through the Primary Seal and Secondary Seals via Faults/Fractures Scenario (AE3.a)



It is unlikely that the sub-seismic fractures have not been closed by creep of the salt. For example, high overpulls noted when drilling well 42/25-1 through the Röt halite may be indicative of creep. Leakage might occur on closed fractures that are not fully sealed due to the roughness of the fracture surfaces. This might occur in the Röt clay and overburden, but it is less likely to occur in the halite.

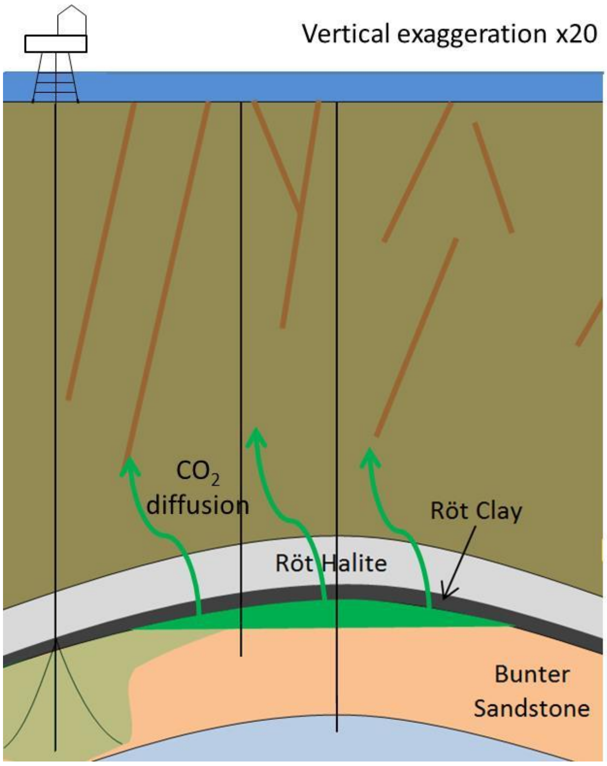
The fracture closure pressure of the Röt clay is higher than the expected peak BHP, so opening of fractures by pressure increase around the wells and throughout the wider reservoir should not be possible. There are unlikely to be weaker areas of rock in which the fracture closure pressure is significantly lower because key controls on the closure pressure are the weight of the overburden and the regional tectonic stress field. This expectation is supported by comparison of the fracture closure pressures in the Bunter sandstone and the Röt clay, which are similar despite their significantly different lithologies. The fracture closure pressure in the Röt halite is also likely to be higher than the peak reservoir pressure for the same reason. This expectation is supported by calculations of the fracture gradient with depth. The calculated fracture gradient is consistent with the results of the mini-frac tests on the Röt clay and Bunter sandstone, so there is confidence in the calculation results for the Röt halite.

It is possible that there could be thermal fracturing of the sandstone around the injection wells. The injection horizons should be located sufficiently far from the Röt clay that there is no risk of fracturing it. Fractures through the Röt clay could potentially occur if the extent of thermal fracturing has been underestimated, however it is exceedingly unlikely that thermal fractures could extend right through the Röt halite. Even if this was to occur, the reservoir gas pressure and hence the gas pressure in the fracture, would not be sufficient to hold the fracture open in the halite.

Overall, it is very unlikely that there is a pre-existing sub-seismic fracture CO_2 leakage pathway, or that existing fractures could be widened by CO_2 injection and thereby become leakage pathways. However, there is residual uncertainty due to the limit of resolution of seismic data.

A.4.2 AE3.b Diffuse Leakage

Figure A.8 Leakage through the Primary Seal and Secondary Seals by Diffusion Scenario (AE3.b)



There are two possible mechanisms for diffuse leakage. The first is diffusion of CO_2 dissolved in brine (Figure A.8) and the second is the diffused release of CO_2.

Rates of diffusion of dissolved CO_2 through the primary seal and secondary seals are expected to be very low due to the nature of the lithologies, as supported by the documented function of these formations as seals for the Bunter sandstone gas fields in the southern North Sea. Rates of diffusion might be increased if unconnected micro-fracturing is present, but would still be low. The highest potential flux would be associated with increased diffusion through micro-fractures into the larger faults that are visible on the seismics, if the larger faults are open. However, as described for AE3.a, this is unlikely to be the case.

Free CO_2 would also be able to enter micro-fractures and thereby migrate over an area as wide as the area of micro-fracturing. Such migration could be considered diffuse. Where the micro-fractures connect to form a continuous pathway to the seabed or an open fault, the initially diffuse migrating CO_2 would become progressively focused, so that any CO_2 emissions at the seabed would tend to be at a number of localised points across a wider area. Alternatively diffusion could be increased through a combination of movement of a free CO_2 phase through micro-fractures, dissolution and diffusion through the rock into another micro-fracture.

Residual uncertainty remains because there is only limited spatial data on the properties of the rocks and micro-fractures cannot be detected by seismics.

A.5 Alternative Evolution Scenario AE4: Increased Displacement of High Salinity Formation Waters

This scenario considers that the amount of formation water discharged to the seabed is greater than expected (AE4.a) or the salinity is higher than expected (AE4.b). Discharge to the seabed may occur via fractures (Figure A.9) or at outcrop (Figure A.10), although discharge via fractures is unlikely, see AE3.a. A brine outflow rate of up to $3000m^3$/day has been estimated at the outcrop, if it is fully open to Endurance during phase 1 development. This compares with a maximum CO_2 injection rate of 2.68MT/yr, at a density of 700 kg/m^3, which equates to $10,400m^3/d$. The rate of discharge from the reservoir is less than the rate of injection due to the compressibility of the rock matrix, which provides storage. If the compressibility is lower than expected, the rate of discharge will be greater, but it cannot be greater by more than a factor of approximately two. If the outcrop is fully open to Endurance, then the total volume of water discharged will be the same as the total volume of CO_2 injected. The compressibility only affects the time period of release and hence the flux of saline water.

The salinity of the water in the Bunter sandstone between the seabed and the reservoir horizon is uncertain. It is anticipated that the salinity will increase with depth and distance from the outcrop, reflecting: diffusive exchange between the seabed and outcrop; potential intrusion of glacial melt water; and thermohaline processes that are thought to have led to loss of halite cement from the Bunter in Endurance and between Endurance and outcrop (Section 5). The pressure in the reservoir indicates that there is a salinity gradient between the seabed and the reservoir and the average density is half-way between seawater and the brine in Endurance (Section 5). However, it is unlikely that the density (and hence salinity) gradient is linear and there is no definitive data regarding the salinity of the water immediately below the outcrop, which is the water that would be discharged. The actual salinity and water composition beneath the outcrop could be verified with a shallow borehole at the outcrop, if the remaining uncertainties are deemed to be unacceptable.

Discharge of brine to the seabed via fractures above the Endurance structure containing the CO_2 is unlikely to occur, because open fracture pathways are not expected (see AE3.a). However, if this was to occur the water would likely be much more saline than the water that would be discharged at outcrop because it would be sourced from deeper in the Bunter sandstone. In the worst case the salinity would be the same as in Endurance.

Figure A.9 Increased Displacement of High Salinity Formation Waters via Fractures Scenario (AE4)

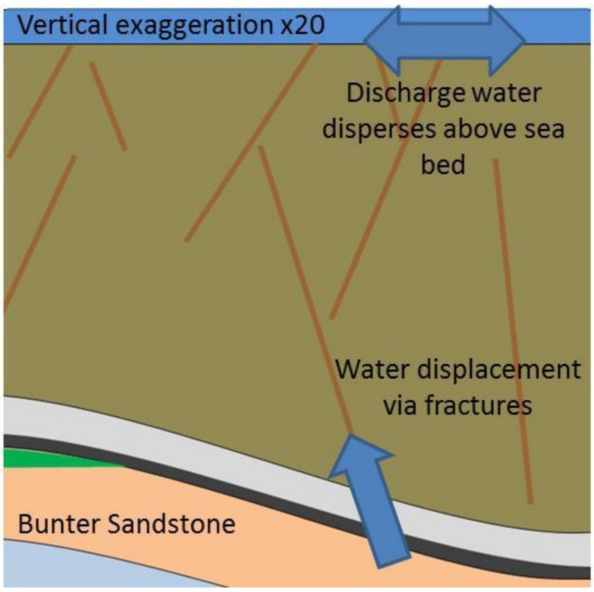
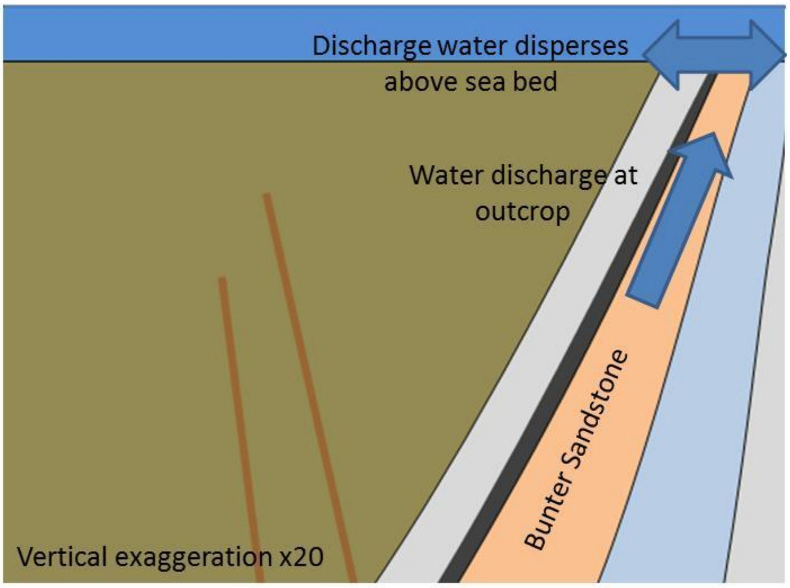


Figure A.10 Increased Displacement of High Salinity Formation Waters via Outcrop (AE4)



Discharge of saline water could potentially lead to an increase in the salinity of pore waters in the seabed sediments. If the discharges are sufficiently saline, concentrated and prolonged, this might affect biodiversity and also biological productivity, of benthic organisms. However the saline discharges would rapidly mix with seawater and be diluted. Therefore there are not expected to be any direct impacts on pelagic or nectonic fauna. Impacts on seabed dwelling organisms also need to be appropriately considered.

A.6 Alternative Evolution Scenario AE5: Well Failure

A.6.1 AE5.a Injection Wells

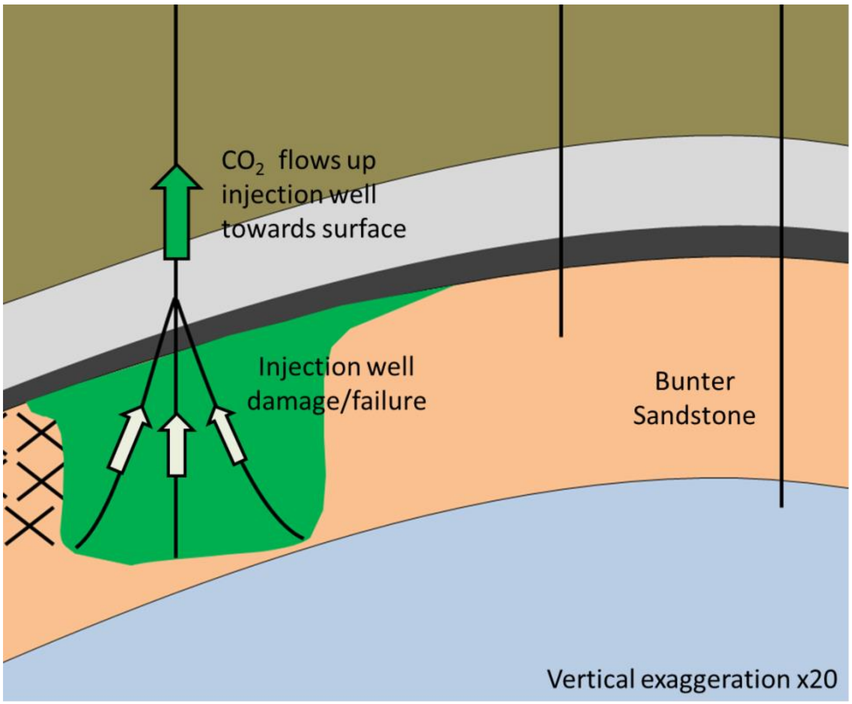
This scenario assumes that one of the injection wells will suffer early well seal failure, or significant accidental damage to the seabed exposure of the abandoned well, for example, as a result of trawling activities post-abandonment (Figure A.11). Three variants are explored:

- failure/ damage during injection (AE5.a.1);
- failure/damage on injection cessation (AE5.a.2); and
- failure/damage a few hundred years after injection cessation (AE5.a.3).

The risk assessment is concerned with post-closure leakage from the injection wells. Therefore, in the context of variant AE5.a.1, it is operational activities that might affect the sealing and abandonment of the wells and their post-closure integrity that are relevant. Specific abandonment plans are being developed for the injection wells to provide the required long-term sealing and containment of CO_2. For example these include use of CO_2 resistant cement formulations and the possible removal of sections of the casing and surrounding cement by milling to ensure seals are in direct contact with the rock. Operational issues that might affect the integrity of the wells and the success of sealing include:

- stresses on the wells due to daily changes in the CO_2 flux as the power station output is changed and when the wells and/or power station are shut down for maintenance;
- if fluid phase changes were to occur in the wells;
- fracturing of borehole cements by induced seismicity and thermal fracturing associated with injection; and
- casing corrosion due to water washing and the resultant CO_2 – water mix in the wells.

Figure A.11 Well Failure: Injection Wells Scenario (AE5.a) (Lower Part of Injection Well only Shown)



If abandonment sealing of the wells was not successful, leakage of free CO_2 could only occur during the early post-closure period (AE5.a.2) when there is free CO_2 around the wells. Once the majority of CO_2 has migrated to the top of the reservoir, significant leakage will not be possible (AE5.a.3). However, leakage of free CO_2 could be followed by longer term leakage of brine up the wells until the reservoir pressure returns to equilibrium. This brine could include a small amount of dissolved CO_2.

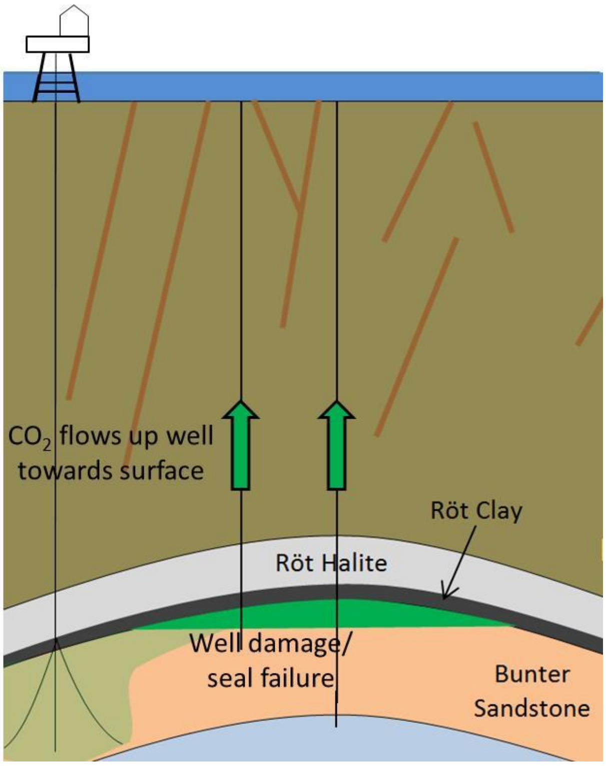
A.6.2 AE5.b Other Wells

This scenario considers leakage from one of the other wells and in particular the two abandoned crestal wells (42/25-1 and 43/21-1) (Figure A.12). It also includes leakage from NGCL's abandoned appraisal well located on the flanks of Endurance (42/25d-3). However leakage from this well is much less likely since it is down-dip of the most likely injection location and therefore may never be exposed to free CO_2. Three variants are explored:

- failure during injection (AE5.b.1);
- failure on injection cessation (AE5.b.2); and
- failure a few hundred years after injection cessation (AE5.b.3).

Although the crestal wells have been abandoned using multiple plugs, their abandonment was not optimised for long-term CO_2 storage and they will be permanently exposed to the free CO_2 trapped at the crest of the anticline. Therefore there is a greater risk of leakage from these wells than from 42/25d-3 or the injection wells, although the risk may still be low. The processes and sequence of events that could lead to leakage from these wells have been considered explicitly and are described in Section 4.4.

Figure A.12 Well Failure: Other Wells Scenario (AE5.b)



A.7 Alternative Evolution Scenario AE6: Lateral Interaction with Other Hydrocarbon Reserves

This scenario is not credible for the reasons discussed in Section 4.3.10.7 and is not considered further.

A.8 Alternative Evolution Scenario AE7: Resource Exploitation Elsewhere Affects System

In this scenario, resource exploitation elsewhere affects the storage site. Other than deliberate intrusion into the storage site to access any hydrocarbon reserves at greater depth than the Bunter sandstone (see AE9), the only viable interactions are associated with extraction of gas from the southern North Sea reservoirs in the Bunter sandstone. Evidence that the Endurance structure is hydraulically connected to these hydrocarbon reservoirs comes from pressure measured in well 42/25-1 in 1990 being around 0.7bar higher than pressure measured in 2013 in well 42/25d-3. It has been suggested that the drop in pressure between 1990 and 2013 is due to gas production at Esmond (Section 4.3.10.8).

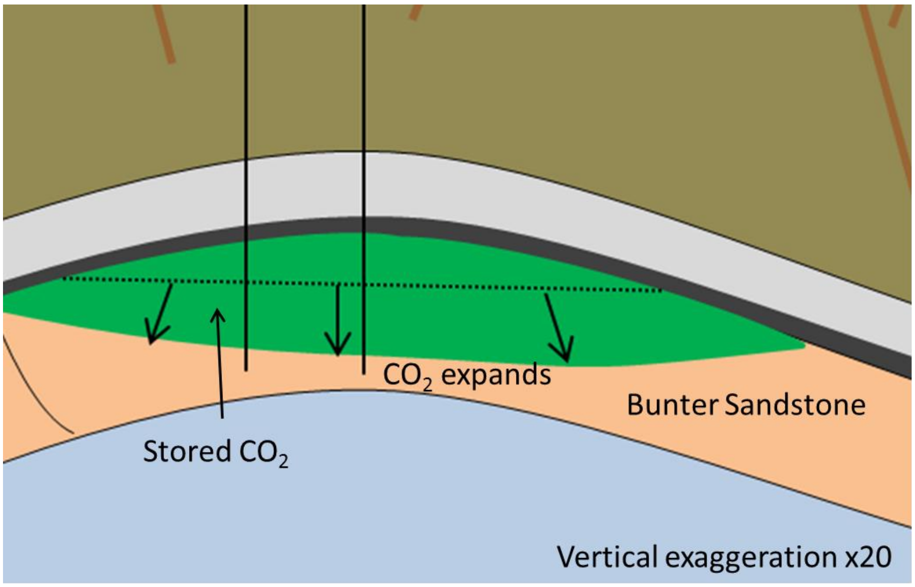
Such a drop in pressure would increase the volume of the gas stored in Endurance (Figure A.13). If the pressure drop was sufficient it could result in the volume of gas expanding beyond the spill point and hence migration out of the storage complex. However, this is very unlikely for phase 1.

The gas fields in the Bunter sandstone are a similar or greater distance from Endurance than Esmond, so the pressure impacts on Endurance would be similar to those already observed. For phase 1 only a small fraction of the reservoir capacity will be used and this factor combined with the small changes that could be caused by a drop in pressure means that the risk that resource exploitation elsewhere could result in the free CO_2 phase expanding and migrating beyond the spill point is extremely small.

Reservoir pressure changes could also affect injectivity, however pressure changes of a few bar would not be significant.

Figure A.13 Resource Exploitation Elsewhere Affects CO_2 Storage System Scenario (AE7)

Rock formations around stored co_2 plume only shown.



A.9 Alternative Evolution Scenario AE8: Increased Seabed Uplift/Tilting

The pressure increase in the reservoir and buoyancy of CO_2 will result in uplift of the seabed (Figure A.14). The extent of uplift will depend on the pressure increase and the geomechanical properties of the rocks. Uplift could be greater than expected due to:

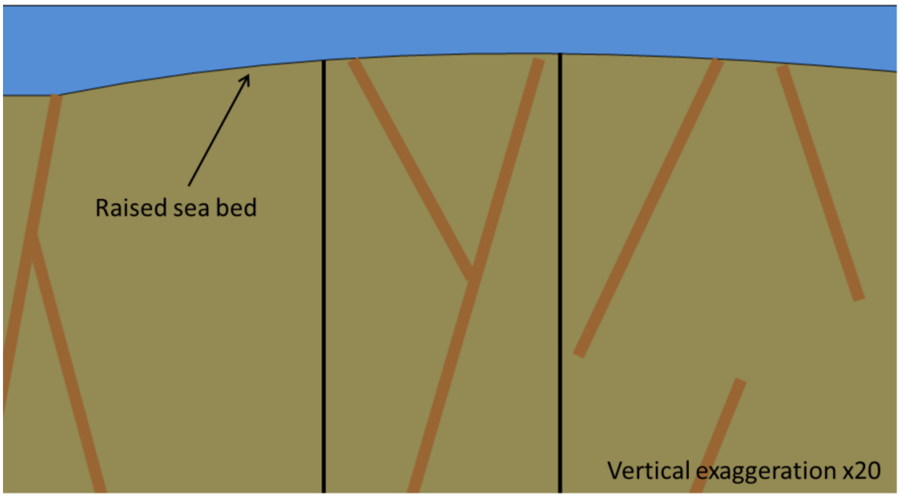
- Greater than expected reservoir pressurisation;
- Uncertainty in the geomechanical properties of the rocks, including due to natural variability;
- Movement on existing fractures, which might result in differential uplift and localised areas of greater than average uplift.

The highest pressures will occur during the operational phase, immediately adjacent to the injection wells. These high pressures will be localised and will increase and decrease in response to cycles of injection and well shut-in (Figure A.3). Because the pressure increase is localised, it is likely to have a smaller impact on the seabed than the pressure increase in the crest of the anticline, which will be over a wider area. The peak pressure at the crest will approximately coincide with the start of the short term post closure phase (Figure A.4). Based on a best estimate crestal pressure increase of 40bar, it was calculated that the amount of uplift could be 9cm at the Röt clay level, but would be less at the seabed. The calculations are cautious because they ignore dissolution and therefore will tend to slightly overestimate the pressure increase. This uplift would be spread over a significant area, so it would not result in significant tilting. Therefore it is not expected to have any significant impacts for development of the wind farm, or any other structures built on the seabed. In the long term post closure phase, uplift will decrease over time as the pressure in the reservoir decreases (Figure A.4).

Uplift could be greater if there was movement on fractures. However, this is unlikely because the peak crestal pressures will be far below the fracture closure pressures of the Röt clay and Röt halite (AE3.a). If there is no movement on existing (closed) fractures in the Röt clay and Röt halite, then there will be no movement in the overlying formations. A worse case in which very weak fractures are present was investigated, uplift at the Röt clay only increased to 0.15m, a small impact on the seabed.

Figure A.14 Seabed Uplift/Tilting Scenario (AE8)

Region of the seabed only shown.



The best estimate crestal pressure increase is 40bar and the maximum is 65bar. This would result in greater uplift and would slightly increase the potential for movement on fractures. But, even if the peak crestal pressure was 65bar, uplift at the seabed would still be small and spread over a wide area.

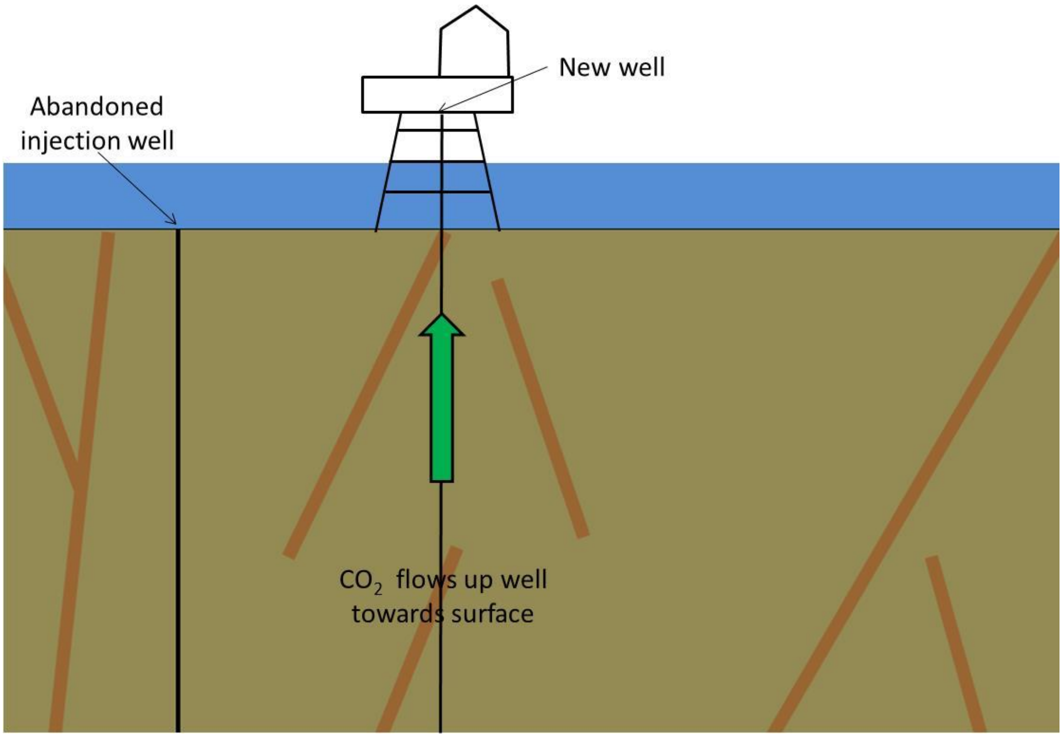
A.10 Alternative Evolution Scenario AE9: Human Intrusion

This scenario assumes there is inadvertent human intrusion into the storage site at some time in the distant future when all records of the site have been lost. It does not include deliberate intrusion into the storage site (Figure A.15). The only viable mechanism for intrusion is by drilling a well into the storage site. It is assumed that the well intercepts the free CO_2 trapped at the top of the anticline. This could result in release of CO_2 gas to the atmosphere if preventative drilling practices are not adopted, or if there is some failure in equipment or operational procedures designed to prevent CO_2 leakage. The magnitude of any such release would depend on the drilling practices including whether blow out preventers were being used. Release to atmosphere would not result in any significant environmental impacts.

At some stage the intruding well would be abandoned. It is most likely that the activities of future intruders would be regulated. Therefore they would be required to properly seal the well during abandonment. If they have the technology to drill into the storage site, they would likely have the technology to successfully seal the well. However, there is a risk that the abandonment design or quality may be poor, leading to long-term leakage. The impacts would be as described for AE5.b.

Figure A.15 Human Intrusion Scenario (AE9)

Sea and geosphere immediately below the seabed only shown.

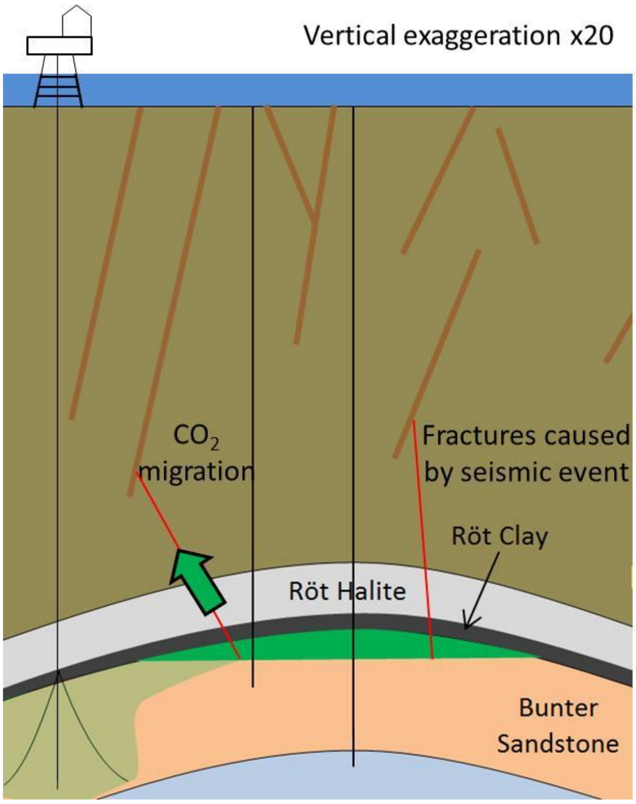


A.11 Alternative Evolution Scenario AE10: Leakage as a Result of Seismic Events

A.11.1 Overview of Leakage as a Result of Seismic Events

The Leakage as a Result of Seismic Events Scenario (AE10) explores the leakage of CO_2 via faults or fractures that are either created or opened by seismicity, whether induced or natural. These situations are illustrated schematically in Figure A.16.

Figure A.16 Leakage as Result of Seismic Events Scenario (AE10)



A.11.2 AE10.a Induced Seismicity

Pressure changes associated with injection and/or ‘lubrication’ of faults by migrating CO_2, could induce seismicity, potentially affecting the primary seal (AE10.a.1) and well seals (AE10.a.2). As described for AE3.a, pressure changes are unlikely to induce seismicity because the maximum CO_2 injection pressure is less than the measured fracture closure pressures.

It is possible that there could be thermal fracturing of the sandstone around the injection wells. The combined stresses due to pressure and temperature changes could increase the potential for induced seismicity. Seismicity could be induced during both injection and post-injection as the pressures and temperatures recover. This includes during periods of well shut-in for power plant/well maintenance. If the combined temperature and pressure changes were sufficient to induce seismicity, the potential impacts can be assessed with reference to other AES. Fracturing of the Röt clay and Röt halite is discussed under AE3.a, while damage to the injection wells including the abandonment seals is discussed under AE5.a.

A.11.3 AE10.b Natural Seismic Events

Natural seismic events could potentially result in fracture generation or movement/re-opening. This could lead to a fracture pathway as discussed under AE3.a. However, the southern North Sea is a tectonically stable area so this is unlikely. Gas fields in the Bunter sandstone in the southern North Sea have retained their integrity for geological timescales (many millions of years), even though they have likely been subjected to greater seismic events in the past than are expected to occur in the future period of interest, for example seismic events associated with Quaternary glacial loading and retreat.

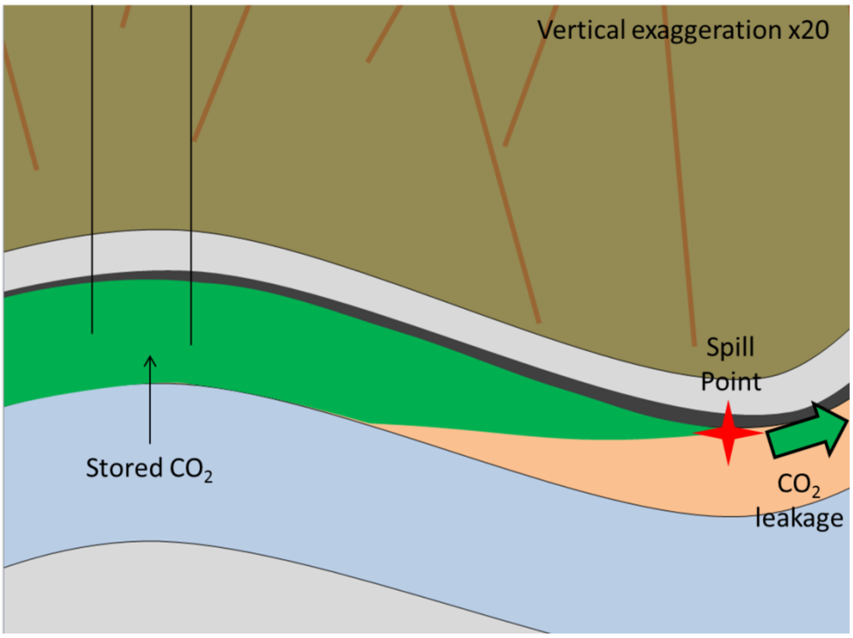
A.12 Alternative Evolution Scenario AE11: Sabotage

Sabotage of the pipeline and injection platform during operations is outside the scope of the risk assessment. However, deliberate damage of the existing abandoned wells on the sea floor during operations or post-closure and deliberate damage of the abandoned injection wells post-closure, is considered. Sabotage is very unlikely due to the difficulty in locating and accessing the abandoned wells. Even worst case damage to the tops of the abandoned wells would not result in leakage due to the presence of multiple plugs and seals at depth. It might lead to accelerated ageing of the wells from the sea floor downwards. This could occur due to reduced isolation of the well components and plugs/seals from seawater and associated solutes; such as dissolved oxygen and sulphate. Ageing of the wells from the sea floor downwards is discussed as part of AE5.b. It is unlikely to lead to release of CO_2.

A.13 Alternative Evolution Scenario AE12: Accidental Over-filling

This scenario assumes that sufficient CO_2 is injected that the gas migrates beyond the spill point in the structural trap (Figure A.17). This is possible because the location and depth of the spill point is estimated from seismic data. Therefore it is uncertain because it is derived from an interpretation of the seismic two-way travel time. Overfilling is not plausible for phase 1, because the total volume of CO_2 to be stored is very small compared with the size of the Endurance structure. This is true even if there are any regional pressure changes (AE7) and accounting for uncertainties in the porosity of the rock.

Figure A.17 Accidental Overfilling Scenario (AE12)



Appendix B Application of Evidence Support Logic

B.1 Overview of Evidence Support Logic

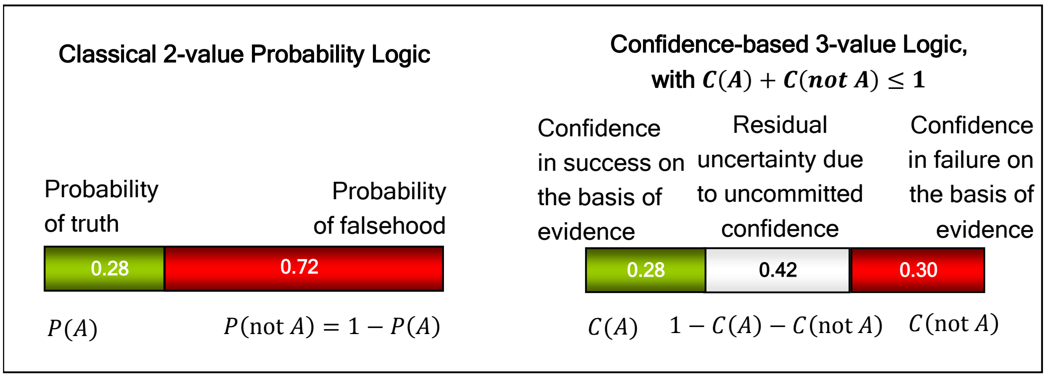
Evidence Support Logic (ESL) involves systematically breaking down a hypothesis under consideration into a logical hypothesis model, the elements of which expose basic judgments and opinions about the quality of evidence associated with a particular interpretation or proposition. A tree structure (henceforth termed a ‘decision tree’ or simply a ‘tree’) is constructed that connects some key hypothesis of interest (for example, ‘The CO_2 volume planned to be stored will be completely and permanently contained’) to supporting hypotheses that can be tested as easily as possible using direct observations of relevant phenomena or model outputs (for example ‘Predictions of post-closure behaviour of the storage complex predict evolution towards long-term stability for any plausible boundary conditions’). In practice, intermediate hypotheses will usually occur within the tree, between these readily testable hypotheses and the top-level hypothesis of interest.

Numerical representations of confidence for and against the truth of each hypothesis at the lowest level of the tree are input by users. These representations of confidence are then combined and propagated through the tree to the top-level hypothesis. The propagation is controlled by numerical sufficiencies (effectively weights) and logical operators that are specified when the tree is constructed. Once a tree is constructed, it may be used to identify what hypotheses are most significant for decision making at any particular stage of a project. This identification can then be used to prioritise subsequent information gathering and analysis activities. Furthermore, the tree provides a record of the developing decision making process throughout a project.

A key feature of ESL is its basis on ‘three value’ logic, in contrast to classical probability theory, which follows 'two value' logic (Figure B.1). In this latter case evidence must either be in favour of a hypothesis, or against it. This approach is sometimes described as a ‘closed world’ perspective, in which evidence ‘for’ and evidence ‘against’ are treated as complementary concepts. However, ESL additionally allows for a measure of uncertainty as well, recognising that belief in a proposition may be only partial and that some level of belief concerning the meaning of the evidence may be assigned to an uncommitted state. Uncertainties are handled as ‘intervals’ that enable the admission of a general level of uncertainty providing recognition that information may be incomplete and possibly inconsistent:

Judgment on evidence for + judgment on evidence against + uncertainty due to overconfidence or uncommitted belief = 1

Figure B.1 Classical Two Value Probability Analysis Compared with Three Value Logic



The ESL approach has been implemented within TESLA software, which provides:

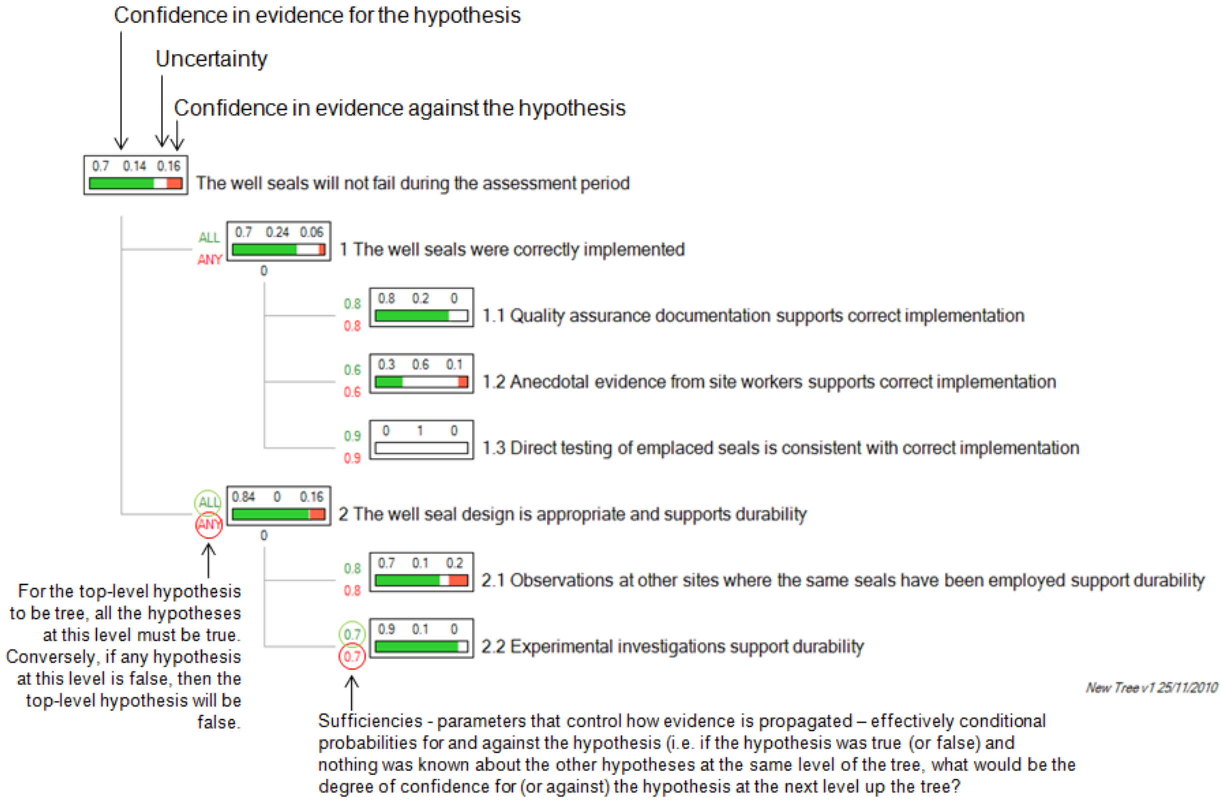
- an interface for constructing and displaying a tree;
- functionality to embed supporting explanations, documents; and web page links within the tree; and
- tools to analyse a tree.

An example of a decision tree, as implemented in TESLA is illustrated in Figure B.2.

TESLA enables users to embed supporting information within a hypothesis model, thereby producing an audit trail for the overall decision. This information can include, inter alia, text, reports (for example pdf files), spreadsheets and links to web pages. A variety of tools are also provided to plot the judgments and outputs in various ways.

Figure B.2 Example Decision Tree

Illustrating how degrees of confidence in hypotheses that closely relate to information or data (at the extreme right) are propagated to determine the degree of confidence in some hypothesis of interest (at top left). An actual tree would typically be considerably larger than this example.



For the top-level hypothesis to be tree, all the hypotheses at this level must be true. Conversely, if any hypothesis at this level is false, then the top-level hypothesis will be false.

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Sufficiencies - parameters that control how evidence is propagated – effectively conditional probabilities for and against the hypothesis (i.e. if the hypothesis was true (or false) and nothing was known about the other hypotheses at the same level of the tree, what would be the degree of confidence for (or against) the hypothesis at the next level up the tree?

B.2 Overview of Decision Trees

The integration work undertaken for the project has focused on the development of the structure and parameterisation of three decision trees that cover the main arguments at the heart of the risk assessment. These trees cover:

1. Containment of CO_2:
   this first tree aims to assess the level of confidence on the basis of available evidence that 'The CO_2 volume planned to be stored will be completely and permanently contained' utilising the wording required by 2009/31/EC CCS Directive. This tree uses a structure that represents the requirements of the Directive, then linking to project-specific evidence sources. The structure is based upon a generic tree developed during the EC CO_2ReMoVe project (http://www.co2remove.eu/) with a few additional bespoke elements to provide more detailed coverage of specific scenarios of interest for the current project. While the primary focus is on containment, consistent with 2009/31/EC CCS Directive risks to human health and the environment are also assessed associated with potential low likelihood leakage scenarios;
2. Displacement of formation fluids:
   this tree complements the 'containment' tree by examining the evidence for the potential displacement of formation fluids (including potential higher salinity waters) and the potential for impacts on receptors
3. Physical effects (seabed deformation); and
   This tree further complements the above trees by structuring arguments associated with the potential for seabed deformation (for example uplift) that may arise due to CO_2 storage, including assessing the potential impacts on other structures on the seabed.

In each case, the outcomes suggest there is substantial confidence in performance for each of these aspects. There is some remaining uncertainty (that may in part be an indication of risk) associated with some of the trees, especially that for containment, but it is anticipated that the outcomes of the current ongoing modelling work (detailed and scoping models) will reduce at least some of this uncertainty.

Sections B.3, B.4 and B.5 give more details of the decision trees summarised in Sections 4.5.2.3 to 4.5.2.5 of the main report. These trees present the outcomes of the assessment, including sources of confidence and areas of remaining uncertainty. Full details are recorded within the tree files themselves and can be viewed either using the TESLA tool or via reports generated by the TESLA tool.

Note that for the containment tree, as this is complex and the original template version was developed for generic application to any CCS site, its 'tree structure' documentation (as recorded in the TESLA tree) contains a lot of generic information that is of secondary importance in understanding the current outcomes. For each of the trees, it is suggested the reader should focus first on the 'hypothesis details' and 'general notes' (confidence) entries that capture the important rationale for the project specific aspects of the risk assessment.

Note on the approach to identifying tree structure, logic and parameters and evidence evaluation.

It is important that the structure of a decision tree and the associated logical operators and parameters (the 'weights' or 'sufficiencies') that together govern confidence propagation through the tree, are appropriate and robust. To build confidence it is important that the tree is generated through an appropriate process involving expert review and that the rationale behind the logical structure is clearly recorded. Similarly, the rationale for the expert evaluation of evidence resulting in confidence values for and against leaf hypotheses needs to be undertaken through an appropriate process, the outcomes of which are clearly recorded.

The rationale for the structure of the trees developed for this study, including the reasoning for the use of logical operators, parameters and confidence values are all recorded in detail in the relevant trees; and the outcomes are summarised in Sections B.3, B.4 and B.5. Key elements of the process used to generate them are summarised below.

Tree structure and associated logic and parameters

For the containment tree, it is relevant to note that the tree structure had a long history of development and testing even before use for the current project. The original version was created for the EC project CO_2ReMoVe. In this project, the tree structure was developed through a number of expert workshops involving a wide range of experts from research institutions and industrial organisations from across the EC, combined with testing and update in between workshops. The structure was specified so as reflect the requirements of 2009/31/EC CCS Directive. The tree was tested by application to two demonstration CO_2 storage projects considered by CO_2ReMoVe. The result was a mature tree structure benefiting from significant expert input and review. For the current project, the CO_2ReMoVe tree structure was reviewed and subject to further minor modifications (mainly expansion of existing hypotheses to add additional detail of particular relevance) as required by the context of the current assessment. This was undertaken in an iterative process involving update and review within Quintessa; and then presentation of the draft tree experts, with related iterations of update, review and testing.

The displacement of formation fluids and physical effects trees do not share the same history of EC project development, but are much simpler trees. Nevertheless the process used to create them was robust. As for the modifications to the containment tree for the current project, an iterative process of tree design, parameterisation and review involving experts both within Quintessa and then within the wider team, coupled with testing of the outcomes using TESLA functionality, was utilised to ensure the trees are appropriate and the rationale for their structure robust.

Evaluation of evidence to obtain confidence values

A similar approach was utilised to evaluate confidence for and against leaf hypotheses on the basis of evidence. For each leaf node, experts considered the available evidence against hypothesis definitions and success and failure criteria. The confidence values were elicited in workshops involving a small number of Quintessa experts; and were then reviewed iteratively within Quintessa and then within the wider team by a further set of appropriate experts. These iterations of review and update serve to provide confidence in the final outcomes.

B.3 Containment Tree

Figure B.3, Figure B.4, Figure B.5 and Figure B.6 below (‘tree plots’ in ESL terminology) summarise the outcomes for the containment tree. Here, confidence for safe containment (green space) dominates at the top level. This reflects the multiple lines of reasoning that:

- the storage reservoir will have sufficient capacity to take the volume of CO_2 planned to be stored; and that chemical and physical effects will not prevent that capacity being accessed at the required rate;
- there is strong evidence that the Storage Site will evolve towards long-term stability and that the expected evolution will be consistent with ensuring containment; and
- there are no ‘what if’ scenarios that could plausibly challenge containment or lead to significant impacts to receptors.

There is a small amount of red space (effectively, representing risk) related primarily to the small possibility that chemical effects could challenge injectivity beyond current expectations. There is also some ‘white space' or residual uncertainty, indicative of missing information that may at least in part turn green (resolve into confidence for performance) once remaining models and performance data become available.

Note that the confidence entries for the lines of reasoning associated with Hypothesis 2 are blank. This is because the generic tree was identified to be used both before and during/after CO_2 injection. The elements assessed by Hypothesis 2 and children correspond to 2009/31/EC CCS Directive requirements post-injection. They have been retained here for consistency with the original published generic tree but evidence values are necessarily absent. The plots presented do not show the child hypotheses that support Hypothesis 2 for that reason.

There are several hypotheses which are associated with notable amounts of confidence against performance, but which do not have an overall influence on the outcomes. These include:

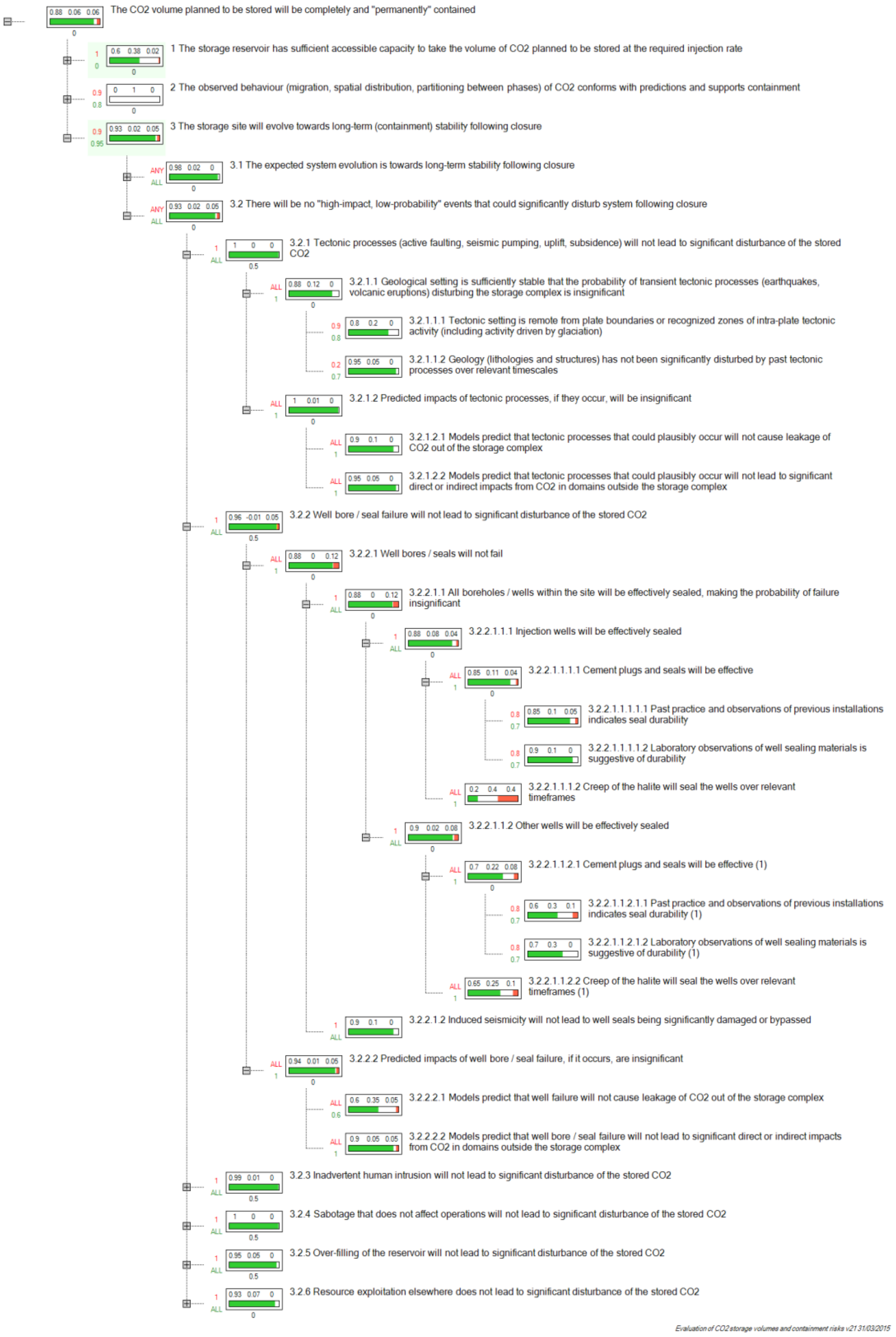
- hypothesis 3.2.3.2.1.1; here the red (40% confidence) reflects the potential that there might be economic resources underlying the storage complex; however this does not have an impact on its parent as its sibling hypothesis (3.2.3.2.1.2) identifies high confidence that people who might seek to access those resources in the future would be able to recognise the existence of the stored CO_2 and take measures to avoid leakage (in any case, 'deliberate' intrusion with knowledge is out of scope of the assessment). This means that the potential presence of an economic resource is immaterial as the risk is small in any case and the logic in the tree (confidence against both, or all, siblings being required for confidence against the parent) reflects this;
- similarly, although models indicate that if there is inadvertent human intrusion into the complex that leakage of CO_2 out of it could result, the models also show that this leakage would be very small and the impacts on receptors would be very small. Combined with the arguments above that inadvertent intrusion is not likely, again the confidence against does not propagate up the tree; and
- finally Hypothesis 3.2.6.1 notes that resource exploitation elsewhere could cause observable (monitorable) interactions (for example pressure changes) within the storage complex, but this does not present a risk because, as represented by its sibling hypothesis 3.2.6.2, the effects of such interactions would be insignificant and would not challenge containment or lead to observable impacts on receptors.

Figure B.3 Tree Plot - Containment (To Hypothesis 3.1, Remainder not Expanded)

- 0.88 0.06 0.06 — 0 — The CO2 volume planned to be stored will be completely and "permanently" contained
  - 1 / 0 — 0.6 0.38 0.02 — 0 — 1 The storage reservoir has sufficient accessible capacity to take the volume of CO2 planned to be stored at the required injection rate
    - 1 / ALL — 1 0 0 — 1.1 The total expected connected pore volume of the storage reservoir is sufficient for the planned CO2 volume
    - 1 / ALL — 0.6 0.38 0.02 — 0 — 1.2 Chemical effects will not prevent the required storage capacity being accessed at the required injection rate
      - 1 / ALL — 0.6 0.38 0.02 — 0 — 1.2.1 Chemical effects near the point of injection will not prevent the required storage capacity being accessed at the required injection rate
        - 1 / 0.9 — 0.6 0.38 0.02 — 1.2.1.1 Halite and hydrate precipitation will not prevent the required storage capacity being accessed at the required injection rate
        - 1 / 0.2 — 0.7 0.3 0 — 1.2.1.2 Other precipitates will not prevent the required storage capacity being accessed at the required injection rate
      - 1 / ALL — 0.85 0.15 0 — 1.2.2 Chemical effects away from the point of injection will not prevent the required storage capacity being accessed at the required injection rate
    - 1 / ALL — 0.75 0.25 0 — 0 — 1.3 Physical effects will not prevent the required storage capacity being accessed at the required injection rate
      - 1 / 0.75 — 0.9 0.1 0 — 1.3.1 Physical features will not prevent the required storage capacity being accessed at the required injection rate
      - 1 / 0.4 — 0.6 0.4 0 — 1.3.2 Physical alteration due to physico-chemical processes will not prevent the required storage capacity being accessed at the required injection rate
  - 0.9 / 0.8 — 0 1 0 — 0 — 2 The observed behaviour (migration, spatial distribution, partitioning between phases) of CO2 conforms with predictions and supports containment
  - 0.9 / 0.95 — 0.93 0.02 0.05 — 3 The storage site will evolve towards long-term (containment) stability following closure
    - ANY / ALL — 0.98 0.02 0 — 0 — 3.1 The expected system evolution is towards long-term stability following closure
      - 0.3 / 0.8 — 0.8 0.2 0 — 0 — 3.1.1 The storage complex contains no plausible leakage pathways by which CO2 could return to the surface or near-surface environments
        - 0.6 / ALL — 0.8 0.2 0 — 3.1.1.1 Wells / boreholes will not provide leakage paths
        - 0.6 / ALL — 0.85 0.15 0 — 3.1.1.2 Structures (faults, fracture zones etc) will not provide leakage paths
        - 0.6 / ALL — 0.9 0.1 0 — 3.1.1.3 Confining rock (primary seal, caprock and overburden to ultimate seal) has sufficient integrity
      - 0.6 / 0.6 — 0.9 0.1 0 — 0 — 3.1.2 The CO2 will not migrate laterally beyond the defined storage complex
        - 1 / ALL — 0.99 0.01 0 — 3.1.2.1 Free CO2 will not migrate laterally beyond the defined storage complex
        - 1 / ALL — 0.9 0.1 0 — 3.1.2.2 Dissolved CO2 will not migrate laterally beyond the defined storage complex
      - 0.9 / 0.8 — 0.96 0.04 0 — 0 — 3.1.3 Predictions of post-closure behaviour of the containment complex predict evolution towards long-term stability for any plausible boundary conditions
        - 0.9 / 0.7 — 0.9 0.1 0 — 3.1.3.1 Multi-phase flow models predict evolution towards no flow of free and dissolved CO2
        - 0.9 / 0.7 — 0.9 0.1 0 — 3.1.3.2 Geomechanical models predict evolution towards no deformation due to CO2 in the long term
        - 0.9 / 0.8 — 0.9 0.1 0 — 3.1.3.3 Geochemical models predict evolution towards long-term chemical stability
      - 0.6 / 0.5 — 0.9 0.1 0 — 3.1.4 Analogues support evolution towards long-term stability
    - ANY / ALL — 0.93 0.02 0.05 — 0 — 3.2 There will be no "high-impact, low-probability" events that could significantly disturb system following closure

Evaluation of CO2 storage volumes and containment risks v21 31/03/2015

Figure B.4 Tree Plot - Containment (Hypotheses 3.2 to 3.2.2, Remainder not Expanded)



The CO2 volume planned to be stored will be completely and "permanently" contained

1 The storage reservoir has sufficient accessible capacity to take the volume of CO2 planned to be stored at the required injection rate

2 The observed behaviour (migration, spatial distribution, partitioning between phases) of CO2 conforms with predictions and supports containment

3 The storage site will evolve towards long-term (containment) stability following closure

3.1 The expected system evolution is towards long-term stability following closure

3.2 There will be no "high-impact, low-probability" events that could significantly disturb system following closure

3.2.1 Tectonic processes (active faulting, seismic pumping, uplift, subsidence) will not lead to significant disturbance of the stored CO2

3.2.1.1 Geological setting is sufficiently stable that the probability of transient tectonic processes (earthquakes, volcanic eruptions) disturbing the storage complex is insignificant

3.2.1.1.1 Tectonic setting is remote from plate boundaries or recognized zones of intra-plate tectonic activity (including activity driven by glaciation)

3.2.1.1.2 Geology (lithologies and structures) has not been significantly disturbed by past tectonic processes over relevant timescales

3.2.1.2 Predicted impacts of tectonic processes, if they occur, will be insignificant

3.2.1.2.1 Models predict that tectonic processes that could plausibly occur will not cause leakage of CO2 out of the storage complex

3.2.1.2.2 Models predict that tectonic processes that could plausibly occur will not lead to significant direct or indirect impacts from CO2 in domains outside the storage complex

3.2.2 Well bore / seal failure will not lead to significant disturbance of the stored CO2

3.2.2.1 Well bores / seals will not fail

3.2.2.1.1 All boreholes / wells within the site will be effectively sealed, making the probability of failure insignificant

3.2.2.1.1.1 Injection wells will be effectively sealed

3.2.2.1.1.1.1 Cement plugs and seals will be effective

3.2.2.1.1.1.1.1 Past practice and observations of previous installations indicates seal durability

3.2.2.1.1.1.1.2 Laboratory observations of well sealing materials is suggestive of durability

3.2.2.1.1.1.2 Creep of the halite will seal the wells over relevant timeframes

3.2.2.1.1.2 Other wells will be effectively sealed

3.2.2.1.1.2.1 Cement plugs and seals will be effective (1)

3.2.2.1.1.2.1.1 Past practice and observations of previous installations indicates seal durability (1)

3.2.2.1.1.2.1.2 Laboratory observations of well sealing materials is suggestive of durability (1)

3.2.2.1.1.2.2 Creep of the halite will seal the wells over relevant timeframes (1)

3.2.2.1.2 Induced seismicity will not lead to well seals being significantly damaged or bypassed

3.2.2.2 Predicted impacts of well bore / seal failure, if it occurs, are insignificant

3.2.2.2.1 Models predict that well failure will not cause leakage of CO2 out of the storage complex

3.2.2.2.2 Models predict that well bore / seal failure will not lead to significant direct or indirect impacts from CO2 in domains outside the storage complex

3.2.3 Inadvertent human intrusion will not lead to significant disturbance of the stored CO2

3.2.4 Sabotage that does not affect operations will not lead to significant disturbance of the stored CO2

3.2.5 Over-filling of the reservoir will not lead to significant disturbance of the stored CO2

3.2.6 Resource exploitation elsewhere does not lead to significant disturbance of the stored CO2

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Figure B.5 Tree Plot - Containment (Hypotheses 3.2.3 to 3.2.4, Remainder not Expanded)

The CO2 volume planned to be stored will be completely and "permanently" contained

1 The storage reservoir has sufficient accessible capacity to take the volume of CO2 planned to be stored at the required injection rate

2 The observed behaviour (migration, spatial distribution, partitioning between phases) of CO2 conforms with predictions and supports containment

3 The storage site will evolve towards long-term (containment) stability following closure

3.1 The expected system evolution is towards long-term stability following closure

3.2 There will be no "high-impact, low-probability" events that could significantly disturb system following closure

3.2.1 Tectonic processes (active faulting, seismic pumping, uplift, subsidence) will not lead to significant disturbance of the stored CO2

3.2.2 Well bore / seal failure will not lead to significant disturbance of the stored CO2

3.2.3 Inadvertent human intrusion will not lead to significant disturbance of the stored CO2

3.2.3.1 There is insignificant likelihood of inadvertent human intrusion

3.2.3.1.1 There are no economic resources that would cause intrusive activities to penetrate the storage complex

3.2.3.1.2 People with the technical capability to intrude into the storage complex would be able to recognize the existence of CO2 and take appropriate measures

3.2.3.2 Predicted impacts of human intrusion, if it occurs, due to the stored CO2 are insignificant

3.2.3.2.1 Future human groups responsible for any unintentional intrusion would implement mitigating actions sufficient to ensure mitigating impacts

3.2.3.2.2 Impacts associated with any unmitigated intrusion events would be insignificant

3.2.3.2.2.1 Models predict that any plausible human intrusion will not cause leakage of CO2 out of the storage complex

3.2.3.2.2.2 Models predict that any plausible human intrusion will not lead to significant direct or indirect impacts from CO2 in domains outside the storage complex

3.2.4 Sabotage that does not affect operations will not lead to significant disturbance of the stored CO2

3.2.4.1 There is insignificant likelihood of sabotage

3.2.4.2 Predicted impacts of any sabotage, if it occurs, are insignificant

3.2.4.2.1 Models predict that any plausible sabotage events will not cause leakage of CO2 out of the storage complex

3.2.4.2.2 Models predict that any plausible sabotage events will not lead to significant direct or indirect impacts from CO2 in domains outside the storage complex

3.2.5 Over-filling of the reservoir will not lead to significant disturbance of the stored CO2

3.2.6 Resource exploitation elsewhere does not lead to significant disturbance of the stored CO2

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Figure B.6 Tree Plot - Containment (Hypotheses 3.2.5 to 3.2.6, Remainder not Expanded)

- The CO2 volume planned to be stored will be completely and "permanently" contained
  - 1 The storage reservoir has sufficient accessible capacity to take the volume of CO2 planned to be stored at the required injection rate
  - 2 The observed behaviour (migration, spatial distribution, partitioning between phases) of CO2 conforms with predictions and supports containment
  - 3 The storage site will evolve towards long-term (containment) stability following closure
    - 3.1 The expected system evolution is towards long-term stability following closure
    - 3.2 There will be no "high-impact, low-probability" events that could significantly disturb system following closure
      - 3.2.1 Tectonic processes (active faulting, seismic pumping, uplift, subsidence) will not lead to significant disturbance of the stored CO2
      - 3.2.2 Well bore / seal failure will not lead to significant disturbance of the stored CO2
      - 3.2.3 Inadvertent human intrusion will not lead to significant disturbance of the stored CO2
      - 3.2.4 Sabotage that does not affect operations will not lead to significant disturbance of the stored CO2
      - 3.2.5 Over-filling of the reservoir will not lead to significant disturbance of the stored CO2
        - 3.2.5.1 There is insignificant likelihood of over-filling
          - 3.2.5.1.1 The capacity is known and accessibility of the capacity is known
          - 3.2.5.1.2 The injected CO2 volumes can be adequately managed so as not to exceed known accessible capacity
        - 3.2.5.2 Predicted impacts of over-filling, if it occurs, are insignificant
          - 3.2.5.2.1 Models predict that over-filling will not cause leakage of CO2 out of the storage complex
            - 3.2.5.2.1.1 Free CO2 will not migrate laterally beyond the defined storage complex due to over-filling
            - 3.2.5.2.1.2 Dissolved CO2 will not migrate laterally beyond the defined storage complex due to over-filling
          - 3.2.5.2.2 Models predict that over-filling will not lead to significant direct or indirect impacts from CO2 in domains outside the storage complex
      - 3.2.6 Resource exploitation elsewhere does not lead to significant disturbance of the stored CO2
        - 3.2.6.1 There is insignificant likelihood of observable additional interactions
        - 3.2.6.2 Predicted impacts of significant additional interactions, if they occur, are insignificant
          - 3.2.6.2.1 Models predict that additional interactions due to resource exploitation elsewhere will not cause leakage of CO2 out of the storage complex as a consequence of CO2 storage
            - 3.2.6.2.1.1 Free CO2 will not migrate laterally beyond the defined storage complex as a consequence of resource exploitation
            - 3.2.6.2.1.2 Dissolved CO2 will not migrate laterally beyond the defined storage complex as a consequence of resource exploitation
          - 3.2.6.2.2 Models predict that resource exploitation elsewhere will not lead to significant direct or indirect impacts from CO2 in domains outside the storage complex

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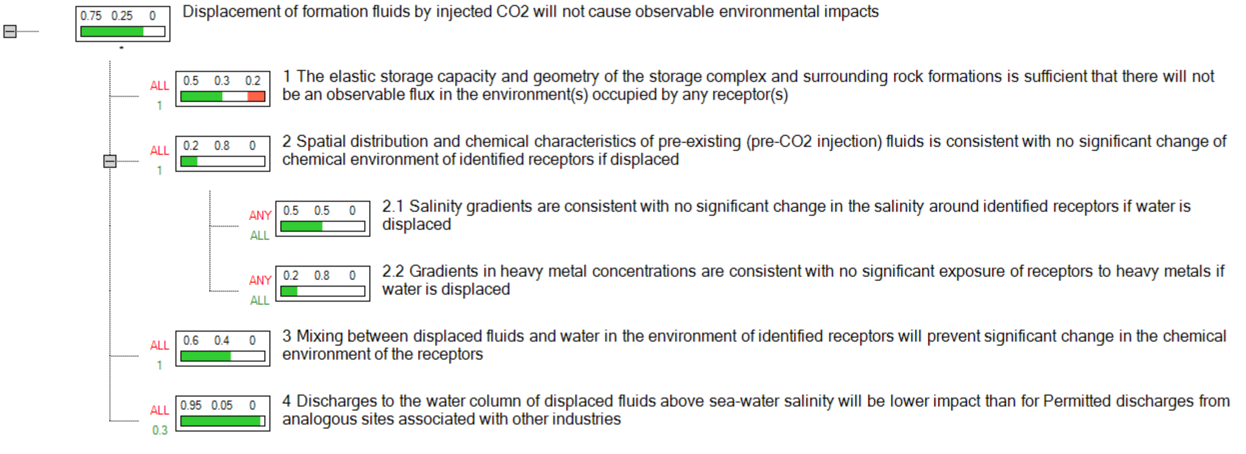
B.4 Displacement of Formation Fluids Tree

Figure B.7 summarises the outcomes for displacement of formation fluids (including the potential for displacement of higher salinity waters, or even brines and impacts on seabed or water column dwelling receptors). Here, confidence that there will not be observable impacts is high with moderate residual uncertainty, based upon analyses of available information, including scoping calculations.

Figure B.7 Tree Plot - Displacement of Formation Fluids



0.75 0.25 0 Displacement of formation fluids by injected CO2 will not cause observable environmental impacts

ALL 1 — 0.5 0.3 0.2 — 1 The elastic storage capacity and geometry of the storage complex and surrounding rock formations is sufficient that there will not be an observable flux in the environment(s) occupied by any receptor(s)

ALL 1 — 0.2 0.8 0 — 2 Spatial distribution and chemical characteristics of pre-existing (pre-CO2 injection) fluids is consistent with no significant change of chemical environment of identified receptors if displaced

ANY ALL — 0.5 0.5 0 — 2.1 Salinity gradients are consistent with no significant change in the salinity around identified receptors if water is displaced

ANY ALL — 0.2 0.8 0 — 2.2 Gradients in heavy metal concentrations are consistent with no significant exposure of receptors to heavy metals if water is displaced

ALL 1 — 0.6 0.4 0 — 3 Mixing between displaced fluids and water in the environment of identified receptors will prevent significant change in the chemical environment of the receptors

ALL 0.3 — 0.95 0.05 0 — 4 Discharges to the water column of displaced fluids above sea-water salinity will be lower impact than for Permitted discharges from analogous sites associated with other industries

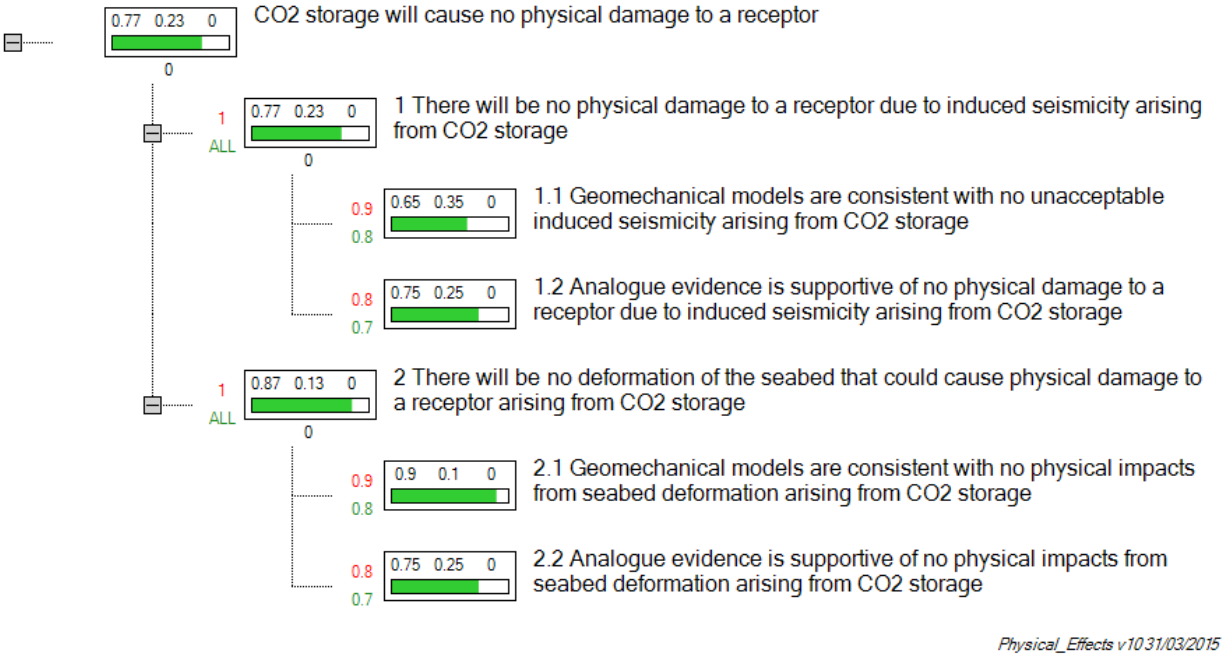
Higher salinity formation waters evaluation v15 (27/04/2015)

The greatest contributor to uncertainty at the top level of the tree is lacking information about chemical gradients within the formation water of the Bunter sandstone immediately below the seabed outcrop. There is less uncertainty about salinity gradients than there is about gradients in the chemical constituents of the formation water. Deductions about salinity can be made from measured reservoir pressures and knowledge about the sources of salinity in the geological sequence(presence of halite), but the nearest compositions of formation water from the Bunter sandstone come from appraisal well 42/25-d3,which is located more than 25km from the outcrop. The degree to which these compositions represent in-situ conditions for certain trace constituents of importance (notably heavy metals) is also uncertain.

B.5 Physical Effects Tree

The outcomes for the assessment of physical effects (including impacts on other receptors as a result of changes to the seabed) are presented in Figure B.8. Confidence in the analysis is again high.

Figure B.8 Tree Plot - Physical Effects



CO2 storage will cause no physical damage to a receptor

1 There will be no physical damage to a receptor due to induced seismicity arising from CO2 storage

1.1 Geomechanical models are consistent with no unacceptable induced seismicity arising from CO2 storage

1.2 Analogue evidence is supportive of no physical damage to a receptor due to induced seismicity arising from CO2 storage

2 There will be no deformation of the seabed that could cause physical damage to a receptor arising from CO2 storage

2.1 Geomechanical models are consistent with no physical impacts from seabed deformation arising from CO2 storage

2.2 Analogue evidence is supportive of no physical impacts from seabed deformation arising from CO2 storage

Physical_Effects v10 31/03/2015

Appendix C Assessment Audit

C.1 Approach

It can never be guaranteed that all risks and FEPs that may influence them have been identified and represented within a set of scenarios. However, by auditing against a number of peer reviewed sources of different kinds, it is possible to minimise doubt that any risk relevant issue has been missed.

For each of the risks and/or FEPs in the sources against which the audit was undertaken it was identified:

- whether or not the risk or FEP is represented by the scenarios in Section4.4 and in Appendix A;
- if the risk or FEP is represented, then indicating:
  - How it is represented (implicitly or explicitly); and
  - In which scenarios is it represented; and
- if the risk or FEP is not represented, then indicating why it is not represented.

Here, a risk or FEP in the source against which the audit is undertaken is deemed to be treated explicitly, if it is represented directly in one or more of the scenarios. A risk or FEP is treated implicitly if it is not represented directly, but one of the risks of FEPs that are represented directly would have the same overall effect. For example, the Generic CO_2 FEP Database contains the FEP 'neotectonics', which is not mentioned in any of the scenario descriptions, but the relevant effects of neotectonics are covered by mention of seismicity; thus 'neotectonics' are represented implicitly.

To determine that all general risks and factors that may influence risks have been represented by the scenarios in Section 4 of the main report and in Appendix A, an initial audit was undertaken against Quintessa's on line Generic CO_2 FEP Database. The database is presently at version 2.0 and has been developed over a period of 12 years, specifically to support the risk assessment of CO_2 storage projects. Initial development of the database was undertaken through EC-supported international collaboration under the Canadian Weyburn Project, via a series of expert workshops. Subsequently, the database has been developed further, most recently during the EC-supported RISCS project (RISCS, 2014). This latest update aimed to capture the results of research into the impacts of CO_2-leakage from underground storage complexes, should it occur. The FEPs included were chosen for their relevance to the long-term safety and performance of the storage system after CO_2 injection has ceased and the injection boreholes have been sealed. FEPs associated with the injection phase are included where these can affect long-term performance and the status of the system at closure. The FEP database has been widely used and referenced, with over 1000 people having registered to access it.

The scenarios were next audited against some marine impact scenarios developed during the RISCS project. These impact scenarios were developed collaboratively by the 24 organisations that participated in RISCS and are designed to describe the characteristics of unexpected CO_2 leakage from underground storage reservoirs. By auditing the scenarios developed for the White Rose CCS Project against the marine RISCS impact scenarios it was aimed to build further confidence that consequences of unexpected CO_2 leakage could be analysed during the White Rose CCS Project.

The next stage in the audit was to check the collection of scenarios against the risks that are identified in 2009/31/EC CCS Directive and associated guidance and against the OSPAR guidance (OSPAR, 2007). This part of the audit was undertaken to check that all risks identified in the legislation applicable to CO_2 storage are covered by the specified scenarios.

Finally, the scenarios were audited against the issues identified in the CO_2QUALSTORE Guideline (DNV, 2010). This audit provides a further check that issues of relevance for site selection and qualification had been covered by the scenarios.

C.2 Outcomes of the Audit

C.2.1 Audit against the Online Generic CO_2 FEP Database

The audit is reported in Table C.1.

Table C.1 Outcome of the Audit of Scenarios and the Online Generic CO_2 FEP Database

Notes: E - Means Explicitly Represented
I - Implicitly Represented
N - Not Represented in the FEP List
The audit only considered only the period covered by the risk assessment, namely 10,000 years.

Generic FEP	Covered by System FEPs?	Notes/Rationale	Generic FEP	Covered by System FEPs?	Notes/Rationale
0 Assessment Basis			4 Geosphere		
0.1 Purpose of the assessment	E	Assessment Basis FEPs covered by the context discussion in Metcalfe et al (2013) and preliminary sections of the main text of this document.	4.1 Geology		
0.2 Endpoints of interest	E		4.1.1 Geographical location	E	
0.3 Spatial domain of interest	E		4.1.2 Natural resources	E	
0.4 Timescales of interest	E		4.1.3 Reservoir type	E	
0.5 Storage assumptions	E		4.1.4 Reservoir geometry	E	
0.6 Future human action assumptions	E		4.1.5 Reservoir exploitation	E	
0.7 Legal and regulatory framework	E		4.1.6 Cap rock or sealing formation	E	
0.8 Model and data issues	E		4.1.7 Additional seals	E	
			4.1.8 Lithology	E	
			4.1.8.1 Lithification/diagenesis	E	
			4.1.8.2 Pore architecture	E	
			4.1.9 Unconformities	E	
			4.1.10 Heterogeneities	E	
			4.1.11 Fractures and faults	E	
			4.1.12 Undetected features	E	
			4.1.13 Vertical geothermal gradient	I	Implicit in Expected Evolution
			4.1.14 Formation pressure	E	
			4.1.15 Stress and mechanical properties	E	
			4.1.16 Petrophysical properties	E	
			4.2 Fluids		
			4.2.1 Fluid properties	E	
			4.2.2 Hydrogeology	E	
			4.2.3 Hydrocarbons	E	
					E

Generic FEP	Covered by System FEPs?	Notes/Rationale
1 External Factors		
1.1 Geological factors		
1.1.1 Neotectonics	I	Covered by seismic FEPs
1.1.2 Volcanic and magmatic activity	N	Not relevant
1.1.3 Seismicity	E	
1.1.4 Hydrothermal activity	N	Not relevant
1.1.5 Hydrological and hydrogeological response to geological changes	E	
1.1.6 Large scale erosion	N	Not relevant
1.1.7 Bolide impact	N	Not relevant
1.2 Climatic factors		
1.2.1 Global climate change	N	Not a major influence
1.2.2 Regional and local climate change	N	Not a major influence
1.2.3 Sea level change	N	Not a major influence
1.2.4 Periglacial effects	N	Not a major influence
1.2.5 Glacial and ice sheet effects	N	Not a major influence
1.2.6 Tropical and warm desert climate effects	N	Not a major influence
1.2.7 Hydrological and hydrogeological response to climate change	N	Not a major influence
1.2.8 Responses to climate change	N	Not a major influence
1.3 Future human actions		
1.3.1 Human influences on climate	N	Not a major influence
1.3.2 Motivation and knowledge issues	I	Covered by Human Intrusion
1.3.3 Social and institutional developments	I	Covered by Human Intrusion
1.3.4 Technological developments	I	
1.3.5 Drilling activities	E	Covered by Human Intrusion
1.3.6 Mining and other underground activities	I E	
1.3.7 Human activities in the surface environment	N	Covered by Human Intrusion
1.3.8 Water management	I	

Generic FEP	Covered by System FEPs?	Notes/Rationale
5 Boreholes		
5.1 Drilling and completion		All well-relevant FEPs listed here covered implicitly or explicitly by Well FEPs and related scenarios
5.1.1 Formation damage	I	
5.1.2 Well lining and completion	E	
5.1.3 Workover	I	
5.1.4 Monitoring wells	I	
5.1.5 Well records	I	
5.2 Borehole seals and abandonment		
5.2.1 Closure and sealing of boreholes	E	
5.2.2 Seal failure	E	
5.2.3 Blowouts	E	
5.2.4 Orphan wells	E	
5.2.5 Soil creep around boreholes	I	Well/sediment interactions implicitly considered

Generic FEP	Covered by System FEPs?	Notes/Rationale
1.3.9 CO_2 presence influencing future operations	I	Not relevant
1.3.10 Explosions and crashes		Implications for other resources are assessed
		Implicit in AE9 and AE11
2 CO_2 Storage		
2.1 Pre-closure		
2.1.1 Storage concept	E	
2.1.2 CO_2 quantities, injection rate	E	
2.1.3 CO_2 composition	E	
2.1.4 Microbiological contamination	I	Implicit in chemistry FEPs
2.1.5 Schedule and planning	E	
2.1.6 Pre-closure administrative control	E	
2.1.7 Pre-closure monitoring of storage	E	
2.1.8 Quality control	E	
2.1.9 Accidents and unplanned events	I	Included in over-filling etc.
2.1.10 Over-pressurising	E	
2.2 Post-closure		
2.2.1 Post-closure administrative control	E	
2.2.2 Post-closure monitoring of storage	E	
2.2.3 Records and markers	N	Not relevant
2.2.4 Reversibility	N	Not relevant
2.2.5 Remedial actions	I	Included in mitigation for injectivity, over-filling etc. scenarios

Generic FEP	Covered by System FEPs?	Notes/Rationale
6 Near-Surface Environment		
6.1 Terrestrial environment		
6.1.1 Topography and morphology	N	Terrestrial environment FEPs are not relevant to this system
6.1.2 Soils and sediments	N	
6.1.3 Erosion and deposition	N	
6.1.4 Atmosphere and meteorology	N	
6.1.5 Hydrological regime and water balance	N	
6.1.6 Near-surface aquifers and surface water bodies	N	
6.1.7 Terrestrial flora and fauna	N	
6.1.8 Terrestrial ecological systems	N	
6.2 Marine environment		
6.2.1 Coastal features	N	System is distant from coast
6.2.2 Local oceanography	E	E
6.2.3 Marine sediments	E	E
6.2.4 Marine flora and fauna	E	E
6.2.5 Marine ecological systems	E	E
6.3 Human behaviour		Human behaviour FEPs essentially implicit in relevant Expected and Alternative Evolution scenarios (Human Intrusion and Sabotage covered elsewhere)
6.3.1 Human characteristics	I	
6.3.2 Diet and food processing	I	
6.3.3 Lifestyles	I	
6.3.4 Land and water use	I	
6.3.5 Community characteristics	I	
6.3.6 Buildings	E	Here considering the nearby wind farm as ‘buildings’

Generic FEP	Covered by System FEPs?	Notes/Rationale
3 CO_2 Properties, Interactions & Migration		
3.1 CO_2 properties		
3.1.1 Physical properties of CO_2	E	
3.1.2 CO_2 phase behaviour	E	
3.1.3 CO_2 solubility and aqueous speciation	E	
3.2 CO_2 interactions		
3.2.1 Effects of pressurisation of reservoir on cap rock	E	
3.2.2 Effects of pressurisation on reservoir fluids	E	
3.2.3 Interaction with hydrocarbons		
	E	
3.2.4 Displacement of saline formation fluids	E	
3.2.5 Mechanical processes and conditions	E	
3.2.6 Induced seismicity	E	
3.2.7 Subsidence or uplift	E	
3.2.8 Thermal effects on the injection point	E	
3.2.9 Water chemistry	E	
3.2.10 Interaction of CO_2 with chemical barriers	E	
	N	A minor effect compared to other chemical processes
3.2.11 Sorption and desorption of CO_2		
	E	
3.2.12 Heavy metal release	E	
3.2.13 Mineral phase	E	
3.2.13.1 Mineral dissolution and precipitation	I	
	I	Encompassed by primary seal failure
3.2.13.2 Ion exchange		
3.2.13.3 Desiccation of clay	E	
	N	Not relevant since no gas
3.2.14 Gas chemistry	E	
3.2.15 Gas stripping	I	Bounded by overall chemical effects
3.2.16 Gas hydrates		
		Bounded by overall chemical effects
3.2.17 Biogeochemistry	I	

Generic FEP	Covered by System FEPs?	Notes/Rationale
7 Impacts		
7.1 System performance		
7.1.1 Loss of containment	E	
7.2 Impacts on the physical environment		
7.2.1 Contamination of groundwater	E	
7.2.2 Impacts on soils and sediments	E	Benthic sediments
7.2.3 Release to the atmosphere	N	Not relevant
7.2.4 Impacts on exploitation of natural resources	E	Benthic marine resources
7.2.5 Release to the marine environment	E	E
7.2.6 Modified hydrology and hydrogeology	E	Implicit in various scenarios
	E	Implicit in various scenarios
7.2.7 Modified geochemistry		
	E	
7.2.8 Modified seismicity		
	E	
7.2.9 Modified surface topography		
	N	Not relevant
7.2.9.1 Sinkhole formation		
	E	E
7.2.10 Impacts on oceans		
7.3 Impacts on flora and fauna		
	E	E
7.3.1 Effect of CO_2 on animals.		
	E	E
7.3.2 Effect of CO_2 on plants and algae		
	E	E
7.3.3 Ecotoxicology of contaminants		
	E	E
7.3.4 Ecological effects		
	I	Implicit in plant/algae impacts
7.3.5 Modification of microbiological systems		
	I	
7.4 Impacts on humans		
		Effects on ecosystems are considered
7.4.1 Health effects of CO2		
	I	
		Effects on ecosystems are considered
7.4.2 Toxicity of contaminants		
	E	
	I	
7.4.3 Impacts from physical disruption		Implicit via potential knock-on effects of plant/animal impacts
7.4.4 Impacts from ecological modification		

Generic FEP	Covered by System FEPs?	Notes/Rationale	Generic FEP	Covered by System FEPs?	Notes/Rationale
3.2.18 Microbial processes	I	Bounded by overall chemical and ecosystem effects			
3.2.19 Biomass uptake of CO_2	E				
	E				
3.3 CO_2 Migration	I	Covered by induced seismicity			
3.3.1 Advection of free CO_2					
3.3.1.1 Fault valving	E				
	E				
3.3.2 Buoyancy-driven flow	E				
3.3.3 Displacement of formation fluids	E				
3.3.4 Dissolution in formation fluids	E				
3.3.5 Water mediated migration	N	Not relevant since no potential for accumulation at the seabed			
3.3.6 CO_2 release processes					
3.3.6.1 Limnic eruption		Dilution of CO_2 in seawater considered			
	E				
3.3.6.2 Marine Stratification and Mixing	E				
3.3.7 Co-migration of other gases					

C.2.2 Audit against Scenarios Developed During the RISCS Project

The RISCS EC project (Research into Impacts and Safety in CO_2 Storage; RISCS, 2014) provided, at a generic level, an overview of potential FEP and scenario descriptions that could plausibly describe an unlikely leakage event. The FEP analysis was captured in updates to the online FEP database and so no additional FEP audit is required.

Specific scenarios identified for marine environments by the RISCS project were:

- localised direct release of free CO_2 via the sediment or directly to the water column above the seabed via a point source;
- diffuse direct release of free CO_2 via the sediment or directly to the water column over a wide area;
- localised release of CO_2-charged water through the sediment or directly to the water column via a point source;
- diffuse release of CO_2-charged water through the sediment and subsequently to the water column over a wide area;
- displacement of saline formation water due to storage activities;
- impacts through inadvertent human intrusion;
- sudden releases of free CO_2 due to the ‘turn-over’ of CO_2 charged seawater in the marine environments;
- releases related to earthquake/seismic activity;
- induced seismicity caused by CO_2 injection;
- sudden leakage of CO_2 caused by over-pressuring during operations; and
- heat shock to organisms surrounding a leakage/discharge location.

All of these scenarios are considered in the present assessment via expected or alternative evolution scenarios, except:

- ‘sudden releases of free CO_2 due to the ‘turn-over’ of CO_2-charged seawater in the marine environment’; and
- ‘heat shock to organisms surrounding a leakage/discharge location’.

For the White Rose storage system, both of these situations are assumed to be so unlikely as to be implausible. It is not plausible that rates of CO_2 release in the unlikely event of a release will be sufficient to cause significant build-up and turnover within the marine environment because the water column is not stationary, but rather is in a constant state of movement due to weather and tidal effects. Similarly it is not plausible that the rate of release of CO_2 at the seabed in any unlikely leakage situation could be at a sufficient rate to cause any heat (or change of temperature in general) shock to organisms for this system.

C.2.3 Audit against Key Requirements of 2009/31/EC CCS Directive and Guidance

The audit is reported in Table C 2.

Table C.2 Outcomes of the Audit of Scenarios against Key Requirements of 2009/31/EC CCS Directive and Guidance Document GD1

Requirement	Reference	Explicitly Addressed?	Where Addressed
Stored CO_2 will be completely and permanently contained	EC (2009)	Y	Expected evolution scenario (and alternative evolution scenario probability arguments)
The storage site is evolving towards a situation of long-term stability	EC (2009)	Y	Expected evolution scenario (and alternative evolution scenario probability arguments)
Potential leakage pathways	EC (2009)	Y	Expected evolution and alternative evolution scenarios
Potential magnitude of leakage events for identified leakage pathways (flux rates)	EC (2009)	Y	Alternative evolution scenarios
Critical parameters affecting potential leakage (for example maximum reservoir pressure, maximum injection rate, temperature, sensitivity to various assumptions in the static geological Earth model(s))	EC (2009)	Y	Alternative Evolution scenarios
Secondary effects of storage of CO_2, including displaced formation fluids and new substances created by the storing of CO_2	EC (2009)	Y	Expected evolution and alternative evolution scenarios
Effects of exposure to elevated CO_2 concentrations in the biosphere (including soils, marine sediments and benthic waters (asphyxiation; hypercapnia) and reduced pH in those environments as a consequence of leaking CO_2)	EC (2009)	Y	Alternative evolution scenarios
Assessment of the effects of other substances that may be present in leaking CO_2 streams	EC (2009)	Y	Alternative evolution scenarios
Effects shall be considered at a range of temporal and spatial scales and linked to a range of different magnitudes of leakage events	EC (2009)	Y	Alternative evolution scenarios
Conformity of the actual behaviour of the injected CO_2 with the modelled behaviour	EC (2009)	Implicit	Expected evolution scenario
Assessment of the safety and integrity of the site in the short and long term	EC (2009)	Y	Expected evolution and alternative evolution scenarios
Assessment of the risk of leakage under the proposed conditions of use	EC (2009)	Y	Expected evolution scenario
Assessment of the risk of leakage - worst-case environment and health impacts	EC (2009)	Y	Alternative evolution scenarios
Direct effects of elevated gas-phase CO_2 concentrations in the atmosphere above a storage complex and in the shallow subsurface and near-surface environments	EC (2011)	Y	Atmosphere not relevant to marine systems, but subsurface and near-surface environments from a marine environment perspective are covered by the Alternative evolution scenarios
Effects of dissolved CO_2 or fluid movement on groundwater chemistry which could lead to water contamination, pollution and other environmental risks	EC (2011)	Y	Water contamination; groundwater resources, are not relevant here, but the effects on chemistry and groundwater movement are considered in the expected evolution and alternative evolution scenarios
Effects that arise from the displacement of fluids by the injected CO_2, including displacement and leakage of other formation fluids, including oil or gas, ground	EC (2011)	Y	Included in expected and alternative evolution scenarios

Requirement	Reference	Explicitly Addressed?	Where Addressed
displacement and induced seismicity			
Leakage, cap rock: Through the pore system in low permeability cap rocks if the capillary entry pressure is exceeded or the CO_2 is in solution	EC (2011)	Y	Considered in expected and alternative evolution scenarios
Leakage, cap rock: If the cap rock is locally absent (includes injection features, pipes and erosion)	EC (2011)	Y	Considered in alternative evolution scenarios
Leakage, cap rock: Through a degraded cap rock as a result of CO_2/water/rock reactions	EC (2011)	Y	Considered in alternative evolution scenarios
Leakage, cap rock: fracturing of the cap rock induced by injection	EC (2011)	Y	Considered in alternative evolution scenarios
Leakage, faults and fractures: via natural faults and/or fractures	EC (2011)	Y	Considered in alternative evolution scenarios
Leakage, faults and fractures: via natural faults and/or Fractures: via induced faulting/fracturing resulting from seismic activity	EC (2011)	Y	Considered in alternative evolution scenarios
Leakage, overfilling/structural spill: Via a spill point (lowest point in structure that can provide lateral closure) if the reservoir is overfilled	EC (2011)	Y	Considered in alternative evolution scenarios
Leakage, updip: Via high permeability zones updip	EC (2011)	Y	Considered in alternative evolution scenarios
Leakage, other: via dissolution of CO_2 into pore fluid and subsequent leakage out of the storage complex by natural fluid flow	EC (2011)	Implicit	Addressed by alternative evolution scenarios
Leakage, wells: operational or abandoned wells (and boreholes)	EC (2011)	Y	Considered in alternative evolution scenarios
Leakage, wells: well blow outs (uncontrolled emissions from drilling and operation of injection wells)	EC (2011)	Y	Considered in alternative evolution scenarios
Leakage, mining: abandoned mine workings, mining induced subsidence	EC (2011)	N	Not relevant for the CO_2 storage system
Leakage, mining: future mining of CO_2 storage reservoir	EC (2011)	Implicit	Unintentional intrusion due to future exploration activities is considered by an Alternative evolutions scenario
Other risks: ground water including effects that arise directly from the effect of dissolved CO_2 in the formation water, including heavy metal mobilisation	EC (2011)	Y	Heavy metal contamination of groundwater resources is not an issue for this assessment given the absence of such resources that could be impacted, but in broader terms chemical effects, including heavy metal mobilisation, are considered in Expected and alternative evolution scenarios
Other risks: indirect effects from groundwater contamination by displaced brine	EC (2011)	N	Displaced brine risks are covered in terms of marine impacts rather than groundwater contamination
Other risks: oil or gas leakage or emissions that could result from the displacement of hydrocarbons in underground formations by CO_2 injection and movement. This may be of particular importance for storage in depleted oil and gas fields and coal seams	EC (2011)	Y	Interactions covered in alternative evolution scenarios
Other risks: relating to movement of other hazardous components such as H_2S	EC (2011)	N	Not directly relevant to the White Rose CO_2 storage system because the injected CO_2 has a high degree of purity and there is

Requirement	Reference	Explicitly Addressed?	Where Addressed
			no other gas within the reservoir
Other risks: ground movement, uplift and/or subsidence	EC (2011)	Y	Explicitly covered in expected evolution and alternative evolution scenarios
Other risks: natural seismicity, seismic hazards and tectonics, include exposure to earthquakes	EC (2011)	Y	Explicitly covered in alternative evolution scenarios
Other risks: effects from sabotage or terrorism	EC (2011)	Y	Explicitly covered in alternative evolution scenarios

C.2.4 Audit against Key Requirements from the OSPAR FRAM (OSPAR, 2007)

The audit is reported in Table C 3.

Table C.3 Outcomes of the Audit of Scenarios against Detailed Requirements from the OSPAR FRAM

Requirement	Explicitly Addressed?	Where Addressed
Migration through the pore system in low permeability cap rocks if the capillary entry pressure at which CO_2 may enter the cap rock is exceeded	Y	Expected evolution scenario (and alternative evolution scenario probability arguments)
Migration, because the cap rock is locally absent, in combination with lateral migration of free or dissolved CO_2 and incidental associated substances (spilling)	Y	Alternative evolution scenarios
Migration through faults or other fractures in the cap rock	Y	Expected and alternative evolution scenarios
Migration through inadequately completed and/or abandoned wells	Y	Alternative evolution scenarios
Migration due to degradation of the cap rock or wells by reaction with acidic formation waters	Y	Alternative evolution scenarios
Potential impacts on amenities, sensitive areas, habitat, migratory patterns, biological communities and marketability of resources and other legitimate uses of the maritime area, including fishing, navigation, engineering uses, areas of special concern and value and traditional uses of the maritime area;	Y	Expected and alternative evolution scenarios. Uses of local area such as trawling influence potential for well-head damage. Impact on adjacent hydrocarbon resources explicitly addressed. Brine displacement and surface uplift scenarios cover remainder of the potential plausible impact scenarios.
Potential impacts on human health	Implicitly	No plausible direct impacts. Plausible indirect impacts via other sensitive areas and resources as described above.

C.2.5 Audit against CO_2QUALSTORE Guideline

The CO_2QUALSTORE Guideline (DNV, 2010) also provides useful guidance on the importance of impacts assessment. It states that, while the fundamental aim of the ‘qualification’ process is to establish that a storage site will meet requirements for injectivity, capacity and containment, the following additional issues are relevant to the evaluation of candidate storage sites:

- *‘Have the most relevant secondary effects of the storage project that may have adverse impact on human health or the environment been considered, including effects of displaced formation fluids and release of heavy metals or other substances with the potential to contaminate vulnerable zones?’*; and
- *‘Are there any other factors which could pose a hazard to human health or the environment (for example, physical structures associated with the project)?’*

The CO_2QUALSTORE guidance is referred to by the EC Directive and Guidance documents and does not provide any additional specific details on the elements required in risk assessment scenarios compared to those documents. Therefore, it is not necessary to add an audit against the CO_2QUALSTORE guidance here.

Appendix D Evidence and Basis for Confidence from the Decision

The following three sections provide outputs from the three decision tress. They summarise the evidence that provides confidence for and against each leaf node hypothesis and the basis for the confidence value assigned to each leaf node hypothesis.

D.1 Containment Tree

Table D.1 Containment Tree

Hypothesis Name	Notes
0 The CO$_2$ volume planned to be stored will be completely and 'permanently' contained	
1 The storage reservoir has sufficient accessible capacity to take the volume of CO$_2$ planned to be stored at the required injection rate	Child hypotheses. Confidence in all of the child hypotheses is required for confidence in this hypothesis, as it is necessary to show the basic capacity is available and its access will not be prevented. Any of the child hypotheses are however sufficient to disprove this hypothesis
1.1 The total expected connected pore volume of the storage reservoir is sufficient for the planned CO$_2$ volume	There is very good evidence that the volume to be injected into the reservoir is very small compared to the total assumed accessible pore volume. The volume of CO$_2$ to be injected into the reservoir is 7.7x107m^3 (assuming 2.86MTPA over 20 years and a density of 700kg/m^3) compared to a likely pore volume available for CO$_2$ storage of 4.6 x109m^3. On this basis, confidence for this hypothesis is very high. Note that dynamic capacity is discussed under hypothesis 1.3.1. A more detailed, integrated description of the geological structure of Endurance including the calculated storage capacity is provided in the risk assessment report
1.2 Chemical effects will not prevent the required storage capacity being accessed at the required injection rate	
1.2.1 Chemical effects near the point of injection will not prevent the required storage capacity being accessed at the required injection rate	
1.2.1.1 Halite and hydrate precipitation will not prevent the required storage capacity being accessed at the required injection rate	Injection of CO$_2$ into a saline aquifer can result in precipitation of halite, which in turn can cause injectivity problems by reducing the permeability of the rock. Halite precipitation is likely to occur in the Bunter sandstone when CO$_2$ is injected into it. The key considerations for this hypothesis are whether injectivity is likely to be impacted by halite precipitation to the extent that CO$_2$ cannot be injected at the required rate and whether available technologies and methodologies can be used to overcome any injectivity problems. There are two mechanisms through which halite precipitation could occur: mineral reactions and evaporation of water into the CO$_2$. The amount of halite that might be precipitated through mineral reactions is orders of magnitude smaller than that precipitated through evaporation, so we are only concerned with the latter process. The amount of halite that may precipitate from a given volume of saline pore water depends on the salinity of the pore water and the proportion of the pore water that evaporates. The pore water in Endurance is highly saline (brine), but its exact salinity, except at the small number (5) of sampling points, is uncertain. There may be some spatial variations in salinity within the reservoir. There is some evidence from cores that halite is present in the reservoir, indicating that pore fluids could be saturated with halite. However, fluid analyses suggest that pore fluids are under saturated with halite. The proportion of the pore water that evaporates depends on: the displacement of pore water by CO$_2$; how much water may be residually trapped; and whether there is any in flow or cycling of saline waters into the area of drying out and precipitation.

Hypothesis Name	Notes
	There may be return of saline water into the area of drying out and precipitation under conditions of continuous injection, or in response to cycles of injection and shut-in. The relationship between the amount of halite precipitated and the reduction in permeability of the rock will depend on the porosity and pore structure of the rock and where the halite precipitates (in pore throats or in the pores). Experiments have been undertaken on Bunter sandstone core from NGCL's exploratory well 42/25d-3 that involved cyclical drying and re-saturation with brine. The results show a notable reduction in permeability (approximately 85%) as the salt saturation increases from 0.05 to greater than 0.15; once 15% of the porosity has been filled with precipitated halite. Further core experiments involving cyclical injection of super-critical CO_2 under reservoir conditions and subsequent imbibation of simulated formation brine showed that this could lead to pore clogging and significant permeability reduction. However, these are small scale experiments. If the permeability is reduced in a small area, it may have no effect on the overall injectivity of a well. Therefore the results need to be considered in the context of the much larger length scales relevant to the injection boreholes and CO_2 plume. Two modelling studies to investigate the effects of halite precipitation at length scales of the injection boreholes and CO_2 plume have shown that as CO_2 is injected into the reservoir it initially spreads laterally, before rising buoyantly. The extent of lateral spreading is controlled by the injection rate and rock permeability. Since the permeability in the Bunter sandstone generally decreases with depth, the chosen injection horizon will have an impact on plume spreading and halite precipitation. Under conditions of continuous injection, significant halite precipitation starts at the base of the dry-out zone and slowly develops upwards, as capillary suctions continuously draws brine into the dry-out zone. The results indicate that a more significant process for halite precipitation is inflow of brine during periods of well shut-in and showed that injectivity can be significantly reduced if this halite precipitation zone starts to envelope the injection well due to cycles of injection and shut-in. The duration of the shut-in will be important because inflow of brine will only start to occur as CO_2 migrates away from the injection well and the pressure in the CO_2 plume decrease. If injection is restarted before the pressure drops to the extent there is significant inflow of brine, then halite precipitation will be limited. These two modelling studies consider the formation scale porosity and permeability variations with depth, but otherwise they make the idealised assumption that the Bunter sandstone is homogeneous. In the real reservoir, the rock will have heterogeneities and anisotropy which will make the 'perfect' modelled situation unlikely. These heterogeneities and effects such as viscous fingering will affect the nature of the CO_2-brine contact. It is extremely difficult to predict what the impacts of these effects might be on the relevant length scales prior to injection. There are technologies that are available to help reduce the loss of injectivity if significant halite precipitation does occur. Water washes can be used at the start of injection to remove halite build up before the next phase of drying occurs. A simulation showed that water washing before injection may be effective in reducing halite precipitation and reducing increases in well BHP during injection. However, they did not examine the effectiveness of water washing for removing existing precipitates. It was found that water washing offered benefits when applied before or following an injection cycle, compared with no water washing. There is significant experience in the use of water washes from gas production and storage reservoirs, for example salt precipitation is frequently experienced in gas production reservoirs containing moderate and higher salinity formation waters. Water washing is routinely used to remove precipitates, although the original permeability is rarely recovered, mainly because the diversion of wash water is inefficient. Although there is less experience of using of washing to remove precipitates and recover injectivity in CCS schemes, this has been achieved, for example washing was used successfully at Snohvit. Seawater would be used for washing. There is the possibility that adding seawater to the reservoir could push conditions into the hydrate stability zone. Formation of hydrate could also block pores and reduce permeability, but this can be prevented by adding MEG to the injected water. Use of MEG to prevent hydrate formation is an established method. It is also possible that there could be precipitation of other

Hypothesis Name	Notes
	minerals, such as anhydrite, but such reactions can also be controlled. From the preceding discussion, it is clear that the design and operation of the system are both important and need to complement each other, in order to minimise the potential for halite precipitation. However, other factors in the design build further confidence that halite precipitation will not prevent injection of CO_2 at the required rate. The system has more than one injection well, such that if injectivity becomes a problem at one well, this well can be shut-in while remedial measures are taken. This may be form part of the routine system operational maintenance for example, routine water washing. The work that has been undertaken to understand the conditions under which halite precipitation may be an issue for injectivity can be used to optimise the injection system design (injection horizon, borehole diameter(s), injection pressure, system operation and maintenance, etc.), however because the design has not yet been finalised there remains some uncertainty in the amount of redundancy. Overall, although halite precipitation is expected to occur, there is sufficient evidence to build moderate to good confidence that this will not lead to a significant loss of injectivity. Additional confidence can be gained in that water washing can be used to remove halite precipitates and if necessary, this can be done regularly as part of the routine system operation. On this basis confidence in support of this hypothesis (green) is assigned a value of 0.6. This is a minimum amount of confidence in support of this hypothesis. A higher level of confidence has not been assigned at this stage because there are still a number of things that are not known. This includes the final, optimised, injection system design which will have to balance the issue of halite precipitation against other important design factors. There are also uncertainties that cannot easily be resolved, for example the potential effects of reservoir heterogeneity and uncertainties associated with limited experience of injecting CO_2 into saline aquifers and the Bunter sandstone at this location. On this basis there is quite a lot of uncommitted confidence (white space). Modelling shows that under certain circumstances it is possible to get significant loss of injectivity through halite precipitation. Therefore it is appropriate to assign some confidence against this hypothesis (red). However, this should only be a small amount because in order for this hypothesis to be false would also require water washing and other potential mitigation measures to be unsuccessful. Therefore there is only very low confidence against this hypothesis. These confidence values are consistent with the opinions given in a workshop by a range of oil industry experts and the opinions provided by a wider range of experts to NGC
1.2.1.2 Other precipitates will not prevent the required storage capacity being accessed at the required injection rate	No additional reactions have been identified that are likely to cause significant clogging adjacent to the injection wells during the operational phase. Geochemical modelling shows that small amounts of anhydrite and calcite may precipitate and small amounts of dolomite may dissolve. Confidence in the geochemical modelling results is high, however there are some uncertainties because only limited underpinning thermodynamic data is available for the conditions in the reservoir. Also only a small number of samples are available from the reservoir, so these may not fully capture the spatial variability in the reservoir
1.2.2 Chemical effects away from the point of injection will not prevent the required storage capacity being accessed at the required injection rate	Geochemical modelling shows that small amounts of anhydrite and calcite may precipitate and small amounts of dolomite may dissolve, but would not significantly change the permeability of the reservoir. Halite precipitation through drying out could also occur and is more likely to affect the permeability. However, this would be much less significant than close to the injection well, as demonstrated by reactive transport modelling and reservoir simulation modelling. The total amount of halite that could be precipitated is small compared with the pore volume of the reservoir. Even if the permeability of the reservoir is locally reduced, the reservoir is so large that alternative flow paths could be exploited. Areas of locally reduced permeability will act as baffles, in a similar way to the lower permeability ooid rich layer at the top of the L2 horizon, which is not expected to impact injection rate or storage capacity. The evidence for this hypothesis is the same as hypothesis 1.2.1 and there is additional confidence for this hypothesis due to the availability of alternative flow paths. This is illustrated by the case modelled including multiple vertical baffles. Therefore the confidence in support of this hypothesis is good to very good.

Hypothesis Name	Notes
	There is some residual uncertainty because only limited thermodynamic data are available to underpin the geochemical modelling for the conditions in the reservoir and only a small number of samples are available from the reservoir, so these may not fully capture the spatial variability in the reservoir. There is also conflicting evidence for the halite saturation in the reservoir: there is some evidence from cores that halite is present in the reservoir, indicating that pore fluids could be saturated with halite; fluid analyses suggests that pore fluids are under saturated with halite. This conflicting evidence will have some effect on the results of the geochemical modelling and calculations of the amount of halite that could precipitate in response to drying out. Further information is also provided in the risk assessment report
1.3 Physical effects will not prevent the required storage capacity being accessed at the required injection rate	
1.3.1 Physical features will not prevent the required storage capacity being accessed at the required injection rate	Evidence for the geological structure of the reservoir and hydrogeological properties is available from seismic data and a number of boreholes, including detailed information from NGCL's appraisal well 42/25d-3. There is no evidence of structures that could lead to compartmentalisation of the reservoir. Substantial additional evidence for the properties of the Bunter at the regional scale is provided in the literature. An injection test showed that it was possible to inject water into Endurance and that there was no evidence for lateral boundaries to the system for 1.2km, which is the spatial limit of the test. In addition, there is evidence that the Bunter sandstone at Endurance is hydraulically connected to the wider regional Bunter sandstone. These two observations give confidence that there are no significant barriers to flow that would prevent the static capacity being accessed. Reservoir simulations that are based on a geological model that is consistent with the observations show that the required storage capacity can be accessed at the required injection rate. Overall, there is very good evidence from the injection tests that there are no physical features that could prevent the required storage capacity being accessed at the required injection rate and this is consistent with seismic and borehole data. If necessary, a brine producer could be installed also, further militating against this risk maturing. Therefore, overall, there is very good confidence in this hypothesis. There is some residual uncertainty due to the potential presence of sub-seismic faults. However, due to the size of the reservoir, it is unlikely that these faults could be sufficiently continuous and interconnected to prevent fluid migration at the reservoir scale. An uncertainty in the reservoir models is that the density of the CO_2 is an approximation that does not include the effects of impurities. Work elsewhere has identified that incorrect phase diagram assumptions can be a risk to accurate pressure predictions. Further information is also provided in the risk assessment report
1.3.2 Physical alteration due to physico-chemical processes will not prevent the required storage capacity being accessed at the required injection rate	Geochemical modelling shows that injection of CO_2 could lead to small amounts of anhydrite and calcite precipitating and small amounts of dolomite dissolving. While dolomite is present in the Bunter sandstone, it does not contribute significantly to the rock strength (Mackay, 2015) therefore dissolution of dolomite will not lead to significant reservoir compaction, loss of porosity and permeability. A layer with elevated concentrations of dolomitic ooids is present towards the top of the L2 horizon on the reservoir. Even if dissolution of these ooids leads to some localised mechanical compaction and reduction in porosity and permeability, this is unlikely to be sufficient to prevent fluid migration at the reservoir scale. Close to the injection wells, pressure changes, cooling and geochemical reactions could all potentially contribute to sand generation and clogging of the wells. Injection pressures will be managed to prevent fracturing of the reservoir, but there is expected to be some thermal fracturing immediately adjacent to the perforated sections of the injection wells. There will be pressure cycles associated with daily variations in the supply of CO_2 depending on operation of the power station and periods of well shut-in for maintenance. There could also be shock waves associated with phase changes in the well, especially during injection start-up. The potential significance of this and design and operational mitigation methods are

Hypothesis Name	Notes
	being assessed. The geochemical reactions close to the wells are expected to be the similar to those further away. Since halite and calcite cements do not significantly bind the Bunter sandstone, these reactions are not expected to lead to significant sand generation and clogging. Similarly, even if water washing results in dissolution of these minerals it should not lead to significant sand generation. Even if there some sand generation, the wells are being designed to minimise the risk of sand clogging and it will also be possible to remove sand during well maintenance. Other factors in the design build further confidence that sand clogging will not prevent the required storage capacity being accessed at the required injection rate. The system has more than one injection well, such that if injectivity becomes a problem at one well, this well can be shut-in while remedial measures are taken. This may be form part of the routine system operational maintenance. Also, fluid flow will generally be from the well into the rock, which suggests sand clogging will be less of an issue compared with a hydrocarbon production well, where flow is from the rock into the well. Overall there is good evidence that away from the wells, alteration due to physico-chemical processes will not prevent the required storage capacity being accessed at the required injection rate. However, close to the wells there is only moderate to good evidence and this is reflected in the confidence in this hypothesis. There is no evidence against this hypothesis, but there is significant uncertainty because the injection system design, operation and maintenance are still being optimised taking into consideration a wider range of factors. There are also uncertainties associated with the limitations of the geochemical modelling and the effects of spatial heterogeneities in rock properties in the reservoir. Further information is also provided in the risk assessment report
3 The storage site will evolve towards long-term (containment) stability following closure	
3.1 The expected system evolution is towards long-term stability following closure	
3.1.1 The storage complex contains no plausible leakage pathways by which CO_2 could return to the surface or near-surface environments	
3.1.1.1 Wells/boreholes will not provide leakage paths	There are three existing abandoned wells in the structure: two older wells at the crest of the anticline and NGCL's recent appraisal well on the flank of the structure. Post-injection there will also be the abandoned injection wells. NGCL's appraisal well 42/25d-3 was constructed and sealed to modern hydrocarbon industry standards, but was not optimised for long-term storage of CO_2. However, it is down dip of the injection wells and is unlikely to be exposed to CO_2, therefore it is of much less concern than the crestal wells. The injection wells will not have long-term exposure to mobile CO_2 after injection, so are only a possible leakage pathway during and for a limited time period following injection. The wells are designed to minimise the chance of leakage during injection and the abandonment approach has been optimised for CO_2 storage and will be consistent with modern best practice. Leakage is more likely to occur from the two older wells in the crest of the anticline which may be exposed to a mobile CO_2 phase for a long period of time. However, these wells were completed with multiple seals over several formations presenting a 'multi-barrier' containment system. The wells would need to be subject to extensive degradation of several seals to provide a potential pathway. If well seals do degrade, salt creep may act to re-seal the well). There is the potential that an overpressure of 40-65bar could form at the bottom of the crestal wells and 90bar at the bottom of the injection wells. However, scoping calculations have shown that even for cautious assumptions, the leak rate of CO_2 from an injection or crestal well with damage to all 3 seals would be small. There is a large amount of wider experience and knowledge of the integrity of well seals from the hydrocarbon industry, wider experience from subsurface gas storage and a smaller body of experience/evidence from the EOR/CCS sector. There is lots

Hypothesis Name	Notes
	of evidence that wells can be successfully sealed, for example at a project workshop, oil industry experts noted the experience from Texas where wells have been successfully sealed to prevent leakage of CO_2 in an EOR scheme. Overall, there is good confidence that the wells will not provide leakage paths, however there is some residual uncertainty principally associated with the quality of sealing of older wells and seal integrity over very long timescales (10,000+ years). Note that poorly completed boreholes/different failure mechanisms outside the expected evolution are covered in the alternative evolution scenario (low probability events) hypothesis
3.1.1.2 Structures (faults, fracture zones and so on) will not provide leakage paths	To provide a leakage pathway, structures would need to form a high permeability connection from the CO_2 in the Bunter to the edge of the storage complex; the top Lias. If there was a single permeable feature through such a thick sequence it could be expected to be observed in seismic data. No such structures have been observed in the seismic data. Smaller interconnected faults/fractures could also provide a pathway but there is no evidence of significant faulting or fracturing and the overburden has very low permeability so connection between structures would be limited. In addition it is unlikely the fractures would be open due to the fracture closure pressure. There are three layers of halite/anhydrite above the Bunter sandstone all of which are likely to creep and reseal any permeable features. It is not anticipated that events such as induced seismicity would be sufficient to create such structures, in particular noting that fractures in the halite would be likely to close by creep. In addition, the adjacent gas fields, which have trapped natural gas in the Bunter sandstone for millions of years, provide strong analogous evidence for the sealing properties of the Röt clay and halite formations and demonstrate a lack of structures that can provide leakage pathways. Together, these observations of the geological structure and of other analogous systems provide very high confidence against leakage. There is some residual uncertainty, for example if there any sub-seismic features, however these would also need to be open which is unlikely given the fracture closure pressure. Further information is also provided in the risk assessment report
3.1.1.3 Confining rock (primary seal, secondary seal and overburden to ultimate seal) has sufficient integrity	There is substantial evidence of the excellent sealing properties of the halite and indeed the Röt clay underneath it. The Röt clay and Röt halite are also overlain by further sealing formations. Moreover the adjacent gas fields, which have trapped natural gas in the Bunter sandstone for millions of years, provide strong analogous evidence for the sealing properties of the Röt clay and halite formations. Additional confidence is provided by very cautious scoping calculations of potential diffuse leak rates assuming there are connected, open, fractures through the Röt Clay and Röt Halite and ignoring the presence of overlying sealing formations. Even with these very cautious assumptions the leak rates are very small. Overall, observations of the caprock and of other analogous systems provide very high confidence against leakage. Further information is also provided in the risk assessment report
3.1.2 The CO_2 will not migrate laterally beyond the defined storage complex	
3.1.2.1 Free CO_2 will not migrate laterally beyond the defined storage complex	Although there will be some lateral migration of free CO_2 adjacent to the injection wells, the dominant direction of migration in the reservoir will be upwards, driven by buoyancy, to the top of the reservoir. Free CO_2 will then migrate laterally along the top of the reservoir to the crest of the anticline. Even accounting for the effects of anisotropy, heterogeneity and lower permeability beds that could act as baffles, the dominant direction of CO_2 migration will still be up-dip towards the crest of the anticline. Because the structure is so large, it is very unlikely that low permeability beds will be sufficiently continuous, or the anisotropy sufficiently great, to deflect CO_2 laterally beyond the defined storage complex. Secondary factors that build additional confidence that free CO_2 will not migrate beyond the defined storage complex are dissolution and residual trapping of free CO_2 and the presence of halite cements that reduce the porosity/permeability of the sandstone outside of the storage site (except between Endurance and the seabed outcrop of the sandstone). Overall it is difficult to conceive that even a very small residual amount of CO_2 could

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	migrate laterally beyond the defined storage complex and even then not enough to challenge claims of containment. Therefore, the confidence for this hypothesis is very high. Further information is also provided in the risk assessment report
3.1.2.2 Dissolved CO_2 will not migrate laterally beyond the defined storage complex	CO_2 will dissolve in the pore water in the reservoir and will then migrate by diffusion. Dissolution of CO_2 will also increase the density of the water causing it to sink to the base of the reservoir and then spread laterally down dip, above the Bunter shale. The limited gas-water contact area at the base of the 'bubble' of gas at the top of the anticline will help reduce the rate of dissolution and the density contrast between CO_2 free and CO_2 charged pore water will be very small (0.1%), so the driving force for sinking of CO_2 charged water will be very small. Model results indicate dissolved CO_2 will first reach the base of the reservoir after 1400 years and will have convected laterally a distance of 1000m after 7000 to 15,000 years, depending on the reservoir permeability and heterogeneity. Diffusion, dissolution and convection will be ongoing processes and are likely to be important in the ultimate fate of CO_2. For example, 50 ~ 65% of the CO_2 may be dissolved in the brine after 18,000 years. Thermohaline convection may also occur in the reservoir, but this was not accounted for in the diffusion, dissolution and convection models. Thermohaline circulation will also affect convection and lateral spreading of dissolved CO_2. Over very long timescales dissolved CO_2 might continue to migrate laterally beyond the confines of the Endurance structure through diffusion and density driven flow. However this will be a very slow process and the halite cemented zone outside the Endurance structure will act to further retard migration of dissolved CO_2. Overall, the timescales for migration of dissolved CO_2 outside the structure will be very long and the flux will be so low that it is not detectable or monitorable. That is, it would not be in any way 'significant', challenging containment arguments or interacting with other resources. On the basis of this interpretation (that detectable or monitorable fluxes are required to fail this hypothesis) there is very high confidence, in support of this hypothesis. Further information is also provided in the risk assessment report
3.1.3 Predictions of post-closure behaviour of the containment complex predict evolution towards long-term stability for any plausible boundary conditions	
3.1.3.1 Multi-phase flow models predict evolution towards no flow of free and dissolved CO_2	The rate of movement of both free and dissolved CO_2 will decrease significantly over time for example, due to trapping in the anticline, with the biggest rate of change being in early decades. By 100s to 1000s of years the rate of change and indeed associated risk, will continue to decrease and will be very low. Some gas may continue to dissolve and density contrasts and diffusion mean the dissolved gas may migrate, but this impact will not be significant. This is further discussed under hypothesis 3.1.2.2. Diffusion, dissolution and convection are likely to be important processes in the ultimate fate of CO_2. For example 50 ~ 65% of the CO_2 may be dissolved in the brine after 18,000 years. Overall there is very good evidence from conceptual process-based models and quantitative calculations that the evolution will be towards no flow and thus stability. Further information is also provided in the risk assessment report
3.1.3.2 Geomechanical models predict evolution towards no deformation due to CO_2 in the long term	CO_2 uplift will track the rate of change of pressures within the system. This implies that the majority of uplift may occur during injection and for a period post-injection, although there is uncertainty concerning the true likely duration of timescales. It may then be followed by a decrease in the seabed surface elevation as pressures dissipate and some or all of the uplift reverses. There will be uplift above the 'bubble' of CO_2 trapped at the crest of the anticline and potentially also above the plume of CO_2 migrating from the injection wells to the crest. Uplift above both areas will decrease as the pressure dissipates. At a project workshop, oil industry experts, including an expert in geomechanics, argued that there is high confidence that the deformation will dissipate with time and stabilise, as it is not plausible that the pressure will do anything other than decrease and equilibrate in the longer term. The results of geomechanical modelling indicate that seabed uplift above the crest of

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	the anticline will be a best estimate of 9cm, to a maximum of 15cm, but this will be spread over a wide area so the impact on seabed gradients will be very small. Overall there is very good confidence that the system will evolve towards no geomechanical deformation in the long term
3.1.3.3 Geochemical models predict evolution towards long-term chemical stability	Precipitation and dissolution will occur in the short term but thereafter the trend will be towards thermodynamic equilibrium, even if true equilibrium will not be reached for all chemical components. More broadly, there is no reason to expect that continual significant change will occur. Effects such as dissolution of carbonate and dissolution of clays will have an impact but not over the long-term. The stored CO_2 and/or surrounding fluids and/or surrounding rocks will evolve physically and/or chemically towards long-term stability. As such there is very good confidence in evolution towards long-term stability on the basis of conceptual models of understanding, supported by existing geochemical models
3.1.4 Analogues support evolution towards long-term stability	There are no directly comparable analogues. However there is evidence from similar structures for example natural CO_2 accumulations in anticlinal structures elsewhere in the world that there is the possibility for very long-term storage. The adjacent natural gas fields in the Bunter sandstone provide similar confidence. Overall, the available analogues, even if not directly similar, provide very good confidence in long-term stability over the timeframes of interest
3.2 There will be no ‘high impact, low probability’ events that could significantly disturb the system following closure	
3.2.1 Tectonic processes (active faulting, seismic pumping, uplift, subsidence) will not lead to significant disturbance of the stored CO_2	
3.2.1.1 Geological setting is sufficiently stable that the probability of transient tectonic processes (earthquakes, volcanic eruptions) disturbing the storage complex is insignificant	
3.2.1.1.1 Tectonic setting is remote from plate boundaries or recognised zones of intra-plate tectonic activity (including activity driven by glaciation)	The North Sea tectonic setting is known to be stable. Plausible events that could occur over the next 100s to 1000s of years would not be sufficient to disturb the integrity of the system. The presence of existing gas resources that have been trapped in the Bunter sandstone for millions of years, withstanding tectonic events, provides analogous evidence of performance. Overall therefore there is very good confidence for this hypothesis. Note that glaciation is beyond the main timescales being considered here (this is more relevant for sub-arctic systems)
3.2.1.1.2 Geology (lithologies and structures) has not been significantly disturbed by past tectonic processes over relevant timescales	There is no evidence from existing rock formations that they have been significantly disturbed by recent tectonic activity. More broadly the tectonic history of the North Sea is relatively well known and there have been no ‘recent’ historic events of a magnitude that could cause an issue for CCS storage. The long-term tectonic stability is reflected in the adjacent structures that have trapped natural gas for millions of years without being disturbed by tectonic activity. On this basis, confidence for this hypothesis is very high
3.2.1.2 Predicted impacts of tectonic processes, if they occur, will be insignificant	

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3.2.1.2.1 Models predict that tectonic processes that could plausibly occur will not cause leakage of CO_2 out of the storage complex	'Models' here are qualitative conceptual models, taking account of the known tectonic setting (far from plate boundaries). Geomechanical models for the behaviour of the storage complex and surrounding domains are also relevant as they provide some insights into how the CO_2 storage system would respond to seismicity. Given the location far from any tectonic plate boundaries and fundamental theoretical understanding of how seismic events impact on deep subsurface environments, there is very high confidence in the truth of this hypothesis. Additional analogue evidence that supports the very high confidence in this hypothesis is provided by the adjacent structures that have trapped natural gas for millions of years without being disturbed by tectonic processes
3.2.1.2.2 Models predict that tectonic processes that could plausibly occur will not lead to significant direct or indirect impacts from CO_2 in domains outside the storage complex	The arguments given for 3.2.1.2.1 also apply here - plausible size tectonic events will not be sufficient to cause significant impacts on storage, based upon analogues and historical experience and observations of impacts of events. Connected open fractures through the overlying rocks would need to be created to significantly challenge containment/lead to observable impacts to receptors via vertical pathways. Based on the tectonic setting and regional history of measured seismic events, the plausible events are not likely to be sufficient to create such pathways. Even if a tectonic event was to occur that reactivated existing fractures, or created new fractures, creep of the halite would close these fractures. Overall, although there are no system-specific quantitative models, nevertheless the 'conceptual' models provide very high confidence
3.2.2 Well bore/seal failure will not lead to significant disturbance of the stored CO_2	
3.2.2.1 Well bores/seals will not fail	
3.2.2.1.1 All boreholes/wells within the site will be effectively sealed, making the probability of failure insignificant	
3.2.2.1.1.1 Injection wells will be effectively sealed	
3.2.2.1.1.1.1 Cement plugs and seals will be effective	
3.2.2.1.1.1.1.1 Past practice and observations of previous installations indicates seal durability	The injection well seals will only be in contact with CO_2 during injection and for a limited time post-injection, as CO_2 migrates to the crest of the anticline. Therefore, durability with respect to CO_2 of the seals in the injection wells only needs to be ensured over a short period of time. The wells will be designed, constructed and sealed using durable materials with the intention of preventing leakage of CO_2. The well design will include multiple well seals over several formations presenting a 'multiple-barrier' containment system. The multiple seals are protected by the surrounding low permeability formations and creep of the halite. Therefore failure of a single seal will take a long time because the full vertical thickness of each seal will have to be degraded before it fails. To generate a continuous transmissive feature would take even longer as all three seals would need to fail and the middle seal cannot fail until either the top or bottom seal has failed and there is a continuous supply of reactive solutes. During injection, there is the potential that an overpressure of 90bar could form at the bottom of the injection wells. This pressure would rapidly decrease post-injection, would have significantly decreased by the time the injection wells are abandoned. Scoping calculations have shown that even for cautious assumptions, including a 90bar overpressure, the leak rate of CO_2 from an injection well with damage to all three seals would be small. There is a large amount of wider experience and knowledge of the integrity of well seals from the hydrocarbon industry, wider experience from subsurface gas storage and a smaller body of experience/evidence from the EOR/CCS sector. Relevant evidence from the literature includes Zhang and Bacchu (2011). There is lots of evidence that wells can be successfully sealed, for example at a project workshop, oil industry experts noted the experience from Texas where wells have been successfully sealed to prevent leakage of CO_2 in an EOR scheme.

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	Overall there is high confidence in performance, although there is some confidence ‘against’ as experience shows occasionally well seals can fail. However, this is considered to be of low likelihood and multiple seal failures would be needed to result in leakage. Further information is also provided in the risk assessment report
3.2.2.1.1.1.1.2 Laboratory observations of well sealing materials is suggestive of durability	As for 3.2.2.1.1.1.1.1, it is notable that the well seals for the injection boreholes will be specifically designed to provide resistance to CO_2. There is a very large body of literature information, backed-up by experimental and modelling work and practical experience, on cement degradation mechanisms. Long-term cement degradation has been studied in the context of CCS and specifically in the context of the site specific conditions at Endurance. Furthermore, degradation of cementitious barriers over timescales of 100,000 to 1,000,000+ years has been extensively studied in the context of radioactive waste disposal. Overall, there is very high confidence in the choice of well sealing material and its robustness, informed by past and present laboratory studies undertaken by a range of bodies in the civil engineering, CCS and nuclear sectors. Further information is provided in the risk assessment report
3.2.2.1.1.1.2 Creep of the halite will seal the wells over relevant timeframes	There is good evidence that the Halite will creep, but it is not possible for this to happen whilst the drilling fluids are in the borehole. Whilst the seals are intact the drilling fluids may be absorbed into the wallrocks and once a seal has failed, the fluids can leave the borehole through the seal into the reservoir. Experience in other fields provides strong confidence that over time drilling fluid will be absorbed into shaley beds within the section, allowing convergence of the borehole. However, it cannot be proven that this process will occur. Were the basal cement plug to fail while convergence of the borehole is incomplete there is a possibility that there could be an open pathway for CO_2 migration to the second cement plug above the open section. Once the basal plug has failed, any remain drilling fluid will be able to leave the borehole and it will be possible for the borehole to close by creep. Therefore the pathway for CO_2 migration would not be permanent. Creep rates are influenced by a variety of considerations (salt type, pressures, temperatures, geometry) and are thus subject to uncertainty but it is reasonable to expect that effective re-sealing due to creep will be established before the next seal fails, if not immediately. There is high confidence in support of this hypothesis because multiple seal failures would need to occur before the open section of the borehole has converged and sealed through creep of the halite. There is remaining uncertainty as to whether the creep rate would be sufficient for certain leak scenarios; indeed there must be some confidence against this hypothesis, reflecting that a leak could occur concurrent with or shortly after well seal failure and that the creep rate would not be sufficient to close the borehole on that timescale. Further information is provided in the risk assessment report
3.2.2.1.1.2 Other wells will be effectively sealed	
3.2.2.1.1.2.1 Cement plugs and seals will be effective (1)	
3.2.2.1.1.2.1.1 Past practice and observations of previous installations indicates seal durability (1)	NGCL’s appraisal well, 42/25d-3, was constructed and sealed to modern hydrocarbon industry standards, but was not optimised for long-term storage of CO_2. However, well 42/25d-3 is down dip of the injection wells and is unlikely to be exposed to CO_2, therefore it is of much less concern than the crestal wells. The crestal wells will be in contact with CO_2 over much longer time scales, so durability of the well seals over these longer time scales is important. The crestal wells were not sealed with CO_2 storage in mind, however the wells were abandoned with multiple seals over several formations presenting a ‘multiple-barrier’ containment system. The multiple seals are protected by the surrounding low permeability formations and creep of the halite. Therefore failure of a single seal will take a long time because the full vertical thickness of each seal will have to be degraded before it fails. To generate a continuous transmissive feature would take even longer as all three seals would need to fail and the middle seal cannot fail until

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	either the top or bottom seal has failed and there is a continuous supply of reactive solutes. Of the two crestal wells, the performance of the well, which was sealed in the 1970s, is the most uncertain - there is incomplete abandonment information and it is known that a different type of cement was used compared to the borehole that was sealed in the 1990s. There is the potential that an overpressure of 40-65bar could form at the bottom of the crestal wells. However, scoping calculations have shown that even for cautious assumptions, the leak rate of CO_2 from a crestal well with damage to all three seals would be small. There is a large amount of wider experience and knowledge of the integrity of well seals from the hydrocarbon industry, wider experience from subsurface gas storage and a smaller body of experience/evidence from the EOR/CCS sector. There is lots of evidence that wells can be successfully sealed, for example at a project workshop, oil industry experts noted the experience from Texas where wells have been successfully sealed to prevent leakage of CO_2 in an EOR scheme. There is moderate to high confidence in seal durability because there is evidence that the wells were constructed and abandoned to good standards and the wells contain multiple, long, concrete seals. However, because the crestal wells were not constructed and abandoned consistent with current good practice techniques for storage of CO_2 there is also some evidence against this hypothesis. There is some uncertainty due to incomplete knowledge concerning the abandonment status of the crestal wells and information on their construction quality assurance. There is some confidence ‘against’ this hypothesis because experience shows occasionally well seals can fail. However, this is considered to be of low likelihood and multiple seal failures would be needed to result in leakage. The confidence values for this hypothesis compared to the equivalent hypothesis for the injection wells (hypothesis 3.2.2.1.1.1.1.1) reflect lower confidence in the older well seals’ performance and the longer exposure to CO_2. There is more confidence against the hypothesis because the old wells were not sealed for CO_2 storage. There is also more uncertainty for the older wells. Further information on abandonment of the crestal wells is provided in the risk assessment report
3.2.2.1.1.2.1.2 Laboratory observations of well sealing materials is suggestive of durability (1)	Class B cement was used for the 1970s borehole and all later boreholes have been sealed with class G cement. There is little bespoke laboratory testing demonstrating durability under expected conditions, but there is a large volume of literature data including (for example) work from other industries on geological disposal of radioactive wastes that will evolve gas. Laboratory experiments associated with those and other industries indicate cements can degrade when exposed to sulphate, chloride and CO_2. However reaction with CO_2 and carbonate precipitation can lead to seals being improved. Overall, given worldwide experience of sealing boreholes, ‘generic’ laboratory experiments and knowledge that the older boreholes were sealed using materials that are consistent with laboratory experiments for a range of similar material types, there is high confidence that existing laboratory experiments can be extrapolated to provide evidence of performance for the timeframes of interest to this assessment (100s to a 1000 years). Further information is provided in the risk assessment report
3.2.2.1.1.2.2 Creep of the halite will seal the wells over relevant timeframes (1)	There is good evidence that the Halite will creep, but it is not possible for this to happen whilst the drilling fluids are in the borehole. Whilst the seals are intact the drilling fluids may be absorbed into the wallrocks and once a seal has failed, the fluids can leave the borehole through the seal into the reservoir. Experience in other fields provides strong confidence that over time drilling fluid will be absorbed into shaley beds within the section, allowing convergence of the borehole. However, it cannot be proven that this process will occur. Were the basal cement plug to fail while convergence of the borehole is incomplete there is a possibility that there could be an open pathway for CO_2 migration to the second cement plug above the open section. Once the basal plug has failed, any remain drilling fluid will be able to leave the borehole and it will be possible for the borehole to close by creep. Therefore the pathway for CO_2 migration would not be permanent.

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	Creep rates are influenced by a variety of considerations (salt type, pressures, temperatures, geometry) and are thus subject to uncertainty but it is reasonable to expect that effective re-sealing due to creep will be established before the next seal fails, if not immediately. There is moderate to high confidence in support of this hypothesis because multiple seal failures would need to occur before the open section of the borehole has converged and sealed through creep of the halite. There is remaining uncertainty as to whether the creep rate would be sufficient for certain leak scenarios; indeed there must be some confidence against this hypothesis, reflecting that a leak could occur concurrent with or shortly after well seal failure and that the creep rate would not be sufficient to close the borehole on that timescale. For the older wells, it is noted that creep may already have started, so there is slightly less confidence against this hypothesis compared with the equivalent hypothesis for the new injection wells (3.2.2.1.1.1.2). There is also more uncertainty and slightly less confidence for this hypothesis compared with the equivalent hypothesis for the new injection wells. This reflects the fact that these wells will be in contact with CO_2 for a much longer time period than the injection wells, the well construction and abandonment was not optimised for storage of CO_2 and there are uncertainties associated with the details and quality of construction and abandonment. Therefore, if a well seal fails, it is more likely that the well will be in contact with CO_2 and CO_2 will be able to migrate past the seal before the borehole is closed by creep of the halite. Further information is provided in the risk assessment report
3.2.2.1.2 Induced seismicity will not lead to well seals being significantly damaged or bypassed	Induced seismicity is most likely to occur during injection when the stress gradients are greatest, however there may also be induced seismicity post-injection as the system evolves to steady state. The injection wells will be at most risk of damage due to induced seismicity. The abandoned crestal wells and NGCL's appraisal well (42/25d-3) are further away and so are at lower risk, although they may still be exposed to weak induced seismicity due to pressure changes throughout the reservoir. Induced seismicity of sufficiently high magnitude may potentially damage the cement around the casing of the injection wells during injection and the casing cement and concrete plugs following abandonment. Such induced seismicity has the potential to damage the cement around the casing of the other wells and the concrete plugs, during and post-injection. The injection wells are being designed to minimise the risk of damage from thermal fracturing and induced seismicity during injection. The injection process will be managed carefully to avoid pressures that could lead to induced seismicity sufficient to cause any sort of impact, for example peak bottom hole pressures will be kept below the fracture closure pressure. Once injection is complete, the injection wells will be abandoned with multiple seals, including at the primary seal and overburden horizons. When the seals are installed, the reservoir pressures and stresses will have diminished from their operational peak, which reduces the potential for damage from induced seismicity. It is considered very unlikely that induced seismicity could lead to these multiple seals being significantly damaged or bypassed. Similarly the existing abandoned wells have multiple seals and again it is considered very unlikely that induced seismicity could lead to these multiple seals being significantly damaged or bypassed. The pressure changes throughout the wider reservoir will be far below the fracture closure pressures, so the risk of significant induced seismicity is low. For all boreholes, even if there was to be an issue, the halite would creep and act to close any such fractures, although depending upon the creep rate this may not happen immediately. Overall there is very high confidence that induced seismicity will not challenge the performance of the sealed boreholes. Further information is provided in the risk assessment report
3.2.2.2 Predicted impacts of well bore/seal failure, if it occurs, are insignificant	

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3.2.2.2.1 Models predict that well failure will not cause leakage of CO_2 out of the storage complex	Conceptual and numerical models considering the potential for leakage if there is well failure, provide moderate to high confidence that there will not be monitorable/observable leakage of CO_2 out of the complex if well bore/seal failure occurs. This is because: • It is very unlikely that any failure, given the multiple seals, length of the wells and effects of the halite, would lead to an open pathway to the seabed • The CO_2 pressures at the historic boreholes (AGR, 2015c) may not be sufficient to provide a driving force for CO_2 migration through a pathway that has some failure but is not open/transmissive • The CO_2 pressure at the injection wells will dissipate after injection Scoping calculations confirm that even if multiple well seal failure occurs and an open annular fracture extends the length of the well (a very unlikely, cautious calculation scenario), leaks of the order of 0.01 - 0.02% of the injection flux may occur. This bounding estimate for an unlikely scenario would not be sufficient to challenge containment and may not be observable by monitoring. However, this very low probability scenario is reflected in some confidence against this hypothesis. Further information is provided in the risk assessment report
3.2.2.2.2 Models predict that well bore/seal failure will not lead to significant direct or indirect impacts from CO_2 in domains outside the storage complex	All the arguments for 3.2.2.2.1 are also relevant here (hence there is some dependence, which in this case is taken into account when assigning confidence values) - there is very low likelihood of observable/significant impacts even if a bore/seal failure does occur. In principle in the 'worst case' (not plausible) of an open borehole there is the potential for some impact on benthic fauna, but it is expected that even in this case any impacts would be very localised and will not significantly reduce biodiversity, biomass/productivity. Here, the test of 'significance' is that impacts are unlikely to be observable. Similarly there is confidence there will be no observable impact higher up the food chain. The recent RISCS EU study outputs (RISCS, 2014) are supportive of this conclusion. It is suggested that a marine environment change of 1 or more pH units would be necessary for observable impacts. Generic studies from RISCS on North Sea conditions indicates this requires very high and sustained release fluxes of CO_2 (1500 Tonnes/day leakage to the water column from a point source), significantly higher than would be plausible even in the most unlikely leaky borehole scenario for the system being assessed here. Scoping calculations indicate that even at the ~1 Tonnes/day rate that could occur for the present system (in the very unlikely event that multiple well seal failure occurs and an open annular fracture extends the length of the well), impacts would be very limited. Overall there is very good confidence in support of this hypothesis, although there is some confidence against because in principal a cautious, but plausible, leak rate might lead to some very localised impacts. Further information is provided in the risk assessment report
3.2.3 Inadvertent human intrusion will not lead to significant disturbance of the stored CO_2	
3.2.3.1 There is insignificant likelihood of inadvertent human intrusion	
3.2.3.1.1 There are no economic resources that would cause intrusive activities to penetrate the storage complex	It is known that there are very deep hydrocarbon resources in the area of the immediately adjacent Garrow field. It is plausible that these could potentially extend laterally to below the Endurance structure, but it is not clear whether the resources would be connected or separate. On that basis it is plausible that there may be some future interest in the economic resources that might underlie the storage system. There is moderate to high uncertainty in this hypothesis, as it is not clear whether there are such resources or whether it would be necessary to penetrate the Endurance structure to access them. However, any evidence that is available is against this hypothesis
3.2.3.1.2 People with the technical capability to intrude into the storage complex would be able to	There is very high confidence for this hypothesis. As noted for 3.2.3.1.1, any hydrocarbons that may underlie the Endurance structure will be very deep. It is extremely unlikely that a future group with the technical capability to explore for very

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recognise the existence of CO_2 and take appropriate measures	deep resources in the marine environment would not either know about (due to records etc.) or otherwise detect and avoid the CCS system
3.2.3.2 Predicted impacts of human intrusion, if it occurs, due to the stored CO_2 are insignificant	
3.2.3.2.1 Future human groups responsible for any unintentional intrusion would implement mitigating actions sufficient to ensure mitigating impacts	As noted for 3.2.3.1.1, any hydrocarbons that may underlie the Endurance structure will be very deep. There is very high confidence in this hypothesis as there are strong arguments that any group with the technical capability to intrude accidentally would also be capable of (for example) sealing the intruding borehole to rectify any impacts and would almost certainly be required to do so by contemporary permitting regimes and so on
3.2.3.2.2 Impacts associated with any unmitigated intrusion events would be insignificant	
3.2.3.2.2.1 Models predict that any plausible human intrusion will not cause leakage of CO_2 out of the storage complex	In the unlikely event that inadvertent human intrusion happens in the future into the CO_2 storage system and if those who intrude do not then abandon wells consistent with ensuring no leakage, it is conceivable (if arguably very unlikely) that an open transmissive borehole feature could be left as a result. On this basis it is possible that observable leakage could occur. Therefore, there must be high confidence against this hypothesis
3.2.3.2.2.2 Models predict that any plausible human intrusion will not lead to significant direct or indirect impacts from CO_2 in domains outside the storage complex	All the arguments for 3.2.2.2.1 are also relevant here (hence there is some dependence) - there is very low likelihood of observable/significant impacts even if a bore/seal failure does occur. In principle in the ‘worst case’ (not plausible) of an open borehole there is the potential for some impact on benthic fauna, but it is expected that even in this case any impacts would be very localised and will not significantly reduce biodiversity, biomass/productivity. Here, the test of ‘significance’ is that impacts are unlikely to be observable. Similarly there is confidence there will be no observable impact higher up the food chain. The recent RISCS EU study outputs (RISCS, 2014) are supportive of this conclusion. It is suggested that a marine environment change of 1 or more pH units would be necessary for observable impacts. Generic studies from RISCS on North Sea conditions indicates this requires very high and sustained release fluxes of CO_2 (1500 Tonnes/day leakage to the water column from a point source), significantly higher than would be plausible even in the most unlikely leaky borehole scenario for the system being assessed here. Scoping calculations indicate that even at the ~1 Tonnes/day rate that could occur for the present system in the very unlikely event that multiple well seal failure occurs and an open annular fracture extends the length of the well, impacts would be very limited. Overall there is very good confidence in support of this hypothesis, although there is some confidence against because in principal a cautious, but plausible, leak rate might lead to some localised impacts. Further information is provided in the risk assessment report
3.2.4 Sabotage that does not affect operations will not lead to significant disturbance of the stored CO_2	
3.2.4.1 There is insignificant likelihood of sabotage	Impacts to operations are out of scope of this element of the assessment. On that basis, sabotage scenarios either consider impacts to the heads of the old wells distant from the injection point, or to any well head once injection has completed. This would require intentional damage to well-heads at the seabed for example by using submersibles. Given the difficulties of achieving this and the very limited impacts that would occur (which would significantly limit motivation) there is a strong argument that such sabotage is extremely unlikely to occur. Therefore there is very high confidence in support of this hypothesis
3.2.4.2 Predicted impacts of any sabotage, if it occurs, are insignificant	

Hypothesis Name	Notes
3.2.4.2.1 Models predict that any plausible sabotage events will not cause leakage of CO_2 out of the storage complex	Conceptual models considering the potential for leakage if there is well failure give confidence that there will not be monitorable/observable leakage of CO_2 out of the complex if well head damage (that is, conceivable sabotage) occurs. This reflects all of the arguments made in 3.2.2.2.1 that well failure will not cause leakage out of the storage complex. However, in addition here, it is key to note that sabotage of this kind will almost certainly not damage any of the borehole seals as damage to the well head is unlikely to damage the top seal in a borehole and will not influence lower seals at all. In effect, this scenario will be very similar to the Expected Evolution scenario. Cautious scoping calculations for a leaky well scenario show that even if sabotage could result in leakage, or accelerated seal degradation, the leakage fluxes and potential impacts would be small. Therefore there is very high confidence in support of this hypothesis. Further information is provided in the risk assessment report
3.2.4.2.2 Models predict that any plausible sabotage events will not lead to significant direct or indirect impacts from CO_2 in domains outside the storage complex	As for 3.2.4.2.1, Conceptual and numerical models considering the potential for leakage if there is well failure provide very high confidence that there will not be monitorable/observable impacts associated with CO_2 if well head damage (conceivable sabotage) occurs. This reflects all of the arguments made in 3.2.2.2.1 that well failure will not cause leakage out of the storage complex - or any other significant changes to the CO_2 distribution etc. The key argument is that sabotage of this kind will almost certainly not damage any of the borehole seals as damage to the well head is unlikely to damage the top seal in a borehole and will not influence lower seals at all. In effect, this scenario will be very similar to the Expected Evolution scenario. Cautious scoping calculations for a leaky well scenario show that even if sabotage could result in leakage, or accelerated seal degradation, the leakage fluxes and potential impacts would be small. Therefore there is very high confidence in support of this hypothesis. Further information is provided in the risk assessment report
3.2.5 Over-filling of the reservoir will not lead to significant disturbance of the stored CO_2	
3.2.5.1 There is insignificant likelihood of over-filling	
3.2.5.1.1 The capacity is known and accessibility of the capacity is known	As noted in previous hypotheses, in particular those under Hypothesis 1, there is very high confidence that the accessible capacity is much larger than the volume of CO_2 required to be injected. The volume of CO_2 to be injected into the reservoir is 7.7x107m^3 (assuming 2.86 MTPA over 20 years and a density of 700kg/m^3) compared to a likely pore volume available for CO_2 storage of 4.6 x109m^3. Confidence here therefore is similar to that arising from Hypothesis 1. Further information is provided in the risk assessment report
3.2.5.1.2 The injected CO_2 volumes can be adequately managed so as not to exceed the known accessible capacity	There is very high confidence here as this is a core part of the operational strategy. CO_2 input, pressure evolution and more broadly system evolution will be carefully monitored during injection to ensure that over-filling cannot occur. There is no reason to suggest that this operational approach will not be successful. Furthermore, as noted in previous hypotheses, in particular those under Hypothesis 1, there is very high confidence that the accessible capacity is much larger than the volume of CO_2 required to be injected. The volume of CO_2 to be injected into the reservoir is 7.7x107m^3 (assuming 2.86 MTPA over 20 years and a density of 700 kg/m^3) compared to a likely pore volume available for CO_2 storage of 4.6 x109m^3. This large excess of capacity over planned injected volume builds further confidence that CO_2 volumes can be adequately managed so that the known accessible capacity will not be exceeded
3.2.5.2 Predicted impacts of over-filling, if it occurs, are insignificant	
3.2.5.2.1 Models predict that over-filling will not cause leakage of CO_2 out of the storage complex	

Hypothesis Name	Notes
3.2.5.2.1.1 Free CO_2 will not migrate laterally beyond the defined storage complex due to over-filling	There is very high confidence for hypothesis 3.1.2.1 that free CO_2 will not migrate laterally beyond the defined storage complex. The key lines of evidence that provide confidence are: buoyancy is the dominant driving force for migration of CO_2 and migration is to the crest of the anticline; the volume of the reservoir is much greater than the volume of CO_2 to be injected; and the dimensions of the reservoir are so large that it is very unlikely anisotropy, heterogeneity and lower permeability beds could deflect CO_2 such that it migrates laterally beyond the defined storage complex. These key lines of evidence are all relevant here. There is also very high confidence that there is insignificant likelihood of overfilling (3.2.5.1). However, for illustrative purposes, the implications of an implausible case of injecting twice the intended volume of CO_2 are considered. In this case the migration behaviour of CO_2 would not be significantly changed (there may be slightly more lateral migration immediately adjacent to the wells) and the volume injected would still be small compared with the volume of the reservoir. Therefore the key lines of evidence above are all still valid and there is very high confidence in this hypothesis
3.2.5.2.1.2 Dissolved CO_2 will not migrate laterally beyond the defined storage complex due to over-filling	As discussed under 3.1.2.2, there is very high confidence that the expected evolution scenario will not lead to observable/monitorable leakage of dissolved CO_2 outside the storage complex. It is possible that there may be a small theoretical flux, but it would not be sufficient to observe, even if monitoring arrangements are in place and so would not challenge the definition of containment or cause direct or indirect observable impacts to receptors. Due to volume arguments, dilution and dissolution processes, it is proposed here that even a doubling of the amount of CO_2 injected compared to plans (argued as an illustrative, cautious, unlikely over-filling scenario) would do no more than cause a proportionate increase the flux of dissolved gas that may leave the storage complex. The flux would still be very small and would not be observable/monitorable. This means there is very high confidence that there would be no change from the expected evolution scenario arising from over-filling
3.2.5.2.2 Models predict that over-filling will not lead to significant direct or indirect impacts from CO_2 in domains outside the storage complex	Consistent with 3.2.5.2.1.1 and 3.2.5.2.1.2, there is high confidence that over-filling will not lead to any observable or monitorable flux of CO_2 out of the system, whether in free or dissolved form. It is perhaps more relevant therefore to consider the potential for indirect impacts via enhanced displacement of formation waters and enhanced uplift of the seabed. Injection of more CO_2 than planned would lead to greater discharges of potentially higher salinity waters to the seabed and water column at the seabed outcrop of the Bunter sandstone. These discharges are considered for the expected evolution scenario in a separate tree. In that tree, it is argued that there is high confidence that the injected volume of CO_2 is significantly lower than that required to lead to observable/monitorable impacts due to displacement of formation waters. For the implausible scenario that double the intended amount of CO_2 is injected, the discharge of water at the seabed outcrop would approximately double. There is high confidence that this would not be sufficient to challenge the main outcomes identified for the expected evolution scenario. It is also relevant to consider the impacts on uplift of the seabed and impacts upon other domains for example, wind farms. This is also covered in a separate tree for the expected evolution scenario. It is argued that the uplift for that scenario will not be of an order that could cause significant impacts on other structures supported by the seabed. For the implausible scenario that double the intended amount of CO_2 is injected, there would be greater uplift of the seabed. However, the amount of uplift anticipated for the expected evolution scenario is sufficiently small that even if this was more than doubled it would not lead to a notable additional risk to those structures. Together, these arguments mean that there is high to very high confidence for this hypothesis
3.2.6 Resource exploitation elsewhere does not lead to significant disturbance of the stored CO_2	

Hypothesis Name	Notes
3.2.6.1 There is insignificant likelihood of observable additional interactions	Arguments here consider the potential for extraction of hydrocarbons elsewhere in the Bunter sandstone formation, or indeed future practice of CO_2 storage elsewhere (distant) within the Bunter formation, to change the expected evolution of the current system. It does not consider the potential for additional input to the storage system being studied, which would be the topic of its own risk assessment. In evaluating this hypothesis, it is notable that pressure impacts on the Endurance structure due to activities in the Esmond field have been observed but are small. Other gas fields in the Bunter are at a similar distance or further away so it is reasonable to expect that impacts would be of a similar level and would also be very limited and indeed that the combined impacts of multiple changes on the CO_2 system during and after injection will also be small. On this basis, it is considered that pressure fluctuations due to extraction elsewhere may be observable (although they would not be significant). A further possibility is CO_2 storage elsewhere in the Bunter formation. There is the possibility that such CO_2 storage could have similar observable pressure effects on the CO_2 currently planned to be stored. However, in contrast to extraction elsewhere, this would lead to pressure increases and might increase storage capacity. Overall these arguments combine to provide moderate to high confidence that such interactions could be observable, but as evaluated under 3.2.6.2 and child hypotheses, they would not be significant. Further information is provided in the risk assessment report
3.2.6.2 Predicted impacts of significant additional interactions, if they occur, are insignificant	
3.2.6.2.1 Models predict that additional interactions due to resource exploitation elsewhere will not cause leakage of CO_2 out of the storage complex as a consequence of CO_2 storage	
3.2.6.2.1.1 Free CO_2 will not migrate laterally beyond the defined storage complex as a consequence of resource exploitation	As for 3.2.6.1, arguments here consider the potential for extraction of hydrocarbons elsewhere in the Bunter sandstone formation, or future practice of CO_2 storage elsewhere (distant) within the Bunter formation, to change the expected evolution of the current system. It does not consider the potential for additional input to the storage system being studied, which would be the topic of its own risk assessment. In evaluating this hypothesis, it is notable that pressure impacts on the Endurance structure presently due to activities in the Esmond field can be observed but are small. Other gas fields in the Bunter are at a similar distance or further away so it is reasonable to expect that impacts would be of a similar level and would also be very limited and indeed that the combined impacts of multiple changes on the CO_2 system during and after injection will also be small. On this basis, it is considered that pressure fluctuations due to extraction elsewhere are very unlikely to cause significant interactions with the stored CO_2. They may be observable within the storage complex in terms of fluctuating pressures, but they will not be sufficient to cause significant effects in terms of overall performance. Indeed the impacts would be less than for over-filling (see Hypothesis 3.2.5). A further possibility is CO_2 storage elsewhere in the Bunter formation. There is the possibility that such CO_2 storage could have similar pressure effects on the CO_2 currently planned to be stored. However, in contrast to extraction elsewhere, this would lead to pressure increases and might increase storage capacity. Moreover, it is a core argument to note that future CO_2 storage would be regulated and would need its own risk assessment showing that impacts on the system under current consideration would not be significant. That is, future CO_2 storage elsewhere would not be allowed unless their risk assessments showed no impact on the CO_2 currently planned to be stored. Overall these arguments combine to provide very high confidence that while there may be some interactions that could potentially be observed, there would not be observable/monitorable deleterious impacts. That is, performance will essentially be as for the expected evolution scenario and will be consistent with lateral containment of CO_2. Further information is provided in the risk assessment report

Hypothesis Name	Notes
3.2.6.2.1.2 Dissolved CO_2 will not migrate laterally beyond the defined storage complex as a consequence of resource exploitation	Similar to the impacts on lateral migration of CO_2 (see 3.2.6.1.1), there is very high confidence that the additional pressure changes due to hydrocarbon extraction/CO_2 storage operations elsewhere would not have a significant impact on lateral migration of dissolved CO_2. As for over-filling also (3.2.5.2.1.2) it is very unlikely that a change from the expected evolution scenario would occur sufficient to cause observable/monitorable migration outside the storage complex
3.2.6.2.2 Models predict that resource exploitation elsewhere will not lead to significant direct or indirect impacts from CO_2 in domains outside the storage complex	There is very high confidence that resource exploitation elsewhere will not lead to any such observable/monitorable impacts. Consistent with arguments for over-filling (3.2.5.2.2) and on leakage from the storage complex (3.2.6.2.1.1 and 3.2.6.2.1.2) the changes that could arise from resource exploitation elsewhere would not be sufficient to cause deviations from the expected evolution scenario of a sufficient magnitude to lead to deleterious impacts associated with CO_2 migration, formation water displacement, or surface uplift. Please see those hypotheses for more detailed arguments

D.2 Displacement of Formation Fluids Tree

Table D.2 Displacement of Formation Fluids Tree

Hypothesis Name	Notes
0 Displacement of formation fluids by injected CO_2 will not cause observable environmental impacts	
1 The elastic storage capacity and geometry of the storage complex and surrounding rock formations is sufficient that there will not be an observable flux in the environment(s) occupied by any receptor(s)	The injection rate of CO_2 at 2.68MT/y corresponds to an addition of 3.8x106m^3/yr of fluid. If this volume of brine were displaced at the seabed over a 5km^2 area, this would correspond to a flux of 2mm/day/m^2 which is unlikely to be observable. This calculation assumes that the area over which the Bunter sandstone is in hydraulic connection with the sea is 5km^2. There is some uncertainty in the area of the hydraulically active outcrop due to overlying Quaternary sediments of unknown permeability. An estimate of the exposed Bunter sandstone outcrop area is 1.4km^2 which, if all flow of displaced brine were here, would result in a flux of 7mm/day/m^2, which still seems unlikely to be observable. In practice, the mass flux of fluids at the outcrop would be less than the mass flux into the formation because the compressibility of both the formation fluids and the reservoir rock will result in additional storage of brine in the reservoir, corresponding to a pressure increase in the reservoir. This is a transient effect, but causes a reduced discharge at the seabed and discharges over a longer timescale than the injection period. Reservoir simulations that take into account the compressibility of the rock give a best estimate discharge rate of 3000m^3/day. Over an area of 5km^2 this equates to a flux of around 0.6mm/day/m^2. Overall, it is anticipated there will be a discharge of fluids from the outcrop to the seabed. Therefore there must be some evidence against this hypothesis. However, the flux will be small and likely discharged over a very large area so there is moderate confidence that it won’t be observable. There are some uncertainties, for example the properties of the Quaternary sediments and how they affect the discharge area and the potential for some more focused discharged associated fractures and relatively permeable beds in the sandstone, which have greater potential to be observable. The significance of this discharge is tested in other hypotheses. Further information is provided in the risk assessment report
2 Spatial distribution and chemical characteristics of pre-existing (pre-CO_2 injection) fluids is consistent with no significant change of chemical environment of identified receptors if displaced	

Hypothesis Name	Notes
2.1 Salinity gradients are consistent with no significant change in the salinity around identified receptors if water is displaced	Immediately below the seabed, formation waters are thought to be very similar in characteristics to seawater. For plausible amounts of displacement (given the volume of CO_2 to be stored) it is likely only these waters could interact with receptors at the seabed. There is, however, uncertainty about the salinity gradient and the chemistry of these waters. For example, there is thought to be a salt dome beneath the area of the outcrop (indeed the existence of such a dome is thought to explain the geometry of the outcrop). This could lead to locally raised salinity of waters that could be displaced. Overall, there is substantial uncertainty here. The evidence suggests that on a general basis the salinity gradient is likely to be consistent with displaced waters at the receptor zone not being of significantly enhanced salinity compared to seawater. However, there is also the possibility that the presence of the outcrop could mean the marine waters very close to the outcrop are already (naturally) of higher salinity. This would imply that displacement of additional waters would have very limited additional impact. Despite the significant uncertainties, there is no specific evidence against this hypothesis and the available evidence provides moderate confidence in support of this hypothesis. Additional information would be necessary to reduce the amount of uncertainty associated with this hypothesis. Further information is provided in the risk assessment report
2.2 Gradients in heavy metal concentrations are consistent with no significant exposure of receptors to heavy metals if water is displaced	Immediately below the seabed, formation waters are thought to be very similar in characteristics to seawater. For plausible amounts of displacement (given the volume of CO_2 to be stored) it is likely only these waters could interact with receptors at the seabed. There is, however, uncertainty about the salinity gradient and the chemistry of the water. There is no evidence from the vicinity of the outcrop as to the heavy metal concentrations in the formation waters within the Bunter sandstone. The closest data come from the appraisal well 42/25d-3 drilled by NGC. However, this well is located more than 25km from the closest seabed outcrop of the Bunter sandstone. Given this fact, these data are of uncertain relevance to the formation water in the Bunter sandstone beneath the seabed outcrop. If it is assumed that the formation water displaced from beneath the outcrop is chemically similar to the formation water sampled from the Bunter sandstone in well 42/25-d3, only diluted with seawater and the composition is compared with relevant water quality standards (OSPAR, WHO), then some tentative conclusions can be made. Based on this assumption and taking into account likely mixing of displaced formation water with pore water in the seabed sediments and the overlying seawater column, there are good reasons to believe that the chemistry of formation water that could plausibly be discharged at the seabed outcrop of the Bunter sandstone would be different from the composition of the deep formation water sampled from the Bunter sandstone in well 42/25-d3. If the water within the Bunter sandstone beneath the outcrop is in fact a mixture between present seawater and brine like that sampled from the Bunter sandstone in well 42/25-d3, then it is plausible that the concentrations of certain contaminants in water discharging from the outcrop, notably certain heavy metals, could rise to levels that would be of concern from an environmental impact perspective. However, only arsenic, lead and zinc would potentially be of concern except under arguably implausible circumstances. It is noteworthy, that even under pessimistic assumptions, the levels of heavy metals would not be of concern throughout the entire period of discharge, as the initial discharges would primarily be of seawater composition. Only the later discharges, which could include a small but increasing component of brine as water from greater depth below the outcrop is discharged, would be of concern. Overall, there is a very large amount of uncertainty associated with this hypothesis. There is a small amount of evidence in support of this hypothesis and this builds a low amount of confidence. Although conceptually later discharges might have higher heavy metal concentrations, there is no specific evidence to underpin confidence against this hypothesis. Additional information would be necessary to reduce the amount of uncertainty associated with this hypothesis. Further information is provided in the risk assessment report

Hypothesis Name	Notes
3 Mixing between displaced fluids and water in the environment of identified receptors will prevent significant change in the chemical environment of the receptors	The primary issue under consideration here is whether mixing in the seawater column will mean that the overall salinity increase for plausible fluid displacement rates and compositions will not be significant even if higher salinity formation waters are displaced into the seawater column. It is notable here that consents/permits for other activities discharging saline waters to seawater are based upon limiting salinity of the seawater to 40% within 50 to 250m of the discharge point. The salinity gradient below the outcrop has been estimated in Section 5.2.1.3 of the risk assessment report. The scoping calculations therein indicate that the salinity of the water discharging to the seabed could increase to up to 45%. Taking into account the seabed currents and hence the water turnover rate, the salinity would be reduced to below 40% immediately above the seabed. There would be much greater mixing and dilution in the overlying water column. Therefore even if the salinity of the water discharging from the outcrop was significantly greater than 45%, it is very unlikely that the salinity will exceed 40% at 50m and even less likely at 250m. A salinity of 40% is around the tolerable upper limit for a number of species. Since the salinity of the water discharging to the seabed could increase to up to 45%, this limit could potentially be exceeded in the seabed. However, the majority of biota is expected to be found in the top few centimetres of the sediment, in which there may be mixing and dilution with seawater. At most 50:50 mixing with seawater is required to decrease the salinity from 45% to 40%. This degree of mixing is plausible, especially noting that the discharge fluxes may not be constant with time. The discharge fluxes will increase as CO_2 is injected into the reservoir, peak immediately following injection and then gradually decrease to zero. Based on the estimated salinity gradient below the outcrop, scoping calculations indicate discharges above 40% salinity are associated with the second half of the discharge period, with the highest salinities associated with small volumetric discharge fluxes towards the end of the discharge period. Therefore there is potential for significant dilution of these small, final, highest salinity discharges. There is good confidence that displacement of formation waters will not lead to significantly elevated salinities in the water column above the outcrop. There is less confidence and more uncertainty on the impact on pore water salinities at and immediately below the seabed. Therefore, overall there is moderate confidence in support of this hypothesis, but significant remaining uncertainty. Further information is provided in the risk assessment report
4 Discharges to the water column of displaced fluids above seawater salinity will be lower impact than for Permitted discharges from analogous sites associated with other industries	The Preesall Underground Gas Storage facility was predicted to eventually discharge around 80Ml of fluid a day at up to 250% salinity through a single diffuser. This compares to a ‘worst case’ for the current study of 5Ml of fluid a day over 5km^2 where the fluid may not be significantly more saline than seawater. The Preesall context is different and it is an Irish Sea installation, however it is clear that the salinities and fluxes associated with the current project would still be much lower than those for the above Consented/Permitted situation. Similarly the Aldborough Gas Storage facility is expected to lead to discharge of around 721m^3/hr (or 17Ml/day) with a salinity of 171%. Again this Consented/Permitted situation will lead to a much larger impact to the seawater column than for the present study. For the examples above, discharges were through a diffuser located 1m above the seabed. Elevation of the diffuser above the seabed encourages mixing, dilution and dispersion of the discharges. However, the releases of saline water will denser than the surrounding water and a fraction of the saline water could conceivably locally pond and interact with the seabed and the fauna that occupy the top few centimetres of the sediment. The EIA for the above facilities note that there may be some (recoverable) impacts to benthic communities. Nevertheless these assessments argue that ponding will not lead to significant impacts to the seabed. This suggests that, in the opinion of those assessors, even large, sustained high salinity fluxes to the near seabed environment are unlikely to lead to significant impacts to seabed biota. Although the EIA for the project suggests that ponding will not be a significant process for the bulk of the discharge, it remains plausible that ponding could lead to an impact similar to that due to discharge of higher salinity waters to the seabed sediments above the outcrop of the Bunter sandstone . Cautious scoping calculations for this study indicate that the salinity of the water

Hypothesis Name	Notes
	discharging to the seabed sediments could increase to up to 45%. This is above the tolerable limit for some species. However, the majority of biota is expected to be found in the top few centimetres of the sediment, in which there will be mixing and dilution with seawater. At most 50:50 mixing with seawater is required to decrease the salinity from 45% to 40%. This degree of mixing is plausible, especially noting that the discharge fluxes will not be constant with time. On this basis, it is likely the salinity will be within tolerable limits for the biota that could otherwise be impacted. The discharges fluxes will increase as CO_2 is injected into the reservoir, peak post-injection and then gradually decrease to zero. Discharges above 40% salinity are associated with the second half of the discharge period, with the highest salinities associated with small volumetric discharge fluxes towards the end of the discharge period. Therefore there is potential for significant dilution of these small, final, highest salinity discharges. Immediately above the seabed the salinity would be reduced to close to ambient and there would be no significant perturbation of the salinity of the water column. Overall, there is very high confidence that discharges of higher salinity waters from the outcrop of the Bunter sandstone will have lower impacts than from analogous sites associated with other industries. Further information is provided in the risk assessment report

D.3 Physical Effects Tree

Table D.3 Physical Effects Tree

Hypothesis Name	Notes
0 CO_2 storage will cause no physical damage to a receptor	
1 There will be no physical damage to a receptor due to induced seismicity arising from CO_2 storage	
1.1 Geomechanical models are consistent with no unacceptable induced seismicity arising from CO_2 storage	Simplified geomechanical models produced for the Endurance structure using the Petrel/Visage software package have been reported. These models show that there is little risk of significant strain and/or failure of the Endurance structure Röt clay and Röt halite seal due to the modelled pressure and temperature changes expected during phase 1 of the CO_2 injection scheme of 2.68MTPA The injection platform will be located around 3.5km from the edge of the Hornsea wind farm zone (noting that turbines installed to date are located further away than this) and also from the Garrow platform (4km). However, the maximum uplift will occur near the anticline in an area much closer to the Hornsea wind farm zone and to the Garrow platform. As described for induced seismicity elements of the 'containment' tree, injection rates and pressures will be carefully monitored and controlled to ensure they remain well below fracture closure pressures and so they are unlikely to induce fracturing or movement on existing fractures. There may be some thermal fracturing adjacent to injection wells, but seismic effects are expected to be insignificant with respect to the effectiveness and safety of storage. Indeed, the 'containment' tree argues that these effects would not impact adversely on the storage complex itself and associated boreholes. On that basis the likelihood of significant impact at the seabed surface or to other structures such as operational boreholes in the Garrow field is very small indeed. It should be noted that the evidence base with which to judge this Hypothesis 1.1 overlaps with that used to judge Hypothesis 2.1 'Geomechanical models are consistent with no physical impacts from seabed deformation arising from CO_2 storage'. However, this dependency is not fixed and depends upon the precise nature of the models used to support the judgments and the inputs to these models. Consequently, a dependency value is not specified in the tree. Rather, dependencies are taken into account when specifying the input confidence values, such that a confidence value is reduced by an amount that corresponds to the judged degree of overlap.

Hypothesis Name	Notes
	Given the limited amount of information there is considerable uncertainty. However, the simplified geomechanical models provide no evidence against the truth of this hypothesis. Overall, there is moderate to high confidence from the geomechanical models that induced seismicity will not produce unacceptable impacts
1.2 Analogue evidence is supportive of no physical damage to a receptor due to induced seismicity arising from CO_2 storage	See the discussion for Hypothesis 1.1. For this hypothesis, the argument is that comparison with a range of different types of analogous systems (hydrocarbon exploitation, gas storage) provides confidence that the pressures generated in the storage system are highly unlikely to lead to observable impacts at the surface and moreover it is extremely unlikely there will be unacceptable impacts that could not be accommodated by these structures. In the North Sea, water injection at the Ekofisk field result in an earthquake of magnitude 4.2. Shaking was felt on the platforms, but there was no damage to platforms or wells. This is within the range of naturally occurring seismic events in the North Sea. As described under Hypothesis 2.2, the hydro-mechanical properties of the Ekofisk field mean that it is subject to large amounts of production compaction, which generates stress on the overlying formations and results in significant seabed subsidence. CO_2 injection at Endurance is not expected to lead to such large stress changes, so the potential for induced seismicity is much lower. It is notable that wind farm and other man-made structures on the seabed are specifically designed to be robust to naturally occurring seismic events and ocean conditions (currents, tides, sediment movement and so on) and typically require a substantial event to cause damage. There are operational boreholes associated with the Garrow field (these do not penetrate the Endurance structure), which are another potential local source of induced seismicity. Seabed infrastructure associated with the project, the wind farm and any other activities in this area will have to be robust to any induced seismicity resulting from production from Garrow. Evans (2008) presents an appraisal of underground gas storage technologies and incidents. The impacts considered include ground subsidence and uplift and induced seismicity. These impacts are not limited to gas storage, but also consider hydrocarbon production, including in the context of gas storage in depleted hydrocarbon reservoirs. It is concluded that changes in ground level and induced seismicity are predictable and can be managed. To achieve this requires detailed site characterisation and geological investigations in order to assess the response of the system to fluid injection and removal and the associated temperature and pressure changes and to determine the required operating limits/constraints. In other industries, minor seismic events have occasionally been recorded as a result of changes to already stressed and pressurised systems. However this is not evidence 'against' this hypothesis as it is not sufficiently analogous to the present system to suggest there could be impacts. Rather, it shows that the analogous evidence 'for' cannot be complete. Finally it is notable that pressure changes associated with hydrocarbon exploitation are much greater than associated with CO_2 injection (even if the pressure changes are of a different type and are not directly analogous). Thus there is analogue evidence that man-made seabed structures of the types local to the storage system are robust to the impacts of operations that involve much larger pressure changes than would plausibly be the case for the current storage system. Overall the available analogue evidence gives high confidence that there would be no physical damage to a receptor as a result of CO_2 storage. Furthermore, there is no analogue evidence that such damage would occur. However, no analogue information comes from exactly the same kind of situation as the planned CO_2 storage in the Endurance structure. Consequently, there is judged to be some uncertainty, albeit very low
2 There will be no deformation of the seabed that could cause physical damage to a receptor arising from CO_2 storage	
2.1 Geomechanical models are consistent with no physical impacts from seabed deformation arising from CO_2 storage	As noted for Hypothesis 1.1, simplified geomechanical models produced for the Endurance structure using the Petrel/Visage software package have been reported. The injection platform will be located around 3.5km from the edge of the Hornsea wind farm zone (noting that turbines installed to date are located further away than this) and also from the Garrow platform (4km). However, the maximum uplift will

Hypothesis Name	Notes
	occur near the anticline in an area much closer to the Hornsea wind farm zone and to the Garrow platform As described for induced seismicity elements of the ‘containment’ tree, injection rates and pressures will be carefully monitored and controlled. This means that there is a low probability that uplift will exceed what is predicted for the Expected Evolution of the system. Existing geochemical models suggest there could be around 9cm (maximum 15cm) of uplift at the surface. This uplift will be spread over a significant lateral distance and means that the seabed surface uplift gradient change will be minimal. As noted for other leaf hypotheses, seabed structures are typically designed to be robust to the significant impacts of subsea conditions and this very small additional stress is likely to be insignificant in comparison. The element of infrastructure most likely to be at risk is perhaps the operational boreholes associated with the Garrow field. However these do not penetrate the Endurance structure. Experience of operating boreholes in other industries where there is minor uplift for example, due to extraction is that the impacts are likely to be low, especially when the boreholes are located some distance horizontally and vertically from the source of the pressure leading to the uplift. On this basis, the models therefore provide strong confidence that no physical impacts will arise as a result of impacts on other structures as a result of CO_2 storage. It should be noted that the evidence base with which to judge this Hypothesis 2.1 overlaps with that used to judge Hypothesis 1.1 ‘Geomechanical models are consistent with no unacceptable induced seismicity arising from CO_2 storage’. However, this dependency is not fixed and depends upon the precise nature of the models used to support the judgments and the inputs to these models. Consequently, a dependency value is not specified in the tree. Rather, dependencies are taken into account when specifying the input confidence values. Overall, geomechanical models provide very high confidence that there will be no significant impacts at the seabed from mechanical deformation due to CO_2 injection. There must inevitably be a very small amount of uncertainty owing largely to the fact that the geomechanical models are simplifications, but there is no evidence from the models that there will be significant seabed physical impacts
2.2 Analogue evidence is supportive of no physical impacts from seabed deformation arising from CO_2 storage	There are no systems that are directly analogous to the White Rose CO_2 storage system. However, less direct analogue evidence from a range of industries (hydrocarbon exploration, gas storage) suggests that uplift will be minimal and that facilities can typically withstand uplift in any case at plausible gradients. The majority of analogue evidence comes from hydrocarbon production which has the potential to result in subsidence. Typically most oil and gas reservoirs only experience small amounts of compaction and surface subsidence. In the North Sea, subsidence was very uncommon until production from a Chalk reservoir in the Ekofisk field. This production did lead to damage to seabed infrastructure. However, this is a hydraulically isolated Chalk reservoir in which production resulted in significant compaction of the Chalk and is therefore not a good analogue for the sandstone aquifer at Endurance. The team of oil industry experts contributing to development of this tree were not aware of any significant subsidence associated with production from the Esmond field, although a production pressure drop there of 35bar was lower than the pressure increase expected at Endurance due to CO_2 storage. Evans (2008) presents an appraisal of underground gas storage technologies and incidents. The impacts considered include ground subsidence and uplift and induced seismicity. These impacts are not limited to gas storage, but also consider hydrocarbon production, including in the context of gas storage in depleted hydrocarbon reservoirs. It is concluded that changes in ground level and induced seismicity are predictable and can be managed. To achieve this requires detailed site characterisation and geological investigations in order to assess the response of the system to fluid injection and removal and the associated temperature and pressure changes and to determine the required operating limits/constraints. Overall, analogue evidence supports the argument that there will be no physical impacts from deformation of the seabed due to CO_2 storage

Appendix E Storage of Carbon Dioxide Regulations

E.1 Schedule I

From The Storage of Carbon Dioxide (Licensing etc) Regulations 2010 (2010 No. 2221).

Monitoring

2. (1) The operator must carry out a programme of monitoring of the storage complex and injection facilities, for the purposes specified in sub-paragraph (3).

2. (2) Such monitoring must include (where possible) the monitoring of the CO_2 plume and (where appropriate) of the surrounding environment.

2. (3) The purposes are as follows:

a. The comparison of the actual and modelled behaviour of the CO_2 (and the naturally occurring formation water) in the storage site;
b. The detection of any significant irregularities;
c. The detection of any migration of $CO_{2;}$
d. The detection of any leakage of $CO_{2;}$
e. The detection of any significant adverse effects on the surrounding environment and in particular on:
    i. Drinking water;
    ii. Human populations; and
    iii. Users of the surrounding biosphere;
f. The assessment of the effectiveness of any corrective measures taken; and
g. Updating the assessment of the safety and integrity, both short- and long-term, of the storage complex (including the assessment of whether the stored CO_2 will be completely and permanently contained).

2. (4) The monitoring must be based on the monitoring plan.

2. (5) The monitoring plan must be updated in accordance with Annex II to 2009/31/EC CCS Directive and in any event within five years of the approval of the original plan, in order to take account of:

a. Changes to the assessed risk of leakage;
b. Changes to the assessed risks to the environment and human health;
c. New scientific knowledge; and
d. Improvements in best available technology.

2. (6) The updated plan must be submitted for approval by the authority.

2. (7) The authority may:

a. Approve that plan; and
b. Require the operator to make such modifications to it as the authority (after consulting the operator) considers necessary and the updated monitoring plan is the plan as so approved or modified.

2. (8) Sub-paragraphs (5) to (7) apply to the further updating of an updated plan as they apply to the updating of the original plan.

Reporting and notification of leakages and significant irregularities

3. (1) The operator must send to the authority a report in respect of each reporting period, containing the information specified in sub-paragraph (5).

3. (2) The report must be sent to the authority no later than four weeks after the end of the relevant reporting period.

3. (3) Unless the authority determines otherwise under sub-paragraph (4), the reporting periods are the period of one year beginning with the commencement of injection and each subsequent yearly period.

3. (4) At any time before the commencement of injection, or during a current reporting period, the authority may notify the operator that (beginning with the next reporting period) reporting periods are to be a period of less than one year that is specified in the notice.

3. (5) The information is:

a. The results of the monitoring carried out under paragraph 2 of this Schedule (including details of the monitoring technology employed);
b. The quantities, properties and composition of the CO_2 streams registered by the operator under paragraph 1. (5) of this Schedule;
c. Proof that the financial security required by paragraph 7 of this Schedule has come into effect and remains in force; and
d. Any other information requested by the authority that the authority considers relevant for the purposes of assessing compliance with the conditions of the storage permit or for increasing knowledge of the behaviour of the CO_2 stored at the storage site.

3. (6) If the operator becomes aware of any leakages or significant irregularities, the operator must immediately notify the authority.

6. (7) If the operator becomes aware of any leakages, or of any significant irregularities which imply the risk of leakage, the operator must immediately notify the person who is the regulator in relation to the storage site for the purposes of legislation implementing the 2003/87/EC Emissions Trading Scheme Directive.