Project acronym and title:

SECURe – Subsurface Evaluation of Carbon capture and storage and Unconventional risks

BEST PRACTICE RECOMMENDATIONS FOR THE ENVIRONMENTAL MONITORING OF SHALE GAS OPERATIONS IN EUROPE

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Public introduction

Subsurface Evaluation of CCS and Unconventional Risks (SECURe) is gathering unbiased, impartial scientific evidence for risk mitigation and monitoring for environmental protection to underpin subsurface geoenergy development. The main outputs of SECURe comprise recommendations for best practice for unconventional hydrocarbon production and geological CO2 storage. The project is funded from June 2018–May 2021.

The project is developing monitoring and mitigation strategies for the full geoenergy project lifecycle; by assessing plausible hazards and monitoring associated environmental risks. This is achieved through a program of experimental research and advanced technology development that includes demonstration at commercial and research facilities to formulate best practice. We will meet stakeholder needs; from the design of monitoring and mitigation strategies relevant to operators and regulators, to developing communication strategies to provide a greater level of understanding of the potential impacts.

The SECURe partnership comprises major research and commercial organisations from countries that host shale gas and CCS industries at different stages of operation (from permitted to closed). We are forming a durable international partnership with non-European groups; providing international access to study sites, creating links between projects and increasing our collective capability through exchange of scientific staff.

Executive report summary

The SECURe programme of work resulted in a series of 41 deliverable reports detailing the outcomes of field, laboratory and desk-based research and reviews, and includes learnings from North America and Australia. Additionally, a series of activities focussed on improving interactions with stakeholders through initiatives such as participatory monitoring. Specific innovations have been progressed by the project, including new ways to monitor and model the natural environment's response to subsurface energy activities. Although the project focuses on risks associated with unconventional hydrocarbons production and CO_2 storage, many of the developed concepts and techniques are applicable (either directly or in-part) to other subsurface activities that alter the in-situ stress and pore-pressure of the subsurface (e.g., geothermal exploitation and energy storage such as hydrogen, compressed air and thermal). The research has been informed by a risk-based assessment undertaken in work package 2 (Risk assessment for leakage and induced seismicity: methodology and case studies), that has to some extent influenced the research programme. This report (D6.9) compiles a series of 5 factsheets, each based on one principal risk posed by unconventional hydrocarbons activities, outlining a series of good practice recommendations based on the research completed in the programme of work. The report is complimented by deliverable report D6.8 which compiles a further 4 factsheets, with a focus on risks associated with CO_2 storage activities.

Contents

1 Introduction

The Horizon 2020 call LCE-27-2017: Measuring, monitoring and controlling the potential risks of subsurface operations related to CCS and unconventional hydrocarbon outlined the requirement for unbiased, research-led data and information to identify and address some of the risks associated with subsurface energy technologies that can support transitions to lower carbon energy systems. The SECURE project represents a coherent series of research activities designed in response to the LCE-27-2017 call. During the period of the SECURe project, several member states and other major industrialised countries have committed to legally binding carbon-reduction targets, with many seeing CCS technologies playing a major role. In the EU, interest in Unconventional hydrocarbon exploitation has lessened considerably, with moratoria in place in some countries, and poor commercial prospects in others; however, interest in shale gas and oil continues in many territories outside the EU, with large-scale exploitation now underway in countries including the US, Canada, Argentina and China.

SECURe brings together experiments based at a series of field sites at different stages of operation (from permitted to closed), and bespoke laboratory experiments and modelling approaches. These experiments have been partly influenced by risk-assessment process that identified the main risks associated with CCS and Unconventional Hydrocarbons Extraction (UHE) through a qualitative bow-tie approach coupled with the development of a semi-quantitative risk assessment tool. The work programme has excellent stakeholder relations, including an engaged Advisory Board consisting of representatives from industry, policy-makers, regulators and academia.

1.1 OBJECTIVES

The SECURe project has met the following specific objectives:

1. Production of a risk assessment framework for assessing the hazards and likelihoods of specific risks that relate to the protection of the environment in CO_2 storage and shale gas operations.
2. Demonstration of good practice in establishing baseline conditions for subsurface geoenergy operations by working across a network of both commercial, pilot and research-scale sites in Europe and internationally, underpinned by laboratory measurements and model up-scaling to the field scale.
3. Development of * specific innovations and new technologies that improve the detection and monitoring of environmental impacts related to geoenergy projects.
4. Investigation of new methods for remediating potential environmental impacts of geoenergy projects specifically to reduce leakage from wells or naturally occurring permeable pathways.
5. Understanding the needs of a range of stakeholders, including local communities, and to engage them through the development of appropriate communication strategies, including participatory monitoring and through the education of early-career researchers.
6. Leveraging good practice through collaboration with leading groups in the USA, Canada and Australia.

1.2 SECURE – DELIVERY OF OBJECTIVES

SECURe has achieved these research objectives by:

1. Developing frameworks for quantifying and managing risks including impact assessment (monitoring and characterisation) for developing and implementing effective remedial strategies and to contribute to the evidence base underpinning policy making;
2. Investigating leakage processes and impacts at the laboratory and field-scale using a portfolio of existing European and North American facilities and field sites to better characterise and quantify relevant risk factors;
3. Developing, applying and testing a range of monitoring technologies, systems and strategies to contribute to effective (good practice) risk evaluation, establishment of baseline conditions and

monitoring and management of impacts;

4. Exploring opportunities of participative monitoring as an aspect of public engagement.

1.3 SECURE PROJECT LEGACY

SECURe has provided a legacy in terms of:

1. Representative experimental and industrial field sites in the CCS and Shale Gas sectors, for deployment of a comprehensive suite of detection and monitoring methods as a proving ground for cutting edge technologies and to enable technology transfer between sectors;
2. A platform for international cooperation and future projects with focus on US and Canada, facilitating the exchange scientific knowledge and researchers;
3. A scientifically sound, unbiased and independent, pragmatic, and cost-effective good practice for baselining, monitoring, mitigation and remediation – within a risk-assessment framework and with community engagement;
4. Models and good practice guidelines for engaging different stakeholders including citizens through participatory monitoring
5. Dissemination of results through engagement with the public.

1.4 APPROACH TO GOOD PRACTICE RECOMMENDATIONS

This report (D6.9), along with a companion report (SECURe project deliverable D6.8, bring together a series of 9 factsheets that outline the good practice recommendations that have been distilled from the research completed by the consortium. Good practice recommendations focus on a series of 'top events'- an outcome that can be realised when control of a particular hazard is lost. Each fact sheet addresses a single 'top event' identified in the SECURe bow-tie risk assessment (Risktec 2021a, 2021b), with 4 events focussing on risks associated with CCS and 5 events focussing on risks associated with Unconventional Hydrocarbons Extraction. Recommendations come from across the 5 technical work packages that make up the research consortium:

WP2: Risk assessment for leakage and induced seismicity: methodology and case studies

WP3: Environmental baseline and monitoring strategies

WP4: Advanced monitoring and sensor technologies

WP5: Impact mitigation and remediation

WP6: Development and exchange of best practice to ensure SECURe impact

The good practice recommendations address the following risks (top events) associated with Unconventional Hydrocarbon Extraction include:

- Shale Gas (Natural Gas in Formation) – Release from Well (during Exploration, Production and Abandonment Phases);
- Shale Gas (Natural Gas in Formation) – Release from Shale Production Zone;
- Fracturing Fluid / Flowback Water (under Pressure) – Release from Well (during Fracturing / between Fracturing / after Fracturing);
- Fracturing Fluid / Flowback (and Formation) Water (in Formation) – Release from Shale Production Zone;
- Seismicity / Earth Movement (Hydraulic Fracturing) – Induced / Triggered Seismicity / Aseismic Earth Movement.

2 Best practice recommendations for the environmental monitoring of shale gas operations in Europe

2.1 COMMON INTRODUCTORY TEXT TO FACTSHEETS

The following text is used on the webpage than links to downloadable versions of each factsheet. It briefly introduces the project and approach to developing each factsheet, addressing a single 'top event' from the bowtie risk assessment with recommendations from specific deliverable reports.

The text reads:

SECURe has gathered unbiased, impartial scientific evidence for risk mitigation and monitoring for environmental protection to support subsurface geoenergy development. Our main research outputs underpin recommendations which we have collated below as nine factsheets.

The risk framework developed by SECURe identified four principal hazards associated with geological carbon dioxide (CO2) storage (carbon capture and storage - CCS), and five associated with unconventional hydrocarbons extraction (UHE).

Our recommendations seek to provide a pragmatic and reasonable response to these concerns: they can be used to inform site development and management strategies from the perspective of multiple stakeholders (operators, regulators, legislators and the general public). Each headline recommendation is underpinned by project technical reports, available here.

The project employed the "Bow Tie" risk assessment approach, which identifies a series of barriers that prevent a principal hazard ('top event') from occurring. Each factsheet addresses a single top event which can occur if control of a hazard is lost, and provides recommendations to help mitigate them.

The top events were identified through a literature review of hazards, threats, consequences and barriers associated with CO2 storage. The recommendations can be considered to inform preventative (e.g. a limit on operations) or mitigative (e.g. a technical measure that limits the chain of consequence arising from the top event) strategies for risk management.

Participatory monitoring formed a key part of SECURe's research. The value of participatory monitoring approaches was captured and embedded within each Bow Tie risk assessment. Because participatory monitoring is relevant to the management of many aspects of the top events, we have created an overview Participatory Monitoring Factsheet - detailing our recommendations in this area.

- Detailed recognition of the storage reservoir and confinement needs to be established, including identification of all existing faults in the possible injection operations' influenced zone (see SECURe reports D3.7 and D3.8). A cost-effective and timely environmental baseline should always be established prior to any CCS activities commencing, supported by early site appraisals. Monitoring programmes demonstrate to stakeholders that sites are evolving as expected, or deviations in behaviour can identify anomalies.
- Methodologies that can attribute the source of CO2 will also be needed. The baseline defines the environmental conditions prior to CCS activities and needs to account for natural and external anthropogenic temporal variation. Therefore, the use of continuous sampling methodologies for at least one year prior to the start of operations is recommended (D3.6).
- In onshore storage operations, the sampling network for environmental baseline monitoring, ongoing monitoring throughout operation and post-operation monitoring should ensure that sampling is undertaken in all major hydrogeological units at suitable depths to protect groundwater from potential contamination. Existing relevant boreholes should be utilised and bespoke boreholes drilled where necessary.

2.2 FACTSHEETS

2.2.1 Release of natural gas from well during exploration, production and after closure

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Unconventional hydrocarbons exploration:

Release of natural gas from well during exploration, production and after closure

SECURe employed the Bow Tie risk assessment approach, which identifies a series of barriers that prevent a principal hazard ("top event") from occurring. This factsheet outlines recommendations that address a single top event that can occur if control of a hazard is lost: the release of natural gas from a well during exploration, production and/or after closure. It should be read in conjunction with the Participatory Monitoring Factsheet, which provides overall guidance on project construction.

The issue

Although unlikely, the unplanned release of natural gas from wells must be fully assessed. Research has identified wells as the most probable leakage pathway during and following extraction, and once wells have been abandoned. Such releases could result in the emission of hydrocarbons to the atmosphere and/or impacts to ecosystems and people. Release via the well annulus could arise through poor-quality and/or degradation of well-engineering barriers. A range of well-engineering assessments, appropriate material selection and monitoring provide effective barriers to prevent the release of hydrocarbons. If an unplanned release were to occur, then remediation options include monitoring, operational responses, well engineering interventions, and the use of natural geological properties to slow the release. These barriers, and preventive and remedial actions, are discussed in detail in SECURe report BGS-01-R-11.

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Risk mitigation recommendations

Maintaining borehole integrity

- **A probabilistic approach to assessing well integrity should be taken, with the goal of minimising the probability of failure**. Assessments should also provide information, which will aid the communication of uncertainty in forward modelling. Research reported in D2.6 suggests uncertainty in parameters relating to reservoir and cement characteristics can be reduced via laboratory experiments. These can test cement integrity for realistic stress states and well materials, and assess operating limits for well pressure to prevent fracturing of the cement sheath.
- Operators should use **cement formulations that minimise shrinkage**, when possible. Cement shrinkage can significantly increase the probability of failure for the unconventional hydrocarbons extraction (UHE) well. Using the modelling and relationships demonstrated in D2.6, appropriate cement properties and operating conditions can be selected to reduce well failure risks. Cement formulations that lead to a softer, more flexible (i.e. more ductile) cement are recommended.
- Microannuli, or small gaps, along the well, and radial fractures emanating from the casing through the cement should be considered in **leakage mitigation strategies.** Any individual fracture may dramatically increase the leakage risk, but fracture networks do not necessarily lead to a continuous, high-permeability path along the wells (D2.6).
- Relationships between cement properties and the impact on (1) shear cracking and (2) cement debonding (for both the formation-cement and casing-cement interfaces) and caprock leakage can help with the **design of appropriate leakage management scenarios** (D2.6).

Monitoring approach

- **Thresholds should be set** for hydrochemical parameters that could indicate contamination in the future (D3.6). Thresholds should be established using environmental baseline data to calculate concentrations of parameters, which would indicate excessive natural temporal variation.
- There is a strong need for **close cooperation of industry and researchers** in planning and conducting both baseline studies and further monitoring activities (as recommended in D3.7 and D3.8). The possibility of connecting observation results with an industrial process is crucial for the interpretation of phenomena observed in the environment. Results obtained from all observation systems should be reported both to the site operator and to regulators. This will ensure that any adverse changes and causes are identified and appropriate actions undertaken to minimise an impact and further risk.
- For production wells in operation and decommissioned multi-well clusters, a **tiered monitoring programme should be established to localise point sources of methane emissions on the ground**. Using data collected with unmanned aerial vehicle (UAV) based systems (D4.1), modelling can be undertaken to localise the source of emissions on the ground. This modelling helps to focus ground investigations to pinpoint the gas source and determine the flux, and can be used within a tiered monitoring programme:
    - UAVs deployed initially to cover large or poor-access areas to highlight key areas of interest (or at the very least, rule out the vast majority of land).
    - Follow-up ground surveys directed by UAV-based data, to pinpoint individual vents or vent clusters.
    - Gas sampling at individual vents for specialised gas analysis (e.g. for tracers or noble gases), and/or deployment of automated equipment at fixed sites/vents to gather time-series data (e.g. to quantify how gas fluxes change seasonally or under different meteorological conditions).

Risk mitigation recommendations (cont.)

Use of models

- **Effective modelling of the containment system**, with model forecasts of well integrity based on a thorough understanding of controlling processes associated with UHE operations (D2.6). Numerical geomechanical well leakage modelling can be used to quantify the probability of well failure for a range of scenarios that are applicable to well re-use and new well applications.

Development of technology

- **Technology development** for both monitoring measurements and interpreting of results needs to be foreseen. All changes in monitoring scope and schedule should be introduced gradually and in parallel to ensure that new and previous results are comparable, if not directly then by means of recounting techniques. (D3.8)
- **We recommend the use of vegetation carbon isotopes as proxies for present and past gas emanations** (D4.6). Vegetation around a gas seep has the potential to act as an integrator of gas emanation over time and, if tree rings are used, as an archive of gas fluxes. This offers opportunities for using vegetation carbon isotopes as proxies for present and past gas emanations, including anthropogenic-induced gas leaks, e.g. from gas storage or natural gas exploitation facilities.
- **The combination of microbial techniques with established geochemical (isotope) methods allows for assessment of the source of leaking gas**. From the work conducted in The Netherlands and France as part of D4.6, we concluded that microbial communities have the potential to be used as a monitoring tool. For specific gene types, it was demonstrated that the relative abundance of these genes is correlated to the gas isotopic composition with a higher relative abundance of both genes in biogenic gas (compared to a thermogenic origin).

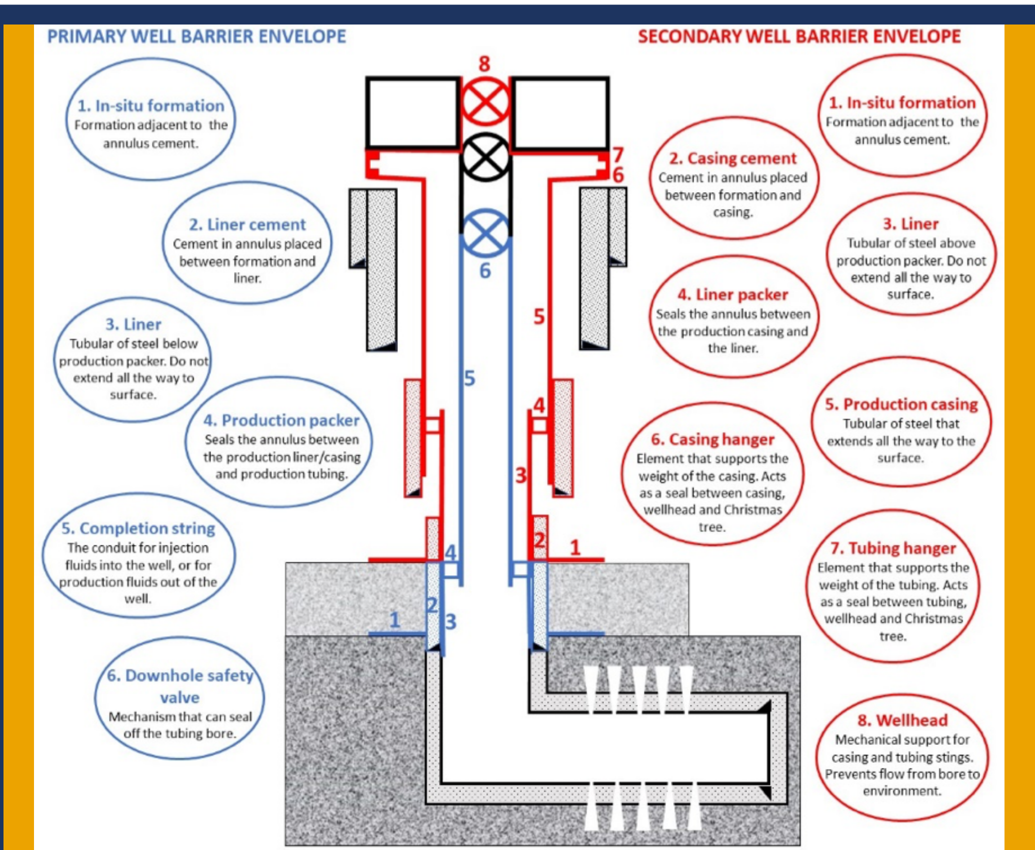

Figure 1: Simplified illustration of well barriers for a typical active shale gas well. Primary well barrier envelope in blue and secondary well barrier envelope in red (from D5.3).

2.2.2 Release of natural gas from the shale production zone

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GOOD PRACTICE AND RISK MITIGATION
FACTSHEET #6

Unconventional hydrocarbons exploration:

Release of natural gas from shale production zone

SECURe employed the Bow Tie risk assessment approach, which identifies a series of barriers that prevent a principal hazard ("top event") from occurring. This factsheet outlines recommendations, which address a single top event that can occur if control of a hazard is lost: the release of natural gas from the shale production zone. It should be read in conjunction with the Participatory Monitoring Factsheet, which provides overall guidance on project construction.

The issue

Although unlikely, the release of natural gas from the production zone must be fully assessed. Such releases could result in the emissions of hydrocarbons to the atmosphere and/or impacts to ecosystems and people. Release from the production zone could arise through abandoned, monitoring or verification wells, via the well annulus, through cements or casing/production liners or along tubing. A range of well engineering assessments, appropriate material selection and monitoring provides effective barriers to prevent the release of hydrocarbons. If unplanned releases were to occur, then remediation options include monitoring, operational responses, well engineering interventions, and the use of natural geological properties to slow the release. These barriers, and preventive and remedial actions, are discussed in detail in SECURe report BGS-01-R-11.

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Risk mitigation recommendations

Monitoring approach

- **A multi-disciplinary approach to assessing fault leakage rates should be taken**, requiring suitable field and laboratory investigations (e.g. analogue studies using outcrop and core) and upscaled hydromechanical modelling (D2.6). This may require the involvement of analogue sites to access suitable sample material and geological outcrops.
- **The potential impact of fractures with high fracture roughness and relatively high permeabilities should be considered** in leakage management scenarios (D2.6) for the most prospective shale gas reservoirs. These have high contents of so-called brittle minerals (e.g. quartz, feldspars, carbonates), making these rocks mechanically strong and brittle, and therefore high in fracture permeability.
- **Thresholds should be set** for hydrochemical parameters that could indicate contamination related to unconventional hydrocarbon exploration (UHE) operations in the future (D3.6). Thresholds should be established using environmental baseline data to calculate concentrations of parameters that would indicate excessive natural temporal variation.
- **Hydrochemical parameters to be used as indicators of contamination should be selected** based on the mineralogy of the aquifer, the characteristics of the potential contaminant (for example, hydraulic fracture fluid release), and the nature of any likely reaction between the two (for example, decreased pH) (D3.6).
- The sampling network for environmental baseline monitoring, ongoing monitoring throughout operation and post-operation monitoring of groundwater should ensure that **sampling is undertaken in all major hydrogeological units at suitable depths** (D3.6). Existing relevant boreholes should be utilised and bespoke boreholes drilled, where necessary.
- Extended datasets of groundwater and soil gas chemistry should be acquired from dedicated monitoring wells to history match and **validate the simulation model** (D3.6).
- **There is a need for independent means to estimate the key subsurface pressure parameters** (formation breakdown pressure, threshold displacement pressure) of the potential leakage pathways to validate pressure management and injection strategies (D3.6).
- **Reliable geochemical monitoring of the formation confinement should include data acquired during the whole lifecycle of a hydrocarbons extraction site** (including the baseline results before injection or production phase), both from the formation and overburden (D3.6). Reliable datasets (e.g. seismic and wireline-logging datasets) of sufficient quality and quantity should contribute to fault-sealing models.
- There is a strong need for **close cooperation of industry and researchers** in planning and conducting both baseline studies and further monitoring activities (as recommended in D3.7 and D3.8). The possibility of connecting observation results with an industrial process is crucial for the interpretation of phenomena observed in the environment. Results obtained from all observation systems should be reported to the site operator and controlling bodies. This will ensure that any adverse changes and causes are identified and appropriate actions undertaken to minimise any impact and further risk.

Risk mitigation recommendations (cont.)

Use of models

- **Geomechanical models should be calibrated using detailed data of geomechanical rock properties of the structure and its surroundings** (D3.6). The Shale Gouge Ratio (SGR) can indicate fault-sealing potential but, for reliable outcomes, calibration of accurate thresholds using available geological information is needed; application to rock types other than sedimentary clastic rocks can be unreliable.
- **Geochemical analyses should be utilised supplementary to fault (and/or fracture) modelling and analyses** to indicate fluid exchange within aquifer/reservoir, migration paths (e.g. along faults and fractures), and possible current leaks within reservoirs (D3.6).

Development of technology

- **Technology development** for both monitoring measurements and interpreting of results should be foreseen. All changes in monitoring scope and schedule should be introduced gradually and in parallel to ensure that new and former results are comparable, if not directly then by means of recounting techniques. (D3.8)
- **Characterisation and monitoring of deep fluids**: gas, noble gases and isotopic compositions are essential parameters for gas storage/formation characterisation and accident prevention. A known disadvantage of conventional industrial sampling equipment is the outgassing of volatiles from in-situ sampling for compositional and isotopic analysis in the laboratory. The downhole sampler and the integrated analysis system developed in SECURe's Work Package 4 (described in D4.8) enable improved characterisation and monitoring of deep fluids.

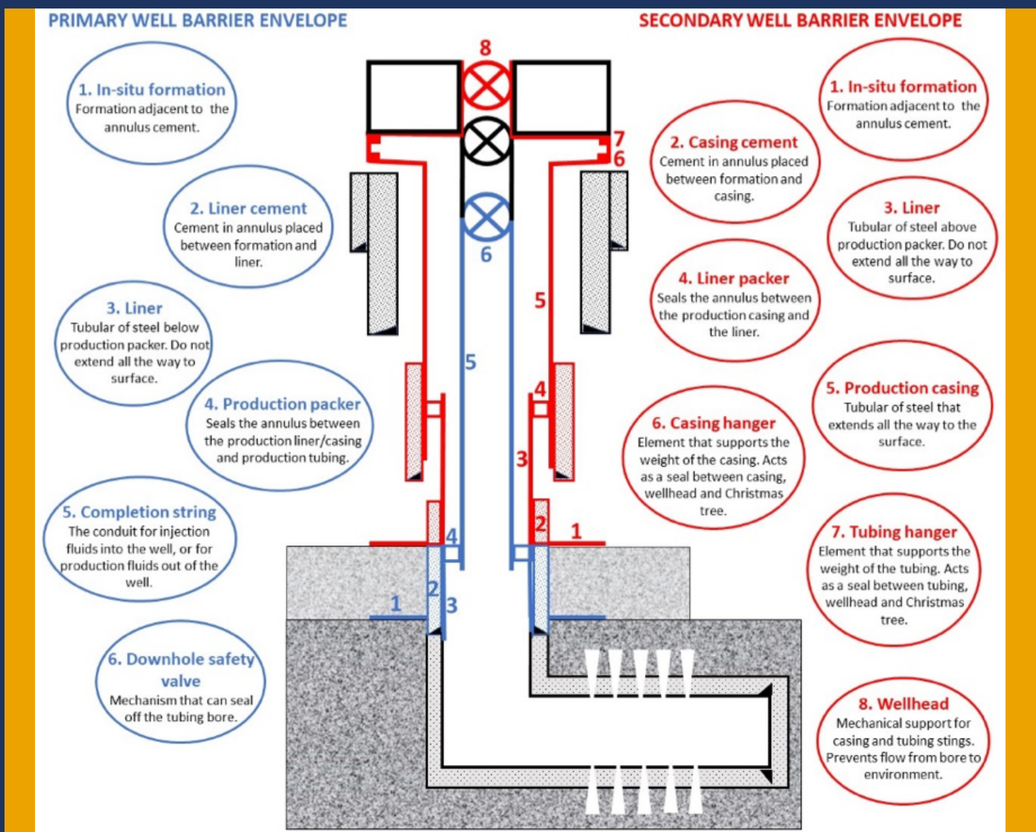

Figure 1: Simplified illustration of well barriers for a typical active shale gas well. Primary well barrier envelope in blue and secondary well barrier envelope in red (from D5.3).

2.2.3 Release of hydraulic fracturing fluid or flowback waters under pressure during, between and following hydraulic fracturing

Unconventional hydrocarbons exploration:

Release of hydraulic fracturing fluid or flowback waters under pressure during, between and following hydraulic fracturing

SECURe employed the Bow Tie risk assessment approach, which identifies a series of barriers that prevent a principal hazard ("top event") from occurring. This factsheet outlines recommendations, which address a single top event that can occur if control of a hazard is lost: the release of hydraulic fracturing fluid or flowback waters under pressure during, between and following hydraulic fracturing. It should be read in conjunction with the Participatory Monitoring Factsheet, which provides overall guidance on project construction.

The issue

The potential release of hydraulic fracturing fluid or flowback waters under pressure during, between and following hydraulic fracturing must be fully assessed in unconventional hydrocarbons extraction (UHE) projects. This could result in releases and/or impacts to ecosystems and people, including other subsurface users. The release of hydraulic fracturing fluid or flowback waters could occur through abandoned, monitoring or verification wells. These releases could occur via the well annulus, through cements or casing/production liners or along tubing. A range of well engineering assessments, appropriate material selection and monitoring provide effective barriers to prevent fluid release. If release were to occur, then remediation options include monitoring, operational responses, well engineering interventions, and the use of natural geological properties to slow the release. These barriers, and preventative and remedial actions are listed in detail in SECURe report BGS-01-R-11.

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Risk mitigation recommendations

Maintaining borehole integrity

- **Well integrity should be ensured** to prevent the leakage of produced waters (D3.3).
- Microannuli, or small gaps, along the well and radial fractures emanating from the casing through the cement should be considered in **leakage mitigation strategies.** Any individual fracture may dramatically increase the leakage risk, but fracture networks do not necessarily lead to a continuous, high-permeability path along the wells (D2.6).
- Under the right conditions, **re-purposing existing wells for hydraulic fracturing can be done** with minimal damage to the cement, provided the status of wells is known and properties of the cement are well-characterised (D2.6).
- Due to the high level of uncertainty in parameters associated with formation and cement behaviour, it is suggested that **a probabilistic approach in assessing well integrity, with the goal of minimising the probability of failure, is used**. However, laboratory experiments can be used to test cement integrity for realistic stress states and well materials, and to assess fracturing of the cement sheath operating limits for well pressure (D2.6).
- **Maintaining well integrity throughout the life cycle of a well** is important for UHE. Statistics on different incidents of well integrity issues indicate that the most vulnerable well components are tubing, casing and cement sheath. The loss of integrity or leakage cannot be meaningfully addressed by looking at different leakage pathways independently of the well barrier envelopes (D5.1).
- **Appropriate management of drilling wastes** is important to ensure there is no leaching of organic chemicals that could directly and/or indirectly impact shallow groundwater quality (D3.3).

Monitoring approach

- **Thresholds should be set** for hydrochemical parameters that could indicate contamination in the future. Thresholds should be calculated using the environmental baseline data to calculate concentrations of parameters that would indicate excessive natural temporal variation (D3.6).
- **Hydrochemical parameters to be used as indicators of contamination should be selected** based on the mineralogy of the aquifer, the characteristics of the potential contaminant (for example, hydraulic fracture fluid release), and the nature of any likely reaction between the two (for example, decreased pH) (D3.6).

Risk mitigation recommendations (cont.)

Establish baseline environmental conditions

- Knowledge about the waters associated with the unconventional reservoir, i.e. the **characterisation of the formation fluids**, can also be obtained from the monitoring of flowback fluids associated with borehole drilling during the development of unconventional reservoirs or from produced water when the borehole is under production (D3.4).

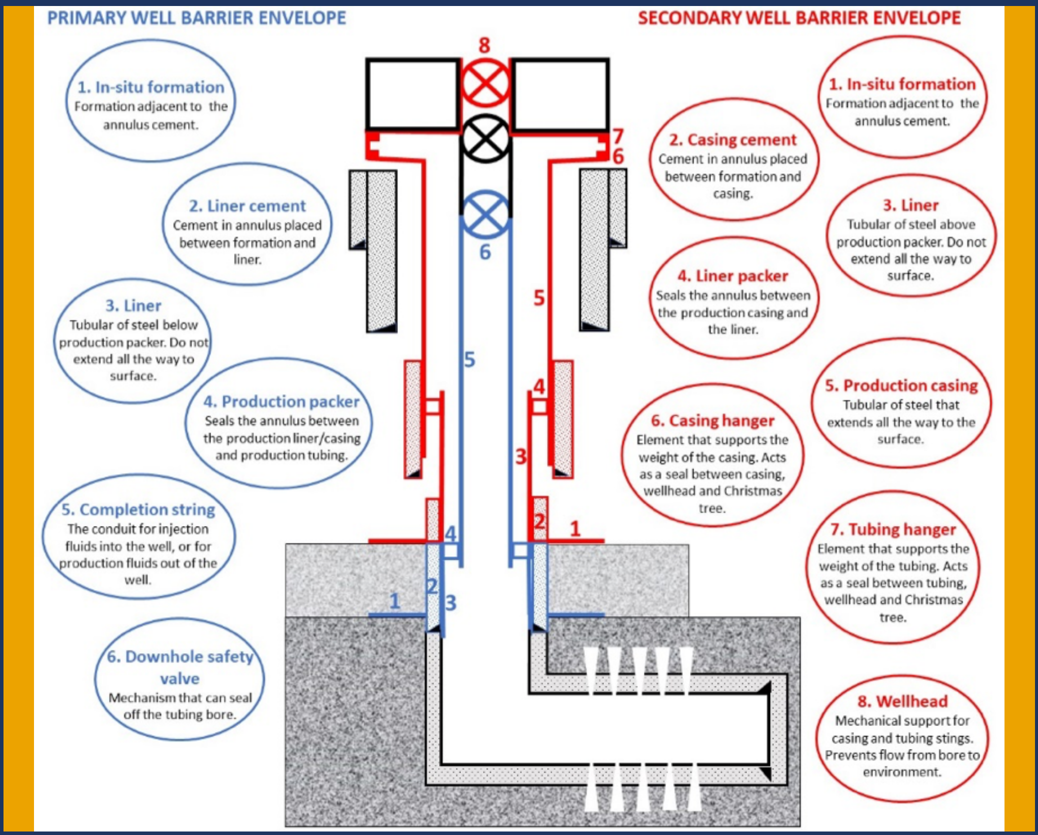

Figure 1: Simplified illustration of well barriers for a typical active shale gas well. Primary well barrier envelope in blue and secondary well barrier envelope in red (from D5.3).

2.2.4 Release of hydraulic fracturing/flowback or formation fluids from the shale production zone

GOOD PRACTICE AND RISK MITIGATION
FACTSHEET #8

Unconventional hydrocarbons exploration:

Release of hydraulic fracturing/flowback or formation fluids from the shale production zone

SECURe employed the Bow Tie risk assessment approach, which identifies a series of barriers that prevent a principal hazard ("top event") from occurring. This factsheet outlines recommendations, which address a single top event that can occur if control of a hazard is lost: release of hydraulic fracturing/flowback or formation fluids from the shale production zone . It should be read in conjunction with the Participatory Monitoring Factsheet, which provides overall guidance on project construction.

The issue

Although considered to be of lower risk than release via wells, the potential release of hydraulic fracturing, flowback or formation fluids from the hydrocarbon reservoir must be fully assessed. Such releases could result in emissions and/or impacts to ecosystems and people, including other subsurface users. Potential release mechanisms have been identified via existing or legacy wells, capillary leakage through the primary seal, or via fracture and fault networks or via lateral migration during or after hydraulic fracturing. Faults may be reactivated and new fractures induced from stresses during injection or natural seismicity.

A range of site engineering, operational strategies, corrective actions, monitoring site selection and operational strategies, and monitoring provide effective barriers to prevent releases. If release were to occur, then remediation options include monitoring, operational responses, well engineering interventions, and the use of natural geological properties to slow the release. These barriers, and preventive and remedial actions, are discussed in detail in SECURe report BGS-01-R-11.

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Risk mitigation recommendations

Monitoring approach

- **Thresholds should be set** for hydrochemical parameters, which could indicate contamination in the future (D3.6). Thresholds should be calculated using environmental baseline data to establish concentrations of parameters that would indicate excessive natural temporal variation.
- **Hydrochemical parameters to be used as indicators of contamination should be selected** based on the mineralogy of the aquifer, the characteristics of the potential contaminant (for example, hydraulic fracture fluid release), and the nature of any likely reaction between the two (for example, decreased pH) (D3.6).
- The sampling network for environmental baseline monitoring, ongoing monitoring throughout operation and post-operation monitoring should ensure that **sampling is undertaken in all major hydrogeological units at suitable depths** (D3.6). Existing relevant boreholes should be utilised and bespoke boreholes drilled, where necessary.
- Monitoring is required from baseline characterisation to operational and post-operational monitoring, to be able to detect any contamination events (D3.6).

Use of models

- A **multi-disciplinary approach to assessing fault leakage rates should be taken.** This requires suitable field and laboratory investigations (e.g. analogue studies using outcrop and core) and upscaled hydromechanical modelling (D2.6).
- Acquisition of extended data (including geochemical, temperature and pressure conditions) from dedicated monitoring wells and their subsequent usage will allow history match and validation of the simulation model (D2.6).
- Geomechanical models should be calibrated using detailed data of geomechanical rock properties of the structure and its surroundings (D2.6).
- Reliable datasets (e.g. seismic and wireline-logging datasets) of sufficient quality and quantity should contribute to fault-sealing models (D2.6).
- Fault juxtaposition results should be calibrated **by other data and methods**, since results solely from juxtaposition plots may lead to misinterpretation (D2.6).
- **The Shale Gouge Ratio (SGR) is an indicator of fault-sealing potential**, but, for reliable outcomes, calibration of accurate thresholds using available geological information is needed; application to rock types other than sedimentary clastic rocks can be unreliable (D2.6).

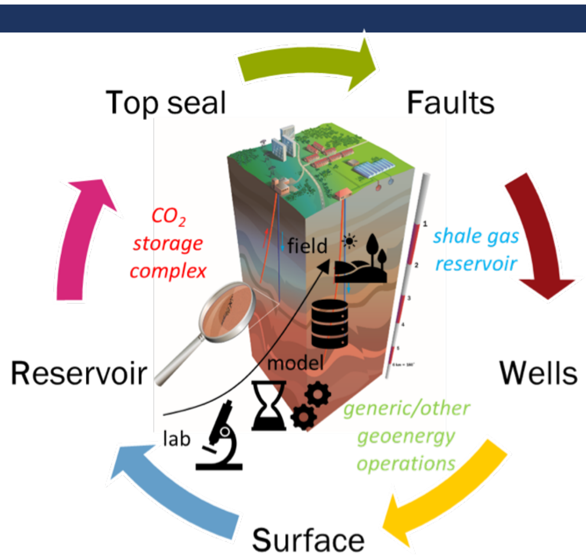

Figure 1: Application domains (CO_2 storage complex, shale gas reservoir and generic/other geo-energy operations), topics or impact areas/risk receptor (R-Reservoir, T-Top seal, F-Faults, W-Wells, S-Surface), and tools or methods (lab experiments, modelling, field cases - as indicated by symbols and text in figure) for research within WP2 of the SECURe project (from D2.6).

2.2.5 Induced/triggered seismicity or aseismic earth movement associated with hydraulic fracturing

Unconventional hydrocarbons exploration:

Induced/triggered seismicity or aseismic earth movement associated with hydraulic fracturing

SECURe employed the Bow Tie risk assessment approach, which identifies a series of barriers that prevent a principal hazard ("top event") from occurring. This factsheet outlines recommendations, which address a single top event that can occur if control of a hazard is lost: induced/triggered seismicity or aseismic earth movement associated with hydraulic fracturing. It should be read in conjunction with the Participatory Monitoring Factsheet, which provides overall guidance on project construction.

The issue

The potential for induced or triggered seismicity and aseismic earth movements must be fully assessed for unconventional hydrocarbons extraction (UHE) projects. Such processes could result in nuisance seismicity, damage to buildings and local infrastructure, and triggered seismic events. These may require injection to be halted, with consequent economic impacts and long-term environmental impacts. For such a hazard to occur requires an increase in pore pressure above site-specific thresholds, which may lead to microseismicity post-hydraulic fracturing. If critically pre-stressed faults are present, seismic events may be triggered. A range of site engineering assessments, operational strategies and monitoring provide effective barriers to prevent seismicity. These barriers, and preventive and remedial actions, are discussed in detail in SECURe report BGS-01-R-11.

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Risk mitigation recommendations

Monitoring approach

- **A closed loop of seismic monitoring**: we consider (near) real-time data assimilation and model updating as crucial for a robust estimation and update of seismic risks during injection operations (D2.6).

Establish baseline environmental conditions

- It is fundamental to **establish the baseline level of natural seismicity through a baseline monitoring campaign before the onset of subsurface activities** in the area of operation; it is important to obtain continuous or repeated observations of a situation to detect changes, which may occur over time (D3.2). During operations, a local network should be deployed for monitoring and mitigation purposes (D4.2). If a "traffic light system" is used as a mitigation tool, it is important that the monitoring network has a detection level below the acceptable level of microseismicity as determined by the authorities:
    - Determine the acceptable level of microseismicity in the location of interest. This decision rests on both scientific knowledge (e.g. understanding of local risk, local geological conditions, presence of faults, subsurface stress regime, shallow geological conditions) and political considerations (e.g. site safety, avoidance of public nuisance, optimising operational parameters)(D4.2);
    - Perform a site survey to establish the signal-to-noise conditions and calculate the required network density and configuration to obtain the desired detection level. The detection level is key to be able to mitigate before the acceptable level of microseismicity is exceeded;
    - Decide the level of network redundancy in the event of one or more seismograph stations failing. It is also important to decide the level of network maintenance and data analysis.
- It is important to emphasise that seismic monitoring cannot serve as the sole monitoring technology. It should be part of a larger monitoring plan encompassing other geophysical, geological and geochemical technologies.

Use of models

- **Rapid semi-analytical modelling to help address uncertainties**: this should be used in a closed-loop approach, where computationally intensive models are difficult to use (D2.6).
- **Rate-and-state seismicity theory to assess changes in seismicity rates** based on Coulomb stressing rates (rather than on Coulomb stress changes) should be considered to forecast the evolution of seismicity, in terms of frequency-magnitude distribution of events associated with the injection of fluids in a reservoir (D2.6).
- Statistical modelling should be included in "traffic light systems" relying on observations. However, large uncertainties and complex causal relations need to be taken into account (D2.6).
- **The use of predictive model frameworks** (validated against observed data) **can optimise injection strategies** to allow maximisation of injection volumes and minimised induced seismicity (D5.6). Additionally, injection operations and mitigation measures for induced seismicity greatly benefit from optimisation of spatio-temporal injection strategies as **seismic risks can be reduced under continuing injection operations.**

Risk mitigation recommendations (cont.)

Development of technology

- Based on the results of **laboratory acoustic emission (AE) tests** in D5.2, we recommend that **some mitigation strategies for seismicity be tested at larger scale**. One could, for example, closely monitor precursors to hydraulic fracturing with downhole acoustic sensors, such as DAS cables, when the well pressure is slowly increased; this supposes that some shear deformation occurs around the borehole, due to rock heterogeneity and completion geometry (presence of cement sheath and perforations). If initial microcracking is recorded, one could simply hold the well pressure at this constant level or, alternatively, cycle it up and down from or around this value to induce fatigue and stress corrosion. Once an initial fracture is thus obtained, it is speculated that reopening and further propagation could be obtained at lower well pressure and with less acoustic energy release.
- **Laboratory experiments**, if possible on relevant field cores, can be used **to understand the propagation of microseismicity in the subsurface**, primarily in calibration of models for the area considered (D5.2). These can shed light on localisation of AE sources. This can correct any early interpretation of underground events leading to microseismicity occurrence and suggest corrective action, such as injection rate reduction, or even suspension of injection.

Image 1: Seismometer installation in the field to monitor for earthquakes. This is an important part of establishing natural baseline conditions and can identify impacts of human activity in the subsurface. Credit: BGS © UKRI

2.2.6 Participatory monitoring

SECURe factsheets - participatory monitoring

SECURe has gathered unbiased, impartial scientific evidence for risk mitigation and monitoring for environmental protection to support subsurface geoenergy development. Our main research outputs underpin recommendations, which we have collated as nine factsheets.

The risk framework developed by SECURe identified four principal hazards associated with geological CO_2 storage and five associated with unconventional hydrocarbons extraction.

Our recommendations seek to provide a pragmatic and reasonable response to these concerns: they can be used to inform site development and management strategies from the perspective of multiple stakeholders (operators, regulators, legislators and the general public). Each headline recommendation is underpinned by project technical reports, available here

The project employed the "Bow Tie" risk assessment approach, which identifies a series of barriers that prevent a principal hazard ("top event") from occurring. Each factsheet addresses a single top event, which can occur if control of a hazard is lost, and provides recommendations to help mitigate them.

The top events were identified through a literature review of hazards, threats, consequences and barriers associated with CO_2 storage. The recommendations can be considered to inform preventative (e.g. a limit on operations) or mitigative (e.g. a technical measure that limits the chain of consequence arising from the top event) strategies for risk management.

Overall recommendations

- A detailed recognition of the storage reservoir and confinement needs to be established, including identification of all existing faults in the possible injection operations' influenced zone (see SECURe reports D3.7 and D3.8). A cost-effective and timely environmental baseline should always be established prior to any CCS activities commencing, supported by early site appraisals. Monitoring programmes demonstrate to stakeholders that sites are evolving as expected, or deviations in behaviour can help to identify anomalies.
- Methodologies that can attribute the source of CO_2 will also be needed. The baseline defines the environmental conditions prior to CCS activities and needs to account for natural and external anthropogenic temporal variation. Therefore, the use of continuous sampling methodologies for at least one year prior to the start of operations is recommended (D3.6).
- In onshore storage operations, the sampling network for environmental baseline monitoring, ongoing monitoring throughout operation and post-operation monitoring should ensure that sampling is undertaken in all major hydrogeological units at suitable depths to protect groundwater from potential contamination. Existing relevant boreholes should be utilised and bespoke boreholes drilled, where necessary.

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Gaining community trust: benefits of participatory monitoring

Participatory monitoring formed a key element of SECURe's research. The value of participatory monitoring approaches was captured and embedded within each Bow Tie risk assessment. At the same time, the recommendations relating to participatory monitoring have broad relevance to CO_2 storage, unconventional hydrocarbons extraction and other subsurface low-carbon geoenergy activities. Ethical research approaches underpin these activities and should be considered an important part of understanding how a broad range of stakeholders perceives subsurface geoenergy activities.

Why do we need to monitor a storage site?

- As CO_2 storage occurs at significant depths, monitoring data and the knowledge developed from these observations require significant expertise to aid their interpretation and make value judgements about the safety and efficiency of the storage processes.
- Developing innovative monitoring tools and participative monitoring methods can support the understanding of the subsurface by non-expert stakeholders and give them more insight into the impact of the activities on the environment and the way potential risks are being managed.
- SECURe has developed improved participatory monitoring tools that, although focused on CCS and shale gas activities, are also relevant for other subsurface activities, such as geothermal projects or the storage of heat and gases (for example, hydrogen).

What are the potential benefits of supporting local communities in participatory monitoring?

- Involving local stakeholders at all stages of the design and implementation of a project, including decisions on what is monitored and the monitoring approach itself, can improve trust in the proposed activities and risk management strategies.
- The cost of setting up a participatory monitoring programme is small compared with losing the social licence to operate due to a lack of public acceptance.

How can CO_2 storage projects enable local community engagement?

- To create legitimacy, a stakeholder participation process should be open to new information and insights to allow for (re)positioning and enrichment of viewpoints, including minority opinion.
- To create and implement a technological design, thinking beyond the technology itself is needed, iteratively including institutions and stakeholder interactions to genuinely embed it in a societal context.
- Research undertaken in SECURe indicates that geoenergy expert opinion is currently divided on the benefits of participatory monitoring, particularly around procedural justice values. Given the often pivotal role geoenergy experts can play in projects, further work is needed to build "expert acceptance" to improve societal acceptance of innovative geoenergy projects.

Gaining community trust: benefits of participatory monitoring (cont.)

How should participatory monitoring be managed within the project?

- One of the challenges identified in our research is successfully aligning the different speeds of progress, for example gaining permits versus developing new participatory monitoring programmes.
- We recommend a process management approach to address societal requirements rather than a project management approach. Investing effort at the beginning of the project to evaluate and develop a participatory monitoring programme may require additional time within project development. However, a successful programme can greatly speed up subsequent activities (such as obtaining planning permits and avoiding judicial process).

RECOMMENDATIONS

- Project teams should be multidisciplinary.
- Engagement should start early in project formulation, with investment of appropriate resources.
- The benefits of participatory monitoring should be highlighted to gain more acceptance from experts.
- Project transparency should be ensured; dialogues should be based on equality with everyone's concerns taken seriously.
- Stakeholders should jointly explore their potential roles in a project's monitoring efforts.

SECURe
Subsurface Evaluation of CCS and Unconventional Risks

References

RISKTEC. 2021a. Bowtie analysis- Unconventionals. *Risktec report number SECURe project BGS-01-R-11, Issue 1 dated 18 May 2021.*

RISKTEC. 2021a. Bowtie analysis- Carbon storage. *Risktec report number SECURe project BGS-01-R-12, Issue 1 dated 29 April 2021.*