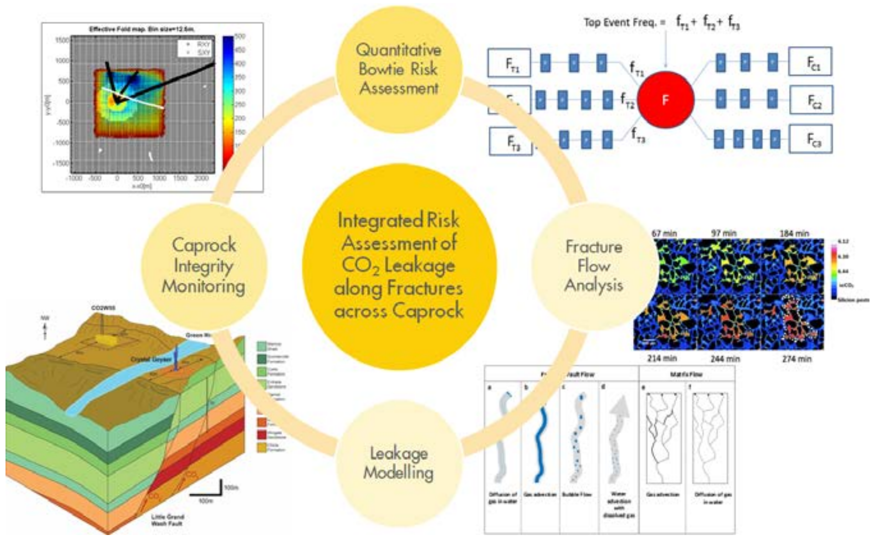
Final report of the DETECT Project

December 2020



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The project has been funded through the ERANET Cofund ACT (Project no. 271497), the European Commission, the Research Council of Norway, the Rijksdienst voor Ondernemend Nederland, the Bundesministerium für Wirtschaft und Energie, and the Department for Business, Energy & Industrial Strategy, UK.

Executive summary

Solid, substantiated risk assessment and mitigation measures ensuring safe and efficient CO_2 storage improves public trust and facilitates societal acceptance. This is essential to enable large-scale deployment of Carbon Capture and Storage (CCS). DETECT has generated guidelines and technologies for determining the risk of CO_2 leakage along fractures across the primary caprock using an integrated monitoring and hydro-mechanical-chemical modelling approach. For this purpose, we have performed laboratory studies to provide relevant parameters for CO_2 leakage modelling at small, meso, and large scales, incorporating analogue data where possible. We have tested the approach using the Green River natural CO_2 leakage site in Utah, USA (as an analogue) and the North Sea Captain Fairway (as a potential CO_2 storage site). This resulted in an improved understanding of realistic leakage geometries and rates for several representative scenarios. Further, potential containment monitoring technologies that are capable of detecting such caprock integrity issues were identified and assessed. The work built on experience gained from the risk-based Measurement, Monitoring and Verification (MMV) programme for the current Quest and the former Peterhead CCS projects. Project results were implemented within a risk assessment framework using the bowtie method. The bowtie tool developed may serve CO_2 storage operators as a guideline for site-specific containment risk assessments. Together with the quantitative leakage modelling tool, this will allow stakeholders to perform both a qualitative and quantitative assessment of the risk of CO_2 leakage along fractures in the caprock. We recommend additional validation against natural analogues or large-scale leakage tests to further verify the quantitative reliability of the workflow. Finally, the DETECT integrated approach can be used to communicate CO_2 storage leakage risk assessment in a clear, logical, and substantiated manner.

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Figures

The project has been funded through the ERANET Cofund ACT (Project no. 271497), the European Commission, the Research Council of Norway, the Rijksdienst voor Ondernemend Nederland, the Bundesministerium für Wirtschaft und Energie, and the Department for Business, Energy & Industrial Strategy, UK.

1. Identification of the project and report

Project title	DETECT - Determining the risk of CO_2 leakage along fractures of the primary caprock using an integrated monitoring and hydro-mechanical-chemical approach
Project ID	271497
Coordinator	Shell Global Solutions International B.V.
Project website	HWU website https://geoenergy.hw.ac.uk/research/detect/ DETECT page on the ResearchGate
Reporting period	September 2017 – December 2020

Introduction

Motivation

Solid, substantiated risk assessment and mitigation measures ensuring safe and efficient CO_2 storage improves public trust and facilitates societal acceptance as well as accelerating large-scale deployment of Carbon Capture and Storage (CCS).

The DETECT project addressed significant gaps in the general understanding of fluid migration along faults and fracture networks of the primary caprock and the storage seal in general. The accumulation of CO_2 or CO_2-bearing brine below the caprock may result in flow along existing fracture networks (or, at high fluid pressures, create new fracture networks), which may lead to CO_2 migration from the storage reservoir. The cumulative leakage rates depend on pressure differentials, effective stress, the fracture density, tortuosity and aperture size and the connectivity of fracture networks. Furthermore, CO_2 or CO_2-bearing fluids pose an increased complexity over other fluids such as water or hydrocarbons as they can chemically react with the rock, significantly dissolve in formation waters, precipitate new minerals, e.g. calcite, or physically interact with other minerals, e.g. smectite, leading to expansion and the build-up of swelling stresses. Therefore, flux rates also depend on the physical and chemical interactions taking place in a fracture system. These combined effects can result in an increase or decrease in fracture network connectivity and permeability over different temporal and spatial scales.

The combination of all these aspects is challenging and although some fundamental laboratory and modelling studies are available in the literature, an integrated study, involving a complete life cycle risk assessment of CO_2 leakage along fractures in caprocks, was lacking. Added complexity is given by the fact that a leak can only be detected and quantified when geophysical or chemical monitoring tools are able to distinguish relevant changes in gas saturation, pressures or compositions compared to baseline levels. In addition, considering these uncertainties, it is critically important to be able to communicate leakage risks for CO_2 storage operations in a clear, logical, and substantiated manner to all stakeholders. The DETECT project addressed all of these significant gaps.

Accelerating CCS Technologies

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Objectives

DETECT aimed to significantly improve a CO_2 storage operator's ability to evaluate risks of leakage across faulted and fractured caprocks, so as to better inform operators, regulators and other stakeholders in their risk mitigation strategies. The results from this study have been incorporated into CCS industry leading guidance documents which will allow stakeholders to:

1. perform effective caprock and seal integrity risk assessment
2. communicate clearly and logically assessed caprock integrity risks
3. understand realistic leakage rates and related implications
4. select realistic and efficient leak rate modelling approaches
5. select reliable, cost effective and innovative containment monitoring technologies
6. demonstrate quantitative risk assessment applicable beyond investigated risks

All of these elements are expected to substantially contribute to accelerating implementation of the CCS technology by providing pragmatic and reliable tools to reduce risks and costs for CO_2 storage operations. As planned, DETECT has delivered an integrated approach to (qualitatively and quantitatively) determine the risk of geologic leakage across the primary caprock (Figure 1).

Key targets

All key targets for the DETECT project have been achieved and are listed here:

1) WP2 (RWTH Aachen University, Heriot-Watt University): Laboratory experiments to determine the impact of reservoir stress changes, chemical reactions, and swelling clays on fracture flow properties.
2) WP3 (Shell, Heriot-Watt University): Field studies to characterize fault and fracture network geometries.
3) WP3 (Shell, Heriot-Watt University): Hydro-mechanical-chemical modelling to determine the flow in a single fracture and connected matrix, assess the potential for upscaling of flow in fault damage zones, and to develop capabilities for fault zone leak path modelling of storage complexes.
4) WP4 (Shell): Identify containment monitoring technologies suitable to detect leakage across caprock and to determine the expected monitoring performance based on fracture flow rates modelled.
5) WP5 (Risktec): Integrated qualitative and quantitative risk assessment to determine passive safeguards (from lab and modelling) and active safeguards (from monitoring) for bowties and risk models. Generation of guidance bowties and tools for efficient risk assessment.
6) Dissemination: Publish scientific articles, contribute to conferences and workshops to engage experts and stakeholders in the field. Create and maintain a web-based platform to provide transparent documentation of the key results for government agencies, operators, and the public.

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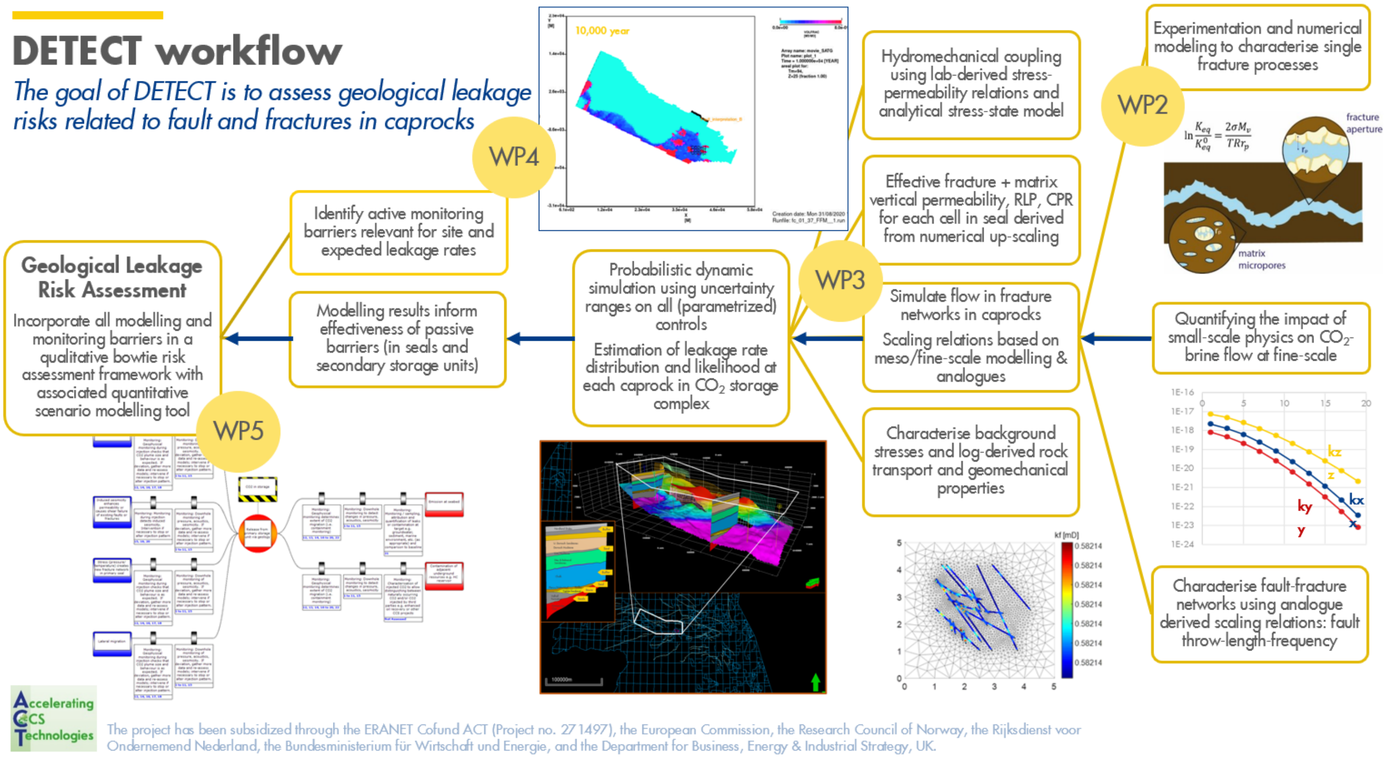

Figure 1. The DETECT workflow.

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2. Short description of activities

WP2 – Fracture flow, mineralisation, clay swelling

Overview

Fractures and faults are common in the geological subsurface and depending on the scale of the deformation, such structures can be localised through geophysical methods. Below geophysical resolution, assumptions on fracture density, connectivity and mineralogy are required. In any case, flow through such fractures under changing pressure, temperature and fluid chemistry conditions requires an understanding of how relevant flow occurs over different time scales to assess leakage risks and monitoring requirements. This work package addresses this point by conducting dedicated laboratory studies focusing on pressure (effective stress) as well as fluid chemistry changes, including the concentration of CO_2 in the pore fluids. We studied carbonate precipitation as a function of fluid chemistry and nucleation surfaces, swelling of clays in contact with CO_2 as well as the change in fracture apertures upon changes in pore pressure. This WP provides fundamental and new data on these points and provides input to upscaled modelling in WP3.

Method and data

Hydromechanical coupling in fractures (WP2.1): We have started this sub-WP by developing a database summarising effective stress/permeability relationships of various sealing formations, indicating that permeabilities vary by ~7 order of magnitude, making it difficult to generalise the data for use as analogue in any leakage assessment along caprock fractures. Various sites have been selected to obtain additional samples (Opalinus Shale, Switzerland, Crato Basin, Brazil, Carmel Formation, Utah, Nash Point/Mercia shales, UK); some of the samples were difficult to fracture or plug, which limits the experimental results of this sub-WP to samples from Carmel, Nash Point and Opalinus. To run these experiments, we used a new permeameter able to determine permeabilities across this wide range of values, under reservoir conditions. We have further developed concepts to experimentally obtain fracture surface roughness data. Results have been parameterised and used in upscaled modelling in WP3. In addition, we used 7 printed fractures to specifically focus on stress-permeability relationships with a pre-defined surface roughness. This is important to link to multi-phase flow, contact mechanics and to better understand the significance of this property in evaluating caprock integrity.

Self-sealing by mineralisation (WP2.2): There is a clear gap in the generalised understanding of fracture mineralisation in caprocks and its impact on CO_2 leakage rates. Experiments are set up to understand the mechanisms controlling the loci of precipitation and to parametrise fracture permeability relationships during mineralisation. Complementary capillary, mixed glass bead column and rock plug flow experiments are carried out in order of increasing complexity. Based on the capillary experiments, experimental conditions were optimised, i.e., reasonable duration (<30 days) and sufficient precipitation volume with maximised effect on permeability, for a saturation leading to stable crystal growth as representative for the subsurface. Consequently, glass bead and rock plug experiments were

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carried out at 30°C and a saturation index of 1.57, controlled by mixing $CaCl_2$ and $NaHCO_3$ solutions. Calcite crystal growth rates remain well above the heterogeneous calcite nucleation rates on mica or quartz, and above homogeneous nucleation rates in the fluids. Mixed glass bead columns are considered as simplified analogues of clastic rocks, while real rock experiments at controlled effective stress are essential to draw conclusions about subsurface conditions. Three main glass bead column experiments, with a flow rate of 1 mL/min, were carried out with varying compositions of the glass bead-calcite mixture. We conducted five experiments with fractured sample plugs of varying mineralogy in a cylindric triaxial flow cell at reservoir stress, pressure and temperature conditions.

Clay swelling (WP2.3): As CO_2-induced clay swelling is linked with the CO_2-uptake behaviour of clays, we first aimed at obtaining information on the major controls (water content, hydration state, interlayer cation) by means of high-pressure CO_2 sorption experiments on well characterised standard clays. In parallel, a new experimental set-up was constructed and tested to measure swelling stress and permeability of compacted clay powder (resembling a clay-filled fracture). With this apparatus, the experimental conditions can be flexibly adjusted to investigate the clay swelling and permeability at relevant stress, CO_2 pressure and temperature conditions. Among others, the following types of experiments were successfully conducted: (1) a long-term flow experiment (> 200 days) on Na^+-smectite at relevant *in-situ* conditions with water, brine, and carbonated water/brine to study the effect of dissolved CO_2 on clay swelling and flow. (2) Swelling and flow experiments at dry conditions on various types of clays using inert (He) gas and CO_2 as a function of pressure and initial stress. (3) Swelling and flow experiments upon successive *in-situ* hydration of swelling clays using inert (He) gas and CO_2 as a function of pressure.

Results

Hydromechanical coupling in fractures (WP2.1): We identified two groups of stress-permeability relationships of which one group has higher permeabilities, with values ranging between ~1E-13 and ~1E-16 m^2. Values for the other group ranges between ~1E-17 and ~1E-20 m^2. The former group is characterised by rather brittle rocks with generally high matrix permeabilities (possibly around micro-Darcy ranges, 1E-18 m^2). These sealing units form the upper end of acceptable permeabilities for caprocks above CO_2 storage reservoirs, being composed of low clay contents. The latter group is more ductile, high in clay content and shows permeabilities which are close to matrix permeabilities. Many of these formations are expected to self-seal in CO_2 storage operations.

Self-sealing by mineralisation (WP2.2): A preferential flow path developed in the glass bead experiments, analogous to fractures in a porous matrix. The loci and volume of precipitation are governed by the interplay of saturation, flow rate and presence of nucleation sites. Saturation controls nucleation but also whether nucleation or crystal growth dominates. Fluid supersaturation should not be too high (SI<~2, pH 8.5, 30°C), to sustain stable crystal growth. Seed crystals, their mineralogy and size, or the presence of other nucleation sites are therefore essential. Preferential precipitation was observed to occur along

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fractures, with the biggest volume of precipitates at the first contact with calcite crystals (nucleation sites). The control of the mineralogy and chemical system (e.g., prograde vs. retrograde solubility), nucleation sites (including fracture roughness) and flow rates on mineralisation are confirmed in the rock plug experiments. We found that samples containing swelling clays show a substantial reduction of fluid flow rates before mineralisation entirely seals the fractures. The experiments confirm the complete sealing by mineralisation of fractures, reducing permeability to matrix values (<1E-17m^2) for sustained flow and supersaturation.

Clay swelling (WP2.3): CO_2 uptake of clays is strongly controlled by hydration state and clay type (illite, smectite (Na^+, Ca^{2+}), kaolinite). Swelling clays at an intermediate hydration state between 0 - 1W can intercalate additional CO_2 which is controlled by the interlayer cation type (Na^+, Ca^{2+}). In contrast, CO_2 uptake under dry conditions is considered to occur on clay surfaces only; CO_2 uptake on 2W hydrated clays is similar to dissolution in the corresponding water content of the samples. The uptake data can directly be related to unconfined CO_2-swelling behaviour of smectites. During the long-term flow experiment (> 200 days) at fully saturated conditions no significant changes in swelling stress and fluid flow were observed upon changing to a carbonated fluid. This indicates that hydrated clays (> 1W) do not swell upon CO_2 exposure. In contrast, experiments at dry and intermediate hydration states show the development of CO_2-induced swelling pressures of up to 3 MPa. These increase with pore pressure and decrease with increasing initial stress and are not significantly impacted by the hydration state. We conclude that knowledge of the hydration state is crucial to assess the clay swelling potential. Under relevant CO_2 storage conditions, Ca^{2+} smectite will always be > 1W hydrated and the likelihood for Na^+ smectite to be partially hydrated (0 – 1W) is considered low due to the large depths (> 2.5 km) required. Substantial dry-out would be required which is rather unrealistic as concluded in WP3. In conclusion we find that subsurface conditions for realistic CO_2 storage scenarios do not favour CO_2-induced clay swelling.

Impact

The experimental data generated here provides direct input to the upscaled modelling in WP3 and new knowledge of the sealing of fractures upon changes in pressure and fluid chemistry. It also allows to better understand risks associated with caprock formations composed of a specific mineralogy. Results and conclusions directly feed into risk assessment of WP5 and therefore help informing best practice guidelines for assessing the risk of fracture leakage.

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WP3 – Fracture characterisation and modelling

Overview

Modelling is required to understand and quantify the impact and interplay of geological, geomechanical, geochemical and fluid parameters on CO_2 migration rates through the primary seal and the potential subsequent migration through secondary reservoir(s) and seal(s). Previous studies have only addressed some elements of this. DETECT has progressed insights and modelling capabilities, by systematically following a multiscale approach: 1) investigating fundamental parameter controls by systematically integrating experimental data (WP2) into both empirical and sophisticated single-fracture models (WP3.2); 2) feeding WP3.2 results, together with fracture characterisation study results (WP3.1), into meso-scale fracture network models (WP 3.3); 3) feeding WP 3.3 results into large-scale models covering reservoir to surface and laterally a wide area including multiple faults.

Method and data

Fracture Characterisation (WP3.1): A variety of locations across Europe, Brazil and the USA were studied to analyse fault zones hosted in mudrocks: 1) *Little Grand Wash Fault, Green River, Utah:* Integrated core data, drone imagery, scanlines, and a 3D structural model to obtain a fault zone fracture model; 2) *Intra-Opalinus Clay Main Fault (MF), Mont Terri Rock Laboratory, Switzerland:* The underground lab in Mont Terri provides access to four outcrops of the Main Fault which have been mapped in detail by SWISSTOPO, digitised within this study and used for upscaled modelling; 3) *Konusdalen Fault Zone, Svalbard, Norway:* Collaboration with the University of Svalbard on digital analysis of this fault zone bases on high-resolution images; 4) *Mercia Mudrock, Whitby Shale, Nash Point Shale and Kimmeridge Clay:* Studied UK-based outcrops of these formation as potential regional caprocks for CO_2 storage. Most outcrops provide insufficient preservation to allow detailed network analysis. Samples used for laboratory testing (WP2); 5) *Lacustrine Carbonates, Crato Basin, Brazil*: Collaboration with the University of Pernambuco, Brazil to access quarries. Samples used for laboratory testing (WP2).

To obtain information on fault and fracture attributes and on their mutual geometrical relationships (i.e., density and connectivity), the freely available MATLAB software package 'FracPaQ' was used. It was designed to generate quantitative fracture pattern data, with user control over the outputs and can quantify the length, orientation, connectivity, intensity and density of any 2D fracture pattern. In addition, the Shell in-house package 'SVS' was used to generate fracture networks based on physical and statistical input control parameters.

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WP3.1 collected data on fault attributes (damage zone width, fracture density, fracture connectivity) from the published literature to provide input data for the meso and large-scale fault modelling.

Fine-scale (single-fracture) modelling (WP3.2): Semi-analytical formulations available in the literature (Barton-Bandis[8], McDermott[9] and Persson[10,11] models) were tested against measured fracture permeability-stress data available from WP2 and published literature. For lower stiffness mudrocks these models did not perform well. Therefore, an empirical model was developed with two shape parameters, both of which could be correlated to the elastic (Young’s) modulus of the host rock. Moreover, full-physics coupled hydromechanical-flow models (Stokes based) were built in MRST to improve understanding of fundamental controls on fracture permeability-stress relations. Darcy-based numerical models were built that (like the MRST models) explicitly consider fracture surface roughness, to predict multiphase flow properties (relative permeabilities and capillary pressures). The results of these approaches could be successfully integrated into parameter-dependent effective relations that were used in the meso-scale and large-scale modelling. The Darcy-based models were successfully extended into Reactive Transport Models to quantify fundamental controls on mineral dissolution/precipitation.

Meso-scale (fracture network) modelling (WP 3.3): MRST virtual element elastic representation was used and a simplified, efficient, contact mechanics scheme was developed. The scheme was validated against a full contact mechanics scheme using the commercial tool Abaqus. The MRST model calculates the effective fracture network permeability for any anisotropic stress boundary condition. The model was subsequently coupled to single and multiphase flow, using a further (successfully validated) simplification in the internal stress handling. The model was applied to digital fracture datasets from Mt Terri, Green River and Konusdalen. Furthermore, for single-phase permeabilities, comparisons were conducted against topology-based analytical models developed by Saevik & Nixon[14] in order to verify this analytical approach for fracture networks of interest. Finally, invasion percolation based algorithm to obtain breakthrough capillary pressure for fracture networks were developed.

Large-scale (storage complex to surface) modelling (WP 3.4): The large-scale model uses the Shell in-house simulator MoReS. Structure and matrix properties are upscaled from 3D models built in the commercial software Petrel, using available geological and seismic data for Green River and for the North Sea Captain Fairway area. MoReS scripting language is used to compute background stresses based on geomechanical input. Subseismic fault locations and displacements are filled in using literature scaling relations (for the Green River case this step is skipped), and fracture damage zone attributes are assigned based on WP3.1 results (for Green River) and (for Green River and the North Sea) scaling relations from the open literature. The North Sea application

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employs the Saevik & Nixon[14] analytical fracture network connectivity approach, rather than using the meso-scale results directly, because this allows full consideration of key control parameters such as fault displacement. Single-fracture permeabilities are computed using the empirical (Young’s modulus dependent) model developed in WP 3.2.

Results

For Green River, large-scale model realisations (with all input parameters well within the a-priori parameter uncertainty ranges) produce credible matches to measured CO_2 surface leak rate data (Appendix 2 – Work Package 3, Figure 4). For the North Sea (Captain Fairway) application (Appendix 2 – Work Package 3, Figure 5), the large-scale model predicts unmeasurably low CO_2 migration across primary seal with base case parameter settings, even if fracture networks are assumed diagenetically uncemented, and no migration to top secondary seal (Storage Complex boundary) in any of the 2395 modelled realisations, including the realisation that stacks the most adverse parameter combinations.

Modelling technologies developed under WP3.1-3.3 include: 1) empirical fracture stress-permeability model; 2) MRST models for coupled hydromechanical-flow modelling at single-fracture and fracture network scale (validated against Mt Terri fracture network measured data); 3) invasion percolation algorithm to obtain breakthrough capillary pressure for fracture networks ; 4) Darcy-based multiphase and Reactive Transport Models (RTMs) (MoReS-PHREEQC based) at single-fracture and simplified fracture network scale, with explicit roughness representation. 5) large-scale flow models implementing fault damage zone scaling relations and dynamic stress-dependent effective caprock permeabilities, capillary pressures and relative permeabilities (MoReS based). For storage reservoirs containing traces of carbonates, the single-fracture RTMs tend to predict self-plugging of the fracture network, on the order of 100 to 1000 years. This effect could not be incorporated reliably into the large-scale models (which therefore ignore the self-plugging potential), however these results feed directly into bowties developed under WP5.

The DETECT modelling work provides/confirms the following conclusions on effective geological barriers: 1) High caprock ductility (low Young’s modulus) $\rightarrow$ fracture networks have low permeability; 2) High secondary reservoir permeability (even low to moderate permeability can be sufficient) $\rightarrow$ leaked CO_2 dissolves near base secondary reservoir, preventing further vertical migration out of storage complex; 3) Good storage reservoir connectivity to wider aquifer $\rightarrow$ main leakage driving force quickly dissipates after site closure.

Impact

An integrated fine-to large-scale fracture characterisation and modelling workflow has been developed to predict the potential range of leak rates at any

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level of interest (e.g., top primary seal; top storage complex; seabed). The large-scale model results can feed directly into qualitative and quantitative containment risk assessment, with the caveat that further validation against natural analogues or large-scale leakage tests is recommended to further validate the quantitative reliability of the workflow. Modelling technologies have been developed for credible fracture leakage modelling at single-fracture scale, fracture network scale and storage complex scale. These technologies have been or will soon be published in the open literature.

WP4 – Containment monitoring for caprock Integrity

Overview

One of the goals of the DETECT project was to identify monitoring tools capable of detecting CO_2 migration across fractures and faults in the caprock. For this purpose, predicted performance of state-of-the-art containment monitoring technologies were compared with results from coupled hydro-mechanical flow and reactive transport simulations which in turn have incorporated insights from comprehensive laboratory studies. The WP4 final report summarised in this section (see Appendix 3 – Work Package 4) covers the monitoring feasibility studies done for a range of candidate technologies that have been pre-selected for their potential to detect leakage across the caprocks within a CO_2 storage complex. The studies include modelling and analytical approaches to estimate the performance of the selected containment monitoring technologies for a North Sea storage site in the Captain Aquifer. Several leakage and reservoir scenarios were investigated including an extreme high-leakage case as a low likelihood end member. Insights from Measurement, Monitoring and Verification (MMV) programmes of the Quest CCS[13] and the former Peterhead[14] projects were incorporated where relevant. Considering both cost and feasibility, the most promising technologies for the purpose of detecting CO_2 leakage across the caprock are in-well technologies including downhole pressure temperature gauges, fiber optic monitoring and logging techniques.

Method and data

The overview of the containment monitoring technologies generated earlier, and the outcome of the first bowtie workshop was used to first organise and then reduce the list of potential technologies based on leakage scenarios considered, estimated potential to perform the required monitoring tasks (resolution, space, time), TRL, cost, and operational constraints.

The shortlisted containment monitoring technologies identified in the early phases of the project have undergone individual feasibility studies considering simple leakage scenarios across the caprock. For the selected in-well monitoring technologies, analytical or modelling studies have been done to determine the expected performance under relevant geological and well configuration scenarios. Resolution differs for each technology, and signal characteristics depend on

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background noise, fluid phase and composition, depth, geology (structure, rock types) and well geometry. For the feasibility studies we focused on North Sea scenarios selecting the Captain Sandstone Fairway which includes the Goldeneye depleted hydrocarbon reservoir among other potential CO_2 storage sites.

Data Sources for DETECT CO_2 Storage Scenarios

To identify a suitable North Sea scenario for DETECT, we used information from the former Peterhead CCS Project and the British Geologic Survey (BGS) CO_2 Store Atlas (http://www.co2stored.co.uk/home/index). The DETECT project team selected a location within the Captain Sandstone Fairway for the large-scale leakage scenario modelling done in year 3 of the DETECT project. For this purpose, available data sources included Shell Petrel models of the Moray Firth & Central North Sea basin, Captain Sandstone Fairway and the Goldeneye reservoir models. For the containment monitoring feasibility studies, we used a simple model provided by WP3 lead Jeroen Snippe (Shell) assuming a storage location in the Captain Sandstone Fairway.

Method

For the Captain Sandstone Fairway saline aquifer as a CO_2 storage site, conceptual leakage models were built to evaluate the signals related to changes of pressure, temperature and saturation away from a leakage path. The detectable distance was estimated using current available monitoring tools such as, for example, PDG and DTS (Distributed Temperature Sensing). In addition to the numerical modelling, analytical solutions (valid under certain simplifying assumptions) were investigated to validate the numerical modelling and to obtain a better understanding of the dependence of detectable distance in the seals on parameters such as permeability and rock heat capacity. In total, five scenarios were assessed including low, medium and high leakage rates with different reservoir and overburden properties. We also reviewed internal feasibility studies from ongoing and previous CCS projects to identify geophysical technologies that have the potential to detect leakage across the caprock, including promising novel technologies, particularly if they have the potential to reduce monitoring costs like fiber optic technologies.

Results

The most promising technologies for detecting CO_2 leakage across the caprock are in-well technologies:

1. Pressure and temperature monitoring with downhole gauges or Distributed Temperature Sensing (DTS) installed on casing.
2. Microseismic monitoring with downhole geophones (if a monitoring well is available) or Distributed Acoustic Sensing (DAS) (if multiple wells are available).
3. Time-lapse wire line logging techniques such as Neutron and Thermal Neutron Capture (TNC) tools may detect CO_2 leakage if a permeable formation is located above the main injection reservoir in a high leakage scenario.
4. 4D DAS VSP, in reflection or refraction mode, or time-lapse DAS cross-well (to be verified with site-specific feasibility studies).

We suggest installing downhole pressure and temperature gauges along the wellbore at the depth of the primary reservoir, first seal, second reservoir and second

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seal. Site specific application should be reviewed based on tailor made model simulations during the feasibility and/or concept selection phase of a CO_2 storage project. Time-lapse wire line (WL) logging techniques such as neutron and thermal neutron capture (TNC) tools may also detect CO_2 leakage if a permeable formation is located above the main injection reservoir for high leakage rates but would not be effective for low rates. For medium leakage rates, WL logging effectiveness depends on formation properties in the overburden. Even for a high leakage case, the techniques are likely to detect CO_2 leakage only after some time when saturation change at the location of the monitoring well are significant enough. The disadvantage of time-lapse logging is that it requires well intervention and could only be performed several times per year (no permanent acquisition is possible).

Geophysical monitoring technologies

Geophysical methods can be separated into two groups (surface and borehole) according to the location of sources and/or receivers. For the purpose of detection leakage across fractures in caprocks, traditional surface seismic methods lack (in general) resolution, sensitivity, or are impractical given their cost. Identifying fractures or small faults, which presumably are unresolved in conventional surface seismic data, is a problem that calls for data with higher resolution. High resolution 4D surveys may be suitable to monitor containment breach in the overburden and shallow sections. In general, considering that seismic changes may be associated to thin flow units, 4D seismic may have better sensitivity than 3D seismic, but seismic repeatability and azimuthal coverage must be good enough. This reduces the probability of success of conventional technologies like streamers. All the selected borehole technologies, including time-lapse DAS (Distributed Acoustic Sensing) VSP (Vertical Seismic Profiling), DAS microseismic, time-lapse DAS cross well, and time-lapse sonic deep imaging, have been assessed to be promising technology options, but a more detailed site-specific feasibility analysis is recommended to define the range of conditions at which the technology can detect fracture opening, fault reactivation, or CO_2 leakage along fractures or faults.

We have carried out a high-level screening of twelve technologies with the potential to monitor effectively CO_2 leakage along fractures or faults. From these, we have discarded three technologies based on limited resolution or sensitivity. Previous feasibility studies for the former Peterhead CCS project and numerous experiments in hydraulic-fracturing settings suggest multi-well microseismic monitoring using DAS can monitor fault reactivation or induced fracturing. Once a fibre-optic cable is installed, other methods such as 4D DAS VSP, in reflection or refraction mode, or time-lapse DAS cross-well, could be carried out to monitor amplitudes and travel time changes of direct, reflected, refracted and converted waves, which could be associated with CO_2 migration along fractures. However, proper site-specific feasibility studies are necessary to determine the limits of these methods. The availability of a fibre-optic cable might also enable a modified version of the borehole acoustic reflection survey (BARS) method to obtain even higher resolution images of fractures in the vicinity of the injectors. With increased horizontal and vertical resolution, a high-resolution seismic survey may be able to resolve some fracture/fault paths, especially in the shallow subsurface, but the relative lower repeatability and

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limited azimuth may reduce the change of success of monitoring CO_2 movement within these fractures.

Impact

Containment monitoring technologies capable of detecting leakage across caprocks/seals are key elements of active barriers in a containment bowtie risk assessment framework. To establish the initial effectiveness of such technologies, site-specific feasibility studies must be done and once the site is operational, the performance of the monitoring technology verified. Over time, the effectiveness of these barriers may change depending on the CO_2 storage site and monitoring tool performance. The work done here offers a guide for stakeholders to efficiently select and assess appropriate containment monitoring technologies within a bowtie risk assessment framework. Besides new insights from our feasibility studies, we share insights and work done for both the former Peterhead and Quest CCS projects.

WP5 – Qualitative and quantitative risk assessment

Overview

It is important to be able to communicate about leakage risks for CO_2 storage operations in a clear, logical and substantiated manner to all stakeholders. Although bowtie diagrams have been found to be one of the most effective methods in a number of projects, these have been developed on a case-by-case basis and the approaches adopted and amount of information presented have been variable. Properly executed bowtie analysis allows for easy-to-understand evaluation of the leakage risk scenarios that exist and the barriers that are in place to manage them and identifies areas where further study should be prioritised.

WP5 creates a set of standardised, template bowties for use as a starting point for project-specific assessments, allowing efficiency improvements and comparisons between options to be made. WP5 also integrates quantitative risk approaches into the bowtie methodology to provide numerical insights into the risks present.

Method and data

WP5 commenced with a literature survey[1] to gain a comprehensive, current view of using bowtie analysis in CCS projects, as well as approaches to quantifying bowties and/or CO_2 leakage. The remaining scope was completed in a series of workshops, held throughout the project, providing for close collaboration with the other WPs and the involvement of subject matter experts in the development of the WP5 output.

Results and discussion

The WP5 scope of work can be summarised in three areas: 1) overall bowtie template for all leakage paths (‘parent’ bowtie model), 2) specific bowtie analysis for fracture-related leak mechanisms (‘child’ bowtie), 3) quantitative risk tool.

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Overall bowtie model

A bowtie (Figure 2) is a widely used graphical risk analysis method[2,6], mapping out the potential causes that may lead to an unwanted event, and how this may then result in unwanted consequences. On the left side of the bowtie are the prevention barriers that act to halt the unwanted event, and on the right side, the mitigation barriers that act to reduce the likelihood or magnitude of the consequences. The figure below shows how this can be applied to the risk of CO_2 release from underground storage.

A series of template bowties[5] has been produced covering a complete range of possible leakage paths (e.g. via the primary seal, laterally, from the injection well or via CO_2 contact with legacy wells). These template bowties have also been developed into a simple software tool[7], allowing users to create customised bowties to initiate a risk assessment of a particular site.

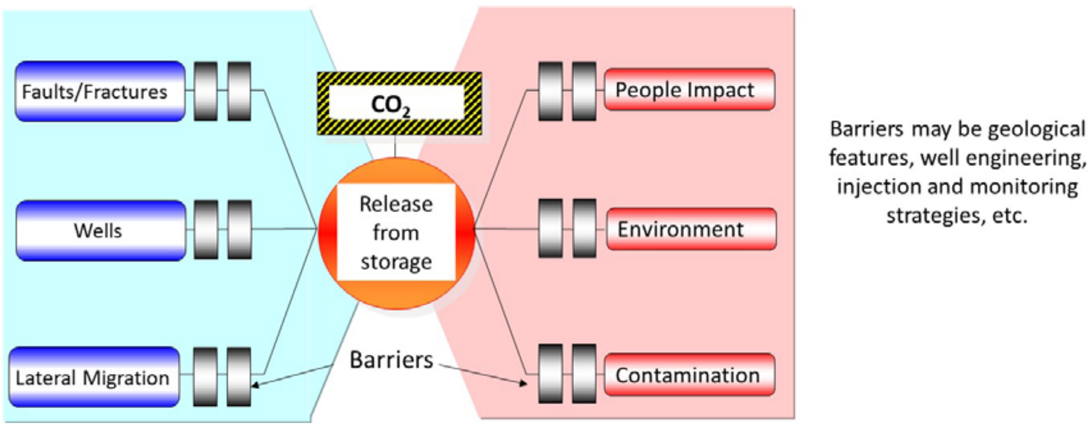

Figure 2. The bowtie model for qualitative risk assessment.

For each bowtie barrier, the template bowties provide barrier-specific descriptors allowing users to assign effectiveness ratings (Good/Fair/Poor). This effectiveness is determined by the extent to which the barrier exists or is implemented at a specific site and also by the barrier’s inherent capability to perform its role. The user can also record a certainty rating (High/Medium/Low) for the effectiveness level, e.g. based on the amount and quality of information available.

Several barriers represent monitoring activities, and these have been integrated with the WP4 output by including a look-up of the bowtie barrier effectiveness for a range of available monitoring technologies and expected CO_2 leakage rates (which may be estimated by the WP5 quantitative risk tool – see below). The user can thus compare the bowtie barrier effectiveness of proposed monitoring technologies.

The output from this customisation process is a comprehensive, standardised bowtie forming the starting point for further, site-specific bowtie analysis.

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Fracture-related leak mechanisms

The bowtie model was extended to include detailed analysis of the effects studied in the WP2 work packages on the flow of CO_2 through fractures. For each of Pressure (WP2.1), Reactive (WP2.2) and Clay Swelling (WP2.3) Effects, key parameters influencing the flow of CO_2 through the fracture network were identified, and also the relative importance of each on the overall leakage rate was estimated.

These key parameters were represented by barriers on a ('child') bowtie and also on logic trees[5] which detail the inter-relationship of the parameters to estimate the change (+/-) in leak rate for each effect. These were then combined to derive an overall effectiveness ranking for the barrier on the main ('parent') bowtie.

This approach allows for detailed examination and understanding of one of the key barriers in CO_2 storage, the geological properties of the caprock with regard to CO_2 flow through faults and fractures, and the influence that site-specific variables will have on its effectiveness.

Quantitative risk tool

It proved impractical to integrate a quantitative model into the bowtie structure that produced meaningful results (e.g. probability of CO_2 leak rate through fractures) and that was also relatively simple to run. Instead a stand-alone quantitative model[3,4] was developed which generates results without the need for intensive, detailed simulation analysis. The model structure is shown below in Figure 3.

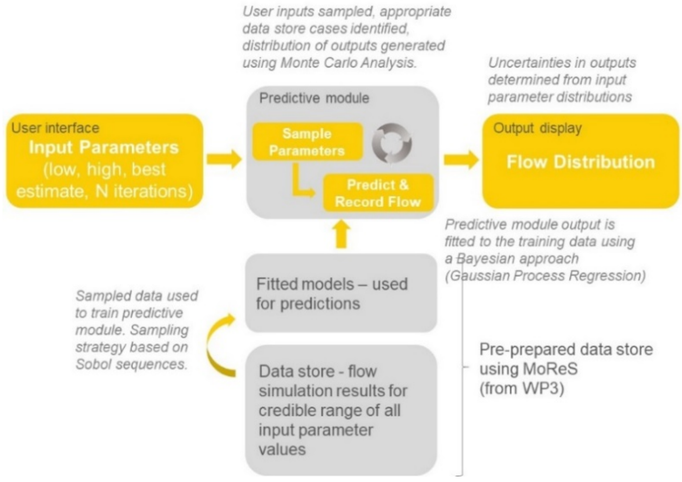

Figure 3. The quantitative model.

The **User Interface** allows selection of input parameters characterising the storage facility. The **Data Store** contains a range of detailed simulations (provided by WP3) covering a range of input parameters. Sampled data from the store are used for predictions based on the input variables, without necessitating an unmanageable amount of detailed simulation runs. Although the

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data store is initially populated from the MoReS simulation tool (from WP3), it will accept data from others.

The **Calculation / Predictive Module** forms the main predictive element, where the user inputs are sampled to generate probability distributions for predicted flow rates at a range of locations (e.g. primary and secondary seals) over a user chosen time frame. As noted above, this can be integrated with the choice of monitoring technologies, based on predicted flow rate and placement depth.

Impact

WP5 has produced a suite of qualitative, semi-quantitative and quantitative risk assessment tools, integrated with WP2, WP3 and WP4, which will improve consistency and quality of risk assessments, bring about considerable efficiency savings and provide insight into the risks associated with CO_2 leakage through fractures.

By using the comprehensive, overall bowtie model, future projects' risk assessments will benefit from the expert knowledge contained in the detailed bowtie diagrams. The resulting, customised bowties consider all leak path types from the storage complex, presenting a risk assessment suitable to communicate to all stakeholders. Linking the bowtie monitoring barrier effectiveness and the WP4 output allows a project to easily demonstrate the contributions of monitoring activities to managing CO_2 leakage risk, and to aid determining the most reasonably practicable techniques.

The child bowtie and its accompanying, semi-quantitative, logic-tree analyser tool provides projects with a straightforward and reproducible way of evaluating the effects of the caprock geological properties in altering CO_2 flow through fractures, based on known key parameters. Further, the methodology is transferrable, and can therefore be used to evaluate any similar aspect of CO_2 storage in detail.

Finally, the quantitative risk tool allows rapid prediction of CO_2 flow rates via fractures, without the need for specialist, resource-intensive simulation. Although the tool is provided with a fully populated data store for a typical North Sea storage site, this can be replaced with data relevant to a specific project. Again, the methodology is transferrable and is described fully, meaning that a similar quantitative risk tool could be created for a different type of leak path. Deliverables and link to the bowtie tool can be found in Appendix 4 – Work Package 5.

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3. Project Impact

The DETECT project has achieved the goals as planned and Shell is now preparing to apply the workflow in the near future to a number of ongoing international projects. As a result, we expect to further develop the capabilities advanced here and hope that this will encourage additional deployments by other operators. The aim is to commercialise the technology via a growing CCS funnel in Europe. Additional applicable base for the DETECT workflow include hydrogen storage, energy storage and geothermal projects where the risk of geological leakage will also have to be managed.

The workflow and tools delivered by the DETECT project are expected to contribute significantly to support safe and efficient deployment of CCS at large scale by:

- Reducing Risks: DETECT will improve an operator’s and other stakeholder’s ability to evaluate risks related to leakage across faults and fracture networks in the primary caprock and the storage seal. The approach developed is a first important step in managing this complex problem and we expect further progress in the near future.
- Provide Assurance: Stakeholders will receive a comprehensive and pragmatic overview of relevant containment monitoring technologies with a focus on reliability, innovation and cost reduction.
- Improve Communication: Above workflow and the bowtie tool will allow a much improved communication of realistic risks associated with CO_2 storage which is critically important to promote CCS as a viable and safe mitigation for climate change.
- Reduce Costs: Another key challenge to overcome for a CCS industry to develop to the scales needed to successfully address climate change, is clearly related to costs. DETECT aims to make a significant contribution to reduce costs by improving efficiency related to risk assessment for CO_2 storage and containment monitoring, while maintaining the highest safety standards expected by society.

Below a summary of the impacts achieved by individual work packages:

WP2: The experimental data generated in DETECT provides direct input to the upscaled modelling in WP3 and new knowledge of the sealing of fractures upon changes in pressure and fluid chemistry. It also allows to better understand risks associated with caprock formations composed of a specific mineralogy. Results and conclusions directly feed into risk assessment of WP5 and therefore help informing best practice guidelines for assessing the risk of fracture leakage.

WP3: An integrated fine-to large-scale fracture characterisation and modelling workflow has been developed to predict the potential range of leak rates at any level of interest (e.g. top primary seal; top storage complex; seabed). The

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large-scale model results can feed directly into qualitative and quantitative containment risk assessment, with the caveat that further validation against natural analogues or large-scale leakage tests is recommended to further validate the quantitative reliability of the workflow. Modelling technologies have been developed for credible fracture leakage modelling at single-fracture scale, fracture network scale and storage complex scale. These technologies have been or will soon be published in the open literature.

WP4: Containment monitoring technologies capable of detecting leakage across caprocks/seals are key elements of active barriers in a containment bowtie risk assessment framework. To establish the initial effectiveness of such technologies, site-specific feasibility studies must be done and once the site is operational, the performance of the monitoring technology verified. Over time, the effectiveness of these barriers may change depending on the CO_2 storage site and monitoring tool performance. The work done here offers a guide for stakeholders to efficiently select and assess appropriate containment monitoring technologies within a bowtie risk assessment framework. Besides new insights from our feasibility studies, we share insights and work done for both the former Peterhead and Quest CCS projects. The work done in WP4 should allow stakeholders to more efficiently select, assess and implement monitoring as active barriers in the overall containment risk assessment framework of a CO_2 storage project.

WP5: WP5 has produced a suite of qualitative, semi-quantitative and quantitative risk assessment tools, integrated with WP2, WP3 and WP4, which will improve consistency and quality of risk assessments, bring about considerable efficiency savings and provide insight into the risks associated with CO_2 leakage through fractures. By using the comprehensive, overall bowtie model, future projects' risk assessments will benefit from the expert knowledge contained within the detailed bowtie diagrams. The link between monitoring barrier effectiveness on the bowties and the output from WP4 means that projects can easily demonstrate the contribution made by monitoring activities to managing CO_2 leakage risk and can determine the most reasonably practicable monitoring techniques. The child bowtie and its accompanying, semi-quantitative, logic-tree analyser tool provides projects with a straightforward and reproducible way of evaluating the effects of the caprock geological properties in altering CO_2 flow through fractures, based on known key parameters. Finally, the quantitative risk tool allows rapid prediction of CO_2 flow rates via fractures, without the need for specialist, resource-intensive simulation. Although the tool is provided with a fully populated data store for a typical North Sea storage site, this can be replaced with data relevant to a specific project.

Communication, public acceptance and gender balance

Thanks to the extensive dissemination activities performed by the DETECT consortium, the work has been noted with interest by current and future CO_2 storage operators and research organisations across the globe. The final webinar was very well attended with over 150 participants from industry and academia. The bowtie framework will allow clear and logical communication with a broad range of stakeholders at the various levels of complexity required.

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By transparently managing geologic leakage risks with workflows and tools that are based on sound research and deep scientific insight (made available in established peer-reviewed publications), we expect to contribute to improving public acceptance of CO_2 storage.

Finally, the gender balance was excellent in the leading positions of the project (50% male/female), WP2 and W3 contributors were mainly male, WP4 was 100% female, and WP5 was 50% male/female.

5. Collaboration and coordination within the Consortium

The management structure followed the DESCA model with the Supervisory Board (SB) as the ultimate decision making body in this consortium. The SB was composed of one representative from all the beneficiaries and was led by Dr Dean who was also acting as the Project Coordinator (PC) for the daily management of the project. The PC’s role required ensuring the overall progress of the project, verifying that the global aspects of the projects are carried out and making sure that objectives with regard to training and science are met.

The DETECT project was structured to enable the timely and efficient overall management of project activities and deliverables. The number of partners in DETECT was intentionally very small comprising only of four partners with the key capabilities required to achieve the delivery of a focused, pragmatic and truly integrated approach to CO_2 storage risk assessment. To assure high technical quality of the deliverables, a Stakeholder Advisory Board (SAB) was invited for regular, unbiased reviews of the project. Dr Claus Otto (Curtin University, Australia), Quentin Fisher (Leeds University, UK), Zoe Shipton (University of Strathclyde, UK), Philip Ringrose (Equinor, Norway), and Mark Trupp (Chevron, Australia) have joined the SAB. In addition, we held workshops with Shell subject matter experts and with Equinor to ensure high quality technical deliverables relevant for CO_2 storage operators.

We are pleased to report that the collaboration was very fruitful, and no major issues occurred other than the challenges related to COVID-19 and the associated laboratory shut-downs. This was successfully mitigated by the ACT coordinators with a four month extension of the project, resulting in the December 31st, 2020 end date. We achieved all milestones and completed deliverables as planned with only minor delays at times associated with staffing challenges at Heriot-Watt University. In addition, other bilateral collaborations between Shell and Utrecht University (Netherlands) as well as the Mont Terri project (Switzerland) benefitted the DETECT project. Shell also hosted 4 internships with young researchers from academia in the Netherlands and the UK (each 4 months long) which directly benefitted the DETECT project.

Added value of transnational cooperation was based on the unique and complementary expertise from the four DETECT:

1. Shell’s significant operational and subsurface Front End Engineering and Development (FEED) experience from its CCS projects (UK and Canada), designing risk-based MMV plans and performing Reactive Transport Modelling for CO_2 storage.

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2. RWTH Aachen houses research institutes CIM (Clay and Interface Mineralogy) and LEK (Geology and Geochemistry of Petroleum and Coal). The institutes are respected for their analytical expertise concerning the mineralogical, geochemical and petrophysical characterisation of rocks, regularly called upon by industry.

3. Within DETECT two HWU institutes have participated, the Institute of Petroleum Engineering (IPE) and the Lyell Centre (LC): IPE is widely recognised as one of the internationally leading centres' of excellence in petroleum engineering and petroleum geoscience.

4. Risktec provides independent and specialist risk management consulting services to companies in the major hazard industries, to help them manage health, safety, security, environmental and business risk. For example, Risktec has supported projects like the former Peterhead CCS project, the Net Zero Teesside and the Northern Lights projects.

We expect that the transnational cooperation of DETECT allows achieving the objectives of accelerating CCS technology by leveraging unique expertise of the individual partners to deliver efficient and effective CO_2 storage technologies to ultimately attain a common goal, namely reducing climate impacts from burning fossil fuels with CCS. With a functional EU regulation, cost and public acceptance are the main barriers for large scale implementation for CCS in Europe. DETECT has aimed to make a significant contribution to reducing costs by improving efficiency related to geologic risk management for CO_2 storage in addition to generating tools to communicate risks and thus improve public acceptance. With a working and affordable CCS technology and considering the implementation of hundred such projects in Europe, several thousand jobs could be secured while effectively mitigating climate impact and sustaining energy security.

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6. Dissemination activities including list of publications

DETECT publications are made available via our page on Research Gate website: ResearchGate and the HWU website: https://geoenergy.hw.ac.uk/research/detect/. Below a list of DETECT project contributions to industry conferences, external workshops and publications.

Industry conferences, internal and external workshops

2018:

- A. Busch, S. Zihms (2018). Poster presentation at EGU meeting, April 12th, Vienna, Austria.
- F. Doster (2018). Talk at PROTECT workshop, April, Geilo, Norway.
- H. Claes (2018). Talk at 6th International Geologica Belgica Meeting, September.
- M. Dean (2018). Poster at GHGT-14, presentation at Curtin University and CSIRO, Australia.
- M. Dean (2018). Poster at Shell Geophysical Conference, Amsterdam, Netherlands.
- N. Kampman, K. Bisdom (2018). Posters at EAGE CO2 Storage Workshop. *Opening Versus Self-Sealing Behaviour of Single Fractures; Quantifying the Risk of CO_2 Leakage Along Fractures Using an Integrated Experimental, Multiscale Modelling and Monitoring Approach in Mudstone Caprocks During CO_2 Migration.* Utrecht, Netherlands.
- K. Bisdom, N. Kampman, N. Forbes Inskip, T. Phillips, M. Zhang, A. Busch (2018). Poster at 37th Technical Meeting of the Mont Terri Project. *Numerical and experimental insights into rough fracture (relative) permeability.* Switzerland.
- R. Fink (2018). Poster at GeoBonn, September, Germany.

2019:

- O. Tucker (2019). Poster at IEAGHG Fault workshop, Calgary, Canada.
- M. Dean, J. Snippe (2019). Oral presentation at Shell Reservoir Surveillance Team, Amsterdam, Netherlands.
- J. Snippe (2019). Oral presentation at the Pre-ACT Stakeholder Meeting Brussels, Belgium.
- J. Snippe (2019). CSIRO virtual workshop.
- M. Dean (2019). Oral presentation at a virtual Northern Lights MMV partners meeting.
- J. Snippe, N. Kampman, K. Bisdom, M. Dean (2019). Shell/Equinor DETECT virtual workshop.
- R. Fink (2019). Conference paper and presentation at 6th EAGE shale workshop. *Hydration state and interlayer cation type (Ca^{2+}, Na^{+}) control CO_2 sorption behaviour of SWy-2 montmorillonite.*

2020:

- J. Snippe, N. Kampman, K. Bisdom, M. Dean (2020). Shell internal technical review workshop, Amsterdam, Netherlands.
- R. Rizzo, H. Fazeli, C. Maier, R. March, D. Egya, F. Doster, A. Kubeyev, N. Kampman, K. Bisdom, J. Snippe, K. Senger, P. Betlem, T. Phillips, N. Forbes Inskip, O. Esegbue, A. Busch (2020). Oral presentation at GET2020, *Understanding fault and fracture networks to de-risk geological leakage from subsurface storage sites.*
- F. Doster, A. Busch. Oral presentation at SCCS ACT projects webinar.
- M. Dean, S. Hurst, N. Kampman, F. Doster, J. Snippe (2020). DETECT final webinar.

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- T. Phillips, N. D. Forbes Inskip, G. Borisochev, O. Esegbue, T. Bultreys, V. Cnudde, K. Bisdom, N. Kampman, and A. Busch (2020). *Laboratory-Based Investigation into the Fluid Flow Properties of Natural and 3D-printed Rough Fractures.* 1st Geoscience & Engineering in Energy Transition Conference, 16th – 18th November, Strasbourg, France (held online).
- T. Phillips, T. Bultreys, A. Mascini, N. Kampman, K. Bisdom, N. D. Forbes Inskip, S. A. M. den Hartog, V. Cnudde, A. Busch, (2020). *A systematic investigation of the intrinsic flow properties of fractures using a combined 3D printing and micro-computed tomography approach.* Interpore 12th Annual Meeting (held online).

2021 (Planned):

- S. Hurst, A. Lidstone, M. Beeson (2021). EAGE Energy Transition Online Series "Putting Carbon Underground – Key strategies to reach Net Zero Emissions". *Bowtie Risk Management of Underground CO_2 Storage.*
- R. Rizzo, H. Fazeli, F. Doster, N. Kampman, K. Bisdom, J. Snippe, K. Senger, P. Betlem, A. Busch (2021). EGU2021. Session on role of fault and fracture in geo-energy applications.

Publications

- A. Kubeyev (2019). ARMA conference paper: *Geomechanics Numerical Code for Modelling Contact in Fractures using VEM.*
- R. Fink, P. Bertier, B. Krooss, P. Weniger (2019). *Hydration State and Interlayer Cation Type (Ca2+, Na+) Control CO2 Sorption Behaviour of SWy-2 Montmorillonite.* In Sixth EAGE Shale Workshop (Vol. 2019, No. 1, pp. 1-5). European Association of Geoscientists & Engineers.
- T. Philips et al. (2020). *Controls on the intrinsic flow properties of mudrock fractures: A review of their importance in subsurface storage.* Earth-Science Reviews.
- A. Busch et al. (2020). *Swelling clay minerals and containment risk assessment for the storage seal of the Peterhead CCS project.* IJGGC, 2020.
- K. Bisdom, P. A. Swaby (2020). *Green River Fault and Fracture Structural Model. Conceptual model for hydromechanical leakage modelling and upscaling for the Green River site, Utah, USA.* Unrestricted Shell report SR.20.00919, Shell Global Solutions International B.V., Amsterdam.

Book Chapter (in print):

- A. Busch (Heriot-Watt University) published a book chapter (pp.283-303) in Geological Carbon Storage, *Migration and Leakage of CO_2 From Deep Geological Storage Sites: Subsurface Seals and Caprock Integrity*. November 2018.

- R. March, C. Maier, F. Doster, S. Geiger (2021), *A unified Framework for Flow Simulation in Fracture Reservoirs.*
- K. A. In Lie, O. Møyner (2021). *Advanced Modelling with the MATLAB Reservoir Simulation Toolbox (MRST)*, Cambridge University Press, 2021.

Submissions and in preparation for publication

- T. Phillips, T. Bultreys, K. Bisdom, N. Kampman, S. Van Offenwert, A. Mascini, V. Cnudde, A. Busch (2020). *Systematic Investigation into the Control of Roughness on the Flow Properties of 3D-Printed Fractures.* (submitted to Water Resources Research in 2020).
- A. Kubeyev, N. D. Forbes Inskip, T. Phillips, Y. Zhang, C. Maier, K. Bisdom, A. Busch, F. Doster (2020). *Numerical modelling of stress-permeability relationship for rough fractures using rock*

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mechanics and Stokes equation. Elsevier, (submitted to International Journal of Rock Mechanics and Mining Sciences in 2020).

- R. March, D. Egya, D, C. Maier, A. Busch, F. Doster (2020). *Numerical computation of stress-permeability relationships of fracture networks in a shale rock* (submitted to Computers and Geotechnics in 2020).
- H. Claes, T. Miranda, T.C. Falcao, J. Soete, Z. Mohammadi, L. Zieger, M. M. Erthal, J. Aguilar, J. Schmatz, A. Busch, R. Swennen. Model for calcite spherulite formation in organic, clay-rich, lacustrine carbonate shales (Barbalha Formation, Aptian, Araripe Basin, NE Brazil). Submitted to Marine and Petroleum Geology 2020.
- H. Claes et al. Self-sealing by mineralization of faults in CCS caprocks: Insights from laboratory flow experiments (working title). In preparation.
- N. D. Forbes Inskip, T. Phillips, K. Bisdom, G. Borisochev, A. Busch, P. Meredith (2021). *An investigation into the controls on fracture tortuosity in anisotropic rocks and the impact on fluid flow in the upper crust.* Journal of Geophysical Research: Solid Earth (to be submitted 2021).
- R. Fink, A. Busch, B. M. Krooss, P. Bertier. CO2 uptake behaviour of smectite as a function of water content and its relation to clay swelling (working title).
- R. Rizzo, H. Fazeli, F. Doster, N. Kampman, K. Bisdom, J. Snippe, K. Senger, P. Betlem, A. Busch. DETECT workflow applied to Svalbard dataset (working title).
- C. Maier, R. March, D. Egya, K. Bisdom, N. Kampman, F Doster. A quick estimation of capillary pressure barriers in fractured caprocks. In preparation.
- N. Kampman, C. Maier, K. Bisdom, R. March, J Snippe, F Doster. Stress-Sensitive Two-Phase Flow Properties of Fractured Networks for Fault Related CO_2 Leakage Modelling. In preparation.
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Conclusion

The DETECT project set out to tackle a very challenging and complex problem with a focused consortium of relevant experts. We have made first important steps in developing tools and capabilities to manage leakage risks across fractures in the caprock in a comprehensive manner. The workflow has been applied to the Green River natural CO_2 leakage site in Utah, USA (as an analogue) and the North Sea Captain Fairway (as a potential CO_2 storage site). As a result of our work, we have improved understanding of underlying mechanisms that either enhance or inhibit leakage in existing faults and fracture networks in caprocks. Further, DETECT progressed insights into realistic fracture geometries and flow rates for several representative scenarios. In addition, we have identified containment monitoring technologies that are capable of detecting such caprock integrity issues. We have also delivered pragmatic and efficient risk-assessment tools and workflows for operators integrating learnings from DETECT and projects like Peterhead and Quest.

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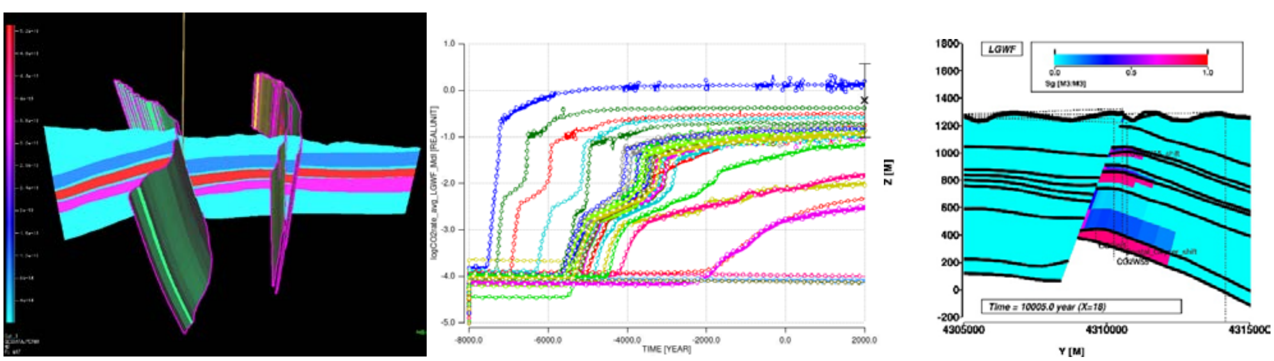
Appendix 1 – Work Package 2

All deliverables have been or will be published in the open literature (see section 6).

Appendix 2 – Work Package 3

WP3 - Green River fault and fracture structural model:

All deliverables have been or will be published in the open literature (see section 6). Some key results are illustrated in Figure 4 and Figure 5. MRST code is available on https://bitbucket.org/HWUCarbonates/mrst-hwu-fractures and https://bitbucket.org/HWUCarbonates/mrst-hwu-fracpack .



(a) (b) (c)

Figure 4: Green River large-scale model: (a) N-S cross section with reservoir layers highlighted and with Grand Wash Fault (left) and Salt Wash Graben (right) included; (b) surface leak rate (log scale) as function of time for base case model and sensitivity runs with measured data uncertainty range indicated by the vertical black line on right hand side; (c) cross-section of gas saturation at end of simulation for one of the matching models. In the shallower sections all CO_2 dissolves in the formation water but then exsolves near surface. The model is initialised with free gas only present in the deepest reservoir layer.

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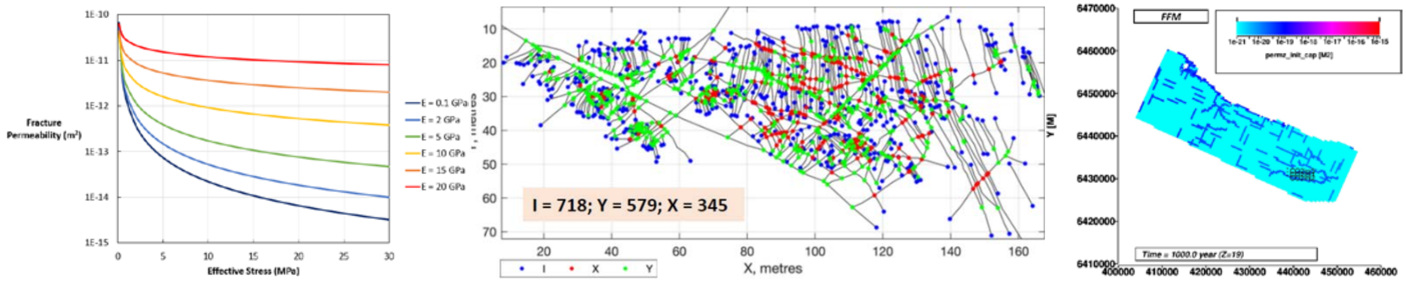

(a) (b) (c)

Figure 5: North Sea application: (a) empirical single-fracture stress-permeability model; (b) Konusdalen fracture characterisation; (c) effective damage zone vertical permeability through primary seal (base case realisation, assuming uncemented fractures).

Appendix 3 – Work Package 4

WP4 - Containment Monitoring Feasibility Studies – Final Report

DETECT WP4 Report Final Unrestricted.pdf

WP4 – Containment Monitoring Technologies – Performance Matrix

DETECT WP4 Matrix Final Unrestricted.xlsx

WP4 – Containment & Environmental Monitoring Technologies – Catalogue

Containment & Environmental Monito

Appendix 4 – Work Package 5

All deliverables will be published at https://risktec.tuv.com/eu_detect

SGSI-12-R-04 i1 Qualitative Bowtie C

SGSI-12-R-01 Issue 1 Literature Survey.p

SGSI-12-R-05 Quantitative Model

SGSI-12-R-06 Quantitative Model

SGSI-12-R-07 Bowtie Analysis i1.p

SGSI-12-R-08 Risk Assessment Guide i1

SGSI-12 Bowtie Template Tool User (

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