EXECUTIVE SUMMARY

Risktec is contributing to Work Package (WP) 2 of the SECURe project, leading subtask 2.1.3: Risk Framework and Barrier Performance Indicators. Risktec has developed a bowtie analysis-based risk assessment framework, which is a key objective in development of a semi-quantitative risk assessment tool (SqRAT). The bowties were initially developed from a literature review that captured the hazards, threats, consequences and barriers associated with unconventional hydrocarbon production and geological CO₂ storage. The bowties are generic in nature, representing typical scenarios that can be applied to many potential future projects, rather than being representative of any one project or development.

The bowtie scope is divided into two parts:

a) Unconventionals;

b) Carbon Storage.

This report presents bowties, and effectiveness and uncertainty descriptors associated with the Unconventionals scope. A sister report has been developed to consider the Carbon Storage scope.

The Unconventionals bowties are listed in the following table.

<table>
<thead>
<tr>
<th>Bowtie No.</th>
<th>Hazard</th>
<th>Top Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>SECURe -01</td>
<td>Shale Gas (Natural Gas in Formation)</td>
<td>Release from Well (during Production and Abandonment Phases)</td>
</tr>
<tr>
<td>SECURe -02</td>
<td>Shale Gas (Natural Gas in Formation)</td>
<td>Release from Shale Production Zone</td>
</tr>
<tr>
<td>SECURe -03</td>
<td>Fracturing Fluid / Flowback Water (under Pressure)</td>
<td>Release from Well (during Fracturing / between Fracturing / after Fracturing)</td>
</tr>
<tr>
<td>SECURe -04</td>
<td>Fracturing Fluid / Flowback (and Formation) Water (in Formation)</td>
<td>Release from Shale Production Zone</td>
</tr>
<tr>
<td>SECURe -05</td>
<td>Seismicity / Earth Movement (Hydraulic Fracturing)</td>
<td>Induced / Triggered Seismicity</td>
</tr>
</tbody>
</table>

The risks analysed by the above bowties are presented by the following figure.

The bowtie risk assessment framework was developed initially from a comprehensive literature review and then subject to review in workshops to capture the technical knowledge and experience of SECURe project stakeholders. The bowtie risk assessment framework forms the basis of development of the SqRAT following the process shown in the figure below. The effectiveness and uncertainty descriptors are pivotal to this process. These descriptors are presented in Appendix A of this report.
The workshops held to develop the bowtie risk assessment framework and SqRAT are presented in the following table.

<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utrecht Workshop</td>
<td>22/05 – 23/05</td>
<td>Netherlands Organisation for Applied Scientific Research (TNO) Offices, Netherlands</td>
<td>Initial draft bowties were developed prior to the workshop based on the literature review. The initial bowties were further developed during the workshop, involving experts from WP2 to gain agreement of their structure, logic and completeness.</td>
</tr>
<tr>
<td>GA Meeting</td>
<td>12/06</td>
<td>Wroclaw, Poland</td>
<td>The presentation introduced the work that had been carried out so far by Risktec into the input of the WP2 framework. The latest drafts of the bowties were displayed for comment by attendees.</td>
</tr>
<tr>
<td>Heriot-Watt University (HWU)</td>
<td>10/07 – 11/07</td>
<td>Enterprise Oil Building at the Institute of Petroleum Engineering, UK</td>
<td>The purpose of this workshop was to ensure that the bowties captured the knowledge and experience of technical experts from the university, to ensure that they form a suitable, technically accurate basis for development of the risk framework.</td>
</tr>
<tr>
<td>British Geological Survey (BGS) Workshop</td>
<td>22/07</td>
<td>BGS Environmental Science Centre, UK</td>
<td>The bowties were further developed during the workshop.</td>
</tr>
<tr>
<td>WP2/WP5 Meeting Workshop</td>
<td>25/02 – 26/02</td>
<td>TNO Offices, Netherlands</td>
<td>The purpose of the workshop was to discuss any specific comments or questions that attendees had raised based on previous reviews of the bowties from workshops attended in 2019 and to agree the bowtie risk assessment framework in advance of Milestone 7 (M7) in May 2020.</td>
</tr>
</tbody>
</table>
Support the evaluation of the risks described by the SECURe bowties in the development of the semi-quantitative tool, to rank different risk factors from the bowtie framework in terms of their relative significance and importance. This was achieved by semi-quantitatively ranking the risk of bowtie threats most relevant from the bowtie risk framework and likely to represent the highest risks to Unconventional Gas Exploitation.

The SqRAT provides a means for comparison between different potential sites (that have also been assessed using the tool), and a roadmap to increase site readiness for commercial application that can be prioritised in terms of risk, uncertainty, benefit and cost.

The SqRAT has been developed based on the output of the bowtie risk assessment framework, the semi-quantitative workshop, and the output of the other tasks in WP2. The semi-quantitative risk assessment tool is a key output of the SECURe project, WP2, subtask 2.1.3. As far as possible, this tool is meant to bring together the quantitative research from SECURe project Tasks 2.2 - 2.4, documenting the factors that influence the likelihood of release paths and seismicity, the reliability of control measures, and the estimated rates or volumes of releases. When using the SqRAT, the user will be expected to answer questions regarding the relevance of threats and receptors, the effectiveness of barriers, and the uncertainty surrounding the assessment of barrier effectiveness. This will ultimately enable users to easily undertake an initial screening risk assessment and / or prioritise further work for different prospective sites, based on the good practice recommendations that are outputs of the SECURe project.

Next Steps – Semi-quantitative Risk Assessment Tool and Guidance Note

Sub-task 2.1.3 will be completed once the SqRAT has been developed and a guidance note prepared to assist potential users. The SqRAT is Excel based.

The users of the SqRAT will be expected to answer factual questions by identifying the most appropriate effectiveness and uncertainty descriptor for each relevant barrier, without needing to make any subjective judgements. This report provides the basis of this user interface, the effectiveness and uncertainty descriptors, in Appendix A. The guidance note will describe the information that a potential user needs to know for generating the outputs described in Section 4.7 to enable risk-based comparison of different prospective unconventional gas production sites.

---

1 This workshop was carried out online due to travel and contact restrictions imposed during the COVID-19 pandemic.
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<th>Issue</th>
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<td>18th May 2021</td>
<td>E Hurdle / M Beeson / A Spence / M Kupoluyi</td>
<td>M Taylor</td>
<td>Lisa Williams</td>
<td>First Issue</td>
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</table>

## DISTRIBUTION

- SECURe Project WP2
  - Elisa Calignano, TNO (SECUre WP2 Lead)
- File
  - Risktec Solutions Limited, Warrington, United Kingdom
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<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ALARP</td>
<td>As Low as Reasonably Practicable</td>
</tr>
<tr>
<td>API</td>
<td>American Petroleum Institute</td>
</tr>
<tr>
<td>BGS</td>
<td>British Geological Survey</td>
</tr>
<tr>
<td>CBL</td>
<td>Cement Bond Log</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon Capture and Storage</td>
</tr>
<tr>
<td>CCPS</td>
<td>Centre for Chemical Process Safety</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>CSF</td>
<td>Critical Success Factor</td>
</tr>
<tr>
<td>EBA</td>
<td>Environmental Baseline Assessment</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>GA</td>
<td>General Assembly</td>
</tr>
<tr>
<td>H₂S</td>
<td>Hydrogen Sulphide</td>
</tr>
<tr>
<td>HSE</td>
<td>Health and Safety Executive</td>
</tr>
<tr>
<td>HWU</td>
<td>Heriot-Watt University</td>
</tr>
<tr>
<td>IADC</td>
<td>International Association of Drilling Contractors</td>
</tr>
<tr>
<td>ICI</td>
<td>Imperial Chemical Industries</td>
</tr>
<tr>
<td>M</td>
<td>Milestone</td>
</tr>
<tr>
<td>MAH</td>
<td>Major Accident Hazard</td>
</tr>
<tr>
<td>NORM</td>
<td>Naturally Occurring Radioactive Material</td>
</tr>
<tr>
<td>OTS</td>
<td>Off The Shelf</td>
</tr>
<tr>
<td>PSA</td>
<td>Petroleum Safety Authority</td>
</tr>
<tr>
<td>SEC</td>
<td>Specific Electrolyte Conductance</td>
</tr>
<tr>
<td>SECURe</td>
<td>Carbon Capture and Storage and Unconventional Risks</td>
</tr>
<tr>
<td>SqRAT</td>
<td>Semi-quantitative Risk Assessment Tool</td>
</tr>
<tr>
<td>SRL</td>
<td>Storage Readiness Level</td>
</tr>
<tr>
<td>SSS&amp;SS</td>
<td>Site Selection Studies and Site Surveys</td>
</tr>
<tr>
<td>TDS</td>
<td>Total Dissolved Substances</td>
</tr>
<tr>
<td>TNO</td>
<td>Netherlands Organisation for Applied Scientific Research</td>
</tr>
<tr>
<td>WP</td>
<td>Work Package</td>
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</table>
1 INTRODUCTION

1.1 SECURe Overview

The Subsurface Evaluation of Carbon Capture and Storage (CCS) and Unconventional Risks (SECURe) project aims to gather unbiased, impartial scientific evidence for risk mitigation and monitoring for environmental protection to underpin subsurface geoenery development. The project has been funded from June 2018 to May 2021. The SECURe partnership comprised major research and commercial organisations from countries that host unconventional (shale gas) and CCS industries at different stages of operation (from permitted to closed). The main outputs of SECURe will comprise recommendations for good practice for unconventional hydrocarbon production and geological carbon dioxide (CO₂) storage.

The project will develop monitoring and mitigation strategies for the full geoenergy project lifecycle by assessing plausible hazards and monitoring associated environmental risks. This will be achieved through a program of experimental research and advanced technology development that will be demonstrated at commercial and research facilities to formulate best practice. SECURe aims to 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). SECURe will form a durable international partnership with non-European groups; providing international access to study sites, creating links between projects and increasing collective capability through exchange of scientific staff.

There are seven Work Packages (WPs) for the SECURe project, listed as follows:

WP1. Ethics requirements
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
WP7. Management and co-ordination

Figure 1 shows the above WPs and the way they interact, and was originally developed for the Grant Agreement document [Ref. 1]. Subsequently, WP1 was included and the WP renumbered accordingly and Figure 1 has been revised to show the current WP numbering.

Figure 1: Work Packages and their Interactions [Ref. 1]
1.2 Risk Framework and Barrier Performance Indicators

Risktec is contributing to WP2 in the SECURe project: Risk assessment for leakage and induced seismicity: methodology and case studies. The following is a description of the specific subtask to be carried out, as set out in the Grant Agreement [Ref. 1]:

This SECURe subtask aims to integrate the outcomes of WP2 into a risk assessment framework, develop guidelines, and provides inputs for the other work packages in terms of indicators for monitoring and communication of risks. An initial set of bow-ties will be developed in BowtieXP software based on current understanding of risks associated with CO2 and shale gas reservoirs.

These bow-ties will identify possible leak pathways, the controls (e.g. geology, well integrity, monitoring) that may be expected to be in place and mitigation strategies that may be employed. These initial bow-ties will be reviewed in a workshop, involving representatives from all other WPs to gain agreement of their structure, logic and completeness.

In conjunction with this, a semi-quantitative risk assessment tool will be prepared that brings together the quantitative data available from the results of Tasks 2.2–2.4, documenting the factors that influence the likelihood of release paths, the reliability of control measures, and the estimated rates or volumes of releases. Sensitivity studies will be performed to examine the importance of key variables. Based on the final risk assessments, guidelines will be produced allowing location specific consideration of the most effective use of monitoring required performance standards and key performance indicators, as provided by the other WPs.

The SECURe bowtie risk assessment framework was finalised during a workshop held on 25th and 26th February 2020, meeting the requirements of SECURe Milestone 7 (M7).

The bowtie risk assessment framework is divided into two parts:

- Unconventionals
- Geological Carbon Storage

Upon completion of the bowties [Ref. 2] the next step was to develop the effectiveness and uncertainty descriptors for the bowtie barriers, which provide the link between the qualitative, generic bowtie risk assessment framework and the semi-quantitative risk assessment tool. The effectiveness and uncertainty descriptors for the geological and engineering barriers for unconventional hydrocarbon production have now been completed and are described in this report. A similar report has been issued for Carbon Storage [Ref. 3].

The process for development of the bowties and the Semi-quantitative Risk Assessment Tool (SqRAT) is described in detail in Section 4.

1.3 Purpose of Report

The bowtie analysis seeks to synthesise the output of the SECURe project into a generic risk assessment framework that can be applied to any site / project proposing to develop unconventional hydrocarbon production.

The development of the bowtie risk assessment framework is the first major step in completion of subtask 2.1.3 (Section 1.2). This report describes the work carried out in support of SECURe subtask 2.1.3 with particular focus on the effectiveness and uncertainty descriptors, in support of development of the SqRAT.

The effectiveness and uncertainty descriptors are necessary to provide a means to relate the generic risk assessment framework bowties to specific sites and providing indicators for the performance of barriers.
1.4 Structure of Report

Section 1 has provided an overview of the project and defined the aim of the work and includes the specific subtask to be carried out as per the Grant Agreement [Ref. 1]. The rest of the report contains the following information:

- Section 2 – This contains the basis of the risk assessment framework, which has been created from the literature review on unconventionals [Ref. 4]. The literature review has highlighted a number of risks present within unconventionals and these are discussed in more detail in this section.
- Section 3 – This provides an overview of the bowtie risk assessment framework for unconventional hydrocarbon production.
- Section 4 – This describes the process for developing the bowties, effectiveness and uncertainty descriptors and the SqRAT.
- Section 5 – This provides a discussion of the potential usefulness of the risk assessment tool and describes the link between uncertainty and the Storage Readiness Level (SRL) framework.
- Section 6 – Concludes the work that has been undertaken and gives suggestions for further work that could be carried out.
- Section 7 – References.
- Appendix A – Description of the effectiveness and uncertainty descriptors for geological and engineering barriers, preceded by presentation of the full threat / consequence context in which they appear in the bowties.
- Appendix B – This provides an introductory explanation of bowtie analysis and shows how the technique can be used to support a process of reducing risk to As Low As Reasonably Practicable (ALARP) levels.
2 BASIS OF RISK ASSESSMENT FRAMEWORK

2.1 Introduction

The risk assessment framework was initially drafted following a comprehensive literature review [Ref. 4]. The aim of the literature review was to investigate existing information available for the extraction of shale gas and inform the development of the bowties, as described in Section 1.2. Information was gathered and reviewed in order to support the identification of elements within the bowties, as well potential methods for use in the quantification, risk assessment and identification of critical success factors. The follow sections describe the main risks associated with unconventional hydrocarbon production.

2.2 Shale Gas Extraction

Shale is a common type of low permeability sedimentary rock formed from deposits of mud, silt, clay and organic matter. Shale gas mainly consists of methane, although other gases may also be present. Shale gas does not readily flow into a well. Additional stimulation by hydraulic fracturing (often termed fracking) is required to increase permeability, an illustration of hydraulic fracturing is shown in Figure 2.

Figure 2: An Illustration of Hydraulic Fracturing [Ref. 5]

Once a well has been drilled and cased (completed), explosive charges fired by an electric current perforate holes along selected intervals of the well within the shale formation from which shale gas is produced (production zone). Pumps are used to inject fracturing fluids consisting of water, sand or ceramic beads (proppant) and chemicals, under high pressure into the well [Ref. 5]. The injection pressure generates stresses in the shale that exceed its strength, opening up existing fractures or creating new ones. The fractures extend a few hundred metres into the rock and the newly created fractures are kept open by the proppant. Additional fluids are pumped into the well to maintain the pressure in the well so that fracture development can continue and proppant can be carried deeper into the formation [Ref. 6].

A well may be too long to maintain sufficient pressure to stimulate fractures across its entire length. Plugs may be inserted to divide the well into smaller sections (stages or zones). Stages are fractured sequentially, beginning with the stage furthest away and moving towards the start of the well. After fracturing, the plugs are drilled through and the well is depressurised. This creates a pressure gradient so that gas flows out of the shale into the well.
Fracturing fluid flows back to the surface (flowback water) but it now also contains saline water with dissolved minerals from the shale formation (formation water). Fracturing fluid and formation water returns to the surface over the lifetime of the well as it continues to produce shale gas (produced water). Although definitions vary, flowback water and produced water collectively constitute wastewaters [Ref. 5].

Shale gas extraction consists of three stages [Ref. 5]:

**Stage 1 – Exploration:** A small number of vertical wells (perhaps only two or three) are drilled and fractured to determine if shale gas is present and can be extracted. This exploration stage may include an appraisal phase where more wells (perhaps 10 to 15) are drilled and fractured to characterise the shale; examine how fractures will tend to propagate; and establish if the shale could produce gas economically. Further wells may be drilled (perhaps reaching a total of 30) to ascertain the long-term economic viability of the shale.

**Stage 2 – Production:** The production stage involves the commercial production of shale gas. Shales with commercial reserves of gas will typically be greater than a hundred metres thick and will persist laterally over hundreds of square kilometres. These shales will normally have shallow dips, meaning they are almost horizontal. Vertical drilling would tend to pass straight through them and access only a small volume of the shale. Horizontal wells are likely to be drilled and fractured. Once a shale formation is reached by vertical drilling, the drill bit can be deviated to run horizontally or at any angle.

**Stage 3 – Abandonment:** Like any other well, a shale gas well is abandoned once it reaches the end of its producing life when extraction is no longer economic. Sections of the well are plugged, (filled with cement) to prevent gas flowing into water-bearing zones or up to the surface and the production system removed.

### 2.2.1 Well Construction Good Practice

In the UK, good practice is to have three strings of casing with at least two (intermediate and production casing) passing through and thereby isolating any freshwater zones [Ref. 5], which is considered good practice from an international perspective.

Inadequately sealed well casing can lead to migration of gas to surface [Ref. 8]. Once drilled, but before casings are installed and cemented, instruments can be run down the wellbore to detect naturally occurring (gamma) radiation and measure the density and porosity of the formation [Ref. 5 and 6]. This could form part of an EBA or site characterisation. The diameter of the wellbore can be measured using callipers so that casings are installed accurately [Ref. 5].

Once installed and prior to further drilling, casings are pressure tested to ensure sufficient mechanical integrity and strength so that they can withstand pressures exerted at different phases of the well’s life, such as those exerted during the fracturing process [Ref. 5 and 6].

A number of issues have arisen with casings including poor implementation and surface casing leaking to the atmosphere due to pressure build up. These aspects have been factored into the bowties and are described in more detail in the literature review [Ref. 4].

Good practice for well construction should be implemented, including pressure testing and cement bond logs, to verify rock formations have been properly isolated [Ref. 5]. A set of API standards is available unconventional gas exploitation including well construction [Ref. 6]. Inspections should be carried out to confirm that operators have remediated any defective well cementation effectively. Inspections should also be carried out at safety-critical stages of well construction and hydraulic fracturing [Ref. 5].

Figure 3 and Figure 4, provides examples of good practice well design including, Conductor Casing, Surface Casing, Intermediate Casing, Production Casing and Cementation [Ref. 5]. Well integrity is inferred during operations by pressure testing. This is confirmed by monitoring annular pressures, as well as testing seals and valves at casing joints [Ref. 5 and 6].
2.3 Well Integrity Risks

The SECURE WP2 deliverable D2.5 [Ref. 11] identified different types of cement failure that can compromise well integrity, which are described further in the input panel, below. These different types of failure include, microannulus, debonding, shear failure, tensile cracks, and disking. Further to this, several numerical studies were conducted to determine the impact on wellbore stresses under expected operational conditions.

The main uncertainty was around the quality of the input parameters, therefore a probabilistic approach was taken. The results of the studies conducted have furthered scientific understanding of the risks associated with hydraulic fracturing operations (and carbon storage) to well integrity.
There are several types of cement failure that could occur in a wellbore, jeopardizing the cement integrity. The cement can debond from the casing or the formation, creating what is called a "microannulus" (Gasda et al., 2004; Roy et al., 2018). Microannuli are generally treated as single fractures with a certain aperture and can lead to significant leakage through the annular space (Moghadam et al., 2020). Debonding occurs when the stresses at the cement/casing or cement/formation interfaces become tensile (Lavrov, 2018). This condition could occur when wellbore pressure or temperature drop significantly, resulting in casing contraction (Chu et al., 2018). During CO2 injection, wellbore temperature drops significantly. Therefore, debonding is one of the major concerns regarding the cement integrity of CO2 injection wells. Cement can also undergo shear failure, tensile cracks, and disking (Bois et al., 2011) depending on the downhole conditions and cement properties.

Numerical models attempt to calculate the stress distribution around the wellbore. The state of stress in the cement and its change after an operation can indicate the type of failure that could occur in the annulus. These calculations usually include assumptions regarding the initial conditions of cement and the wellbore (Saint-Marc et al., 2008). The stress state in the wellbore changes throughout the life of the well, from the drilling stage, to completion, well testing, production, and injection phases. Therefore, numerical procedures have been developed that solve for stresses during all the stages of the well’s life to keep track of all the changes in cement stress (Bosma et al., 1999; Gray et al., 2009). Gray et al., (2009) outlined a workflow to use a finite element model to simulate the well stresses. Their modelling framework only included the impact of casing pressure. In this study, we use a similar numerical procedure as Gray et al. (2009) but also include the impact of temperature on wellbore stresses.

The accuracy of the results of the modelling workflow depends on the quality of the input parameters. However, many of the input parameters for well integrity are uncertain. In this study, we implemented a probabilistic approach in analysing the cement integrity (Orlic et al., 2018). Therefore, the results portray the probability of cement failure (i.e. debonding, etc.) considering certain distributions for the input parameters. Two case studies are performed as part of this project. The first case study simulates the re-use of an offshore gas well for CO2 injection in the Netherlands. The second case study investigates the well integrity risks for a shale gas well in Poland. The results of this work assist operators and regulators to understand the well integrity risks associated with various operations such as carbon sequestration and hydraulic fracturing.
2.3.1 **Cementation**

Cement needs to completely surround casings to provide a continuous annular seal between casings and the rock formation, as well as between casings. Best practice is to cement casings all the way back to the surface, depending on local geology and hydrogeology conditions [Ref. 5].

Poor cementation could result from error in well design, error in drilling design, error during drilling and inadequate cementing can all lead to an uncontrolled release of gas and fluid from the well bore at surface during drilling operations (Blowout) [Ref. 8]. Cement failure as a result of degradation can be caused by H₂S, thermal cracking, de-bonding (micro-annulus between cement and casing), pre-existing channels or insufficient displacement. [Ref. 9].

Despite the quality of the initial cementation (indicated by an adequate Cement Bond Log (CBL), some wells can still leak over time. One possible explanation is the tendency of cement to shrink [Ref. 5]. Cement shrinkage may be caused by one (or a combination) of several distinct mechanisms associated with drying, cooling and autogenous (sealed system) effects. A cement formulation that is resistant to one mechanism will not necessarily be resistant to another. Shrinkage can reduce radial stresses, weakening cement bonds with the surrounding rock and leading to circumferential cracks. These cracks can grow vertically due to resulting changes in horizontal stresses and pressure gradients. Gas and other contaminants may accumulate slowly in these cracks, enter shallow strata or even leak at the surface many years after production or well abandonment.

Even the presence of surface casing provides no assurance against gas leakage at the surface from the surrounding ground. The problems of cement shrinkage and cracking over time have led to the development of new resistant cement formulations [Ref. 5].

2.3.2 **Cement Failure**

The SECURE WP2 deliverable D2.5 [Ref. 11] describes the output of numerical geomechanical modelling undertaken as part of SECURE WP2. These models have been developed and used to assess the integrity of annular cement under various downhole and operational conditions [Ref. 11]. Two case studies were performed as part of this work. The first case study investigated the well integrity risks for a shale gas well in Poland. The second case study simulated the re-use of an offshore gas well for CO₂ injection in the Netherlands and is described in the Carbon Storage sister report to this report [Ref. 3]. Fault zone analysis was carried out for the investigations into hydraulic fracturing, using four sites. Four deterministic parameters were varied in the analysis and were chosen by the operators. Different cement formulations were chosen depending on desired level of shrinkage and mechanical properties. Plastic strain accumulation and mode of failure for all the simulations in each case were recorded, but for this case study, shear failure in cement was the only mode of failure observed.

The following conclusions were obtained regarding cement integrity after hydraulic fracturing based on the results of the shale gas case study [Ref. 11]:

- The probability of failure increases with cement stiffness, shrinkage, and frack pressure while decreases with cement strength (i.e. cohesion).
- Cement shrinkage can significantly increase the probability of failure. When possible, operators should use cement formulations that lead to smallest shrinkage level possible.
- Using cement formulations that lead to softer cement is recommended. Designing the cement Young's modulus close to 5 GPa can minimize the probability of failure even for a shrinking cement. It is more important to use a softer cement (lower stiffness) than a stronger cement (higher cohesion).
- An increase in frack pressure (in this case a 10% increase) only slightly raises the probability of failure.
- Probabilistic simulations are recommended for well integrity analyses, in order to account for the uncertainty of input parameters.

The output of this work has been incorporated into the effectiveness descriptors applicable to well engineering barriers (Appendix A).
2.3.3 **Code Violations**

Reference 12 draws on code violations in Pennsylvania database from 2009 – 2014 as a basis for well integrity failures. Potential well integrity threats / escalation factors, therefore, include the following:

- Improper pressure control;
- Improper casing to protect fresh groundwater;
- Improper casing and cementing procedures;
- Improper casing and cement to prevent migration to fresh groundwater;
- Improper cement installation; and
- Inadequate or leaking plug to prevent vertical flow.

All of the above have been captured in respective barriers as part of effectiveness descriptors because they add no further information beyond stating that the barrier does not function as intended.

2.3.4 **Well Integrity Leaks**

The Royal Society and Royal Academy of Engineering [Ref. 5] has identified the following potential issues that could impact well integrity:

- **Blowout** - Any sudden and uncontrolled escape of fluids from a well to the surface;
- **Annular leak** - Poor cementation allows contaminants to move vertically through the well either between casings or between casings and rock formations;
- **Radial leak** - Casing failures allow fluid to move horizontally out of the well and migrate into the surrounding rock formations.

Well integrity threats / pathways are the most significant sources of groundwater contamination [Ref. 12]. Leakage scenarios are also illustrated in Figure 5, [Ref. 12].

**Figure 5: Well Integrity Threats / Leakage Scenarios**

2.3.5 **Leakage from the Production zone via Wells**

Leakage from the production zone could occur through several pathways [Ref. 14]. Research has identified wells to be the most probable leakage pathway during and after injection, once wells have been abandoned [Ref. 15]. Examples of possible well leakage scenarios are presented in Table 1 [Ref. 9]. In the event of
release from a well, it is possible for natural gas or formation fluid to migrate along different paths through the casing, annulus cement and cement plugs.

### Table 1: Scenarios generated from the Features, Events and Processes analysis (Well Br-73) [Ref. 9].

<table>
<thead>
<tr>
<th>Well Leakage Path Category</th>
<th>Leakage Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abandoned wells</td>
<td>Leakage between cement fill and outside of casing</td>
</tr>
<tr>
<td></td>
<td>Leakage between cement plug and inside of casing</td>
</tr>
<tr>
<td></td>
<td>Leakage through cement well plug</td>
</tr>
<tr>
<td></td>
<td>Leakage through casing</td>
</tr>
<tr>
<td></td>
<td>Leakage in cement fill fractures</td>
</tr>
<tr>
<td></td>
<td>Leakage between cement fill and formation rock</td>
</tr>
</tbody>
</table>

#### 2.3.6 Well (and Site) Engineering Barriers

Barriers interrupt the progression from threat to top event (preventive barriers) or top event to consequence (mitigation barriers). A number of barriers have been identified for well engineering and are discussed in more detail in the following sub-sections.

##### 2.3.6.1 Positioning of Wells

Any fracking site should be placed away from highly populated areas as even a small seismic event, even if not causing a loss of seal integrity, could likely unsettle the local population [Ref. 16]. Fracking sites should be areas that are essentially seismically inactive, have relatively low probability for the occurrence of earthquakes with M > 5 and situated away from major faults [Ref. 9]. On-site parameters include caprock porosity, number of wells and production zone permeability [Ref. 14].

##### 2.3.6.2 Well Integrity Assessment

Prior to commencing operations such as hydraulic fracturing fluid injection, a well usually undergoes testing to ensure its integrity under pressure. These tests are relatively straightforward, with the well top and bottom (or in the zone to be tested), pressured up and its ability to hold pressure measured [Ref. 17].

One function of the wellbore is to seal flow of fluids at deep reservoirs. Injection well integrity can be monitored using geophysical well integrity logs. These can include casing corrosion logs and temperature and acoustics measurements. The minimum packer setting depth is determined by the minimum formation strength to withstand the maximum pressure during the well injection lifetime in order to avoid an underground blowout that cannot be detected with the surface monitoring systems. In addition to these, geophysical well integrity logs can provide measurements of downhole petrophysics, caprock pressure, saturation and fluid chemistry. Very detailed information provided around the well can be used to calibrate performance modelling [Ref. 18].

##### 2.3.6.3 Primary Barrier Envelope

Based on the schematic in Figure 6 from the NORSOK D-010 Standard [Ref. 7], the following are the components of the Primary Barrier Envelope:

- In-situ formation as assessed by site analysis;
- Production Packer;
- Liner Cement;
- Casing / Production Liner;
- Liner Hanger Packer;
- Completion String / Production Tubing;
- DHSV.
2.3.6.4 Secondary Barrier Envelope

Based on the schematic in Figure 6 from the NORSOK D-010 Standard [Ref. 7], the following are the components of the Secondary Barrier Envelope:

- In-situ formation as assessed by site analysis;
- Casing Cement (Intermediate);
- Casing (Intermediate);
- Tie-back Packer;
- Tie-back Production Casing;
- Production Liner Hanger (with Seal Assembly);
- Casing Hanger;
- Tubing Hanger (Neck Seal and Body Seal);
- Wellhead / Xmas Tree (including Annulus A valve).

2.3.6.5 Abandonment (Primary, Secondary and Open to Surface) Barrier Envelope

Based on the NORSOK D-010 Standard [Ref. 7], the following are the components of the abandonment barrier envelopes:

- Casing Cement (Primary);
- Cement Plug (Primary);
- Casing Cement (Secondary);
- Cement Plug (Secondary);
- Casing Cement (Off The Shelf (OTS));
- Cement Plug (OTS).

2.4 Induced / Triggered Seismicity Risks

There are two types of seismicity associated with hydraulic fracturing [Ref. 5]:

1. Induced Seismicity: Microseismic events are a routine feature of hydraulic fracturing and are due to the propagation of engineered fractures;
2. **Triggered Seismicity**: Large seismic events are generally rare but can be induced by hydraulic fracturing in the presence of a pre-stressed fault.

Induced seismicity is the term for seismic energy caused by hydraulic fracturing that may physically damage the production zone in an area where there were previously no seismic effects, nor any concern about the potential for seismic effects. This may result in earthquakes, or an existing critically stressed (or almost critically stressed) fault/fracture to slip, open up or reactivate [Ref. 4]. Triggered seismic energy caused by hydraulic fracturing may physically damage the production zone in an area where seismic events have occurred in the past or at a fault that has the potential for seismicity. This may result in earthquakes, or cause an existing critically stressed (or almost critically stressed) fault/fracture to slip, open up or reactivate.

There are numerous mechanisms that can generate seismicity such as: fluid injection, production-related reservoir compaction, presence of low-porosity reservoirs, high injection pressures, the use of fluids/proppants, the stress regimes and the presence of natural fractures and faults [Ref. 15].

The non-stationary spatial pattern of seismicity accords with evidence that the crust is critically stressed in most intraplate regions [Ref. 19]. Stress measurements made in boreholes commonly show that stress is close to the depth-dependent strength of the crust as estimated by laboratory experiments (e.g. Brudy et al., 1997; Zoback and Healy, 1984) [Ref. 19, 20 and 21]. The ambient pore pressure is generally close to hydrostatic, the crust is pervasively faulted, and faults that are well oriented for slip in the ambient stress field are commonly close to failure. This is consistent with observations that human-induced seismicity may occur, and even be large, in regions that have been historically aseismic.

The likelihood of induced seismicity is dependent upon site specific input parameters including: depth of production zone, likely fault orientations and stress field, injection rates, and site specific material properties [Ref. 16]. There are potentially two activities involved in shale gas extraction that could induce seismic events, these being hydraulic fracturing and wastewater disposal. Consequences to this hazard could lead to the threat of damage to well integrity and the hazardous scenario of Leak from the Production Zone, as well as potential for damage to surface structures / public perception of earth movements [Ref. 4].

With regard to shallow injection-induced seismicity of relatively small magnitudes (e.g. Mw< 3), it has been recognised that the frequency content might be too high to cause any structural damage, but may still be felt and considered alarming by humans as shown in Figure 7.

**Figure 7**: Schematic of injection-induced fault reactivation, wave propagation, and ground motions, and potential impact on surface structures and human perception [Ref. 16]

The amount of stress released in an induced earthquake is not necessarily the same as the anthropogenic stress added because pre-existing tectonic stress may also be released [Ref. 19]. Therefore earthquakes
may be disproportionately large compared with the associated industrial activity that may be induced. Knowledge of the magnitude of the largest earthquake that might be induced by a project, $M_{\text{MAX}}$, is important for hazard reduction. Faults near to failure are pervasive in the continental crust and induced earthquakes may therefore occur essentially anywhere [Ref. 19].

The lack of a relationship between $M_{\text{MAX}}$ and operational parameters such as injection rate, coupled with the difficulty of predicting which projects will be seismogenetic and which not, suggests that non-operational parameters are important [Ref. 19]. The pre-existing stress state is the most obvious such parameter. Several lines of research indicate that most faults in the crust are nearly critically stressed, though they may not be optimally oriented to slip under ambient conditions. The local geology, in particular pre-existing faults and fractures, are important for understanding the extreme variations in seismogenesis between apparently similar projects in different locations. In order for large earthquakes to occur, long faults that are suitably orientated and stressed must pre-exist [Ref. 19].

Shear slip on fault planes, with or without crack-opening or closing components, is the most common earthquake source process [Ref. 19]. Factors involved in nucleation i.e. the onset of motion, include:

- Coefficient of friction on the fault plane;
- Compressive normal stress on the fault plane;
- Pore pressure in the fault zone; and
- Shear stress on the fault.

Groundwater influences earthquake occurrence. Overwhelming, observational data show that pore pressure in fault zones strongly influences seismicity [Ref. 19], because fluid pressure diffuses through a more permeable fracture or fault system for a distance. In the case of reference 24 this was ~2 km to a fault that was critically stressed and triggered earthquakes by increasing the pore pressure within the fault.

If the fault is already critically stressed over a significant area, there may be nothing limiting the size of triggered earthquakes except the properties of the fault, the existing stresses on the fault and initial rupture energy (Steacy and McCloskey, 1998; Olson and Allen, 2005) [Ref. 24, 29 and 30]. McGarr et al. (2002) [Ref. 22] suggested the following terms for consideration of anthropogenic seismicity:

- “induced” earthquakes where the stress change caused by human activity is comparable to the shear stress causing a fault to slip,
- “triggered” where the anthropogenic stress change is much smaller, and
- “stimulated” where there are insufficient data to make the distinction [Refs. 19 and 23].

However, for most purposes relating to the development of the risk assessment framework for SECURe, it is reasonable to refer to induced seismicity only as all seismic events probably release pre-existing strain energy, and are therefore triggered [Ref. 19].

The triggering of earthquakes by the addition of pore pressure effectively reduces normal stress on the fault (Nicholson and Wesson, 1990) [Refs. 24 and 25]. The magnitude of that increase and the area of fault that experiences increases in pore pressure may partially control the magnitude of a triggered earthquake. This would be consistent with the work of Shapiro et al. (2007), which shows that the number of larger earthquakes increases with duration of injection in certain cases [Refs. 24 and 26].

2.4.1 Fault Dynamics

The input panel below describes the consideration and modelling of fault dynamics carried out as part of SECURe deliverable 2.5 [Ref. 11]. This deliverable concludes the following with respect to fault dynamics:

- Model results show that cooling of the reservoir due to injection of cold fluids causes significant thermal stresses on the fault.
- It was seen that fault area that is critically stressed increases as the cooling front propagates from the injection well into the reservoir.
- A local high Coulomb stressing rate and a temporarily increase of seismicity rates can be related to the ‘passage’ of the cooling front through the fault plane
- The fast, semi-analytical model SRIMA was used to give a first order estimate of the stress evolution on a fault close to a single injection well.
Pore pressure and temperature changes caused by the injection of CO2 or the re-injection of waste water associated to the production of shale gas may lead to fault reactivation and induced seismicity. In order to assess the potential of fault reactivation and seismicity, and enable mitigation, it is crucial to understand the interplay between the operational factors and the evolution of pressures, temperatures and associated changes in the stress fields near these faults. Here we developed a workflow to assess the (spatio-temporal) evolution of seismicity associated to injection of cold fluids into a reservoir. Model results show that cooling of the reservoir due to injection of cold fluids causes significant thermal stresses on the fault. We observe an increase of fault area that is critically stressed, as the cooling front propagates from the injection well into the reservoir. A local high Coulomb stressing rate and a temporary increase of seismicity rates can be related to the ‘passage’ of the cooling front through the fault plane.

The case we presented should be considered as a synthetic example of the workflow. The seismicity evolution that we computed heavily depends on input parameters for seismicity modelling, such as the assumptions on background seismicity rates, range of stress drops, and the choice of rate-and-state seismicity parameters. Most of these parameters are poorly constrained before the start of the operations. These parameters need to be assessed based on information which becomes available from seismic monitoring, such as details on the specifics of the network used for seismic monitoring (e.g. level of completeness, which is used to define Mwmin), observed background seismicity (e.g. for constraining background seismicity rates), fault area (used to constrain Mwmax) and during the injection operations (relation operations and e.g. evolution of seismicity rates). Near-real-time data-assimilation techniques should be used to continuously update and optimize parameter ranges and models, based on observations from seismic monitoring networks during the operations.

As numerical analysis is time-consuming, for (near-)real-time data assimilation and model optimization, fast methods are needed, which are based on analytical and semi-analytical approaches for the assessment of fault stress evolution and stressing rates. SRIMA can be used to give a first order estimate of the stress evolution on a fault close to a single injection well. It is noted though that in the current implementation of SRIMA, seismicity potential (in terms of friction or slip tendency) of the fault segments in the reservoir is overestimated, whilst locally seismicity potential of the fault segments in the base and seal near the cooling front is underestimated. Furthermore, the use of the Myklestad solution in SRIMA for derivation of the stresses assumes the presence of a cooled cylinder, and hence a sharp temperature front that propagates through the reservoir in time. A drawback of this assumption is the occurrence of high and (unrealistically) abrupt changes in stressing rates on the fault, once the temperature front reaches the fault. The fast (semi-) analytical approaches such as SRIMA need to be further extended to enable their use in the current workflow.

Currently the method presented is based on the assumption that the rupture area of the seismic events is circular, i.e. with aspect ratio of 1:1. Models show that, as both seal and underburden are mostly stabilizing during the injection phase, the height of the critically stressed area does not significantly grow into the burden. As a consequence, in our workflow the maximum magnitude that can be modelled is controlled by the height of the reservoir. The workflow needs to be extended to include seismic rupture areas with aspect ratio’s larger than 1. Fixed stress drops are used to compute the moment magnitudes of seismic events from rupture area. The workflow can be further extended by incorporating a distribution of likely stress drops.
2.4.2 **Induced / Triggered Seismic Events**

Seismic waves may travel directly from the source to the location of a receptor that could potentially be damaged [Ref. 8]. Ground subsidence during and post-exploration leads to ground settlement at surface [Ref. 8]. Detection limits of seismic monitoring are influenced by background noise including traffic, trains and other industrial noise, as well as natural noise, such as wind [Ref. 5]. Given the average background noise conditions in mainland UK, a realistic detection limit of BGS’ network is magnitude 1.5 ML. For regions with more background noise, the detection limit may be closer to magnitude 2-2.5 ML. Vibrations from a seismic event of magnitude 2.5 ML are broadly equivalent to the general traffic, industrial and other noise experienced daily (see Figure 8).

**Figure 8: Annual Frequency and Effects at the Surface [Ref. 5]**

<table>
<thead>
<tr>
<th>Magnitude (M,)</th>
<th>Frequency in the UK</th>
<th>Felt effects at the surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.0</td>
<td>Not detected by BGS’ network</td>
<td>Not felt</td>
</tr>
<tr>
<td>-2.0</td>
<td>Not detected by BGS’ network</td>
<td>Not felt</td>
</tr>
<tr>
<td>-1.0</td>
<td>Not detected by BGS’ network</td>
<td>Not felt</td>
</tr>
<tr>
<td>0.0</td>
<td>Not detected by BGS’ network</td>
<td>Not felt</td>
</tr>
<tr>
<td>1.0</td>
<td>100s each year</td>
<td>Not felt, except by a very few under especially favourable conditions.</td>
</tr>
<tr>
<td>2.0</td>
<td>25 each year</td>
<td>Not felt, except by a very few under especially favourable conditions.</td>
</tr>
<tr>
<td>3.0</td>
<td>3 each year</td>
<td>Felt by few people at rest or in the upper floors of buildings; similar to the passing of a truck.</td>
</tr>
<tr>
<td>4.0</td>
<td>1 every 3-4 years</td>
<td>Felt by many people, often up to tens of kilometres away; some dishes broken; pendulum clocks may stop.</td>
</tr>
<tr>
<td>5.0</td>
<td>1 every 20 years</td>
<td>Felt by all people nearby; damage negligible in buildings of good design and construction; few instances of fallen plaster; some chimneys broken.</td>
</tr>
</tbody>
</table>

Induced seismic events may cause damage to local infrastructure [Ref. 8]. Nuisance earthquakes are those that cause societal inconvenience [Ref. 19]. This inconvenience may be physical or psychological. It includes objectionable damage to infrastructure or the environment, public concern, annoyance or distress about ground shaking, noise or environmental effects such as hydrological changes. In addition to the nuisance of seismic deformations (i.e. earthquakes), aseismic deformations can alter the surface and cause nuisance such as infrastructure damage, flooding and other changes to groundwater circulation [Ref. 19].

The fundamental purpose of hydraulic fracturing in gas-bearing shale is to crack the rock. Therefore, all successful hydraulic fracturing jobs induce earthquakes but an aim is that they do not cause nuisance. [Ref. 19]. Meeting this objective is helped in the USA and Canada by operating in regions of low population density. Seismic monitoring is often carried out because the earthquake locations indicate the location and volume of the fracture network created. However, if nuisance seismicity is not induced there is little reason to report it publically.

No seismological parameter, e.g. magnitude or intensity of ground shaking, can quantify nuisance because it is dependent on the culture of those affected. Nuisance earthquakes are those that need health and safety management [Ref. 19].

Earthquakes were triggered by the hydraulic fracturing operations at a well on the Eola-Robberson oil field in South Central Oklahoma in January 2011 [Ref. 24]. The earthquakes were up to 2.9 M<sub>s</sub> with 16 of M 2.0 or greater. They occurred about 24 hours after commencement of fracking at a distance of about 2.5 km horizontally from the well, associated with a fault about 166º strike sub-parallel to other minor fault sets in the area and dips steeply to the west [Ref. 24]. The area in question relating to the induced seismicity in Oklahoma is a highly folded, fractured and faulted thrust belt which could reasonably provide a number of highly permeable pathways for pressure to reach a critically stressed fault.
2.4.3 **Induced Seismicity and Earth Observation Monitoring**

The Alberta Energy Regulator regulations use a traffic light system to enable people to report induced seismicity. However, thresholds for reporting seismicity are different for different areas of the Alberta province. These thresholds were agreed upon by stakeholders rather than scientifically determined. If ground motion is detected on site then operations in the area must cease.

Seismic data for the map is taken from real time stations with at least one year of data recorded as a baseline. Faults have mainly been found to be rooted at the basement and these are critically stressed. Hydraulic conductivity has been found to be the main reason for induced seismicity.

2.5 **Emission Risks**

2.5.1 **Surface Release (Shale gas)**

Venting and flaring of methane and other emissions are controlled in the UK through conditions of Petroleum Exploration and Development Licences. The health and safety regulator places similar controls under the Borehole Sites and Operations Regulations 1995 and Offshore Installations and Wells (Design and Construction) Regulations 1996 [Ref. 5]. Methane from exploration boreholes is most frequently combusted from flares leading to a release of CO$_2$ to atmosphere [Ref. 10].

One US study from Cornell University concluded that the carbon footprint of shale gas extraction is significantly larger than from conventional gas extraction owing to potential leakages of methane [Ref. 31]. The same study recognised the large uncertainty in quantifying these methane leakages, highlighting that further research is needed [Ref. 5].

Policymaking would benefit from research into the climate risks associated with the extraction and subsequent use of shale gas [Ref. 5]. A potential threat to this hazard is the escape of gas from above ground infrastructure on the well pad, due to human error [Ref. 8]. Although credible from the literature available, it was concluded to be out of scope for the SECURe project, therefore, was not considered further.

2.5.2 **Surface Release (Fracturing Fluid / Flowback Water / Wastewater)**

Fracturing fluid consists of water, proppant and chemicals under high pressure into the well [Ref. 5]. This hazard takes into consideration scenarios related to sub-surface leaks from the production zone, and not loss of containment of stored fracking fluid on the surface and associated mitigation barriers such as linings and bunds. Proppants (sand) brought to site for fracturing that operations can be released into the air during mixing and storing [Ref. 8] were also out of scope.

After completion of the hydraulic fracturing process, some quantity of fracturing fluid returns through the open head of the borehole to the surface. Hydrocarbons are one of the most characteristic components of the spent fracturing fluid [Ref. 10]. Very high salt content manifesting itself in high Specific Electrolyte Conductance (SEC) and Total Dissolved Substances (TDS) cause the fluid to be toxic to most living organisms. Therefore, the fluid cannot be disposed to the natural environment without control. When drilling boreholes (for unconventional gas) more space is needed for the rig, more waste is generated and more noise is emitted to the environment than in the conventional deposits [Ref. 10]. This is particularly important when performing numerous and extensive hydraulic fracturing jobs on the shales. In such conditions, the reuse of fracturing fluid for the successive hydraulic fracturing jobs is a good solution. However, this requires very efficient technologies of treating the fluid mainly from hydrocarbons, dissolved salts and chemicals used when preparing the fluid. In some regions, increased concentrations of radioactive elements can be also expected in fracturing fluids that return to the surface after the job, as shown in Figure 9 [Ref. 10]. There is also the potential for radio-nuclide contamination of fluid from some shales.
Surface spills of fracturing fluid may pose a greater contamination risk than hydraulic fracturing itself [Ref. 5]. These wastewaters typically contain salt, natural organic and inorganic compounds, chemical additives used in fracturing fluid and Naturally Occurring Radioactive Material (NORM) [Ref. 5]. Very little is currently known about the properties of UK shales to explain what fraction of fracture fluid will return as flowback water, as well as the composition of formation waters and produced water.

Disposal wells may be required if wastewater volumes exceed the capabilities of onsite, closed-loop storage tank systems [Ref. 5]. Injection of waste fluids into porous and permeable rock formations has been the primary disposal option for waste fluids from the US oil and gas industry. Disposal wells are often depleted oil and gas wells, but wells can be drilled specifically for disposal if it is economical to do so. The site of disposal wells depends on geological conditions and regulations. In the USA, some wastes are transported to disposal sites by truck or pipeline. The hazard of leaks or spills of wastewater is not unique to shale gas extraction but common to many industrial processes [Ref. 5]. Although credible from the literature available, it was concluded to be out of scope for the SECURe project, therefore, was not considered further.

2.6 Other Risks

A number of risks that were initially taken into consideration have been ruled out since the development of the parent bowtie, as described in Figure 15. These risks are discussed in the following subsections.

2.6.1 Overall Water Use

Overall water use in hydraulic fracturing is important [Ref. 5]. Estimates indicate that the amount needed to operate a hydraulically fractured shale gas well for a decade may be equivalent to the amount needed to water a golf course for a month; the amount needed to run a 1,000 MW coal-fired power plant for 12 hours and the amount lost to leaks in United Utilities’ region in north west England every hour. The rate of abstraction is also important. Hydraulic fracturing is not a continuous process. Water is required periodically during drilling and then at each fracturing stage. Operators could consult water utilities companies to schedule operations to avoid periods when water supplies are more likely to be under stress [Ref. 32].

The water demand is environmentally important for hydraulic fracturing. One ‘frac job’ requires as much as a tens of cubic meters of water used in a few days’ time [Ref. 10]. Very rarely such amounts are available from local sources on demand. A momentary consumption of such a big amount of water could also negatively influence the groundwater and surface water resources.

Hydraulic fracturing water requirements may limit the ability of local water companies to maintain adequate supply to their customers [Ref. 8]. Hydraulic fracturing requirements result in over abstraction by water companies from surface or groundwater sources in order to meet their supply obligations. Although credible this has been proposed to be out of scope for the SECURe project, therefore, has not been considered further.
2.6.2 Drilling Waste

One of the most important issues whilst performing borehole exploration is the transportation of cuttings from the horizontal sections and their geomechanical stability [Ref. 10]. The drilling waste (for unconventional gas) can be divided into two physiochemical properties:

- Cuttings coming from all drilled rocks in the borehole profile;
- Drilling mud.

A potential threat for this hazard is that waste from operations is not treated properly by the waste management contractor [Ref. 8]. Deep wells increase the amount of waste generated, and Figure 10 highlights the overview of performing a hydraulic fracturing in a horizontal borehole [Ref. 10].

![Figure 10: Schematic of Hydraulic Fracturing in a Horizontal Borehole](image)

The drilling boreholes for unconventional waste requires more space is needed for the rig, more waste is generated and more noise is emitted to the environment than in the conventional deposits. This is particularly important when performing numerous and extensive hydraulic fracturing jobs on the shales. Although credible, this has been proposed to be out of scope for the SECURe project, therefore was not considered further.

2.6.3 Vehicle Movement

Leakage during transport of shale gas has been identified as one of two possible sources of leakage, where the other source is from the production zone [Ref. 33]. A road traffic accident off site involving site vehicles can cause the release of methane onto public roads.

A leak from vehicle tanks containing shale gas during transport has the potential to contaminate the environment. Although credible from the literature available, it was concluded to be out of scope for the SECURe project, therefore, was not considered further.

2.6.4 Noise

Noise emissions accompanying drilling of deep shale gas exploration boreholes may be an important environmental issue [Ref. 10]. When drilling boreholes (for unconventional gas) more space is needed for the rig, more waste is generated and more noise is emitted to the environment than in the conventional deposits. This is particularly important when performing numerous and extensive hydraulic fracturing jobs on the shales. Although considered credible, it was concluded to be out of scope for the SECURe project, therefore was not considered further.
### 2.6.5 Subsidence

There is a close link between reservoir compaction, subsidence and induced (triggered) seismicity resulting from extraction of gas [Ref. 34]. Reference 34 describes gas depletion from the Groningen field (a conventional gas field), the largest fault density is in the centre of the field. This area corresponds to the largest reservoir compaction and the area of the most induced seismicity. The Groningen surface subsidence has shallow and deep causes. Shallow subsidence is caused by the compaction of clay, oxidation of shallow peat, and artificially modified groundwater levels. Deep subsidence results from reservoir compaction related to gas production. As a result of this gas depletion, the reduction of gas pressures causes compaction in the reservoir, as illustrated in Figure 11. The elastic properties of the overburden transfer the compaction almost instantaneously to the surface and this is measurable as subsidence.

**Figure 11: Schematic of the Relation between Gas Production and the Resulting Subsidence and Seismicity [Ref. 34]**

![Schematic of the Relation between Gas Production and the Resulting Subsidence and Seismicity](Image)

Stress changes induced in the reservoir by pressure depletion cause compaction, which is visible at the surface as subsidence [Ref. 34]. Close to existing faults, compaction induces shear stress changes on the fault because of the initial inability of faults to move. Depending on the friction of the faults and magnitude of the stress change, faults can slip, resulting in (triggered) seismic events. Compaction can be considered to be the driving force of seismicity, albeit details of the connecting mechanisms are not well defined. The elastic properties of the overburden transfer the compaction almost instantaneously to the surface, and this is measurable as subsidence [Ref. 34], which may in turn affect buildings. In fact, one way of measuring subsidence is to measure the effect on buildings. The risk of subsidence has been identified as credible from the conducted literature review but very unlikely to be applicable to unconventional gas exploitation (or geological carbon storage). It was therefore, rule out of scope for the SECURe project.

### 2.7 Expert Judgement

In support of the semi-quantitative workshop, a literature review was carried out focussing on good practice for expert judgement. This literature review is presented in full in the semi-quantitative workshop briefing note [Ref. 38].

Many elements and risk factors associated with the fields of interest represented by the SECURe project do not have a wealth of historical data available to draw upon. Furthermore, some geological aspects of Unconventional Hydrocarbon Production do not easily conform to traditional models of component failure and the failure modes present resist classification into categories that can easily be represented by historical data. Hence, some degree of expert judgement is required to achieve an estimation of semi-quantitative risk.

Risk assessment based on expert judgement is intended to reflect the state of expert’s knowledge, industry experience and information on a technical question at the time of response [Ref. 39]. The expert judgement process is made up of three main phases, namely: expert selection, expert opinion elicitation, and expert opinion aggregation. The reasoning behind how opinions are formed and the inter-relation of the phases are
also considered in the expert judgement process. It essential that the expert has an adequate background in the field of interest at a desired level of detail.

Figure 12 has been adapted from Reference 38 for a more generic demonstration of how opinions may be collected from experts and then combined with data and information available for risk assessments. The different elements of a risk assessment that require input data are also shown in Figure 12, as the causes and consequences of unwanted events. However, it also demonstrates the level of uncertainty associated with the data collected, expert judgement and the risk assessment. The inter-relation of all these aspects should be considered when making risk-informed decisions.

**Figure 12: Integration of Expert Judgement with Quantitative Risk Assessment** [Ref. 38]

Reference 41 describes a study where certain expressions, obtained from interviews of individuals, were correlated against numerical values. Using relationships like those shown in Figure 13 can help bridge the gap between interview or survey results and numerical quantification of beliefs. Further research is available regarding transforming verbal expressions into quantitative or numerical probability values. This is useful when polling experts, weighing evidence, and devising quantitative measures from subject judgments. The values presented in Figure 13 were used as a basis for the likelihood descriptors and ranges used in the semi-quantitative workshop.
The purpose of the semi-quantitative workshop was to support the ranking of the risks described by the SECURe bowties. This was achieved by a process of semi-quantitative risk ranking of the leak paths that are most relevant to the SECURe project and likely to represent the highest risks in Unconventional projects. These leak paths were presented in terms of bowtie threats and top events, and associated barriers. The right-hand side of the bowtie was then assessed by consideration of the potential risk reduction effect of selected barriers in mitigating risk of a top event. More information on the semi-quantitative workshop can be found in Section 4.6.
3 SECURE BOWTIE RISK ASSESSMENT FRAMEWORK

3.1 Overview

The bowtie methodology has been adopted as the risk assessment framework for CCS. A detailed description of the methodology is presented in Appendix B. Application of bowtie risk assessment within the oil and gas industry is mature; it has been in fairly widespread use since the mid-1990s and tends to be used to illustrate how MAHs are managed [Ref. 35]. In this context, MAHs include hydrocarbons being extracted, processed, stored and distributed (where the unwanted events could be loss of containment, fires, explosions, etc.). Typically a bowtie diagram will illustrate the causes, consequences and controls for the unwanted event of loss of hydrocarbon containment from a pipeline or storage vessel for example. Often each cause considers a specific mechanism by which loss of containment can occur e.g. corrosion, erosion, overpressure, overfilling.

The structure of the CCS bowties is shown in Figure 14. A parent bowtie, Figure 15, was developed to present the overall risk register for CCS, at a high level [Ref. 2]. This parent bowtie shows which hazards and risks are in scope for the SECURe project and links to the four ‘child’ bowties as shown in Figure 14 and Table 2.

![Figure 14: Bowtie Risk Framework for Unconventionals](image)

Table 2: Unconventionals Bowties

<table>
<thead>
<tr>
<th>Bowtie No.</th>
<th>Hazard</th>
<th>Top Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>SECURE -01</td>
<td>Shale Gas (Natural Gas in Formation)</td>
<td>Release from Well (during Production and Abandonment Phases)</td>
</tr>
<tr>
<td>SECURE -02</td>
<td>Shale Gas (Natural Gas in Formation)</td>
<td>Release from Shale Production Zone</td>
</tr>
<tr>
<td>SECURE -03</td>
<td>Fracturing Fluid / Flowback Water (under Pressure)</td>
<td>Release from Well (during Fracturing / between Fracturing / after Fracturing)</td>
</tr>
<tr>
<td>SECURE -04</td>
<td>Fracturing Fluid / Flowback (and Formation) Water (in Formation)</td>
<td>Release from Shale Production Zone</td>
</tr>
<tr>
<td>SECURE -05</td>
<td>Seismicity / Earth Movement (Hydraulic Fracturing)</td>
<td>Induced / Triggered Seismicity</td>
</tr>
</tbody>
</table>
The risk assessment framework was agreed at a final workshop (see Section 4.2, for an overview of the development process), thus achieving the M7 SECURe project milestone. The framework was created to provide a picture of risk management that is easily accessible to people who are not experts in Unconventional Gas, CCS, or risk management. This is necessary for enabling wider communication both within and outside of the project.

The bowtie analysis has synthesised the output of the SECURe project into a generic risk assessment framework that could be applied to any site / project proposing develop geological unconventionals hydrocarbon production. The final risk assessment framework bowties are shown in the Appendix of the final issue of the Bowtie Workshop Report [Ref. 2] and are also presented in full in Appendix A of this report.

The bowties contextualise the SECURe Project within a risk management framework, potentially providing insight into interfaces between packages of work within the project and externally, provided that the bowtie elements (particularly barriers) are well-defined by experts in the field. The bowties form the basis of a generic template for risk management of unconventionals.

The SECURe bowties are generic, and are intended to cover every possible leak path. Figure 16 is a schematic of the unconventional hydrocarbon production and shows the scope of the SECURe project bowtie risk framework in terms of potential leak paths and seismicity. This includes well related leak paths and geological leak paths. Consequences are essentially receptors, such as the atmosphere, groundwater, or adjacent operations.
Figure 15: Unconventionals (Risk Register) Loss of Control of Unconventional Gas System(s) – Parent Bowtie
Figure 16: Potential leak pathways from Unconventionals Hydrocarbon Production

- **Other geological layers and seals**
- **Geological leak paths**
- **Well-related leak paths**
- **Extent of Formation**
- **Production Zone**
- **Seismicity**
3.2 Barrier Development

The barriers depicted by the SECURE bowties presented in the Bowtie Workshop Report [Ref. 2] and this report are colour coded by barrier type. Barrier type is defined by the core ‘mechanism’ by which the barrier is implemented. Barrier type colour coding definitions are provided in Table 3.

Figure 17 shows the barrier colouring (as described in Table 3), as well as typical barrier descriptions\(^2\). The bowtie barriers are generic in nature i.e. they have to represent typical scenarios that can be applied to many potential future projects, rather than being representative of any one project or development. These generic barriers are constructed around two key elements:

- Variable Parameters.
- Supporting Activities.

<table>
<thead>
<tr>
<th>Colour</th>
<th>Barrier Type</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>Inherent/Natural Feature</td>
<td>Inherent or natural feature that does not vary from site to site. For example the potential for sea water to absorb natural gas / contaminants (e.g. formation fluid).</td>
</tr>
<tr>
<td>Dark Blue</td>
<td>Geological Properties</td>
<td>Geological features that vary from site to site, for example, caprock, layers/seals, reservoir effects. These barriers are present in nature; site selection processes are required in order to ensure that sites with suitable geology are selected.</td>
</tr>
<tr>
<td>Orange</td>
<td>Operational Strategies</td>
<td>Operational strategy barriers are intended to represent development of philosophies, approaches and plans to mitigate an identified hazard release or prevent a threat leading to a release of a hazard. These barriers require human involvement for development of the strategy based on site selection studies, analysis, modelling and review of ongoing monitoring data. Examples of these types of barriers include hydraulic fracturing/injection strategy and well abandonment plans.</td>
</tr>
<tr>
<td>Green</td>
<td>Engineering (Design, Equipment, Positioning)</td>
<td>Engineered barriers, for example, equipment selection, well positioning, well and platform design. These barriers will require human involvement through design, installation and testing and maintenance to varying degrees.</td>
</tr>
<tr>
<td>Yellow</td>
<td>Monitoring</td>
<td>Monitoring barriers are the actions carried out that are intended to detect potential threats before they result in the release of a hazard, or detect the release of a hazard before it leads to serious consequences. These barriers require human involvement for initiation and review of data.</td>
</tr>
<tr>
<td>Dark Red</td>
<td>Corrective Action</td>
<td>Corrective action barriers are the incorporation of new procedures, (e.g. drilling a relief well, remediating a well) in response to obtained monitoring data. These are meant to mitigate an identified hazard release. These barriers require human involvement for development of new strategies, analysis, modelling and review of ongoing monitoring data.</td>
</tr>
</tbody>
</table>

\(^2\) Note that Figure 17 shows a bowtie example for the geological carbon storage bowties; this has been retained in this report as it represents the best example.
<table>
<thead>
<tr>
<th>Colour</th>
<th>Barrier Type</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purple</td>
<td>Stakeholder Consultation</td>
<td>Consultation barriers mitigate risks as perceived by relevant stakeholders, particularly members of the public but also regulators, partners and employees. These barriers encapsulate the activities that will be undertaken to effectively communicate risks, and initiate and support effective dialogue between stakeholders and developers.</td>
</tr>
<tr>
<td>Grey</td>
<td>Third Party</td>
<td>Barrier implemented by a third party, over which the end-user of the bowtie or project has no direct influence.</td>
</tr>
</tbody>
</table>

These parameters and activities are also presented on the bowtie in Figure 17. The supporting activities (described further in Section 3.2.2) are shown beneath the barriers in bold colours, whereas the variable parameters (described further in Section 3.2.1) are shown in lighter, pastel colours.

The construction around variable parameters and supporting activities is fundamental to the determination of barrier effectiveness and uncertainty when the generic bowties are applied to a specific site (see Appendix A). The barriers, parameters and activities were reviewed as part of a series of bowtie workshops (see Section 4.2).

Figure 17: Bowtie Barrier Representation

The text on the barriers describe how the barrier acts to stop (either fully or partially) the threat from causing the hazard, or how the barrier mitigates the consequence (either by preventing it from occurring or reducing the severity should it occur). The wording of the barrier is intended to be potentially applicable to any site, by leaving it open to the eventual user of the risk assessment framework to determine the extent to which the barrier is implemented (for a specific site), and assess the effectiveness of the implemented barrier.

The eventual user will have the ability to assign effectiveness and uncertainty levels to each barrier, based on the information available to them at the time. The effectiveness and uncertainty ratings can therefore change as the project becomes more mature. The proposed relationship between barrier effectiveness and uncertainty, and variable parameters and supporting activities is summarised in Appendix A.
3.2.1 **Variable Parameters**

Variable parameters (shown as lighter, pastel colours in Figure 17) are barrier features that have the potential to vary from site to site or throughout the lifecycle of a project. The following is an example of the variable parameters identified from literature review that have been used in the final bowties [Ref. 2]:

**Geological Parameters**
- Pore Pressure
- Stress states, fracture density, connectivity and orientation of fractures;
- Permeability (fault / fracture network)

**Operational Parameters**
- Injection rate
- Volume of injected fluid
- Annular pressure

**Engineering Parameters**
- Well Design and Integrity
- Site location and design

Each parameter has the potential to affect the integrity and effectiveness of a bowtie barrier, either positively or negatively. For example, as shown in the first barrier in Figure 17, the extent to which fault and fracture networks resist the flow of natural gas affects the potential for natural gas to be released from the production zone, leading to occurrence of the top event. Similarly, the operational strategy influences the injection rate parameter. All parameters that have been used in the development of the bowties are presented in the Bowtie Report [Ref. 2].

3.2.2 **Supporting Activities**

In most cases, successful and effective implementation of barriers is reliant on supporting activities and the extent to which these procedures are carried out effectively, in accordance with good practice.

The following are examples of activities that underpin the barriers in the bowtie:
- Preliminary Site Selection Studies and Site Surveys (SSS&SS)
- Environmental Baseline Assessment (EBA)
- Flowback monitoring through chemical / radioactive tracers
- Sub-surface Fault modelling to estimate induced seismic hazard

Supporting activities serve to inform the understanding and implementation of barriers. Therefore, the extent to which these activities are carried out effectively directly affects the uncertainty associated with any assessment of the effectiveness of a bowtie barrier at a specific site. For example, preliminary SSS&SS provide information on the extent to which geological formations may serve as effective barriers. If SSS&SS are not carried out effectively then this will directly affect the uncertainty over any assessment of geological barrier effectiveness for a specific site. As a further example, the EBA is not a barrier in itself, but serves to inform the understanding of the output from monitoring activities, for example, seismicity or groundwater monitoring. Detection of seismic events or methane contamination of groundwater through monitoring activities in itself cannot fully inform effective decision making without an understanding of the baseline levels prior to project activities. All supporting activities used in the development of the bowties are presented in Ref. 2.

3.2.3 **Effectiveness of Barriers**

The NORSOK standard has been used as a basis for development of effectiveness descriptors for well related threats. For each of the well barrier elements shown in Figure 6 (Section 2.3.6) the standard provides a detailed table of requirements. These tables are referenced from the effectiveness descriptors as shown in Appendix A. The effectiveness and uncertainty of the geological and engineering barriers has a direct input into the effectiveness requirement and capability of the operating and monitoring strategy.
3.3 Well–related Leak Paths, Threats and Barriers

Figure 16 shows a schematic of all of the leak paths described by the bowtie risk assessment framework. This section considers well-related leak paths.

Well-related leak paths are considered in the following bowties:

- **SECURE-01 – Shale Gas (Natural gas in Formation) - Release from Well (during Production and Abandonment Phases)**
- **SECURE-02 – Shale Gas (Natural gas in Formation) - Release from Shale Production Zone**
- **SECURE-03 – Fracturing Fluid / Flowback Water (under Pressure) - Release from Well (during Fracturing / between Fracturing / after Fracturing)**
- **SECURE-04 – Fracturing Fluid / Flowback (and Formation) Water (in formation) - Release from Shale Production Zone**

These bowties describe the pathways by which unconventional shale gas, fracturing fluid or formation water may leak from safe containment within a well. The left hand side of these bowties consider containment within the well itself, or containment within the formation, with wells potentially providing a preferential leakage path outside of the production zone.

The right-hand side of the bowties describe the receptors that are potentially vulnerable to leakage from these pathways, as well as the barriers that may attenuate or mitigate leakage once it is outside of the production zone. The following sub-sections describe the well related leak paths in more detail.

Figure 6 shows the well schematic and has been used as a basis for development of the well engineering barriers [Ref. 7]. It illustrates the elements that make up the primary and secondary well barrier envelopes.

### 3.3.1 SECURE-01 Release from Well (during Production and Abandonment Phases) (Natural Gas)

SECURE-01 considers releases from wells. There are three threats on this bowtie:

1. Hydrocarbon in well annulus (Annulus A) (see Section 3.3.1.1 and Appendix A, Figure 28, Figure 29, Figure 30 and Figure 31);
2. Leak along / through cement (external leak) – Failure of cement bond and/or casing / production liner (see Section 3.3.1.2 and Appendix A, Figure 32, Figure 33, Figure 34 and Figure 35);
3. Natural Gas migrates through plugged well (see Section 3.3.1.3 and Appendix A and Figure 36).

The following subsections describe these threats in more detail.

#### 3.3.1.1 Threat 1: Hydrocarbon in well annulus (Annulus A)

Hydrocarbon may enter the Annulus A from the tubing or production zone as a result of failure of the primary well barrier envelope or through failure of the secondary well barrier envelope, as shown in by the blue arrows in Figure 18. From Annulus A, the hydrocarbon could then leak into the formation, as shown by the red arrows in Figure 18. Therefore, the engineering barriers are responsible both for preventing flow into the annulus and flow from the annulus to the formation. In addition, hydrocarbon could enter the Annulus A due to failure of good practice around casing design, and leak in a similar manner as described.
There are eight (8) degradation factors that could reduce the effectiveness of the primary and secondary well barrier envelopes: damage to primary barrier envelope well cement caused by fluid injection during hydraulic fracturing, poor quality cement, cement degradation over time leading to development of cracks and potential for leakage, corrosion of liner, degradation of elastomers in production packer and damage to well caused by induced seismicity during fracking. Surface casing venting releasing methane to the atmosphere as a result of pressure build up in the annulus A is a degradation factor for good practice in tubing and casing design.

A release from the well could occur above the formation (Figure 16), in which case there is there is the potential for the release to impact receptors as depicted on the right hand side of the bowtie (Appendix A). This may potentially be mitigated by geological layers and / or formation seals.

3.3.1.2 Threat 2: Leak along / through cement (external leak) – Failure of cement bond and / or casing / production liner

For unconventional shale gas extraction, it is important that the casing cement and liner cement maintains its integrity over the thickness of the formation, preventing crossflow between the production zone and permeable formations overlying the production zone. There is potential for a leak to occur along / through the cement, as indicated by the red arrow in Figure 19.
There are two (2) degradation factors that could occur for failure of the primary engineering barrier envelope: damage to the primary barrier envelope well cementation caused by fluid injection during hydraulic fracturing or damage to well caused by induced seismicity during fracking.

SECURe WP2 has undertaken research into well integrity that is captured by this threat and degradation factors, as described in SECURe deliverable D2.5 [Ref. 11]. This included research into the potential for well cementation to be damaged as a result of mechanical cycling as well as numerical geomechanical modelling to assess the integrity of cementation under various downhole and operational conditions. Two case studies were completed as part of this work and a number of conclusions were drawn. It was concluded that soft, low shrinkage cement is the most effective way to reduce the probability of failure at the well interfaces. More detail is provided regarding this in Section 2.3, and this is also considered in the effectiveness descriptors for barriers against this threat, as described in Appendix A.

A release from the well could occur above the formation (Figure 16), in which case there is the potential for the release to impact receptors as depicted on the right hand side of the bowtie (Appendix A). This may potentially be mitigated by geological layers and integrity of the formation.

3.3.1.3 **Threat 3: Natural Gas migrates through plugged well**

Natural gas may migrate through a plugged well. This could be the result of failure of the cement plug, or the casing cement (see Figure 20).
This threat is intended to represent leakage that could occur following completion of the gas extraction lifecycle of the well, however, it could occur if a project-related well is formally abandoned in preference to other wells. Abandoned wells may provide a preferential pathway for natural gas out of the production zone. A release from an abandoned well could then occur above the formation (Figure 16), in which case there is the potential for the release to impact receptors as depicted on the right hand side of the bowtie (Appendix A). This may potentially be mitigated by geological layers and integrity of the formation.

### 3.3.2 SECURE-02 Release from Shale Production Zone (Natural Gas)

SECURE-02 considers releases through legacy wells that are not part of Unconventionals project. This is covered by the following threat:

1. **Existing / Legacy Wells** (see Section 3.3.2.1, Appendix A and Figure 46).

The following subsection describes this threat in more detail.

#### 3.3.2.1 Threat 1: Existing / Legacy wells

Existing or legacy wells have the potential to provide a preferential leak path outside of the formation, as illustrated in Figure 21. Such wells may exist as a result of hydrocarbon exploitation and the knowledge of the condition of these wells may vary. This threat may be applicable to a single legacy well, however, its significance as a potential leak path will scale proportionally to the number of legacy wells, and inversely to the condition of these wells.

This threat may be mitigated through site and well engineering, both in terms of integrity assessment of the legacy wells and positioning of injection wells with understanding of the location of hydraulic fracturing in relation to well leak paths.
Figure 21: Potential Leak Pathways from Unconventional Gas – Existing / Legacy Wells

A release from an existing / legacy well could then occur above the formation (Figure 16 and red box on Figure 21), in which case there is there is the potential for the release to impact receptors as depicted on the right hand side of the bowtie (Appendix A). This may potentially be mitigated by geological layers above the production zone. However, existing legacy wells may also provide a preferential release path from outside of the formation as indicated by the orange box on Figure 21. Such secondary release pathways are considered as degradation factors on the right hand side of each bowtie (Appendix A).

3.3.3 SECURE-03 Release from Well (during Fracturing / between Fracturing / after Fracturing) (Fracturing Fluid / Formation Water)

SECURE-03 considers releases from wells during hydraulic fracturing, between fracturing and after fracturing. There are two threats on this bowtie that are related to leak paths:

1. Fracturing Fluid in well annulus (Annulus A) (see Section 3.3.1.1 and Appendix A, Figure 55, Figure 56 and Figure 57);
2. Leak along / through cement (external leak) – Failure of cement bond and/or casing / production liner (see Section 3.3.1.2 and Appendix A, Figure 58 and Figure 59).

Threat 1 is conceptually similar to SECURE-01 threat 1, with the proviso that this is now considering fracturing fluid in the well annulus, and Threat 2 is conceptually similar SECURE-01 threat 2. Please refer to Sections 3.3.1.1 and 3.3.1.2 for discussions of these leak paths respectively.

3.3.4 SECURE-04 Release from Shale Production Zone (Fracturing Fluid / Formation Water)

SECURE-02 considers releases through legacy wells that are not part of Unconventionals project. This is covered by the following threat:

1. Existing / Legacy Wells (see Section 3.3.2.1, Appendix A and Figure 62);

Threat 1 is conceptually similar to SECURE-02 Threat 1, please refer to Section 3.3.2.1 for discussion of this leak path.

3.4 Geological Leak Paths, Threats and Barriers

Figure 16 shows a schematic of all of the leak paths described by the bowtie risk assessment framework. This section considers geological leak paths.

Geological leak paths are considered in the following bowties:

- SECURE-02 – Shale Gas (Natural gas in Formation) - Release from Shale Production Zone
- SECURE-04 – Fracturing Fluid / Flowback (and Formation) Water (in formation) - Release from Shale Production Zone

This bowties describe the pathways by which shale gas, fracturing fluid or formation water may leak from the production zone. The left hand side of these bowties consider containment within the production zone,
with the potential for geological discontinuities or features of the formation itself to potentially provide a preferential leakage path outside of the production zone.

The right-hand side of the bowties describe the receptors that are potentially vulnerable to leakage from these pathways, as well as the barriers that may attenuate or mitigate leakage once it is outside of the production zone. The following sub-sections describe the well related leak paths in more detail.

3.4.1 SECURE-02 Release from Shale Production Zone (Natural Gas)
SECURE-02 considers releases of natural gas from the production zone, as a result of geological features, either new (induced) or existing. There are four threats on this bowtie that are related to geological leak paths:

2. Presence of fracture network / fault (see Section 3.4.1.1, Appendix A and Figure 62);
3. Fracture propagation beyond target production zone (see Section 3.4.1.2, Appendix A and Figure 43);
4. Natural seismicity fracture development or fault reactivation (see Section 3.4.1.3, Appendix A and Figure 44);
5. Lateral migration (see Section 3.4.1.4, Appendix A and Figure 45).

3.4.1.1 Threat 2: Presence of fracture network / fault
The presence of a geological fault and associated fracture network may provide a preferential path for release from the shale production zone. However, because existing fracture networks or faults with communication beyond production zone would likely render production zone not commercially viable, this threat is of reduced significance.

3.4.1.2 Threat 3: Fracture propagation beyond target production zone
This threat describes the potential for fracture propagation beyond the target production zone. This is determined by the extent to which the shale constrains the growth of fractures / seals induce fracture networks, flow along fault / fracture network or this thickness of the production zone.

The significance of this threat is determined by the operating (fracturing) strategy in relation to the geological properties of the formation. This includes consideration of operational parameters such as injection rate, flowback rate / recovery time, and flowback fluid concentration.

3.4.1.3 Threat 4: Natural seismicity fracture development or fault reactivation
This threat is included in the bowtie for completeness, however, consideration of natural seismicity is not a primary focus for the SECURE project research. It is likely that significant natural seismicity risk would render the proposed gas extraction location unfavourable.

3.4.1.4 Threat 5: Lateral migration
The other geological leak paths considered in this section consider vertical flow out of the production zone. Threat 5 considers migration outside of the lateral confines of the production zone. While this is only represented by a single threat on the generic bowtie, this lateral migration could occur in any compass direction at a specific site and the risk would be determined by the effectiveness of the geological barriers in each direction.

The significance of this leak path is primarily determined by the geological features of the production zone, in particular with regard to the presence of existing leak paths such as wells. This threat may be mitigated through site and well engineering, in terms of the positioning of wells with understanding of the potential for locations of significant lateral leak paths.

3.4.2 SECURE-04 Release from Shale Production Zone
SECURE-04 considers releases of natural gas from the production zone, as a result of geological features, either new (induced) or existing. There are four threats on this bowtie that are related to geological leak paths:

2. Presence of fracture network / fault (see Section 3.4.1.1, Appendix A and Figure 63);
3. Fracture propagation beyond target production zone (see Section 3.4.1.2, Appendix A and Figure 64);
4. Natural seismicity fracture development or fault reactivation (see Section 3.4.1.3 Appendix A and Figure 65).

5. Lateral migration (see Section 3.4.1.4, Appendix A and Figure 64).

6. Displacement of formation fluid (see Section 3.4.2.1, Appendix A and Figure 67).

The following subsections describe these threats in more detail. However, because Threats 2, 3, 4, and 5 are conceptually similar to SECURE-02 Threats 2, 3, 4 and 5 please refer to Sections 3.4.1.1, 3.4.1.2, 3.4.1.3, and 3.4.1.4 for discussion of this geological leak paths. Threat 6 is described in the following subsection.

### 3.4.2.1 Threat 6: Displacement of formation fluid

This threat describes the potential for displacement of formation fluid from other parts of the production zone and other geological layers. The extent to which this threat is significant is determined by the hydraulic properties of the production zone and other strata.

### 3.5 Seismicity

Figure 16 shows a schematic of all of the leak paths described by the bowtie risk assessment framework and identifies the potential for seismic effects leading to the exacerbation of leak paths and the potential for direct consequences.

Seismicity is considered in the following bowtie:

- SECURE-05 – Seismicity / Earth Movement (Hydraulic Fracturing) - Induced / Triggered Seismicity

Seismicity can be induced, triggered, or natural. Injection of hydraulic fracturing fluid will lead to induced microseismicity. however, this will not cause any noticeable effect unless these microseismic events reactivate an existing fault, i.e. a triggered seismic event. For this to occur there must be a pre-stressed fault present within or adjacent to the complex, and this must be reactivated by injection.

### 3.5.1 SECURE-05 Induced / Triggered Seismicity

SECURE-05 considers induced and triggered seismicity as a result of hydraulic fracturing. This is covered by the following threats:

1. Hydraulic Fracturing – increase in pore pressure (see Appendix A and Figure 72);
2. Wastewater Disposal – increase in pore pressure (see Appendix A and Figure 73);
3. (Criticality) pre-stressed fault present (see Appendix A and Figure 74).

Threats 1 and 2 relate to the fluid injection itself, which will generally only lead to microseismic events. When threat 1 and 2 are combined with threat 3, which relates to the presence of a critically pre-stressed coincident with fluid injection, the top event may be realised.

The significance of these threats is influenced by the extent to which permeability of production zone distributes the injection pressure throughout the production zone preventing any localised build-up of pressure as well as the properties of any significant faults, including frictional properties, size and locations.

Successful investigation of this barrier, in terms of the location of significant faults networks, means that the threat may also be mitigated through site and well engineering, in terms of the positioning of injection wells with understanding of the potential for the fluid injection to affect these faults.

These threats may be further mitigated by seismic monitoring and application of traffic light systems to ensure that the operating strategy (injection rate / pressure / volume) is controlled to minimise microseismicity.
4 SEMI-QUANTITATIVE RISK ASSESSMENT TOOL DEVELOPMENT PROCESS

4.1 Overview of Methodology and Approach

Subtask 2.1.3 (see Section 1.2) aims to integrate the outcomes of WP2 into a risk assessment framework, develop guidelines, and provide inputs for the other work packages in terms of indicators for monitoring and communication of risks. A high level overview of this work is illustrated in Figure 23. The process followed is shown in more detail in Figure 22. Outputs are shown in green, as based on the inputs from the partners in the SECURe project and wider literature, shown in blue.

Draft bowties, see Section 3, were developed from a literature review and then reviewed in workshops with participants from the SECURe project in order to create the bowtie risk framework. A project bowtie was developed to support synthesising the output of the SECURe project into a generic risk assessment framework. This is a simplification of the bowtie risk framework, which focusses on showing to which elements of risk SECURe research contributes; for example, improvement of potential monitoring barriers, understanding seismicity threats, improving remediation techniques.

Effectiveness and uncertainty descriptors were developed from the bowtie risk assessment framework and project bowtie, supported where necessary by the literature review. These characterise the extent to which a barrier is effective, as well as the limitations of knowledge around that assessment of effectiveness. Output from this was then fed into a semi-quantitative workshop. The workshop considered the subjectively-ranked extent that barrier effectiveness affects the risk in terms of severity and duration of a leak, and associated likelihood over different timescales by conducting sensitivity studies, where different barriers were considered to be good or poor in combination.

Output from the workshop has supported the development of the semi-quantitative risk assessment tool. This brings together the output into a series of forms and questions that elicit factual information about a particular site. A comparison is made between what is known about the site against the effectiveness and uncertainty descriptors. Output from the tool consists of both a set of prepopulated bowties for further detailed qualitative assessment and an overall indication of risk and the uncertainty bands surrounding that assessment of risk. More detail regarding each of the areas in Figure 23 are discussed in the following sections.

Figure 22: Semi-quantitative Risk Assessment Tool Inputs and Outputs
Figure 23: Semi-quantitative Risk Assessment Tool Development Process

- Bowtie Risk Framework
  - 2 x Parent Bowties (CCS and Unconventionals)
  - 2 x sets of detailed bowties, 9 x bowties in total including:
    - Well Integrity
    - Geological Leak Paths
    - Seismicity
  - Developed in 3 x workshops and at the 2019 general assembly

- Semi-Quantitative Risk Assessment Tool

- Literature Review

- Project Bowtie
  - Effectiveness descriptors based on barrier parameters
  - Uncertainty descriptors based on activities that underpin barriers

- Semi-Quantitative Workshop
  - Workshop to judge likelihood, consequence and duration over different timescales
4.2 Literature Review

The literature review shown in Figure 23, is described in Section 2. The aim of the literature review [Ref. 4] was to investigate existing information available for Unconventional gas exploitation and inform the development of the bowties. The risk framework was related to current literature, to ensure the bowties were based on a firm foundation of knowledge in the field.

4.3 Validation of Bowtie Risk assessment Framework

Draft bowties were developed from the literature review [Ref. 4] and then reviewed in workshops with participants from the SECURe project. This was a key objective for the risk framework (see Section 1.2). Nine detailed bowties developed; four CO₂ storage bowties [Ref. 3] and five unconventionals bowties. The hazards and top events for the carbon storage bowties are presented in Table 2 and the bowtie risk framework is described in detail in Section 3.

Thebowtie analysis synthesised the output of the SECURe project into a generic risk assessment framework that could be applied to any site / project proposing to develop unconventional hydrocarbon production. These bowties were then further developed in a number of workshops involving experts from both WP2 and other significant areas of the SECURe project to develop the structure, logic and completeness. Three initial workshops were held in Utrecht, Edinburgh and Keyworth. In addition, the bowties were displayed at the annual General Assembly (GA) meeting and attendees were encouraged to make comments on them. A further workshop has been held during the WP2/WP5 meeting to agree the risk assessment framework in advance of M7 in May 2020.

The aim of each workshop was to capture the technical understanding and experience of the attendees in the bowtie analysis to ensure that they form a suitable, technically accurate basis for development of the risk assessment framework. The final workshop had the additional aim to agree the risk assessment framework. An overview of the workshops and the GA presentation is provided in Table 4.

<table>
<thead>
<tr>
<th>Name</th>
<th>Date</th>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utrecht Workshop</td>
<td>22/05 – 23/05 2019</td>
<td>Netherlands Organisation for Applied Scientific Research (TNO) Offices, Netherlands</td>
<td>Initial draft bowties were developed prior to the workshop based on the literature review. The initial bowties were further developed during the workshop, involving experts from WP2 to gain agreement of their structure, logic and completeness.</td>
</tr>
<tr>
<td>GA Meeting</td>
<td>12/06 2019</td>
<td>Wroclaw, Poland</td>
<td>The presentation introduced the work that had been carried out so far by Risktec into the input of the WP2 framework. The latest drafts of the bowties were displayed for comment by attendees.</td>
</tr>
<tr>
<td>Heriot-Watt University (HWU) Workshop</td>
<td>10/07 – 11/07 2019</td>
<td>Enterprise Oil Building at the Institute of Petroleum Engineering, UK</td>
<td>The purpose of this workshop was to ensure that the bowties captured the knowledge and experience of technical experts from the university, to ensure that they form a suitable, technically accurate basis for development of the risk framework.</td>
</tr>
<tr>
<td>British Geological Survey (BGS) Workshop</td>
<td>22/07 2019</td>
<td>BGS Environmental Science Centre, UK</td>
<td>The bowties were further developed during the workshop.</td>
</tr>
<tr>
<td>WP2/WP5 Meeting Workshop</td>
<td>25/02 – 26/02 2020</td>
<td>TNO Offices, Netherlands</td>
<td>The purpose of the workshop was to discuss any specific comments or questions that attendees had raised based on previous reviews of the bowties from workshops attended in 2019 and to agree the</td>
</tr>
</tbody>
</table>
The workshops have been attended mainly by experts from WP2, but the bowties have also been developed through input from members of other WPs across the wider SECURE project and the advisory board. Throughout this process the bowtie elements (threats, barriers, degradation factors and consequences) have been scrutinised to ensure that they form a suitable, technically accurate basis for development of the risk framework. The bowtie analysis synthesised the output of the SECURE project into a generic risk assessment framework that could be applied to any site / project proposing to develop extraction of shale gas.

4.3.1 Workshop Methodology

The purpose of each bowtie workshop was to subject the draft bowties to review by the given experts in order to capture the knowledge and experience of technical personnel from within the SECURE project. This has been carried out through the scrutiny of the bowtie elements (threats, barriers, degradation factors and consequences).

The workshops reviewed and developed the bowtie diagrams, using the following general method:

1. Review threats and consequences.
2. Review the barriers for each threat and consequence line, in turn, in order to:
   a. Agree and develop barrier text.
   b. Identify degradation factors for barriers where specific conditions were known.
   c. Comment on the effectiveness of barriers.
   d. Discuss the level of uncertainty that may surround barrier effectiveness.
   e. Identify activities that support the implementation of barriers or understanding of their effectiveness (for example, site characterisations, geological analysis, reservoir modelling, or monitoring activities).
3. Where workshop attendees had specific competences, fields of research, or areas of interest, the workshop discussions were focussed on relevant bowties, and/or types of barriers.

The bowtie scope is divided into unconventionals and carbon storage. This report contains the unconventional bowties; presented in Appendix A. All bowties are presented in the bowtie workshop report [Ref. 2] and there is also an equivalent to this report for Carbon Storage [Ref. 3].

4.4 Project Bowtie

In addition to the risk framework bowties, two project bowties [Ref. 43] were developed to provide insight into interfaces between the work packages, tasks and subtasks within the SECURE Project. These are an abridged version of the risk framework bowties; one project bowtie for exploitation of unconventional gas (shale gas) and one for geological carbon storage. Each of the WPs described in Section 1.1 constitute a number of tasks and subtasks. An overview of the SECURE subtasks is presented in [Ref. 43] based on the review of the WP subtasks described in the Grant Agreement [Ref. 1] and subsequent presentations at General Assembly meetings.

The project bowties demonstrate the contribution of the SECURE project to the reduction of risk associated with unconventional hydrocarbon exploitation by increasing the strength and effectiveness of barriers through increasing knowledge and understanding. It shows the interaction of the subtasks and deliverables with barriers in order to demonstrate how the different elements of the SECURE project combine to achieve the project objectives. The project bowties focus showing how SECURE research contributes to the reduction of risk; for example, improvement of potential monitoring barriers, understanding seismicity threats, improving remediation techniques.

While the project bowties should not be confused with the risk assessment framework bowties, the project bowties do contribute to the objectives of SECURE subtask 2.1.3. They support the determination of the input required, from different SECURE project beneficiaries, for development of accurate effectiveness and
uncertainty descriptors (see Section 4.5). The project bowties are presented in full in the Project Bowtie report [Ref. 43].

4.5 Effectiveness and Uncertainty Descriptors

Effectiveness and uncertainty descriptors were developed from the bowtie risk framework, the project bowties and supported by the literature review, where required. They take inputs from the outputs of SECURe research wherever possible (see Section 3.2).

The descriptors characterise the extent to which a barrier is effective, as well as the limitations of knowledge around that assessment of effectiveness (uncertainty). The effectiveness and uncertainty descriptors are the means by which the generic bowties may be converted into a site-specific risk assessment, and they are pivotal in the transition from bowtie risk framework to risk assessment tool.

The effectiveness descriptors are constructed around variable parameters (Section 3.2.1) and the uncertainty descriptors are constructed around the supporting activities (Section 3.2.2); this is fundamental to the determination of barrier effectiveness and uncertainty when the generic bowties are applied to a specific site. This relationship between effectiveness and uncertainty is represented diagrammatically in Figure 24. For the purposes of this model; effectiveness is a measure of aleatory uncertainty, and uncertainty is a measure of epistemic uncertainty, i.e. the extent to which information is known about the parameters that determine effectiveness.

Effectiveness of a barrier is based on variable parameters, such as permeability or well integrity. Barrier effectiveness reflects the users’ current understanding of how good the barrier should be. The effectiveness of a barrier is determined initially by the extent to which the barrier exists or is implemented at a specific site and also by the inherent capability of the barrier to perform its prevention/mitigation role (e.g. is the barrier big/strong/efficient enough?). The effectiveness corresponds to three discrete levels: good, fair, or poor level effectiveness. They are based around the parameters that underpin the bowtie barrier.

In the context of the SECURe risk assessment framework bowties, levels of barrier effectiveness are defined by effectiveness descriptors, based around the variable parameters (Section 3.2.1) identified for the generic barrier. For example, the effectiveness of the orange operational strategy barrier shown in Figure 17, is directly related to the volume of fluid actually injected, the injection rate and the geological properties that inform the strategy development, e.g. the geometry of the storage complex and primary seal.

The significance / risk of the degradation factors applicable to the barrier also influence effectiveness. As a general rule a larger number of applicable and significant degradation factors will mean a less effective barrier because multiple mechanisms for undermining the barrier are present. The significance of the degradation factor(s) can however be mitigated by the effective implementation of degradation factor barriers. In general, these are described by the effectiveness descriptors in the main threat barrier;
effectiveness descriptors have not been developed for all degradation factor barriers to reduce the complexity of the SqRAT.

Some types of control are more effective than others. For example, eliminating the hazard altogether or substituting it for a less hazardous one is the most effective type of control. However, there are effective control measures other than elimination which are included in the project design, occur naturally at the storage site, or will be part of the injection and monitoring procedures and systems.

During bowtie analysis, the effectiveness of each control is often assessed by a bowtie workshop team, based on their experience and knowledge. This highlights those controls that are judged to be least effective and therefore could be a focus for risk reduction effort if improving their efficacy or introducing additional controls is considered to be reasonably practicable. Assigning effectiveness ratings to controls also allows for a project to better judge where suitable and sufficient measures are in place to prevent a release mechanism, or to mitigate its consequences.

The output of the SqRAT includes draft bowties, prepopulated with effectiveness rankings for barriers based on the selected effectiveness descriptors. This provides the opportunity for further assessment by a workshop team to produce a detailed qualitative risk assessment, including ALARP assessment, supported by potential risk reduction measures identified and prioritised automatically by the SqRAT. The draft bowties are presented in a bowtie template using the matrix presented in in Figure 25 (or similar) to reflect combined effectiveness and uncertainty.

**Figure 25: Effectiveness and Uncertainty Descriptors Matrix**

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>Fair</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty Low</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.5.2 **Barrier Uncertainty**

The *uncertainty* of a barrier is based around the extent to which activities (see Section 3.2.2) that enable the increase of knowledge are carried out. The supporting activities associated with a barrier are the means by which a project will seek to understand or control the effectiveness of a barrier; any shortcomings in quality or completeness of these activities will therefore increase the uncertainty over barrier effectiveness. Uncertainty reflects the users’ current confidence in the barrier effectiveness, based on the information they have available at the time of making the judgement. Figure 24 shows how the level of uncertainty is determined by the quality and completeness of the activities (Section 3.2.2) underpinning the barrier. As for effectiveness, there are three discrete levels of uncertainty: low, medium, or high.

Bowties that consider geology differ from more traditional MAH bowties for operating facilities, where many years of operating experience and the predominantly engineered/man-made nature of the majority of the
prevention and mitigation measures can provide a reasonable degree of certainty about the effectiveness and reliability of controls. For geological plays, there may only be limited, or no information about the exact geological properties, and appraisals about their effectiveness may rely on analogies with nearby locations or modelling estimations. The uncertainty of a control reflects the users’ current confidence in the control effectiveness, based on the information they have available at the time of making the judgement.

A completed geological bowtie diagram presents a snapshot of the effectiveness and uncertainty of the prevention and mitigation controls in place for each leak path at the time of the analysis, and in the opinion of the bowtie workshop participants. By considering the uncertainty of identified controls, the project has the opportunity to identify those controls for which greater certainty may be required to enable a decision (e.g. location acceptability) to be made, and hence commission further work in these areas.

To gain the most benefit from the bowtie analysis, it is recommended that it is initiated during the early stages of a Unconventional gas project. Consequently, there may be limited information available about certain prevention or mitigation controls, and therefore, the uncertainty associated with each control’s effectiveness rating may be higher. However, such early application will provide a prioritised set of measures for reduction in barrier uncertainty. As a project progresses, the initial bowties can then be revisited to modify control effectiveness and uncertainty when additional information becomes available e.g. from modelling and further analysis, updated design work, the results of validation wells. It would then be expected that uncertainty (and effectiveness) would change over the lifecycle of the project as more information is collected. It should be noted, however, that there is no requirement for every control to be identified as ‘effective’ and ‘reasonably certain’; it is important that the ratings assigned reflect the realistic status of each control such that informed decisions can be made about the acceptability of risks.

The output of the SqRAT includes draft bowties, prepopulated with uncertainty rankings for barriers based on the selected uncertainty descriptors. This provides the opportunity for further assessment by a workshop team to produce a detailed qualitative risk assessment, including ALARP assessment, supported by potential information gathering measures (e.g. characterisation activities) identified and prioritised automatically by the SqRAT. The draft bowties are presented in a bowtie template using the matrix presented in Figure 25 (or similar) to reflect combined effectiveness and uncertainty.

4.6 Semi-Quantitative Risk Assessment Workshop

A semi-quantitative workshop was held online (using Microsoft Teams) on 7th October 2020 in order to support the evaluation of the risks described by the SECURe bowties in the development of the semi-quantitative tool, to rank different risk factors from the bowtie framework in terms of their relative significance and importance. This was achieved by semi-quantitatively ranking the risk of bowtie threats most relevant from the bowtie risk framework and likely to represent the highest risks in Unconventional Gas Exploitation.

The workshop provided data points for quantification of risk as an input into the development of the SqRAT. It also provide guidance on the importance of key variables, as documented in SECURe deliverable D2.5 [Ref. 11].

Many elements and risk factors associated with the fields of interest represented by the SECURe project do not have a wealth of historical data available to draw upon. Furthermore, the geological aspects of unconventional hydrocarbon production do not easily conform to traditional models of component failure and the failure modes present resist classification into categories that can easily be represented by historical data. Hence, some degree of expert judgement is required to achieve an estimation of semi-quantitative risk. The workshop used answers from questions regarding the relevance of threats and receptors, the effectiveness of barriers, and the uncertainty surrounding the assessment of barrier effectiveness, which were set to good, fair or poor.

4.6.1 Scope

The scope of the workshop was a review of pre-selected bowtie threat / consequence pairs (leak paths) and associated key barriers. The workshop included:

- Evaluation of selected bowtie threat / consequence pairings (leak paths), in terms of:
  - Severity of the leak;
  - Duration of the leak;
Bowtie Analysis

- Unconventionals

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- Likelihood, including consideration of the timescale over which realisation of the leak path is most likely to occur;
- Evaluation of the impact of varying the effectiveness of key barriers on the risk of leakage.

In advance of the workshop a set of simplified barrier effectiveness and uncertainty descriptors were prepared. These simplified versions of the effectiveness descriptors were used during the workshop to assist with providing distinctions between good and poor barrier effectiveness, and evaluating the impact of this on leak path risk. The workshop did not consider the uncertainty descriptors.

4.6.2 Methodology

The workshop was based on a series of worksheets developed in Microsoft Excel, each of which was dedicated to a particular leak path, in terms of threat / top event pairings and associated key barriers.

The approach initially considered the leak only as far as the top event, including for example, release from primary containment and release from wells. The different types of receptors that were identified in the bowties were not considered in the workshop, and it was assumed that releases could lead to any of the consequences and receptors identified in the bowties. The workshop considered the potential severity and duration of a leak along the selected leak path, in terms of the matrix presented in Table 5.

Table 5: Severity / Duration Matrix

<table>
<thead>
<tr>
<th>Severity (Release Rate)</th>
<th>Small (≤10t/day)</th>
<th>Medium (≤100t/day)</th>
<th>Large (≤1000t/day)</th>
<th>Catastrophic (&gt;1000t/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>Short (≤1 year)</td>
<td>Medium (≤10 yrs)</td>
<td>Long (≤100 yrs)</td>
<td>Extended (&gt;100 yrs)</td>
</tr>
</tbody>
</table>

The workshop then assessed the likelihood of the leak path, using the band definitions presented in Table 6. When assessing likelihood, different timescales of interest of leakage were considered, for example, 10,000 years\(^3\) for storage and 30 years for injection. Furthermore, it was assumed that each of the key barriers identified were set to a good level of effectiveness.

Table 6: Likelihood Band Definitions

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Almost Impossible</td>
<td>Never heard of in the Industry or in the team’s experience in similar industries. Probability of occurrence of &lt;1% over the timescale selected</td>
</tr>
<tr>
<td>Very Unlikely</td>
<td>Never heard of in the industry, but encountered in the team’s experience of similar industries. Probability of occurrence of &lt;10% over the timescale selected</td>
</tr>
</tbody>
</table>

\(^3\) Assuming that over geological timescales, the probability of leakage is ~1 for a valid leak path.
<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Likely</td>
<td>Heard of in the industry, or expected to occur based on the team’s experience of similar industries. Probability of occurrence of ~70% over the timescale selected</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>Expected to occur. Probability of occurrence of &gt;90% over the timescale selected</td>
</tr>
</tbody>
</table>

Once the likelihood of the leak path was evaluated for the timescales of interest, the relative contribution of each of the key barriers was assessed through sensitivity analysis by varying the effectiveness of each of the barriers in turn and then revisiting the likelihood ranking. Once threats and selected barriers from the left-hand side of the bowtie had been considered, right-hand side, mitigation barriers were taken into consideration. Selected mitigation barriers were assessed against selected top events in order to understanding potential effects on severity, duration, and likelihood of leakage to receptors at different timescales. For each threat and barrier, any reliable sources of quantitative information that could be related to the threat, any barriers, or particular threat/barrier effectiveness combinations was also noted.

4.6.3 Semi-quantitative Workshop Results

4.6.3.1 Identified Leakage Pathways

Bowties SECURe-01 to 05 (Table 2) describe leakage pathways for natural gas, formation water / flowback water, and fracturing fluid from wells and the shale gas production zone. The left-hand side of these bowties details threats, which describe the initial leakage outside of primary containment, be that the well or the production zone. The right-hand side of these bowties describes the receptors that are potentially vulnerable to leakage from these pathways, as well as the barriers that may attenuate or mitigate leakage once it is outside of the primary containment. Bowtie SECURe-05 (Table 2) is different in the sense that it does not study leakage pathways but instead focusses on the causes and consequences of seismicity.

Leak paths and seismicity hazards described by the SECURe bowties are presented in Section 3.3, 3.4, and 3.5 and are presented in full in the bowtie report [Ref. 2] and Appendix A of this report. These leak paths and seismicity risks were prioritised, prior to the workshop, on the basis of discussions that had taken place during the bowtie workshops, to ensure that workshop time was best focussed on the most significant and likely to represent the highest risks in Unconventional Gas projects. During the semi-quantitative workshop each of these leak paths and seismicity hazards and associated key barriers, were reviewed and semi-quantitatively risk ranked over different timescales.

Table 7 presents the results of the leak path risk ranking when all of the applicable barriers are set to a ‘Poor’ level of effectiveness. Magnitude of release was ranked for severity and duration. Likelihood is ranked for two timescales (10,000 years and 30 years as indicated in the table by (1) and (2) respectively).
Table 7: Unconventional threat leak pathways in terms of potential risk over different timescales ('Poor' effectiveness of barriers)

<table>
<thead>
<tr>
<th>Unconventionals Threat Leak Path</th>
<th>Severity</th>
<th>Duration</th>
<th>Rank</th>
<th>Timescale (1)</th>
<th>Likelihood (1)</th>
<th>Timescale (2)</th>
<th>Likelihood (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas flows vertically out of the production zone through new fractures created during hydraulic fracturing, beyond the target production zone</td>
<td>Small (≤10 t per day)</td>
<td>Medium (≤10 yrs)</td>
<td>Low</td>
<td>10,000 Years</td>
<td>Almost Certain (P = 0.9)</td>
<td>30 Years</td>
<td>Likely (P = 0.7)</td>
</tr>
<tr>
<td>Natural gas flows vertically outside of the production zone through abandoned (former) production / fracturing well</td>
<td>Very Small (≤1 t per day)</td>
<td>Long (≤100 yrs)</td>
<td>Low</td>
<td>10,000 Years</td>
<td>Almost Certain (P = 0.9)</td>
<td>100 Years</td>
<td>Likely (P = 0.7)</td>
</tr>
<tr>
<td>Natural gas release from production / fracturing well (during production or fracturing phase)</td>
<td>Small (≤10 t per day)</td>
<td>Medium (≤10 yrs)</td>
<td>Low</td>
<td>100 Years</td>
<td>Likely (P = 0.7)</td>
<td>30 Years</td>
<td>Almost Certain (P = 0.9)</td>
</tr>
<tr>
<td>Fracturing fluid flows vertically out of the production zone through new fractures created during hydraulic fracturing, beyond the target production zone</td>
<td>Medium (≤100 t per day)</td>
<td>Short (≤1 year)</td>
<td>Low</td>
<td>30 Years</td>
<td>Almost Certain (P = 0.9)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Fracturing fluid release from production / fracturing well (during a fracturing phase)</td>
<td>Large (≤1,000 t per day)</td>
<td>Short (≤1 year)</td>
<td>Medium</td>
<td>100 Years</td>
<td>Likely (P = 0.7)</td>
<td>30 Years</td>
<td>Almost Certain (P = 0.9)</td>
</tr>
<tr>
<td>Displacement of formation fluid outside of the production zone as a result of hydraulic fracturing</td>
<td>Small (≤10 t per day)</td>
<td>Short (≤1 year)</td>
<td>Very Low</td>
<td>10,000 Years</td>
<td>Likely (P = 0.7)</td>
<td>30 Years</td>
<td>Likely (P = 0.7)</td>
</tr>
</tbody>
</table>
4.6.3.2 Significant Risk Factors

This section describes the risk ranking exercise carried out for each significant leakage pathway. Table 8 presents the five leak pathways that have been assessed as the highest risk for the production zone.

**Table 8: Unconventional threat leak pathways top 5 risks**

<table>
<thead>
<tr>
<th>#</th>
<th>Leak Path (from Well or Production Zone)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Release of fracturing fluid from well during hydraulic fracturing</td>
</tr>
<tr>
<td>2</td>
<td>Release of natural gas from production well during production</td>
</tr>
<tr>
<td>3</td>
<td>Vertical migration of natural gas outside of the production zone through new fractures created during hydraulic fracturing</td>
</tr>
<tr>
<td>4</td>
<td>Vertical migration of fracturing fluid outside of the production zone through new fractures created during hydraulic fracturing</td>
</tr>
<tr>
<td>5</td>
<td>Vertical migration of natural gas outside of the production zone through abandoned (former) production / fracturing well</td>
</tr>
</tbody>
</table>

Sensitivity studies were conducted on each of the barriers for the significant leak paths. These sensitivity studies were carried out by varying the effectiveness of single barriers from ‘poor’ to ‘good’ and revisiting the risk ranking. The output from these sensitivity studies for unconventionals is presented in Table 9. The Primary Well Barrier Envelope can result in the significant reduction in risk of leakage when that barrier is a ‘good’ level of effectiveness for Unconventional Gas.

**Table 9: Barriers for Unconventional significant leak pathways with potential for greatest risk reduction**

<table>
<thead>
<tr>
<th>#</th>
<th>Barriers for Unconventional Significant Leak Paths</th>
<th>Applicable Leak Paths</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Well Engineering - Primary Barrier Envelope: Prevents flow of hydrocarbons into annulus from tubing or production zone</td>
<td>Release of natural gas from production well during production</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Release of fracturing fluid from well during hydraulic fracturing</td>
</tr>
<tr>
<td>2</td>
<td>Well Engineering: Secondary Well Barrier Envelope: Prevents flow of hydrocarbons into annulus from production zone or into environment (subsurface or atmospheric) from annulus</td>
<td>Release of natural gas from production well during production</td>
</tr>
<tr>
<td>3</td>
<td>Well Engineering: Extent to which tubing and casing design adopts good practice, e.g. three casing strings (Surface, Intermediate, and Production) - Production casings extending below the aquifer level</td>
<td>Release of natural gas from production well during production</td>
</tr>
<tr>
<td>4</td>
<td>Geological Properties: Properties of fault / fracture network constrains flow along fault / fracture network</td>
<td>Vertical migration of natural gas outside of the production zone through new fractures created during hydraulic fracturing</td>
</tr>
</tbody>
</table>

In order to assess the effect of barriers on the right-hand side of the bowtie, a standard initial risk was postulated, in terms of release duration, severity and likelihood over four timescales. The path from a top event to a receptor / consequence was shown in the form of a simple bowtie including top event, nominal
receptor / consequence and the barrier of interest. The initial risk is an unmitigated risk, which has the barrier effectiveness set to ‘poor’. This is shown in the first row of Table 10.

The effectiveness of each right-hand side barriers was then set to ‘good’ to test the effect on this initial risk. The resultant risk reduction level when each of the barriers are at ‘good’ level of effectiveness is shown in Table 10 for the unconventional pathways. Although the severity and duration is the same for each of the barriers in Table 10, it is the separation of shale formation from potential receptors that was assessed to result in the lowest overall likelihood across the different timescales; therefore, this has the greatest risk reduction potential for releases from shale gas sites.

**Table 10: Effect of barriers for mitigation / attenuation of gas leak pathways**

<table>
<thead>
<tr>
<th>Barriers for Unconventional consequence leak pathways</th>
<th>Severity</th>
<th>Duration</th>
<th>Rank</th>
<th>Likelihood for 10,000 years</th>
<th>Likelihood for 1,000 years</th>
<th>Likelihood for 100 years</th>
<th>Likelihood for 30 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>All barriers</td>
<td>Medium (≤100 t per day)</td>
<td>Medium (≤10 yrs)</td>
<td>Medium</td>
<td>Almost Certain (P = 0.9)</td>
<td>Almost Certain (P = 0.9)</td>
<td>Almost Certain (P = 0.9)</td>
<td>Likely (P = 0.7)</td>
</tr>
<tr>
<td>Mitigated Risk – Barrier set to ‘good’ effectiveness</td>
<td>Medium (≤100 t per day)</td>
<td>Medium (≤10 yrs)</td>
<td>Medium</td>
<td>Almost Certain (P = 0.9)</td>
<td>Likely (P = 0.7)</td>
<td>Very Unlikely (P = 0.1)</td>
<td>Almost Impossible (P = 0.01)</td>
</tr>
<tr>
<td>Geological Properties: Extent to which geological layers above the production zone / between the production zone and receptors slow down movement of natural gas</td>
<td>Medium (≤100 t per day)</td>
<td>Medium (≤10 yrs)</td>
<td>Medium</td>
<td>Almost Certain (P = 0.9)</td>
<td>Likely (P = 0.7)</td>
<td>Very Unlikely (P = 0.1)</td>
<td>Almost Impossible (P = 0.01)</td>
</tr>
<tr>
<td>Geological Properties: Separation of shale formation from potential receptors</td>
<td>Medium (≤100 t per day)</td>
<td>Medium (≤10 yrs)</td>
<td>Medium</td>
<td>Almost Certain (P = 0.9)</td>
<td>Almost Certain (P = 0.9)</td>
<td>Likely (P = 0.7)</td>
<td>Very Unlikely (P = 0.1)</td>
</tr>
<tr>
<td>Geological Properties: Extent to which geological layers / formation seals well and prevents / slows down release of natural gas</td>
<td>Medium (≤100 t per day)</td>
<td>Medium (≤10 yrs)</td>
<td>Medium</td>
<td>Almost Certain (P = 0.9)</td>
<td>Almost Certain (P = 0.9)</td>
<td>Likely (P = 0.7)</td>
<td>Very Unlikely (P = 0.1)</td>
</tr>
<tr>
<td>Geological Properties: Site characterisation identifies potential for radiological / toxic hazards</td>
<td>Medium (≤100 t per day)</td>
<td>Medium (≤10 yrs)</td>
<td>Medium</td>
<td>Almost Certain (P = 0.9)</td>
<td>Almost Certain (P = 0.9)</td>
<td>Likely (P = 0.7)</td>
<td>Very Unlikely (P = 0.1)</td>
</tr>
</tbody>
</table>
4.6.3.3 Summary of Results

Each of the tables shown in Section 4.6.3 have provided further input into the determination of the relative importance of key variables in terms of the significance of different leak paths in terms of potential magnitude and likelihood over different timescales, as well as the importance of individual factors in terms of their potential to mitigate risk.

In addition to leak pathways, seismicity was also considered during the semi-quantitative risk assessment workshop. As well as being an important factor for natural gas leakage, the extent to which there are significant faults and fracture networks is also the most important risk factor for the occurrence of significant seismic events, i.e. those events with the potential to lead to measurable effects on receptors identified in the bowtie risk framework.

The outputs from the bowtie risk framework, project bowtie, effectiveness and uncertainty descriptors and semi-quantitative workshop were then brought together to develop the SqRAT, as described in Section 4.7.

4.7 Semi-Quantitative Risk Assessment Tool

The overall development process for the SqRAT is depicted by Figure 23. The development process pivots around the effectiveness and uncertainty descriptors which are presented in Appendix A. The effectiveness and uncertainty descriptors are the means by which the generic risk assessment framework is channelled into the SqRAT. As described in Section 4.6, the effectiveness descriptors also provided the basis for the expert judgement risk ranking exercise carried out as part of the semi-quantitative workshop. An example worksheet is presented in Figure 26.

Figure 26: Semi-quantitative Workshop Example Worksheet

<table>
<thead>
<tr>
<th>Severity</th>
<th>Small</th>
<th>Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>(10^6 hrs)</td>
<td>(10^10 yrs)</td>
</tr>
<tr>
<td>Timescale</td>
<td>10,000 Years</td>
<td>Storage / Injection Timescales</td>
</tr>
<tr>
<td>Likelihood</td>
<td>Almost Certain</td>
<td>Injection / Production</td>
</tr>
<tr>
<td>Likelihood</td>
<td>Very Unlikely</td>
<td>New industrial experience, but encountered in previous industrial experience</td>
</tr>
</tbody>
</table>

The semi-quantitative workshop carried out sensitivity studies, risk ranking scenarios based on altering effectiveness of barriers between ‘good’ and ‘poor’ ratings, using simplified version of the corresponding descriptors to guide the workshop, as shown in Figure 26. This provides an important data point for the SqRAT, however, because the effectiveness descriptors need to take into account three grades of effectiveness ‘good’, ‘fair’ and ‘poor’, the SqRAT interpolates between the risk ranking outputs in order to derive appropriate risk ranking values for the scenarios that were not reviewed in the workshop.

The users of the SqRAT are expected to answer factual questions by identifying the most appropriate descriptor for each relevant element, without needing to make any subjective judgements. The outputs from the SqRAT are as follows:

- Risk ranking of each relevant risk (leak paths and seismicity);
- Recommendations for further activities to reduce uncertainty, for example, site characterisation activities, prioritised in terms of:
o Greatest risk reduction benefit through consideration of the effectiveness of barriers that would most benefit through reduced uncertainty;

o Greatest reductions in overall cumulative uncertainty, for example, because a study reduces uncertainty of a number of important barriers;

- Recommendations for potential risk reduction measures, prioritised in terms of greatest risk reduction benefit;
- Outline monitoring and verification plan, and operating strategy;
- Draft bowties with barriers graded for effectiveness and uncertainty based on user responses.

The SqRAT provides a means for comparison between different potential sites (that have also been assessed using the tool), and a roadmap to increase site readiness for commercial application that can be prioritised both in terms of risk and uncertainty reduction benefit and cost.

The draft bowties output from the tool are pre-populated with threats, consequences, degradation factors and barriers, which have been graded for effectiveness and uncertainty based on the user inputs. The bowties that can be used as a basis for a detailed qualitative analysis to support containment permit or safety case. Leak paths are shown in Appendix A.

The SqRAT is intended to be a simple and straightforward approach to support site selection but could provide the basis for the detailed qualitative risk assessment through review of the draft bowties in a workshop or series of workshops with detailed consideration of potential for further risk reduction and ALARP demonstration.
5 DISCUSSION AND PROGRESSION TO FURTHER WORK

5.1 Discussion of Semi-Quantitative Workshop Results

Well integrity, particularly the primary well barrier envelope, is a significant risk factor for unconventional gas exploitation (and geological CO₂ storage). Furthermore, well integrity is of particular significance for the leakage pathway through existing / legacy wells. This pathway occurs both on the left-hand side and the right-hand side of the SECURe risk framework bowties (as shown in Figure 16 and described in Section 3.3.4. The SECURe project considers the effect of pressure and temperature cycling on well cement sheaths in terms of both leakage risk and the potential for remediation (WP5), along with the techniques for well integrity assessment [Ref. 11].

The output of the semi-quantitative workshop is described in full as applicable to exploitation of unconventional gas in Section 4.6 and SECURe deliverable D2.5 [Ref. 11].

5.2 Potential Future Research

The SqRAT will not be finalised upon completion of the SECURe project, however, the SqRAT will be in a suitable form for use and trial on a potential future project. The following further research could be carried out associated with the SqRAT:

- Bespoke software could be developed to optimise the use of the tool and processing of data;
- The SqRAT should be trialled and improved based on the results of the trial(s);
- The tool should be developed, potentially as follows:
  - Development and improvement of effectiveness and uncertainty descriptors based on future research into unconventional hydrocarbon production.
  - Development of concept and implementation of cumulative uncertainty measures.

The SqRAT output from the SECURe project provides a strong basis for future research and the development of a semi-quantitative risk assessment approach for risk reduction of future Unconventional Hydrocarbon projects.
6 CONCLUSIONS AND FURTHER WORK

6.1 Conclusion

A bowtie risk assessment framework has been developed based on comprehensive literature review [Ref. 4] and the following steps:

- The bowties have captured the knowledge and experience of technical experts in WP2 through scrutiny of the bowtie elements (threats, barriers, degradation factors and consequences) within the workshops held in Utrecht 22nd-23rd May 2019, HWU 10th-11th July 2019, and BGS 22nd July.
- The output of the workshop on the 22nd and 23rd May 2019 has contributed to providing a picture of risk management that is easily accessible to people who are not experts in Risk Management, CCS, or Unconventional Gas, enabling:
  - Wider contribution from the project (for example, presentation on large prints at the GA meeting in June 2019).
  - Wider communication both within and outside of the project; for example, the developed bowties could be simplified and subsequent refinement, for communication to wider stakeholders.
- The bowtie display and presentation on bowties at the GA meeting on the 12th June 2019 has enabled wider contribution from other WPs beyond WP2.
- The HWU workshop in Edinburgh on the 10th and 11th July 2019 and BGS workshop in Keyworth on the 22nd July 2019 have enabled further development of the bowties by capturing the technical understanding and experiences from field experts.
- The bowtie workshop that took place during the WP2/WP5 meeting at TNO offices in Utrecht on the 25th and 26th February 2020 was to agree the bowtie risk assessment framework in advance of the WP2 milestone in May 2020.

Effectiveness and uncertainty descriptors have been developed. These are pivotal to the development of the SqRAT and are presented for further review in Appendix A of this report.

A semi-quantitative workshop was held 7th October 2020 in order to support the evaluation of the risks described by the SECURE bowties in the development of the semi-quantitative tool, to rank different risk factors from the bowtie framework in terms of their relative significance and importance. This was achieved by semi-quantitatively ranking the risk of bowtie threats most relevant from the bowtie risk framework and likely to represent the highest risks in Unconventional Gas Exploitation.

The workshop also provided data points for quantification of risk as an input into the development of the SqRAT. It also provide guidance on the importance of key variables, as documented in SECURE deliverable D2.5 [Ref. 11].

The SqRAT provides a means for comparison between different potential sites (that have also been assessed using the tool), and a roadmap to increase site readiness for commercial application that can be prioritised both in terms of risk and uncertainty reduction benefit and cost.

The SqRAT is intended to be a simple and straightforward approach to support site selection but could provide the basis for the detailed qualitative risk assessment through review of the draft bowties in a workshop or series of workshops with detailed consideration of potential for further risk reduction and ALARP demonstration.

A number of further research opportunities have been identified, both for development of the SqRAT and from consideration of synergy with the SRL framework concept. The SqRAT output from the SECURE project provides a strong basis for future research and the development of a semi-quantitative risk assessment approach for improvement of SRL.

The SqRAT has been developed based on the output of the bowtie risk assessment framework, the semi-quantitative workshop, and the output of the other tasks in WP2. The semi-quantitative risk assessment tool is a key output of the SECURE project, WP2, subtask 2.1.3. As far as possible, this tool is meant to bring together the quantitative research from SECURE project Tasks 2.2 - 2.4, documenting the factors that influence the likelihood of release paths and seismicity, the reliability of control measures, and the estimated rates or volumes of releases. When using the SqRAT, the user will be expected to answer questions regarding...
the relevance of threats and receptors, the effectiveness of barriers, and the uncertainty surrounding the assessment of barrier effectiveness. This will ultimately enable users to easily undertake an initial screening risk assessment and/or prioritise further work for different prospective sites, based on the good practice recommendations that are outputs of the SECURe project.

6.2 Next Steps – Semi-quantitative Risk Assessment Tool and Guidance Note

Sub-task 2.1.3 will be completed once the SqRAT has been developed (see Section 5.2) and a guidance note prepared to assist potential users. The SqRAT is Excel based.

The users of the SqRAT will be expected to answer factual questions by identifying the most appropriate effectiveness and uncertainty descriptor for each relevant barrier, without needing to make any subjective judgements. This report provides the basis of this user interface, the effectiveness and uncertainty descriptors, in Appendix A. The guidance note will describe the information that a potential user needs to know for generating the outputs described in Section 4.7 to enable risk-based comparison of different prospective unconventional gas exploitation.
### REFERENCES

<table>
<thead>
<tr>
<th>Ref</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>European Commission, Innovation and Networks Executive Agency, Energy Research, Grant Agreement, Annex 1 (part A), Research and Innovation Action; Number – 764531 – SECURe</td>
</tr>
<tr>
<td>3</td>
<td>Risktec Solutions Ltd. (2021), Prepared for SECURe Project, Bowtie Analysis – Carbon Storage, BGS-01-R-12, Issue 1.0</td>
</tr>
<tr>
<td>4</td>
<td>Risktec Solutions Ltd. (2021), Prepared for SECURe Project, Unconventionals Literature Review, BGS-01-R-02, Issue 1.0</td>
</tr>
<tr>
<td>7</td>
<td>NORSOK D-010, June 2013. Well integrity in drilling and well operations, Rev. 4.</td>
</tr>
</tbody>
</table>


43. Risktec Solutions Ltd. (2020), Prepared for SECURe Project, Project Bow-ties, BGS-01-R-01, Issue 2.0, 16th July 2020

44. CCPS (2018) Center for Chemical Process Safety of the American Institute of Chemical Engineers (in association with the Energy Institute), Bow Ties in Risk Management: A Concept Book for Process Safety, September 2018


47. Rafael March, David Egya, Christine Maier, Andreas Busch, Florian Doster, Numerical computation of stress-permeability relationships of fracture networks in a shale rock, Institute of Geoenergy Engineering, Heriot-Watt University, Edinburgh, December 2020
Appendix A  EFFECTIVENESS AND UNCERTAINTY DESCRIPTORS

This appendix provides the effectiveness and uncertainty descriptors for each of the barriers incorporated into the SqRAT. Each section of the appendix provides the full threat or consequence context, followed by tables that include the effectiveness and uncertainty descriptors and simplified bowties for each threat or consequence.
SECURe-01 – Release from Well (during Production and Abandonment Phases)

Figure 27: SECURe-01 High Level Bow-tie

- Hydrocarbon in well annulus (Annulus A)
- Leak along / through cement (external leak) – Failure of cement bond and/or casing / production liner
- Natural Gas migrates through plugged well
- Release from Well (during Production and Abandonment Phases)
- Emissions to atmosphere from well – environmental impact
- Groundwater / Soil contamination from natural gas released from well - impact to ecosystems (flora & fauna) and / or people
Figure 28: SECURe-01 Threat 1 – Full Context

- Hydrocarbon in well annulus (Annulus A)
- Well Engineering: Primary Barrier Envelope
  - Prevents flow of hydrocarbons into annulus from tubing or production zone
  - Well engineering and design 101
  - Cement quality additives 101
- Well Engineering: Secondary Well Barrier Envelope
  - Prevents flow of hydrocarbons into annulus from production zone or into environment (subsurface or atmospheric) from annulus
  - Well engineering and design 101
- Cementation related escalation factors applicable to primary Well Barrier Envelope and are also applicable to Secondary Well Barrier Envelope
  - Well Engineering: Extent to which tubing and casing design abides good practice, e.g., three casing strings (surface, intermediate, and production) production casing extending below the aquifer level
  - Well engineering and design 101
- Well Examinations: Well records examined by an ‘independent and competent person’ (well examiner) and defects corrected
  - Well engineering and design 101
- Monitoring: Annular Pressure Monitoring
  - Pressure Monitoring 101
  - Annular pressure
- Hydrocarbon in well annulus (Annulus A)
- Corrective Actions: Remedial measures (e.g., remediation and repair, plugging or abandonment)
  - Corrective action: Well abandonment
- Well engineering and design 101
- SECURe Project Issue: 1.0
- Risktec Solutions Limited
- Appendix A: Page A.3 of A.101
Figure 29: SECURe-01 Threat 1 Barrier 1 Degradation Factors (1 of 2)

- **Hydrocarbon in well annulus (Annulus A)**
  - Well Engineering - Primary Barrier Envelope: Prevents flow of hydrocarbons into annulus from tubing or production zone
  - Well engineering and design 101
  - Cement quality additives 101
  - Primary Well Barrier Envelope Design and Integrity (Injection / Production)

- **Monitoring:**
  - Pressure Monitoring 101
  - Annular pressure
  - Downhole pressure

- **Operational Strategy:**
  - Hydraulic fracturing strategy - prevents damage to well and includes testing and any necessary repair following each fracturing stage

- **Corrective Action:**
  - Repair well / replace components, e.g. tubing, lines, remediation fluid
  - Remediation of well pressure monitoring 101

- **Release from Well (during Production and Abandonment Phases)**

- **Damage to Primary Barrier Envelope well cementation (WPS) caused by fluid injection during hydraulic fracturing (e.g. fatigue due to pressure cycling)**

- **Monitoring of sample wells only, e.g. 10%**

- **Poor quality cement / Cement bond logs identify defects in cementation / Cement improperly placed / Cement shrinkage**

- **Well Engineering:**
  - Identification of poor quality cementation and remedial cement job before subsequent sections are drilled
  - Cement quality additives 101
  - Cement quality test 101
  - Cement bond log 101
  - Remediation of well
  - Well Design and Integrity

- **Well Engineering:**
  - Shrinkage resistant cement formulations
  - Well engineering and design 101
  - Cement bond log 101
  - Well Design and Integrity

- **Well Examination:**
  - Well records examined by an independent and competent person (well examiner) and defects corrected
  - Pressure testing of well casing 101
  - Cement bond log 101
  - Well Design and Integrity

- **Cement (mechanical and chemical) degradation over time leads to development of cracks and potential for leakage**

- **Monitoring:**
  - Monitoring of cementation through repeated cement bond logs (CBL) and / or fibreoptics
  - Cement bond log 101
  - Fibreoptic monitoring 101
  - Well Design and Integrity
Figure 31: SECURE-01 Threat 1 Barrier 2 Degradation Factors
### Table 11: SECURe -01 Threat 1 – Engineering Barrier 1

#### Uncertainty Descriptors

<table>
<thead>
<tr>
<th>Well engineering and design</th>
<th>Site Selection Studies and Site Surveys</th>
<th>Cementation Quality</th>
<th>Pressure testing of well casing</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Design and installation processes have been successfully audited and / or certified and design demonstrably complies with NORSOK D-010 or equivalent standard.</td>
<td>- Overlying permeable strata have been characterised to a high degree of resolution; transport pathways have been identified.</td>
<td>- Monitoring of cementation through cement bond logs (CBL) and / or fibreoptics has been carried out.</td>
<td>- After cement has been placed in the annulus, the cement sheath has been evaluated to determine that no leaks are detectable. The evaluation confirms that the top of cement is in accordance with the design depth. - Casings have been pressure tested after installation and prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and has been carried out based on NORSOK D-010 Section 4.2.3.6.</td>
</tr>
</tbody>
</table>

#### Effectiveness Descriptors

<table>
<thead>
<tr>
<th>Well engineering - Primary Barrier Envelope: Prevents flow of hydrocarbons into annulus from tubing or production zone</th>
<th>Design and Installation</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) The in-situ formation (prior to fracking) shall achieve or be capable of achieving the requirements of NORSOK D-010 Table 51 and Table 52 (if applicable). In particular: - the formation shall be impermeable with no flow potential - the formation integrity shall exceed the maximum wellbore pressure induced.</td>
<td>1) The in-situ formation (prior to fracking) shall achieve or be capable of achieving the requirements of NORSOK D-010 Table 51 and Table 52 (if applicable). In particular: - the formation shall be impermeable* with no flow potential - the formation integrity shall exceed the maximum wellbore pressure induced.</td>
<td>1) The in-situ formation cannot achieve or be capable of achieving the requirements of NORSOK D-010 Table 51 and Table 52 (if applicable).</td>
<td>1) The in-situ formation cannot achieve or be capable of achieving the requirements of NORSOK D-010 or any equivalent standard. There are known design flaws / significant potential requirements to be addressed.</td>
<td></td>
</tr>
</tbody>
</table>

#### Barrier Description

**Good**
- Design and Installation
  1. The in-situ formation (prior to fracking) shall achieve or be capable of achieving the requirements of NORSOK D-010 Table 51 and Table 52 (if applicable). In particular: - the formation shall be impermeable with no flow potential - the formation integrity shall exceed the maximum wellbore pressure induced.

**Poor**
- Design and Installation
  1. The in-situ formation cannot achieve or be capable of achieving the requirements of NORSOK D-010 or any equivalent standard. There are known design flaws / significant potential requirements to be addressed.

---

*For monitoring purposes: During fracturing there is more monitoring that takes place - pressure monitoring in every annulus - observing pressure in every annulus, react immediately if pressure in annulus goes up.*
### Variable Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Well Barrier Envelope Design and Integrity (Injection / Production)</strong></td>
<td></td>
</tr>
</tbody>
</table>

2) All relevant elements of the Primary Well Barrier Envelope are/will be designed and installed in accordance with the requirements of NORSOK D-010, particularly:
- Production Packer (Table 7),
- Liner Cement (Table 22),
- Casing / Production Liner (Table 2),
- Liner Hanger Packer (Table 7),
- Completion String / Production Tubing (Table 25).

**Operational**

3) The elements of the Primary Well Barrier Envelope in 2) show no signs of defect, damage, or corrosion.

*The wellbore may intersect permeable strata; however, there is no reason to suspect the integrity of the well at these intersections.

2) All relevant elements of the Primary Well Barrier Envelope are/will be designed and installed in accordance with the requirements of NORSOK D-010, particularly:
- Production Packer (Table 7),
- Liner Cement (Table 22),
- Casing / Production Liner (Table 2),
- Liner Hanger Packer (Table 7),
- Completion String / Production Tubing (Table 25).

**Operational**

3) The elements of the Primary Well Barrier Envelope in 2) show signs of minor defect, damage, or corrosion, however, these are not expected to cause significant impairment to the integrity of the well.

derogate against any or all of the specific requirements of NORSOK D-010, particularly:
- Production Packer (Table 7),
- Liner Cement (Table 22),
- Casing / Production Liner (Table 2),
- Liner Hanger Packer (Table 7),
- Completion String / Production Tubing (Table 25).

**Operational**

3) The elements of the Primary Well Barrier Envelope in 2) show signs of defect, damage, or corrosion. These are expected to cause significant impairment to well integrity.

integrity and strength to withstand pressures exerted at different phases of the well lifecycle and has been carried out based on NORSOK D-010 Section 4.2.3.6.

Well engineering and design
- It is not possible to demonstrate that the design complies with NORSOK D-010 or equivalent standard.

Site Selection Studies and Site Surveys
- Overlying permeable strata have not been characterised

Cementation Quality
- Cementation quality assurance process are in place but are not certified

Pressure testing of well casing
- Casings have NOT been pressure tested after installation or prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and/or has NOT been carried out based on NORSOK D-010 Section 4.2.3.6.
Table 12: SECURE -01 Threat 1 – Engineering Barrier 2

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Well engineering and design</strong></td>
</tr>
<tr>
<td>- Design and installation processes have been successfully audited and/or certified and design demonstrably complies with NORSOK D-010 or equivalent standard.</td>
</tr>
<tr>
<td>- Probabilistic simulations for well integrity analyses have been carried out in order to account for the uncertainty of input parameters.</td>
</tr>
<tr>
<td><strong>Site Selection Studies and Site Surveys</strong></td>
</tr>
<tr>
<td>- Overlying permeable strata have been characterised to a high degree of resolution; transport pathways have been identified.</td>
</tr>
<tr>
<td><strong>Cementation Quality</strong></td>
</tr>
<tr>
<td>- Monitoring of cementation through cement bond logs (CBL) and/or fibreoptics has been carried out.</td>
</tr>
<tr>
<td>- Cementation quality assurance procedures and practice implementing six sigma or equivalent are in place and successfully audited and certified.</td>
</tr>
<tr>
<td><strong>Pressure testing of well casing</strong></td>
</tr>
<tr>
<td>- After cement has been placed in the annulus, the cement sheath has been evaluated to determine that no leaks are detectable. The evaluation confirms that the top of cement is in accordance with the design depth.</td>
</tr>
<tr>
<td>- Casings have been pressure tested after installation and prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and has been carried out based on NORSOK D-010 Section 4.2.3.6.</td>
</tr>
</tbody>
</table>

>> Monitoring

Note from semi-quantitative workshop: During fracturing there is more monitoring that takes place - pressure monitoring in every annulus - observing pressure in every annulus, react immediately if pressure in annulus goes up.

**Low**

**Well engineering and design**
- Design and installation processes demonstrably complies with NORSOK D-010 or equivalent standard, but has some weaknesses or areas of omission. For example, well may be repurposed from an existing well and evidence of compliance with the standard may not be available for all well barrier elements.

**Cementation Quality**
- Cementation quality assurance process are in place and successfully audited and certified.

**Pressure testing of well casing**
- Casings have been pressure tested after installation and prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and has been carried out based on NORSOK D-010 Section 4.2.3.6.

**Medium**

**Well engineering and design**
- Design and installation processes demonstrably complies with NORSOK D-010 or equivalent standard, but has some weaknesses or areas of omission. For example, well may be repurposed from an existing well and evidence of compliance with the standard may not be available for all well barrier elements.

**Cementation Quality**
- Cementation quality assurance process are in place and successfully audited and certified.

**Pressure testing of well casing**
- After cement has been placed in the annulus, the cement sheath has been evaluated to determine that no leaks are detectable. The evaluation confirms that the top of cement is in accordance with the design depth.
- Casings have been pressure tested after installation and prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and has been carried out based on NORSOK D-010 Section 4.2.3.6.

**High**

**Well engineering and design**
- It is not possible to demonstrate that the design complies with NORSOK D-010 or equivalent standard.

**Cementation Quality**
- Cementation quality assurance process are in place but are not certified.

**Pressure testing of well casing**
- Casings have NOT been pressure tested after installation or prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and/or has NOT been carried out based on NORSOK D-010 Section 4.2.3.6.
### Effectiveness Descriptors

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design and Installation</strong></td>
<td>1) The in-situ formation shall achieve or be capable of achieving the requirements of NORSOK D-010 Table 51 and Table 52 (if applicable). In particular: - the formation shall be impermeable with no flow potential - the formation integrity shall exceed the maximum wellbore pressure induced. 2) All relevant elements of the Secondary Well Barrier Envelope are / will be designed and installed in accordance with the requirements of NORSOK D-010, particularly: - Casing Cement (Intermediate) (Table 22) - Casing (Intermediate) (Table 2), - Tie-back Packer (Table 7) - Tie-back Production Casing (Table 2) - Production Liner Hanger (with Seal Assembly) (Table 5) - Tubing Hanger (Neck Seal and Body Seal) (Table 10) - Wellhead / Xmas Tree (including Annulus A valve) (Table 12 and 33)</td>
<td>3) The elements of the Secondary Well Barrier Envelope in 2) show signs of minor defect, damage, or corrosion.</td>
<td>3) The elements of the Secondary Well Barrier Envelope in 2) show signs of defect, damage, or corrosion. These are expected to cause significant impairment to well integrity.</td>
</tr>
</tbody>
</table>

### Variable Parameters

<table>
<thead>
<tr>
<th>Well Engineering: Secondary Well Barrier Envelope: Prevents flow of hydrocarbons into annulus from production zone or into environment (subsurface or atmospheric) from annulus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operational</strong></td>
</tr>
<tr>
<td>- In-situ formation as assessed by site analysis - Casing Cement (Intermediate) Design and Integrity - Casing (Intermediate) Design and Integrity - Tie-back Packer Design and Integrity - Tie-back Production Casing Design and Integrity - Production Liner Hanger (with Seal Assembly) Design and Integrity - Tubing Hanger (Neck Seal and Body Seal) Design and Integrity - Wellhead / Xmas Tree (including Annulus A valve) Design and Integrity</td>
</tr>
</tbody>
</table>

### Appendix A: Page A.10 of A.101
## Table 13: SECURe -01 Threat 1 – Engineering Barrier 3

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
<th>Uncertainty Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well Engineering: Extent to which tubing and casing design adopts good practice, e.g. three casing strings (Surface, Intermediate, and Production) - Production casings extending below the aquifer level</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>Design and Installation</td>
<td>1) All tubing and casing of the Well Barrier Envelope are / will be designed and installed in accordance with the requirements of NORSOK D-010, including:</td>
<td>Well engineering and design 101</td>
</tr>
<tr>
<td></td>
<td>- Primary Well Barrier Envelope</td>
<td>1) Design and installation processes have been successfully audited / certified and design demonstrably complies with NORSOK D-010 or equivalent standard.</td>
</tr>
<tr>
<td></td>
<td>- Secondary Well Barrier Envelope</td>
<td>2) Calipers or equivalent method were used to measure the diameters of the wellbores to ensure that the casings were installed accurately.</td>
</tr>
<tr>
<td></td>
<td>Design and Installation</td>
<td>2) Calipers or equivalent method were used to measure the diameters of the wellbores to ensure that the casings were installed accurately.</td>
</tr>
<tr>
<td></td>
<td>The following requirements are taken from Reference 5: The Royal Society and the Royal Academy of Engineering (2012) Shale gas extraction in the UK: A review of hydraulic fracturing.</td>
<td>Well engineering and design 101</td>
</tr>
<tr>
<td></td>
<td>2) Surface casing: The wellbore is sealed with a casing that runs past the bottom of any freshwater bearing zones (including but not limited to drinking water aquifers) and extends all the way back to the surface. Cement is pumped down the wellbore and up between the casing and the rock until it reaches the surface.</td>
<td>Caliper measurement of wellbores 101</td>
</tr>
<tr>
<td></td>
<td>3) Intermediate casing: Another wellbore is drilled and lined by an intermediate casing to isolate the well from non-freshwater zones that may cause instability or be abnormally pressurised. The casing may be sealed with cement typically either up to the base of the surface casing or all the way to the surface.</td>
<td>Pressure testing of well casing 101</td>
</tr>
<tr>
<td></td>
<td>4) Production casing: A final wellbore is drilled into the target rock formation or zone containing shale gas. Once fractured, the shale gas produces into the well. This wellbore is lined with a production casing that may be sealed with cement either to a safe height above the target formation up to the base of the intermediate casing; or all the way to the surface, depending on well depths and local geological conditions.</td>
<td>Pressure testing of well casing 101</td>
</tr>
<tr>
<td>Variable Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Well Design and Integrity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Uncertainty Descriptors

- **Well engineering and design 101**
  1) Design and installation processes have been successfully audited / certified and design demonstrably complies with NORSOK D-010 or equivalent standard.
  2) Calipers or equivalent method were used to measure the diameters of the wellbores to ensure that the casings were installed accurately.
  3) Casings have been pressure tested after installation and prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and has been carried out based on NORSOK D-010 Section 4.2.3.6.

- **Caliper measurement of wellbores 101**
  1) Design and installation processes have been successfully audited / certified and design demonstrably complies with NORSOK D-010 or equivalent standard, but has some weaknesses or areas of omission.
  2) Calipers or equivalent method were used to measure the diameters of the wellbores to ensure that the casings were installed accurately.
  3) Casings have been pressure tested after installation and prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and has been carried out based on NORSOK D-010 Section 4.2.3.6, but has some weaknesses or areas of omission.

### Design and Installation

1. **Pressure testing of well casing 101**
   - 1) Design and installation processes have been successfully audited / certified and design demonstrably complies with NORSOK D-010 or equivalent standard.
   - 2) Calipers or equivalent method were used to measure the diameters of the wellbores to ensure that the casings were installed accurately.
   - 3) Casings have been pressure tested after installation and prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and has been carried out based on NORSOK D-010 Section 4.2.3.6.
Figure 32: SECURE-01 Threat 2 – Full Context

Please refer to Table 13 for Engineering Barrier: Well Engineering: Extent to which tubing and casing design adopts good practice, e.g. three casing strings (Surface, Intermediate, and Production) - Production casings extending below the aquifer level.
Figure 33: SECURe-01 Threat 2 Barrier 1 Degradation Factors (1 of 2)
Figure 35: SECURE-01 Threat 2 Barrier 2 Degradation Factors

- Damage to well caused by induced seismicity during fracturing and/or SCU/Cut-Gas Seismicity threats and left-hand side barriers
- Well Engineering: Positioning of wells / location in relation to other active wells - minimum separation distance adhered to
- Monitoring: Seismicity Monitoring
- Seismic Monitoring 101: Seismicity
- Operational Strategies: Hydraulic fracturing strategy - prevents damage to well and includes testing and any necessary repair following each fracturing stage
- Corrective Action: Repair well / replace components, e.g. tubing, liner, remediation fluid
- Leak along / through cement (external leak) - failure of cement bond and/or casing / production liner
- Well Engineering - Secondary Barrier Envelope Design and Integrity (Injection / Production)
- Casing (Intermediate) Design and Integrity
- Casing Cement (Intermediate) Design and Integrity
- Release from Well during Production and Abandonment Phases
- Corrosion of casing / liner
- Well casing / liner material specified as corrosion resistant
- Inspection (and testing) of well for corroded casing / liner - developed risk based inspection programme focused on identifying the rate of corrosion and informing corrective action
- Well Engineering and Design 101: Well Monitoring 101
- Well Inspection 101: Composition / properties of injected fluid
- Formation fluid properties
- Well Design and Integrity
- SECURE-01: Shale Gas (Natural gas in Formation)
Table 14: SECURE -01 Threat 2 – Engineering Barrier 1

**Uncertainty Descriptors**

**Well engineering and design**
- Design and installation processes have been successfully audited and / or certified and design demonstrably complies with NORSOK D-010 or equivalent standard.
- Probabilistic simulations for well integrity analyses have been carried out in order to account for the uncertainty of input parameters.
- Modelling has been carried out to confirm the required values for cement Young’s modulus, shrinkage resistance, and cohesion / tensile strength.

**Site Selection Studies and Site Surveys**
- Overlying permeable strata have been characterised to a high degree of resolution; transport pathways have been identified.
- Monitoring of cementation through repeated cement bond logs (CBL) and / or fibreoptics has been carried out.
- Cementation quality assurance procedures and practice implementing six sigma or equivalent are in place and successfully audited and certified.

**Pressure testing of well casing**
- After cement has been placed in the annulus, the cement sheath has been evaluated to determine that no leaks are detectable. The evaluation confirms that the top of cement is in accordance with the design depth.
- Casings have been pressure tested after installation and prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and has been carried out based on NORSOK D-010 Section 4.2.3.6.

**Well Examination**
- Well records have been examined by an independent and competent person (well examiner) and defects corrected.

**Well engineering and design**
- Design and installation processes demonstrably complies with NORSOK D-010 or equivalent standard, but has some weaknesses or areas of omission. For example, well may be repurposed from an existing well and evidence of compliance with the standard may not be available for all well barrier elements.

**Site Selection Studies and Site Surveys**
- Overlying permeable strata have been characterised and transport pathways have been identified.

**Cementation Quality**
- Cementation quality assurance process are in place and successfully audited and certified.

**Pressure testing of well casing**
- After cement has been placed in the annulus, the cement sheath has been evaluated to determine that no leaks are detectable. The evaluation confirms that the top of cement is in accordance with the design depth.
- Casings have been pressure tested after installation and prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and has been carried out based on NORSOK D-010 Section 4.2.3.6.
**Barrier Description**

<table>
<thead>
<tr>
<th>Variable Parameters</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well Engineering - Primary Barrier Envelope (integrity of cement and its interfaces with casing and surrounding geology)</td>
<td>Good</td>
</tr>
<tr>
<td>- Liner Cement Design and Integrity</td>
<td>Design and Installation</td>
</tr>
<tr>
<td>1) The use of soft, low shrinkage cement is the most effective way to reduce probability of failure for cement at the well interfaces, therefore:</td>
<td></td>
</tr>
<tr>
<td>a) Liner cement has been designed for a Young’s modulus ~5 GPa.</td>
<td></td>
</tr>
<tr>
<td>b) Cementation formulation is shrinkage resistant.</td>
<td></td>
</tr>
<tr>
<td>2) The in-situ formation shall achieve or be capable of achieving the requirements of NORSOK D-010 Table S1 and Table S2 (if applicable). In particular:</td>
<td></td>
</tr>
<tr>
<td>- the formation shall be impermeable with no flow potential</td>
<td></td>
</tr>
<tr>
<td>- the formation integrity shall exceed the maximum wellbore pressure induced.</td>
<td></td>
</tr>
<tr>
<td>3) Liner Cement is / will be designed and installed in accordance with the requirements of NORSOK D-010, Table 22.</td>
<td></td>
</tr>
<tr>
<td>Operational</td>
<td></td>
</tr>
<tr>
<td>4) The above relevant elements of the Primary Well Barrier Envelope show no signs of defect, damage, or corrosion. Cement is not damaged, and likely to provide cohesion of ~10 MPa.</td>
<td></td>
</tr>
</tbody>
</table>

| Design and Installation |
| 1) The use of soft, low shrinkage cement is the most effective way to reduce probability of failure for cement at the well interfaces, therefore: |
| a) Liner cement has been designed for a Young’s modulus ~7 GPa. |
| b) Cementation formulation is shrinkage resistant. |
| 2) The in-situ formation shall in general achieve or be capable of achieving the requirements of NORSOK D-010 Table S1 and Table S2 (if applicable). In particular: |
| - the formation shall be impermeable with no flow potential |
| - the formation integrity shall exceed the maximum wellbore pressure induced. |
| 3) Liner Cement is / will be designed and installed in accordance with the requirements of NORSOK D-010, Table 22 or equivalent standard. |
| Operational |
| 4) The above relevant elements of the Primary Well Barrier Envelope show signs of minor defect, damage, or corrosion. However, these are not expected to cause significant impairment to the integrity of the well. It is possible to remediate these defects and there is a plan in place to ensure that this occurs within one calendar year, and before they degrade well integrity significantly. Cement may be slightly damaged or degraded, but likely to provide cohesion of between 3 and 10 MPa. |

<table>
<thead>
<tr>
<th>Variable Parameters</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable Parameters</td>
<td>Good</td>
</tr>
<tr>
<td>Well Engineering - Primary Barrier Envelope (integrity of cement and its interfaces with casing and surrounding geology)</td>
<td>Design and Installation</td>
</tr>
<tr>
<td>1) Liner cement has a Young’s modulus &gt;10 GPa. Cement formulation is not shrinkage resistant.</td>
<td></td>
</tr>
<tr>
<td>2) The in-situ formation cannot achieve or be capable of achieving the requirements of NORSOK D-010 Table S1 and Table S2 (if applicable).</td>
<td></td>
</tr>
<tr>
<td>3) Liner Cement is not / will not be designed and installed in accordance with the requirements of NORSOK D-010, Table 22 or equivalent standard.</td>
<td></td>
</tr>
<tr>
<td>Operational</td>
<td></td>
</tr>
<tr>
<td>4) The above relevant elements of the Primary Well Barrier Envelope show signs of defect, damage, or corrosion. These are expected to cause significant impairment to well integrity. Cement is damaged, and likely to provide cohesion of &lt;3 MPa.</td>
<td></td>
</tr>
</tbody>
</table>
### Uncertainty Descriptors

<table>
<thead>
<tr>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Well engineering and design</strong></td>
<td>- Design and installation processes have been successfully audited and certified. - Probabilistic simulations for well integrity analyses have been carried out in order to account for the uncertainty of input parameters. - Modelling has been carried out to confirm the required values for cement Young’s modulus, shrinkage resistance, and cohesion / tensile strength</td>
<td>- Design and installation processes have demonstrably complies with NORSOK D-010 or equivalent standard. - Probabilistic simulations for well integrity analyses have been carried out in order to account for the uncertainty of input parameters. - Modelling has been carried out to confirm the required values for cement Young’s modulus, shrinkage resistance, and cohesion / tensile strength</td>
</tr>
<tr>
<td><strong>Site Selection Studies and Site Surveys</strong></td>
<td>- Overlying permeable strata have been characterised to a high degree of resolution; transport pathways have been identified. - Cementation quality assurance procedures and practice implementing six sigma or equivalent are in place and successfully audited and certified</td>
<td>- Site Selection Studies and Site Surveys - Overlying permeable strata have been characterised to a high degree of resolution; transport pathways have been identified. - Cementation quality assurance procedures and practice implementing six sigma or equivalent are in place and successfully audited and certified</td>
</tr>
<tr>
<td><strong>Cementation Quality</strong></td>
<td>- Monitoring of cementation through repeated cement bond logs (CBL) and / or fibreoptics has been carried out. - Cementation quality assurance procedures and practice implementing six sigma or equivalent are in place and successfully audited and certified</td>
<td>- Cementation Quality - Monitoring of cementation through repeated cement bond logs (CBL) and / or fibreoptics has been carried out. - Cementation quality assurance procedures and practice implementing six sigma or equivalent are in place and successfully audited and certified</td>
</tr>
<tr>
<td><strong>Pressure testing of well casing</strong></td>
<td>- After cement has been placed in the annulus, the cement sheath has been evaluated to determine that no leaks are detectable. The evaluation confirms that the top of cement is in accordance with the design depth. - Casings have been pressure tested after installation and prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and has been carried out based on NORSOK D-010 Section 4.2.3.6.</td>
<td>- Pressure testing of well casing - After cement has been placed in the annulus, the cement sheath has been evaluated to determine that no leaks are detectable. The evaluation confirms that the top of cement is in accordance with the design depth. - Casings have been pressure tested after installation and prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and has been carried out based on NORSOK D-010 Section 4.2.3.6.</td>
</tr>
<tr>
<td><strong>Well Examination</strong></td>
<td>Well records have been examined by an independent and competent person (well examiner) and defects corrected.</td>
<td>Well Examination Well records have been examined by an independent and competent person (well examiner) and defects corrected.</td>
</tr>
</tbody>
</table>

---

**Table 15: SECURE -01 Threat 2 – Engineering Barrier 2**

<table>
<thead>
<tr>
<th>Threat</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Well engineering and design</strong></td>
<td>- Design and installation processes have been successfully audited and certified. - Probabilistic simulations for well integrity analyses have been carried out in order to account for the uncertainty of input parameters. - Modelling has been carried out to confirm the required values for cement Young’s modulus, shrinkage resistance, and cohesion / tensile strength</td>
</tr>
<tr>
<td><strong>Site Selection Studies and Site Surveys</strong></td>
<td>- Overlying permeable strata have been characterised to a high degree of resolution; transport pathways have been identified. - Cementation quality assurance procedures and practice implementing six sigma or equivalent are in place and successfully audited and certified</td>
</tr>
<tr>
<td><strong>Cementation Quality</strong></td>
<td>- Monitoring of cementation through repeated cement bond logs (CBL) and / or fibreoptics has been carried out. - Cementation quality assurance procedures and practice implementing six sigma or equivalent are in place and successfully audited and certified</td>
</tr>
<tr>
<td><strong>Pressure testing of well casing</strong></td>
<td>- After cement has been placed in the annulus, the cement sheath has been evaluated to determine that no leaks are detectable. The evaluation confirms that the top of cement is in accordance with the design depth. - Casings have been pressure tested after installation and prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and has been carried out based on NORSOK D-010 Section 4.2.3.6.</td>
</tr>
<tr>
<td><strong>Well Examination</strong></td>
<td>Well records have been examined by an independent and competent person (well examiner) and defects corrected.</td>
</tr>
</tbody>
</table>
### Barrier Description

<table>
<thead>
<tr>
<th>Well Engineering - Secondary Barrier Envelope (integrity of cement and its interfaces with casing and surrounding geology)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable Parameters</td>
</tr>
<tr>
<td>- Secondary Well Barrier Envelope Design and Integrity (Injection / Production)</td>
</tr>
<tr>
<td>- Casing (Intermediate) Design and Integrity</td>
</tr>
<tr>
<td>- Casing Cement (Intermediate) Design and Integrity</td>
</tr>
</tbody>
</table>

### Effectiveness Descriptors

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Well Engineering and design</strong></td>
<td>- Design does not demonstrably comply with NORSOK D-010 or equivalent standard.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Site Selection Studies and Site Surveys</strong></td>
<td>- Overlying permeable strata have not been characterised</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cementation Quality</strong></td>
<td>- Cementation quality assurance process are in place but are not certified</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pressure testing of well casing</strong></td>
<td>- Casings have NOT been pressure tested after installation or prior to further drilling to ensure sufficient mechanical integrity and strength to withstand pressures exerted at different phases of the well lifecycle and/or has NOT been carried out based on NORSOK D-010 Section 4.2.3.6.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Design and Installation

| 1) The use of soft, low shrinkage cement is the most effective way to reduce probability of failure for cement at the well interfaces, therefore: |
| a) Casing (Intermediate) cement has been designed for a Young's modulus ~5 GPa. |
| b) Cementation formulation is shrinkage resistant. |
| 2) The in-situ formation shall achieve or be capable of achieving the requirements of NORSOK D-010 Table 51 and Table 52 (if applicable). In particular: |
| a) the formation shall be impermeable with no flow potential |
| b) the formation integrity shall exceed the maximum wellbore pressure induced. |
| 3) Casing (Intermediate) Cement is / will be designed and installed in accordance with the requirements of NORSOK D-010, Table 22. |

### Operational

| 4) The above relevant elements of the Primary Well Barrier Envelope show signs of defect, damage, or corrosion. These are expected to cause significant impairment to well integrity. Cement is damaged, and likely to provide cohesion of <3 MPa. |

### Design and Installation

| 1) Casing (Intermediate) cement has a Young's modulus >10 GPa. Cement formulation is not shrinkage resistant. |
| 2) The in-situ formation cannot achieve or be capable of achieving the requirements of NORSOK D-010 Table 51 and Table 52 (if applicable). |
| 3) Casing (Intermediate) Cement is not / will not be designed and installed in accordance with the requirements of NORSOK D-010, Table 22 or equivalent standard. |

### Operational

| 4) The above relevant elements of the Primary Well Barrier Envelope show signs of minor defect, damage, or corrosion, however, these are not expected to cause significant impairment to the integrity of the well. It is possible to remediate these defects and there is a plan in place to ensure that this occurs within one calendar year, and before they degrade well integrity significantly. Cement may be slightly damaged or degraded, but likely to provide cohesion of between 3 and 10 MPa. |
Figure 36: SECuRe -01 Threat 3 – Full Context

- Natural Gas migrates through plugged well
  - Well Engineering - Integrity of Primary Well Barrier Envelope: Extent to which well abandonment plan developed and implemented according to good practice
    - Well abandonment plan
      - Cement plug testing
    - Cement Plug (Primary)
    - Casing Cement (Primary)
    - Casing / Production Liner Design and Integrity
  - Well Engineering - Integrity of Secondary Well Barrier Envelope: Extent to which well abandonment plan developed and implemented according to good practice
    - Well abandonment plan
      - Cement plug testing
    - Cement Plug (Secondary)
    - Casing Cement (Secondary)
    - Casing (Intermediate) Design and Integrity
  - Abandonment Strategy: Development and implementation of monitoring plan for abandonment phase - appropriate record keeping and identification of abandoned well locations
    - Well abandonment plan
      - EBA
      - Define abandonment monitoring and remediation strategy
      - Maintenance of suitable and sufficient records
      - Well abandonment plan
      - Well Design and Integrity
      - Location of wells
  - Additional flow zones at different layers
  - Well Engineering - Integrity of Primary Well Barrier Envelope: Extent to which well abandonment plan developed and implemented according to good practice
    - Well abandonment plan
      - Cement plug testing
    - Cement Plug (Primary)
    - Additional cement plugs in excess of three recommended by NORSOK
### Table 16: SECURE-01 Threat 3 – Engineering Barrier 1

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
</table>
| Well abandonment plan 101 | 1) Development and implementation of well abandonment plan has been successfully audited / certified and well abandonment demonstrably complies with NORSOK D-010.  
2) All abandonment activities have been carried out based on NORSOK D-010 Section 9 to establish well barriers by use of Well Barrier Envelopes and additional features required to execute this activity in a safe manner, with focus on isolation of permeable formations/reservoirs/sources of inflow.  
3) Abandonment Strategy agrees with the requirements and guidelines of NORSOK D-010 Section 9 pertaining to well integrity during: - suspension of well activities and operations - temporary or permanent abandonment of wells  
4) Cement testing of primary and secondary well plugs has been undertaken by a third party and has been carried out based on NORSOK D-010 Table 24. **Operational Monitoring >>>**  
5) There is regular soil and atmospheric monitoring for natural gas leakage at each abandoned well location to verify the integrity of the abandoned well and to instigate a process of remedial action if this is not the case. | 1) Development and implementation of well abandonment plan has been successfully audited / certified and well abandonment demonstrably complies with NORSOK D-010, but has some weaknesses or areas of omission.  
2) All abandonment activities have been carried out based on NORSOK D-010 Section 9 to establish well barriers by use of Well Barrier Envelopes and additional features required to execute this activity in a safe manner, with focus on isolation of permeable formations/reservoirs/sources of inflow.  
3) Abandonment Strategy agrees with the requirements and guidelines of NORSOK D-010 Section 9 pertaining to well integrity during: - suspension of well activities and operations - temporary or permanent abandonment of wells  
4) Cement testing of primary and secondary well plugs has been undertaken by a third party and has been carried out based on NORSOK D-010 Table 24, but has some weaknesses or areas of omission. | 1) Development and implementation of well abandonment plan has not been successfully audited / certified and/or well abandonment demonstrably complies with NORSOK D-010. |
### Variable Parameters

<table>
<thead>
<tr>
<th>Casing to provide a continuous annular seal between casing and rock formations</th>
<th>Casing to provide a continuous annular seal between casing and rock formations</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Integrity of cement bond with surrounding geology has been positively proven.</td>
<td>- Integrity of cement bond with surrounding geology has been positively proven.</td>
</tr>
<tr>
<td>- Casing / Production Liner provides an isolation that stops uncontrolled flow of formation fluid or injected fluid between the casing bore and the casing annulus.</td>
<td>- Casing / Production Liner provides an isolation that stops uncontrolled flow of formation fluid or injected fluid between the casing bore and the casing annulus.</td>
</tr>
<tr>
<td>- Casing / Production Liner designed to withstand all loads and stresses expected during the lifetime of the well</td>
<td>- Casing / Production Liner designed to withstand all loads and stresses expected during the lifetime of the well</td>
</tr>
<tr>
<td>- Casing / Production Liner is designed and installed in accordance with NORSOK D-010 Table 2 or an equivalent standard (such as, ISO 11960, ISO 13679, ISO 10405)</td>
<td>- Casing / Production Liner is designed and installed in accordance with NORSOK D-010 Table 2 or an equivalent standard (such as, ISO 11960, ISO 13679, ISO 10405)</td>
</tr>
</tbody>
</table>

**Operational**

2) The above relevant elements of the Primary Well Barrier Envelope show no signs of defect, damage, or corrosion

---

<table>
<thead>
<tr>
<th>Casing cement (Primary)</th>
<th>Casing cement (Primary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Casing / Production Liner Design and Integrity</td>
<td>- Casing / Production Liner Design and Integrity</td>
</tr>
<tr>
<td>- Wellbore casing is not sealed with cement to provide structural support and to ensure isolation of different rock formations. Cement does not completely surround the casing to provide a continuous annular seal between casing and rock formations</td>
<td>- Wellbore casing is not sealed with cement to provide structural support and to ensure isolation of different rock formations. Cement does not completely surround the casing to provide a continuous annular seal between casing and rock formations</td>
</tr>
<tr>
<td>- No cement bond logs or pressure tests carried out.</td>
<td>- No cement bond logs or pressure tests carried out.</td>
</tr>
<tr>
<td>- Casing / Production Liner is not designed to withstand all loads and stresses expected during the lifetime of the well</td>
<td>- Casing / Production Liner is not designed to withstand all loads and stresses expected during the lifetime of the well</td>
</tr>
<tr>
<td>- Casing / Production Liner is not designed and installed in accordance with NORSOK D-010 Table 2 or an equivalent standard (such as, ISO 11960, ISO 13679, ISO 10405)</td>
<td>- Casing / Production Liner is not designed and installed in accordance with NORSOK D-010 Table 2 or an equivalent standard (such as, ISO 11960, ISO 13679, ISO 10405)</td>
</tr>
</tbody>
</table>

**Operational**

2) The above relevant elements of the Primary Well Barrier Envelope show signs of defect, damage, or corrosion

---

<table>
<thead>
<tr>
<th>cement plug testing 101</th>
<th>cement plug testing 101</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Not all abandonment activities have been carried out based on NORSOK D-010 Section 9 to establish well barriers by use of Well Barrier Envelopes and additional features required to execute this activity in a safe manner, with focus on isolation of permeable formations/reservoirs/sources of inflow.</td>
<td>- Not all abandonment activities have been carried out based on NORSOK D-010 Section 9 to establish well barriers by use of Well Barrier Envelopes and additional features required to execute this activity in a safe manner, with focus on isolation of permeable formations/reservoirs/sources of inflow.</td>
</tr>
<tr>
<td>3) Abandonment Strategy does not agree with the requirements and guidelines of NORSOK D-010 Section 9 pertaining to well integrity during:</td>
<td>3) Abandonment Strategy does not agree with the requirements and guidelines of NORSOK D-010 Section 9 pertaining to well integrity during:</td>
</tr>
<tr>
<td>- suspension of well activities and operations</td>
<td>- suspension of well activities and operations</td>
</tr>
<tr>
<td>- temporary or permanent abandonment of wells</td>
<td>- temporary or permanent abandonment of wells</td>
</tr>
</tbody>
</table>

Cement plug testing 101

4) Cement testing of primary and secondary well plugs has not been undertaken and / or has not been carried out based on NORSOK D-010 Table 24.
### Table 17: SECURE-01 Threat 3 – Engineering Barrier 2

**Barrier Description**

<table>
<thead>
<tr>
<th>Design and Installation</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well Engineering - Integrity of Secondary Well Barrier Envelope: Extent to which well abandonment plan developed and implemented according to good practice</td>
<td></td>
</tr>
<tr>
<td>Design and Installation</td>
<td></td>
</tr>
<tr>
<td>1) All relevant elements of the Secondary Well Barrier Envelope are / will be designed and installed in accordance with the requirements of NORSOK D-010, particularly:</td>
<td></td>
</tr>
<tr>
<td>- Cement Plug (Secondary) (Table 24),</td>
<td></td>
</tr>
<tr>
<td>- Casing Cement (Secondary) (Table 22),</td>
<td></td>
</tr>
<tr>
<td>- Casing (Intermediate) (Table 2).</td>
<td></td>
</tr>
<tr>
<td>Poor</td>
<td></td>
</tr>
<tr>
<td>1) The relevant elements of the Secondary Well Barrier Envelope are not designed and installed in accordance with the requirements of NORSOK D-010, or any equivalent standard. There are known design flaws / significant potential requirements to derogate against any or all of the specific requirements of NORSOK D-010, particularly:</td>
<td></td>
</tr>
<tr>
<td>- Cement Plug (Secondary) (Table 24),</td>
<td></td>
</tr>
<tr>
<td>- Casing Cement (Secondary) (Table 22),</td>
<td></td>
</tr>
<tr>
<td>- Casing (Intermediate) (Table 2).</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td></td>
</tr>
<tr>
<td>1) All relevant elements of the Secondary Well Barrier Envelope are / will be designed and installed in accordance with the requirements of NORSOK D-010, particularly:</td>
<td></td>
</tr>
<tr>
<td>- Cement Plug (Secondary) (Table 24),</td>
<td></td>
</tr>
<tr>
<td>- Casing Cement (Secondary) (Table 22),</td>
<td></td>
</tr>
<tr>
<td>- Casing (Intermediate) (Table 2).</td>
<td></td>
</tr>
<tr>
<td>Fair</td>
<td></td>
</tr>
<tr>
<td>1) All relevant elements of the Secondary Well Barrier Envelope are / will be designed and installed in accordance with the requirements of NORSOK D-010, particularly:</td>
<td></td>
</tr>
<tr>
<td>- Cement Plug (Secondary) (Table 24),</td>
<td></td>
</tr>
<tr>
<td>- Casing Cement (Secondary) (Table 22),</td>
<td></td>
</tr>
<tr>
<td>- Casing (Intermediate) (Table 2).</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td></td>
</tr>
</tbody>
</table>

### Uncertainty Descriptors

<table>
<thead>
<tr>
<th>Well abandonment plan 101</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Development and implementation of well abandonment plan has been successfully audited / certified and well abandonment demonstrably complies with NORSOK D-010.</td>
</tr>
<tr>
<td>2) All abandonment activities have been carried out based on NORSOK D-010 Section 9 to establish well barriers by use of Well Barrier Envelopes and additional features required to execute this activity in a safe manner, with focus on isolation of permeable formations/reservoirs/sources of inflow.</td>
</tr>
<tr>
<td>3) Abandonment Strategy agrees with the requirements and guidelines of NORSOK D-010 Section 9 pertaining to well integrity during:</td>
</tr>
<tr>
<td>- suspension of well activities and operations</td>
</tr>
<tr>
<td>- temporary or permanent abandonment of wells</td>
</tr>
</tbody>
</table>

### Operational Monitoring

1) There is regular soil and atmospheric monitoring for Natural Gas leakage at each abandoned well location to verify the integrity of the abandoned well and to instigate a process of remedial action if this is not the case.

### Natural Gas

- Cement plug testing 101
- 4) Cement testing of primary and secondary well plugs has been undertaken by a third party and has been carried out based on NORSOK D-010 Table 24.

### Well abandonment plan 101

1) Development and implementation of well abandonment plan has been successfully audited / certified and well abandonment demonstrably complies with NORSOK D-010, but has some weaknesses or areas of omission.
2) All abandonment activities have been carried out based on NORSOK D-010 Section 9 to establish well barriers by use of Well Barrier Envelopes and additional features required to execute this activity in a safe manner, with focus on isolation of permeable formations/reservoirs/sources of inflow.
3) Abandonment Strategy agrees with the requirements and guidelines of NORSOK D-010 Section 9 pertaining to well integrity during:
   - suspension of well activities and operations
   - temporary or permanent abandonment of wells

### Medium

<table>
<thead>
<tr>
<th>Well abandonment plan 101</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Development and implementation of well abandonment plan has been successfully audited / certified and well abandonment demonstrably complies with NORSOK D-010, but has some weaknesses or areas of omission.</td>
</tr>
<tr>
<td>2) All abandonment activities have been carried out based on NORSOK D-010 Section 9 to establish well barriers by use of Well Barrier Envelopes and additional features required to execute this activity in a safe manner, with focus on isolation of permeable formations/reservoirs/sources of inflow.</td>
</tr>
</tbody>
</table>
| 3) Abandonment Strategy agrees with the requirements and guidelines of NORSOK D-010 Section 9 pertaining to well integrity during:
  - suspension of well activities and operations
  - temporary or permanent abandonment of wells |

### High

<table>
<thead>
<tr>
<th>Well abandonment plan 101</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Development and implementation of well abandonment plan has not been successfully audited / certified and / or well abandonment does not demonstrably comply with NORSOK D-010.</td>
</tr>
</tbody>
</table>

### Appendix A: Page A.23 of A.101
<table>
<thead>
<tr>
<th>Variable Parameters</th>
<th>Operational</th>
<th>2) The above relevant elements of the Secondary Well Barrier Envelope in 1) show no signs of defect, damage, or corrosion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>- Cement completely surrounds the casing to provide a continuous annular seal between casing and rock formations. Cement completely surrounds the casing to provide a continuous annular seal between casing and rock formations.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Integrity of cement bond with surrounding geology has been positively proven. - Cementation is / will be designed and installed in accordance with NORSOK D-010 Table 22 or an equivalent standard (such as, API RP 108, ISO 10426-1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Casing (Intermediate) provides an isolation that stops uncontrolled flow of formation fluid or injected fluid between the casing bore and the casing annulus. - Casing (Intermediate) designed to withstand all loads and stresses expected during the lifetime of the well</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Casing (Intermediate) is / will be designed and installed in accordance with NORSOK D-010 Table 2 or an equivalent standard (such as, ISO 11960, ISO 13679, ISO 10405)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Operational 2) The above relevant elements of the Secondary Well Barrier Envelope in 1) show no signs of defect, damage, or corrosion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Cement plug is not designed and installed in accordance with NORSOK D-010 Table 24 or an equivalent standard (such as, API Spec 10A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Wellbore casing is not sealed with cement to provide structural support and to ensure isolation of different rock formations. Cement does not completely surround the casing to provide a continuous annular seal between casing and rock formations.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- No cement bond logs or pressure tests carried out. - Casing (Intermediate) designed to withstand all loads and stresses expected during the lifetime of the well</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Casing (Intermediate) is not designed and installed in accordance with NORSOK D-010 Table 2 or an equivalent standard (such as, ISO 11960, ISO 13679, ISO 10405)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Operational 2) The above relevant elements of the Secondary Well Barrier Envelope in 1) show signs of defect, damage, or corrosion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2) NOT all abandonment activities have been carried out based on NORSOK D-010 Section 9 to establish well barriers by use of Well Barrier Envelopes and additional features required to execute this activity in a safe manner, with focus on isolation of permeable formations/reservoirs/sources of inflow.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3) Abandonment Strategy does not agree with the requirements and guidelines of NORSOK D-010 Section 9 pertaining to well integrity during: - suspension of well activities and operations - temporary or permanent abandonment of wells</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4) Cement testing of primary and secondary well plugs has not been undertaken and / or has not been carried out based on NORSOK D-010 Table 24.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cement plug testing 101</td>
</tr>
</tbody>
</table>
### Table 18: SECURE -01 Threat 3 – Engineering Barrier 3

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
<th>Uncertainty Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well Engineering - Integrity of Open to Surface Well Barrier Envelope: Extent to which well abandonment plan developed and implemented according to good practice</td>
<td>Good</td>
<td>Well abandonment plan 101</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1) Development and implementation of well abandonment plan has been successfully audited / certified and well abandonment demonstrably complies with NORSOK D-010.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2) All abandonment activities have been carried out based on NORSOK D-010 Section 9 to establish well barriers by use of Well Barrier Envelopes and additional features required to execute this activity in a safe manner, with focus on isolation of permeable formations/reservoirs/sources of inflow.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3) Abandonment Strategy agrees with the requirements and guidelines of NORSOK D-010 Section 9 pertaining to well integrity during:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- suspension of well activities and operations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- temporary or permanent abandonment of wells</td>
</tr>
<tr>
<td></td>
<td>Fair</td>
<td>Cement plug testing 101</td>
</tr>
<tr>
<td></td>
<td>Poor</td>
<td>4) Cement testing of primary and secondary well plugs has been undertaken by a third party and has been carried out based on NORSOK D-010 Table 24.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5) There is regular soil and atmospheric monitoring for Natural Gas leakage at each abandoned well location to verify the integrity of the abandoned well and to instigate a process of remedial action if this is not the case.</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>Well abandonment plan 101</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1) Development and implementation of well abandonment plan has been successfully audited / certified and well abandonment demonstrably complies with NORSOK D-010, but has some weaknesses or areas of omission.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2) All abandonment activities have been carried out based on NORSOK D-010 Section 9 to establish well barriers by use of Well Barrier Envelopes and additional features required to execute this activity in a safe manner, with focus on isolation of permeable formations/reservoirs/sources of inflow.</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>Cement plug testing 101</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4) Cement testing of primary and secondary well plugs has been undertaken by a third party and has been carried out based on NORSOK D-010 Table 24, but has some weaknesses or areas of omission.</td>
</tr>
</tbody>
</table>

#### Uncertainty Descriptors

**Low**

- All relevant elements of the Open to Surface Well Barrier Envelope are / will be designed and installed in accordance with the requirements of NORSOK D-010 or any equivalent standard. There are known design flaws / significant potential requirements to derogate against any or all of the specific requirements of NORSOK D-010, particularly:
  - Casing Cement (OTS) (Table 22),
  - Cement Plug (OTS) (Table 24).
  - Wellbore casing is not sealed with cement to provide structural support and to ensure isolation of different rock formations. Cement does not completely surround the casing to provide a continuous annular seal between casing and rock formations.
  - Integrity of cement bond with surrounding geology has been positively proven.
  - Cementation is / will be designed and installed in accordance with NORSOK D-010 Table 22 or an equivalent standard (such as, API RP 10B, ISO 10426-1).

**Medium**

- The relevant elements of the Open to Surface Well Barrier Envelope are not designed and installed in accordance with the requirements of NORSOK D-010 or any equivalent standard. There are known design flaws / significant potential requirements to derogate against any or all of the specific requirements of NORSOK D-010, particularly:
  - Casing Cement (OTS) (Table 22),
  - Cement Plug (OTS) (Table 24),
  - Wellbore casing is not sealed with cement to provide structural support and to ensure isolation of different rock formations. Cement does not completely surround the casing to provide a continuous annular seal between casing and rock formations.
  - No cement bond logs or pressure tests carried out,
  - Cementation is not designed and installed in accordance with NORSOK D-010 Table 22 or an equivalent standard (such as, API RP 10B, ISO 10426-1).

**High**

- All relevant elements of the Open to Surface Well Barrier Envelope are / will be designed and installed in accordance with the requirements of NORSOK D-010 or any equivalent standard. There are known design flaws / significant potential requirements to derogate against any or all of the specific requirements of NORSOK D-010, particularly:
  - Casing Cement (OTS) (Table 22),
  - Cement Plug (OTS) (Table 24),
  - Wellbore casing is not sealed with cement to provide structural support and to ensure isolation of different rock formations. Cement does not completely surround the casing to provide a continuous annular seal between casing and rock formations.
  - No cement bond logs or pressure tests carried out,
  - Cementation is not designed and installed in accordance with NORSOK D-010 Table 22 or an equivalent standard (such as, API RP 10B, ISO 10426-1).
<table>
<thead>
<tr>
<th>Variable Parameters</th>
<th>- Cement Plug (OTS) is more than adequate at preventing flow of formation fluids to surface/seabed.</th>
<th>- Cement Plug (OTS) is more than adequate at preventing flow of formation fluids to surface/seabed.</th>
<th>2) NOT all abandonment activities have been carried out based on NORSOK D-010 Section 9 to establish well barriers by use of Well Barrier Envelopes and additional features required to execute this activity in a safe manner, with focus on isolation of permeable formations/reservoirs/sources of inflow.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Cement plug is / will be designed and installed in accordance with NORSOK D-010 Table 24 or an equivalent standard (such as, API Spec 10A)</td>
<td>- Cement plug is / will be designed and installed in accordance with NORSOK D-010 Table 24 or an equivalent standard (such as, API Spec 10A)</td>
<td>3) Abandonment Strategy does not agree with the requirements and guidelines of NORSOK D-010 Section 9 pertaining to well integrity during:</td>
</tr>
<tr>
<td>Operational</td>
<td>2) The above relevant elements of the Open to Surface Well Barrier Envelope in 1) show no signs of defect, damage, or corrosion</td>
<td>2) The above relevant elements of the Open to Surface Well Barrier Envelope in 1) show no signs of defect, damage, or corrosion</td>
<td>- suspension of well activities and operations</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- temporary or permanent abandonment of wells</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cement plug testing 101</td>
</tr>
<tr>
<td></td>
<td></td>
<td>equivalent standard (such as, API RP 10B, ISO 10426-1)</td>
<td>4) Cement testing of primary and secondary well plugs has not been undertaken and / or has not been carried out based on NORSOK D-010 Table 24.</td>
</tr>
</tbody>
</table>
Figure 37: SECURe -01 Consequence 1 – Full Context

- **SECURE-01 Shale Gas (Natural gas in formation)**
  - **Release from Well (during Production and Abandonment Phases)**
  - **Comment:** Emissions to atmosphere from wellhead are out of scope for the SECURe project - this consequence primarily considers release of natural gas from well to geology and subsequent emissions to atmosphere.

- **Geological Properties: Extent to which geological layers / formation seals well and prevents / slows down release of natural gas**
  - **Hydrocarbon:** In-situ formation is assessed by site analysis.
  - **Permeability (other geological layers / formation)**
  - **Porosity (other geological layers / formation)**

- **Well Engineering:** Well pad / surface complex engineering
  - **Well Engineering and Design 101:**
    - **Integrity:**
      - **Wellhead / Xmas tree (including Annulus A valve) Design and Integrity**
      - **Monitoring:** Detection of natural gas leak - well or Xmas tree instrumentation

- **Operational Strategy:**
  - **Hydraulic Fracturing Strategy:** Optimized based on the leak location (project origin).

- **Remedial Action:**
  - **Engineering measures:**
    - **Strategy Correction based on Monitoring:**
      - **Volume of Injected Fluid**
      - **Volume of Flowback Fluid**
      - **Injection Rate**
      - **Flowback Rate / Recovery Time**
      - **Levels of ground gas**
    - **Atmospheric Monitoring 101:**
    - **Ground Gas Monitoring 101:**
    - **Analysis of Data and Identification of Correlations e.g. Temporal Emissions to Air**
    - **Levels of ground gas**
### Table 19: SECUrE -01 Consequence 1 – Geological Barrier 1

**Uncertainty Descriptors**

<table>
<thead>
<tr>
<th>Site Selection Studies and Site Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways</td>
</tr>
<tr>
<td>2) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on: ISO 27914:2017 Section 5</td>
</tr>
<tr>
<td>3) Where permeability cannot be measured directly, fault and fracture network permeability and transmissivity have been calculated based on the intrinsic fracture properties and the in-situ stress conditions with consideration of analogues to known and understood facilities, with known confining stresses, injection pressures, and lithology (including clay content and mechanical strength)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site Selection Studies and Site Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways</td>
</tr>
<tr>
<td>2) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a low resolution based on ISO 27914:2017 Section 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site Selection Studies and Site Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Site selection studies have not been undertaken prior to operation to characterise nearby leakage pathways</td>
</tr>
<tr>
<td>2) And / or geomechanical analysis, geochemical analysis and geological analysis has not been conducted based on ISO 27914:2017 Section 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>Fair</td>
</tr>
</tbody>
</table>

**Geological Properties: Extent to which geological layers / formation seals well and prevents / slows down release of natural gas**

1) The in-situ formation shall achieve or be capable of achieving the requirements of NORSOK D-010 Table 51 and Table 52 (if applicable). In particular:
   - the formation shall be impermeable with no flow potential
   - the formation integrity shall exceed the maximum wellbore pressure induced.
   - Permeability of other geological layers / formation is sufficient to restrict or terminate flow of fluids to other geological layers / formation (< 0.1 nanoDarcy)
   - Ductility of geological layers / formation is sufficient to prevent release of fluids from formation

**Variable Parameters**

- In-situ formation as assessed by site analysis
- Permeability (other geological layers / formation)
- Ductility (other geological layers / formation)

**Effectiveness Descriptors**

<table>
<thead>
<tr>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Geological Properties**

1) The in-situ formation shall achieve or be capable of achieving the requirements of NORSOK D-010 Table 51 and Table 52 (if applicable). In particular:
   - the formation shall be impermeable with no flow potential
   - the formation integrity shall exceed the maximum wellbore pressure induced.
   - Permeability of other geological layers / formation is sufficient to restrict or terminate flow of fluids to other geological layers / formation (< 0.1 nanoDarcy)
   - Ductility of geological layers / formation is sufficient to prevent release of fluids from formation, however this may change with time/operation

**Barrier Description**

- In-situ formation as assessed by site analysis
- Permeability (other geological layers / formation)
- Ductility (other geological layers / formation)
### Table 20: SECURe -01 Consequence 1 – Geological Barrier 2

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
<th>Site Selection Studies and Site Surveys</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Detailed site surveys have been undertaken to characterise nearby leakage pathways. Site Selection Studies and Site surveys have provided data on the geological layers. The data obtained includes the heterogeneity, buffering capacity and geometry.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) Mechanical response of the geological layers to fluid pressure has been determined from the intrinsic geological layer properties and the in-situ stress conditions.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) Potential fluid flow / permeability through the geological layers has been studied based on the complex interplay between the geometrical and chemical heterogeneity of the rock formations, and the coupling of fluid flow and effective stress.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5) Legacy / existing wells penetrating geological layers above the primary seal have been catalogued and integrity assessment carried out.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Barrier Description

- **Geological Properties: Extent to which geological layers above the production zone / between the production zone and receptors slow down movement of natural gas**
  - Heterogeneity of petrophysical properties: Extent to which geological layers above the primary seal / between the storage reservoir and receptors slow down movement of shale gas to other geological layers including SSU if applicable [< 0.1 nanoDarcy]
  - Permeability (other geological layers / formation)

#### Variable Parameters

- **In-situ composition and properties**
  - Permeability of other geological layers / formation is sufficient to restrict or terminate flow of shale gas to other Geological Layers including SSU if applicable [> 0.001 microDarcy]

#### Effectiveness Descriptors

<table>
<thead>
<tr>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geological Properties</strong></td>
<td>1) The following properties are extant in the subsurface: - The quality of variation in petrophysical properties of the geological layers in different directions restricts or terminates the movement of fluids in the geological layers, however this may change with time/operation - Buffering capacity of other geological layers above the primary seal / between the storage reservoir and receptors is sufficient to restrict or terminate movement of shale gas, but this may change with time / operation - Permeability of other geological layers / formation is sufficient to restrict or terminate flow of shale gas to other Geological Layers including SSU if applicable [&lt; 0.001 microDarcy]</td>
<td>1) The following properties are extant in the subsurface: - The quality of variation in petrophysical properties of the geological layers in different directions restricts or terminates the movement of fluids in the geological layers, however this may change with time/operation - Buffering capacity of other geological layers above the primary seal / between the storage reservoir and receptors is sufficient to restrict or terminate movement of shale gas, but this may change with time / operation - Permeability of other geological layers / formation is sufficient to restrict or terminate flow of shale gas to other Geological Layers including SSU if applicable [&gt; 0.001 microDarcy]</td>
</tr>
</tbody>
</table>
## Table 21: SECURE -01 Consequence 1 – Engineering Barrier 1

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Fair</td>
</tr>
<tr>
<td></td>
<td>Poor</td>
</tr>
<tr>
<td><strong>Variable Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Well Engineering: Well pad / surface complex engineering</td>
<td></td>
</tr>
<tr>
<td>- Well Design and Integrity</td>
<td></td>
</tr>
<tr>
<td>- Wellhead / Xmas Tree (including Annulus A valve) Design and Integrity</td>
<td></td>
</tr>
</tbody>
</table>

### Uncertainty Descriptors
- **Low**
  - Well engineering and design 101
    - 1) Design and installation processes have been successfully audited / certified and design demonstrably complies with NORSOK D-010 or equivalent standard.

- **Medium**
  - Well engineering and design 101
    - 1) Design and installation processes have been successfully audited / certified and design demonstrably complies with NORSOK D-010 or equivalent standard, but has some weaknesses or areas of omission.

- **High**
  - Well engineering and design 101
    - 1) Design and installation process have not been successfully audited / certified and / or design does not demonstrably comply with NORSOK D-010 or equivalent standard.

### Effectiveness Descriptors

#### Design and Installation

1. Wellhead / Xmas Tree has been designed and installed in accordance with NORSOK D-010 Table 5 and Table 12 or an equivalent standard (such as, ISO 10423, API Spec 6A, API Spec 6FA, API Spec 6FB API Spec 6FC, ISO 15156, API Spec 17D, ISO 10497)

#### Operational

1. The above relevant elements of the Well Barrier Envelope show signs of minor defect, damage, or corrosion, however, these are not expected to cause significant impairment to the integrity of the well. It is possible to remediate these defects and there is a plan in place to ensure that this occurs within one calendar year, and before they degrade well integrity significantly.

2. The above relevant elements of the Primary Well Barrier Envelope show signs of defect, damage, or corrosion. These are expected to cause significant impairment to well integrity.
Figure 39: SECURè -01 Consequence 2 – Full Context

Please refer to Table 19 for Geological Barrier: Geological Properties: Extent to which geological layers / formation seals well and prevents / slows down release of natural gas
Please refer to Table 20 for Geological Barrier: Geological Properties: Extent to which geological layers above the production zone / between the production zone and receptors slow down movement of natural gas
1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site selection studies and site surveys have provided data on the temporal and spatial migration of redox gradients in potential receptor aquifers.

2) Redox domains have been identified that may be superimposed and stratified depending upon the spatial position relative to the flux of inputs and their temporal position in the annual cycle of infiltration events.

3) Inputs include oxidation from atmospheric oxygen and reducing compounds, predominantly in the form of organic carbon dissolved and particulate from the soil or vadose zone and aquifer sediments.

4) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5.
Table 23: SECURe -01 Consequence 2 – Engineering Barrier 1

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Selection Studies and Site Surveys</td>
<td>1) Site surveys have been undertaken to characterise nearby leakage pathways. Site Selection Studies and Site Surveys has provided data on the location, composition and behaviour of known receptors. 2) Geomechanical analysis, geochemical analysis and geological analysis has characterized subsurface features at a high resolution based on ISO 27914:2017 Section 5 Site Engineering 105 3) Positioning of wells / location of hydraulic fracturing / gas production in relation to potential receptors has been carried out based on detailed environmental impact assessment, including detailed subsurface source-pathway-receptor models.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site Engineering 105</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site Selection Studies and Site Surveys</td>
<td>1) Site surveys have been undertaken to characterise nearby leakage pathways. Site Selection Studies and Site Surveys has provided data on the location, composition and behaviour of known receptors. 2) Geomechanical analysis, geochemical analysis and geological analysis has characterized subsurface features at a low resolution based on ISO 27914:2017 Section 5 Site Engineering 105 3) Positioning of wells / location of hydraulic fracturing / gas production in relation to potential receptors has been carried out based on detailed environmental impact assessment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site Engineering 105</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site Selection Studies and Site Surveys</td>
<td>1) Site surveys have been undertaken to characterise nearby leakage pathways. Site Selection Studies and Site Surveys has provided data on the location, composition and behaviour of known receptors. 2) Geomechanical analysis, geochemical analysis and geological analysis has characterized subsurface features at a very low resolution based on ISO 27914:2017 Section 5 Site Engineering 105 3) Positioning of wells / location of hydraulic fracturing / gas production in relation to potential receptors has been carried out based on detailed environmental impact assessment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site Engineering 105</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Variable Parameters
- Location of receptors

- Design and Installation
1) There are no receptors that could be affected by contamination / dispersion as a result of release from wells or geology. Wells are located at an acceptable distance from known receptors.
2) There are receptors that could be affected by contamination / dispersion as a result of release from wells or geology. Wells are not located at an acceptable distance from known receptors.

- Design and Installation
1) There are no receptors that could be affected by contamination / dispersion as a result of release from wells or geology. Wells are located at an acceptable distance from known receptors.
2) There are receptors that could be affected by contamination / dispersion as a result of release from wells or geology. Wells are located at an acceptable distance from known receptors.

- Design and Installation
1) There are no receptors that could be affected by contamination / dispersion as a result of release from wells or geology. Wells are not located at an acceptable distance from known receptors.
2) There are receptors that could be affected by contamination / dispersion as a result of release from wells or geology. Wells are located at an acceptable distance from known receptors.

- Design and Installation
1) There are no receptors that could be affected by contamination / dispersion as a result of release from wells or geology. Wells are located at an acceptable distance from known receptors.
2) There are receptors that could be affected by contamination / dispersion as a result of release from wells or geology. Wells are not located at an acceptable distance from known receptors.
Figure 40: SECURE -02 High Level Bow-tie

- Emissions to atmosphere - environmental impact
- Groundwater / Soil contamination - Impact to ecosystems (flora & fauna) and / or people
- Release to seabed / seawater - impact to ecosystems (flora & fauna)
- Contamination of neighbouring formations (used for storage or production)
- Contamination of out-of-zone areas where faults might become pressurised
- Emissions to air (onshore) - potential for accumulation and asphyxiation / ignition / toxic effect
- Release of H2S or radioactive gas (Radon) to atmosphere

- Existing / legacy wells
- Presence of fracture network / fault
- Fracture propagation beyond target production zone
- Natural seismicity fracture development or fault reactivation
- Lateral migration

Release from Shale Production Zone

SECURE-02: Shale Gas (Natural Gas in Formation)
Figure 41: SECURE-02 Threat 1 – Full Context
### Table 24: SECURE -02 Threat 1 – Engineering Barrier 1

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Good</strong></td>
<td><strong>Fair</strong></td>
</tr>
</tbody>
</table>

#### Site Engineering: Positioning of wells / location of hydraulic fracturing in relation to known leak pathways

- **Design and Installation**
  1. Wells positioned such that existing / legacy leak paths are beyond the production zone and any expected fluid migration
  2. Existing / legacy wells are of high integrity

- **Variable Parameters**
  - Location of existing / legacy leak paths (e.g. wells, boreholes, mines)
  - Location of other active wells

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
</tr>
</thead>
</table>

**Low**

Site Selection Studies and Site Surveys
1) Site surveys have been undertaken to characterise leakage pathways. Site Selection Studies and Site surveys and Integrity Assessment has provided data on the significance of identified existing/legacy wells in terms of its ability to constrain flow along existing/legacy wells.
2) Site engineering to position wells is based on modelling of fluid behaviour in the storage complex and ISO 27914:2017 Section 7.3.3.

Integrity Assessment 101
3) Integrity assessment of existing / legacy wells or other engineered features, e.g. mine shafts in order to assist in the determination of leak likelihood has been carried out based on NORSOK D-010 Section 15. All wells and other human-made potential leakage pathways have been assessed for integrity.

**Medium**

Site Selection Studies and Site Surveys
1) Site surveys have been undertaken to characterise leakage pathways. Site Selection Studies and Site surveys and Integrity Assessment has provided data on the significance of identified existing/legacy wells in terms of its ability to constrain flow along existing/legacy wells.
2) Site engineering to position wells is NOT based on modelling of fluid behaviour in the storage complex and ISO 27914:2017 Section 7.3.3.

Integrity Assessment 101
3) Integrity assessment of existing / legacy wells or other engineered features, e.g. mine shafts in order to assist in the determination of leak likelihood has been carried out based on NORSOK D-010 Section 15, but has some weaknesses or areas of omission, for example, several wells may not have been assessed (no more than 25%)

**High**

Site Selection Studies and Site Surveys
1) Site surveys have not been undertaken to characterise leakage pathways. Site Selection Studies and Site surveys and Integrity Assessment has provided data on the significance of identified existing/legacy wells in terms of its ability to constrain flow along existing/legacy wells.
2) Site engineering to position wells is NOT based on modelling of fluid behaviour in the storage complex or based on ISO 27914:2017 Section 7.3.3.

Integrity Assessment 101
3) Integrity assessment of existing / legacy wells or other engineered features, e.g. mine shafts in order to assist in the determination of leak likelihood has not been carried out based on NORSOK D-010 Section 15, but has significant weaknesses or areas of omission, for example, >25% of wells have not been assessed.
Figure 42: SECURE-02 Threat 2 – Full Context

- Presence of fracture network / fault
- Existing fracture networks or faults with communication beyond production zone would likely render production zone not commercially viable
- Site Engineering: Positioning of wells / location of hydraulic fracturing in relation to known faults / fracture networks
- Geological Properties: Extent to which degree of fault development and location of significant faults and fractures reduces likelihood of release
- Geological Properties: Properties of fault / fracture network constrains flow along fault / fracture network
- SSS&SS
  - Seismic Survey
  - Sub-surface Fault Modelling
  - Site Engineering: Location of faults and fracture networks
  - Degree of fault / fracture development
  - Location of faults and fracture networks
  - Thickness of Production Zone

- Effective stress (pressure / temperature) of hydraulic fracturing or chemical changes from contact with fluid increases permeability of fault
- See barriers against fracture propagation beyond target production zone
- Selection of Fracturing Fluid: Minimise potential for subsurface chemical reactions
- Operational Strategy: Hydraulic Fracturing Strategy - multi-stage fracturing to address local conditions (e.g. presence of natural faults and proximity to other well systems)
  - Pre-fracturing Injection Tests
  - Define Operational Strategy
  - Multi-stage fracturing
    - Volume of injected fluid
    - Volume of flow back fluid
    - Injection rate
    - Flow back rate / Recovery time
    - Permeability (Fault/Fracture network)

- Release from Shale Production Zone
Table 25: SECURe -02 Threat 2 – Geological Barrier 1

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Good</td>
</tr>
<tr>
<td>Geological Properties: Extent to which degree of fault development and location of significant faults and fractures reduces likelihood of release</td>
<td>1) There are no faults in the vicinity of the production zone, however, the displacement of fault is low with a narrow damage zone and low/no development of a connected fracture network.</td>
</tr>
</tbody>
</table>

**Uncertainty Descriptors**

- **Site Selection Studies and Site Surveys**
  - Site Selection Studies and Site surveys have determined the significance of existing faults and fracture networks in terms of the likelihood to create a potential path for release.
  - The location of seismic faults within the vicinity of the production zone are known and mapped to a high level of detail/resolution.

- **Seismic Survey**
  - The degree of fault / fracture development within the vicinity of the production zone is well understood.
  - The seismic survey was carried out recently (e.g. within the last two years), using modern techniques, methods, and technology to a high seismic resolution.
  - Seismic survey reports acknowledge the limitations of the technology in the identification of fault orientation, fault throw and the definition of target zones and provide conclusions within acknowledged error bounds, supported by risk assessment - noted that sub-seismic faults are unlikely to have a fracture network above porosity threshold.

- **Sub-surface Fault Modelling**
  - Sub-surface fault modelling has been carried out capable of predicting the presence of sub-surface faults (through detailed surface mapping, development of validated geological models, and the data from seismic reflection surveys) at a high resolution to enable accurate comparison with operational data. Exemption available (Medium descriptor applies) where Seismic Surveys have fully mapped the entire primary seal to a high level of detail/resolution.

- **Dissolution**
  - Site Selection Studies and Site surveys have determined the significance of existing faults and fracture networks in terms of the likelihood to create a potential path for release.
  - The location of faults and fracture networks in the vicinity of the production zone are known and mapped to a sufficient level of detail/resolution.

- **Seismic Survey**
  - Significant faults and fracture networks have been identified, but the degree of fault / fracture development in the vicinity of the production zone is not well understood at a detail level.
  - The seismic survey was carried out within the last five years.

- **Sub-surface Fault Modelling**
  - Sub-surface fault modelling has been carried out capable of predicting the presence of sub-surface faults (through detailed surface mapping, development of validated geological models, and the data from seismic reflection surveys) at a low resolution to enable some comparison with operational data and has been carried out based on accepted good practice, but has some weaknesses or areas of omission. Exemption available where Seismic Surveys achieve the descriptor for low level of uncertainty.
### Variable Parameters

<table>
<thead>
<tr>
<th>Degree of fault / fracture development</th>
<th>Location of faults and fracture networks</th>
<th>Thickness of Production Zone</th>
</tr>
</thead>
</table>

- Site Selection Studies and Site surveys have not considered the significance of existing faults and fracture networks in terms of likelihood to create a potential path for release.
- The location of faults and fracture networks within the vicinity of the production zone are not well known and not mapped to a sufficient level of detail/resolution.

**Seismic Survey**
- Seismic surveys have not been carried out, or surveys which have been carried out have significant shortcomings against good practice.
- The seismic survey may be more than ten years old.

**Sub-surface Fault Modelling**
- Sub-surface fault modelling has not been carried out or is not capable of predicting the presence of sub-surface faults and / or there are significant shortcomings against accepted good practice.
Table 26: SECURe -02 Threat 2 – Geological Barrier 2

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Selection Studies and Site Surveys</td>
</tr>
<tr>
<td>- Site Selection Studies and Site surveys have provided data on the significance of existing fault / fracture network(s) in the primary seal in terms of ability to constrain flow along fault / fracture network. Laboratory data:</td>
</tr>
<tr>
<td>- Has been obtained at a high resolution and</td>
</tr>
<tr>
<td>- Includes effective stresses, aperture, surface roughness and total contact area</td>
</tr>
<tr>
<td>- Where permeability cannot be measured directly, fault and fracture network permeability and transmissivity have been calculated based on the intrinsic fracture properties and the in-situ stress conditions with consideration of analogues to known and understood facilities, with known confining stresses, injection pressures, and lithology (including clay content and mechanical strength).</td>
</tr>
<tr>
<td>- Confining stresses have been determined by means of recent well logging of overburden (and other layers above the primary seal) porosity, and consideration of depth of the storage reservoir.</td>
</tr>
<tr>
<td>- Potential fluid flow in fault / fracture network has been studied based on the complex interplay between the geometrical and chemical heterogeneity of the fracture wall rock, and the coupling of fluid flow and effective stress.</td>
</tr>
<tr>
<td>- Mechanical response of fault / fracture network to fluid pressure has been determined from the intrinsic fracture properties and the in-situ stress conditions.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site Selection Studies and Site Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Site Selection Studies and Site surveys have provided data on the significance of existing fault / fracture network(s) in the primary seal in terms of ability to constrain flow along fault / fracture network. Laboratory data:</td>
</tr>
<tr>
<td>- Has been obtained at a low resolution and</td>
</tr>
<tr>
<td>- Includes effective stresses, aperture, surface roughness and total contact area</td>
</tr>
<tr>
<td>- Where permeability cannot be measured directly, fault and fracture network permeability and transmissivity have been calculated based on the intrinsic fracture properties and the in-situ stress conditions with consideration of analogues to known and understood facilities, with known confining stresses, injection pressures, and lithology (including clay content and mechanical strength).</td>
</tr>
<tr>
<td>- Confining stresses have been determined by means of well logging of overburden (and other layers above the primary seal) porosity, and consideration of depth of the storage reservoir. This data may be based on historical data, for example, from hydrocarbon production well logs from a depleted reservoir intended for storage.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1.0</th>
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</thead>
<tbody>
<tr>
<td>Site Selection Studies and Site Surveys</td>
</tr>
<tr>
<td>- Site Selection Studies and Site surveys have NOT provided data on the significance of existing fault / fracture network in terms of its ability to constrain flow along fault / fracture network.</td>
</tr>
<tr>
<td>- Confining stresses are estimated solely as a function of depth</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>Fair</td>
</tr>
<tr>
<td>Geological Properties: Properties of fault / fracture network constrains flow along fault / fracture network</td>
<td></td>
</tr>
<tr>
<td>1) Fracture network effective stress is high (&gt;13 MPA in all orientations). Any fracture network(s) are not critically stressed. Vertical flow is completely restricted by stress states, low connectivity and/or horizontal orientation of fractures AND / OR</td>
<td></td>
</tr>
<tr>
<td>2) Permeability of fracture networks is expected to be low (&lt;1 microDarcy). Permeability of fracture network is expected to terminate flow along fracture network. The lithology of the primary seal has a high clay content, which is consistent with low permeability (self-sealing).</td>
<td></td>
</tr>
<tr>
<td>3) Stress (pressure / temperature) of fracking or chemical changes from contact with fluid will not increase the permeability of fault</td>
<td></td>
</tr>
<tr>
<td>Geological Properties: Property of fault / fracture network constrains flow along fault / fracture network</td>
<td></td>
</tr>
<tr>
<td>1) Fracture network effective stress is medium / high (&gt;9 MPA in all orientations). Vertical flow is largely restricted by stress states, low connectivity and/or horizontal orientation of fractures AND / OR</td>
<td></td>
</tr>
<tr>
<td>2) Permeability of fracture networks is expected to be low / medium (&lt;100 microDarcy). Permeability of fracture network is expected to significantly restrict flow along fracture network. The lithology of the primary seal is intermediate between mechanically strong and high clay content.</td>
<td></td>
</tr>
<tr>
<td>3) Stress (pressure / temperature) of fracking or chemical changes from contact with fluid may increase the permeability of faults in the primary seal to a medium / high level (&gt;100 microDarcy)</td>
<td></td>
</tr>
</tbody>
</table>
### Variable Parameters

- Permeability (Fault/Fracture network)
- Stress states, fracture density, connectivity and orientation of fractures

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3a) Stress (pressure / temperature) of fracking or chemical changes from contact with fluid may increase the permeability of fault, however, it is possible to adjust the operating strategy (injection rate) to mitigate this.</td>
<td>OR</td>
</tr>
<tr>
<td>3b) Stress (pressure / temperature) of fracking or chemical changes from contact with fluid may increase the permeability of faults in the primary seal to a low / medium level (&lt;100 microDarcy)</td>
<td></td>
</tr>
</tbody>
</table>
Table 27: SECURE -02 Threat 2 – Engineering Barrier 1

<table>
<thead>
<tr>
<th>Effectiveness Descriptors</th>
<th>Barriers Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>Site Engineering: Positioning of wells / location of hydraulic fracturing in relation to known faults / fracture networks</td>
</tr>
<tr>
<td>Fair</td>
<td></td>
</tr>
<tr>
<td>Poor</td>
<td>Site Engineering: Positioning of wells / location of hydraulic fracturing in relation to known faults / fracture networks</td>
</tr>
</tbody>
</table>

### Barriers Description

**Variable Parameters**
- Location of faults and fracture networks

#### Design and Installation

1) Well location(s) are selected such that significant faults and fracture networks are a significant lateral distance beyond that which migrating fluid is expected to reach, regardless of any consideration of density or permeability.

2) Well location(s) are selected such that all other faults and fracture networks are at the lateral limits at which the migrating fluid is expected to reach.

- Significant is defined as:
  - Seismic faults;
  - Fracture networks approaching (or above) percolation threshold;
  - Faults / fracture networks with permeability >1 microDarcy

### Uncertainty Descriptors

<table>
<thead>
<tr>
<th>Site Selection Studies and Site Surveys</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Site Selection Studies and Site surveys have determined the significance of existing faults and fracture networks in terms of the likelihood to create a potential path for release.</td>
<td></td>
</tr>
<tr>
<td>- The location of faults and fracture networks are known and mapped to a high level of detail/resolution</td>
<td></td>
</tr>
<tr>
<td>Seismic Survey</td>
<td></td>
</tr>
<tr>
<td>- The degree of fault / fracture development is well understood.</td>
<td></td>
</tr>
<tr>
<td>- The seismic survey was carried out recently, (e.g. within the last two years), using modern techniques, methods, and technology to a high seismic resolution.</td>
<td></td>
</tr>
<tr>
<td>- The seismic survey reports acknowledge the limitations of the technology in the identification of fault orientation, fault throw and width, and the definition of target zones and provide conclusions within acknowledged error bounds, supported by risk assessment - noted that sub-seismic faults are unlikely to have a fracture network above percolation threshold.</td>
<td></td>
</tr>
<tr>
<td>Sub-surface Fault Modelling</td>
<td></td>
</tr>
<tr>
<td>- Sub-surface fault modelling has been carried out capable of predicting the presence of sub-surface faults (through detailed surface mapping, development of validated geological models, and the data from seismic reflection surveys) at a high resolution to enable accurate comparison with operational data. Exemption available (Medium descriptor applies) where Seismic Surveys have fully mapped the entire vicinity of the production zone and surrounding site to a high level of detail/resolution.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site Selection Studies and Site Surveys</th>
<th>Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Site Selection Studies and Site surveys have determined the significance of existing faults and fracture networks in terms of the likelihood to create a potential path for release.</td>
<td></td>
</tr>
<tr>
<td>- The location of faults and fracture networks are known and mapped to a sufficient level of detail/resolution.</td>
<td></td>
</tr>
<tr>
<td>Seismic Survey</td>
<td></td>
</tr>
<tr>
<td>- Significant faults and fracture networks have been identified, but the degree of fault / fracture development in the primary seal is not well understood at a detail level</td>
<td></td>
</tr>
<tr>
<td>- The seismic survey was carried out within the last five years</td>
<td></td>
</tr>
<tr>
<td>Sub-surface Fault Modelling</td>
<td></td>
</tr>
<tr>
<td>- Sub-surface fault modelling has been carried out capable of predicting the presence of sub-surface faults (through detailed surface mapping, development of validated geological models, and the data from seismic reflection surveys) at a low resolution to enable some comparison with operational data and has been carried out based on accepted good practice, but has some weaknesses or areas of omission. Exemption available where Seismic Surveys achieve the descriptor for low level of uncertainty.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site Selection Studies and Site Surveys</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Site Selection Studies and Site surveys have not considered the significance of existing faults and fracture networks in terms of likelihood to create a potential path for release.</td>
<td></td>
</tr>
<tr>
<td>- The location of faults and fracture networks are not well known and mapped to a sufficient level of detail/resolution.</td>
<td></td>
</tr>
<tr>
<td>Seismic Survey</td>
<td></td>
</tr>
<tr>
<td>- Seismic surveys have not been carried out, or surveys which have been carried out have significant shortcomings against good practice</td>
<td></td>
</tr>
<tr>
<td>- The seismic survey may be more than ten years old</td>
<td></td>
</tr>
<tr>
<td>Sub-surface Fault Modelling</td>
<td></td>
</tr>
<tr>
<td>- Sub-surface fault modelling has not been carried out or is not capable of predicting the presence of sub-surface faults and / or there are significant shortcomings against accepted good practice.</td>
<td></td>
</tr>
</tbody>
</table>
Figure 43: SECURE -02 Threat 3 – Full Context

Please refer to Table 26 for Geological Barrier: Geological Properties: Properties of fault / fracture network constrains flow along fault / fracture network.
### Table 28: SECURe -02 Threat 3 – Geological Barrier 1

**Uncertainty Descriptors**

**Site Selection Studies and Site Surveys**
- Site Selection Studies and Site surveys have provided data on the pre-existing stress states of the primary seal across all sections of the seal that could be affected by pressure changes during the injection phase.
- Borehole imaging to assess the strength and properties of the primary seal have been carried out. Subsequent geomechanical analysis provides high confidence that the outputs are fully representative of the entire primary seal.

**Potential for new fracture network formation assessed based on intrinsic fracture properties and the in-situ stress conditions with consideration of analogues to known and understood facilities, with known confining stresses, injection pressures, and lithology (including clay content and mechanical strength).**

---

**Barrier Description**

**Geological Properties: Extent to which shale constrains fracture growth / seals induced fracture networks**

- **Good**
  - Geological Properties
    1) Primary seal is highly resistant to stress effects and formation of new fracture networks. The fracture pressure of the primary seal is >200% of the injection downhole pressure or the expected pressure build-up at the primary seal during injection, whichever is higher.
    2) The lithology of the primary seal has a high clay content, which is consistent with low permeability (self-sealing). Any new fractures are expected to be low permeability (<1 microDarcy) and self-sealing.
    3) Pre-existing stress states (normal and shear) are likely to prevent the formation of new fractures.

- **Medium**
  - Geological Properties
    1) Primary seal is resistant to stress effects and formation of new fracture networks. The fracture pressure of the primary seal is >150% of the injection downhole pressure or the expected pressure build-up at the primary seal during injection, whichever is higher.
    2) The lithology of the primary seal is intermediate between mechanically strong and high clay content. Any new fractures are expected to be low / medium permeability (<100 microDarcy).
    3) Pre-existing stress states (normal and shear) are likely to restrict the formation of new fractures.

- **Poor**
  - Geological Properties
    1) Primary seal may be resistant to stress effects and formation of new fracture networks. The fracture pressure of the primary seal is ~100% of the injection downhole pressure or the expected pressure build-up at the primary seal during injection, whichever is higher.
    2) The lithology of the primary seal is mechanically strong, which is consistent with high permeability. Any new fractures are expected to be medium / high permeability (>100 microDarcy).
    3) Pre-existing stress states (normal and shear) are likely to allow the formation of new fractures.

---

**Variable Parameters**

- Mechanical properties (production zone and other geological layers)
- Pre-existing Stress States – Normal and Shear

---

**Effectiveness Descriptors**

**Release from Shale Production Zone**

- **Good**
- **Medium**
- **Poor**

---

**Appendix A: Page A.45 of A.101**
## Table 29: SECURE-02 Threat 3 – Geological Barrier 3

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Selection Studies and Site Surveys</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site surveys have provided data on the gross thickness the shale formation and additional confining strata above the Production Zone.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Effectiveness Descriptors

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geological Properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness of shale formation / additional confining strata above the Production Zone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Variable Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Thickness of Production Zone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Thickness of additional strata above the Production Zone</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Effectiveness Descriptors

<table>
<thead>
<tr>
<th>Effectiveness Descriptors</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geological Properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Thickness of production zone is sufficient to restrict fault development to the production zone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) The thickness of additional strata above the production zone is sufficient to confine fracture propagation to the production zone</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effectiveness Descriptors</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geological Properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Thickness of production zone is sufficient to restrict fault development to the production zone, however this may change with time / operation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) The thickness of additional strata above the production zone is sufficient to confine fracture propagation to the production zone, however this may change with time/operation</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effectiveness Descriptors</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geological Properties</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Thickness of production zone is not sufficient to restrict fault development to the production zone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) The thickness of additional strata above the production zone is not sufficient to confine fracture propagation to the production zone</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effectiveness Descriptors</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variable Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Thickness of Production Zone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Thickness of additional strata above the Production Zone</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 44: SECURE-02 Threat 4 – Full Context

- Natural seismicity fracture development or fault reactivation
- Natural seismicity should be eliminated as a risk by site selection and seismic causes of fractures are covered in the threat above
- Site Selection: Selection of site based on seismic event history
  - SSS&SS
  - Seismic event history
  - Site Location and Design

- Release from Shale Production Zone
  - SECURE-02: Shale Gas (Natural Gas in Formation)
Table 30: SECURE-02 Threat 4 – Engineering Barrier 1

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Selection Studies and Site Surveys</td>
</tr>
<tr>
<td>1) Site selection studies provide data on seismic event history on site location</td>
</tr>
<tr>
<td>2) Geomechanical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5</td>
</tr>
</tbody>
</table>

**Barrier Description**

| Site Selection: Selection of site based on seismic event history |
| Variable Parameters |
| - Seismic event history |
| - Site Location and Design |

**Effectiveness Descriptors**

<table>
<thead>
<tr>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
</table>

**Design and Installation**

1) There is negligible potential for naturally occurring seismic events
2) Any naturally occurring seismic events occur at microseismic levels (<M0).

1) There is little potential for naturally occurring seismic events

1) There is some potential for naturally occurring seismic events

1) Site selection studies have NOT been undertaken prior to operation to provide data on seismic event history on site location
2) Geomechanical analysis and geological analysis has not been conducted.
Figure 45: SECURE-02 Threat 5 – Full Context

- Lateral migration
  - As production of shale continues, migration becomes less likely
- Geological Properties: Geometry and features of production zone, e.g. faults that act as barriers to lateral migration
  - Fault Seal Analysis
  - Geometry and Features of Production Zone
  - Heterogeneity and Anisotropy
- Site Engineering: Positioning of wells / location of hydraulic fracturing with consideration to geometry and features of production zone and in relation to known/potential locations of leak paths e.g. existing wells
  - Integrity Assessment (I)
    - Geometry and Features of Production Zone
    - Location of existing / legacy leak paths (e.g. wells, boreholes, mines)
    - Location of other active wells
- Operational Strategy: Hydraulic Fracturing Strategy - multi-stage fracturing to address local conditions (e.g. proximity to other well systems)
  - Pre-fracturing Injection Tests
  - Define Operational Strategy
  - Multi-stage fracturing
    - Volume of injected fluid
    - Volume of flow back fluid
    - Injection rate
    - Flow back rate / Recovery time
- Release from Shale Production Zone

SECURE-02: Shale Gas (Natural Gas in Formation)
### Table 31: SECURe -02 Threat 5 – Geological Barrier 1

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Good</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Fair</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Poor</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Geological Properties:**

- **Geometry and features of production zone, e.g. faults that act as barriers to lateral migration**
- **Fault Seal Analysis:**
- **Site Engineering:** positioning of wells / location of hydraulic fracturing with consideration to geometry and features of production zone and in relation to known/potential locations of leak paths e.g. existing wells
- **Heterogeneity and Anisotropy**
- **Variable Parameters:**
  - Geometry and features of Production Zone
  - Heterogeneity and Anisotropy

**Uncertainty Descriptors**

- **Low**
  - **Fault Seal Analysis** identifies properties of lateral fault that resists entry and act as a barrier to laterally seal the production zone and has been carried out based on accepted good practice.

- **Medium**
  - **Fault Seal Analysis** has not been carried out based on accepted good practice.

- **High**
  - **Fault Seal Analysis** fails to identify properties of fault that resists entry and act as a barrier to laterally seal the production zone and / or has not been carried out based on accepted good practice.

**Effectiveness Descriptors**

- **Good**
  - Geological Properties: Geology acts to effectively limit lateral migration of fluids e.g. significant structural dip, impermeable fault, and/or lateral formations with low permeability.

- **Fair**
  - Geological Properties: Geology acts to partially limit lateral migration of fluids e.g. structural dip, low permeability fault and/or lateral formations with low / medium permeability.

- **Poor**
  - Geological Properties: Geology does not act to effectively limit lateral migration of fluids.
### Table 32: SECURe -02 Threat 5 – Engineering Barrier 1

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Selection Studies and Site Surveys</td>
<td>- Site Selection Studies and Site surveys have provided data on the geometry and features of the production zone in terms of the ability to restrict lateral migration fluids</td>
<td>- Features such as faults, have been identified and assessed to determine the maximum extent of the production zone</td>
<td>- The permeability of lateral formations has been fully characterised</td>
</tr>
<tr>
<td>Site Engineering 103</td>
<td>- Decision making for positioning of wells, takes into consideration the presence and significance of known geological features (e.g. faults) and lateral leak paths. This process is supported by risk assessment, which provides a high confidence regarding the conclusions of the decision making process</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Barrier Description

| Site Engineering: Positioning of wells / location of hydraulic fracturing with consideration to geometry and features of production zone and in relation to known/potential locations of leak paths e.g. existing wells |
| Design and Installation |
| 1) Well location(s) are selected such that identified geological features, e.g. lateral leak paths are a significant distance beyond that which the migrating fluids are expected to reach - see barrier for barriers to lateral migration |

#### Effectiveness Descriptors

<table>
<thead>
<tr>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design and Installation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1) Well location(s) are selected such that identified geological features, e.g. lateral leak paths are at the lateral limits at which migrating fluids are expected to reach - see barrier for barriers to lateral migration</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Variable Parameters |
| - Geometry and Features of Production Zone |
| - Location of existing / legacy leak paths (e.g. wells, boreholes, mines) |
| - Location of other active wells |

| Design and Installation |
| 1) Well location(s) are not selected such that identified geological features, e.g. lateral leak paths are beyond or equal to that which the migrating fluids are expected to reach - see barrier for barriers to lateral migration. Migrating fluids are expected to reach lateral leak paths, which may provide a preferential pathway for release from the production zone. |

Note from semi-quantitative workshop: if there is a residual risk of lateral migration, the site would likely be de-selected.
Please refer to Table 19 for Geological Barrier: Geological Properties: Extent to which geological layers / formation seals well and prevents / slows down release of natural gas.
Site Selection Studies and Site Surveys
1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site surveys have provided data on the distance between the production zone and receptors.
2) Potential fluid flow through the geological layers towards receptors has been studied based on the complex interplay between the geometrical and chemical heterogeneity of the rock formations, and the coupling of fluid flow and effective stress.
3) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5

Medium
Site Selection Studies and Site Surveys
1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site surveys have provided data on the distance between the production zone and receptors.
2) Potential fluid flow through the geological layers towards receptors has been studied based on the complex interplay between the geometrical and chemical heterogeneity of the rock formations, and the coupling of fluid flow and effective stress.
3) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a low resolution based on ISO 27914:2017 Section 5, but has some weaknesses or areas of omission based on ISO 27914:2017 Section 5

High
Site Selection Studies and Site Surveys
1) Site selection studies have NOT been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site surveys have provided data on the distance between the production zone and receptors.
2) Potential fluid flow through the geological layers towards receptors has been studied based on the complex interplay between the geometrical and chemical heterogeneity of the rock formations, and the coupling of fluid flow and effective stress.
3) Geomechanical analysis, geochemical analysis and geological analysis has NOT been conducted based on ISO 27914:2017 Section 5

### Table 33: SECURE -02 Consequence 1 – Geological Barrier 1

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geological Properties:</strong> Separation of shale formation from potential receptors</td>
<td>Geological Properties 1) The distances between the production zone and potential receptors results in some extended time for buffering and dissolution by geological layers above and around production zone</td>
<td>Geological Properties 1) The distances between the production zone and potential receptors results in some extended time for buffering and dissolution by geological layers above and around production zone</td>
<td>Geological Properties 1) The distances between the production zone and potential receptors results in some extended time for buffering and dissolution by geological layers above and around production zone</td>
</tr>
<tr>
<td><strong>Variable Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Separation (horizontal or vertical) of Production Zone from Receptors</td>
<td>Note from discussion during Semi-quantitative Workshop: Salt cavern in Kansas leakage accumulated in aquifer above which was slightly up-dip. Migrated over several kilometres until reached basement in city and led to explosions. Distance is not a factor; geometry of layers above seal made most difference.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Uncertainty Descriptors

- **Low**
  - Site Selection Studies and Site Surveys
    - 1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site surveys have provided data on the distance between the production zone and receptors.
    - 2) Potential fluid flow through the geological layers towards receptors has been studied based on the complex interplay between the geometrical and chemical heterogeneity of the rock formations, and the coupling of fluid flow and effective stress.
    - 3) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5

- **Medium**
  - Site Selection Studies and Site Surveys
    - 1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site surveys have provided data on the distance between the production zone and receptors.
    - 2) Potential fluid flow through the geological layers towards receptors has been studied based on the complex interplay between the geometrical and chemical heterogeneity of the rock formations, and the coupling of fluid flow and effective stress.
    - 3) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a low resolution based on ISO 27914:2017 Section 5, but has some weaknesses or areas of omission based on ISO 27914:2017 Section 5

- **High**
  - Site Selection Studies and Site Surveys
    - 1) Site selection studies have NOT been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site surveys have provided data on the distance between the production zone and receptors.
    - 2) Potential fluid flow through the geological layers towards receptors has NOT been studied based on the complex interplay between the geometrical and chemical heterogeneity of the rock formations, and the coupling of fluid flow and effective stress.
    - 3) And / or geomechanical analysis, geochemical analysis and geological analysis has NOT been conducted based on ISO 27914:2017 Section 5
Please refer to Table 19 for Geological Barrier: Geological Properties: Extent to which geological layers / formation seals well and prevents / slows down release of natural gas
Please refer to Table 33 for Geological Barrier: Geological Properties: Separation of shale formation from potential receptors
Please refer to Table 22 for Geological Barrier: Geological Properties: Aquifer Hydrogeochemistry / Redox buffering capacity extent to which the water could degrade natural gas
Figure 48: SECURe-02 Consequence 3 – Full Context

Release from Shale Production Zone

- Monitoring: Seabed monitoring e.g. ROV surveys to identify gas fluxes for input into consideration of remedial action
  - EBA
  - Seabed Monitoring 101
  - Gas flux at seabed

- Remedial Action: Engineering measures to remediate a detected leak of confirmed (project) origin or unwanted release / migration
  - Implement geological remediation
  - Seabed Monitoring 101
  - Gas flux at seabed

- Extent to which ecosystems respond to increases in contaminants (when compared with baseline)
  - Extent to which seawater safely absorbs natural gas / Contaminants (e.g. Formation Fluid)

- While offshore hydraulic fracturing is not common, this consequence could be relevant to onshore (near sea) exploitation for which the production zone extends beneath the sea

- Further unknown impurities are collected from production zone and intermediate layers

See SECURE-04 for consideration of formation water mobilisation

Release to seabed / seawater – impact to ecosystems (flora & fauna)
Figure 49: SECURe-02 Consequence 4 – Full Context

Please refer to Table 19 for Geological Barrier: Geological Properties: Extent to which geological layers / formation seals well and prevents / slows down release of natural gas
Please refer to Table 33 for Geological Barrier: Geological Properties: Separation of shale formation from potential receptors
Figure 50: SECURE-02 Consequence 5 – Full Context

- **SECURE-02: Shale Gas (Natural Gas in Formation)**
- **Release from Shale Production Zone**
- **Contamination of out-of-zone areas where faults might become pressurised**
- **See SECURE-05: Seismicity / Earth Movement**
Figure 51: SECURe -02 Consequence 6 – Full Context

Please refer to Table 19 for Geological Barrier: Geological Properties: Extent to which geological layers / formation seals well and prevents / slows down release of natural gas

Please refer to Table 33 for Geological Barrier: Geological Properties: Separation of shale formation from potential receptors
**Table 34: SECURE -02 Consequence 6 – Engineering Barrier 1**

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Selection Studies and Site Surveys</td>
</tr>
<tr>
<td>1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site Surveys and Site Social Characterisation has provided data on the location, profiles, behaviour and operational activities of all local populations. And 2) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5.</td>
</tr>
<tr>
<td>Site Social Characterisation</td>
</tr>
<tr>
<td>3) Site social characterisation has identified all relevant stakeholders, including the public, and detailed the local technical, economic, ethical and socio-political issues. Site social characterisation has been carried out as part of the site survey and has been conducted based on ISO 27914:2017 Section 4.1.</td>
</tr>
<tr>
<td>Dispersion Modelling</td>
</tr>
<tr>
<td>4) Atmospheric dispersion modelling is capable of simulating fluid dispersion in multiple scenarios at a high resolution ([define resolution]) to enable accurate comparison with operational data and has been carried out based on ISO 27914:2017 Section 5.5.</td>
</tr>
</tbody>
</table>

**Barrier Description**

<table>
<thead>
<tr>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
</tr>
<tr>
<td>Site Engineering: Extent to which site selection minimises the presence of local populations</td>
</tr>
<tr>
<td>Design and Installation</td>
</tr>
<tr>
<td>1) Results from modelling on the suitability of site location shows that in the event of a release it is extremely unlikely that there will be populations within the hazard radius (&gt;200 m)</td>
</tr>
<tr>
<td>Design and Installation</td>
</tr>
<tr>
<td>2) Results from modelling on the suitability of site location shows that in the event of a release it is unlikely that there will be populations within the hazard radius (&gt;100m to local populations)</td>
</tr>
<tr>
<td>Design and Installation</td>
</tr>
<tr>
<td>3) Results from modelling on the suitability of site location shows that in the event of a release there could potentially be populations within the hazard radius (&lt;50 m to local populations)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Location of receptors</td>
</tr>
</tbody>
</table>

**Uncertainty Descriptors**

- Low
- Medium
- High

*Low Site Selection Studies and Site Surveys*

1) Site selection studies have not been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site Surveys and Site Social Characterisation has NOT provided data on the location, profiles, behaviour and operational activities of all local populations. And/or 2) Geomechanical analysis, geochemical analysis and geological analysis has not been conducted based on ISO 27914:2017 Section 5.

*Site Social Characterisation*

3) Site social characterisation has NOT identified all relevant stakeholders, including the public, and detailed the local technical, economic, ethical and socio-political issues. Site social characterisation has NOT been carried out as part of the site survey and / or has not been conducted based on ISO 27914:2017 Section 4.1.

*Dispersion Modelling*

4) Atmospheric dispersion modelling is not capable of simulating fluid dispersion in multiple scenarios and / or has not been carried out based on ISO 27914:2017 Section 5.5.

*Medium Site Selection Studies and Site Surveys*

1) Site selection studies have not been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site Surveys and Site Social Characterisation has NOT provided data on the location, profiles, behaviour and operational activities of all local populations. And 2) Geomechanical analysis, geochemical analysis and geological analysis has not been conducted based on ISO 27914:2017 Section 5, but has some weaknesses or areas of omission.

*Site Social Characterisation*

3) Site social characterisation has NOT identified all relevant stakeholders, including the public, and detailed the local technical, economic, ethical and socio-political issues. Site social characterisation has NOT been carried out as part of the site survey and / or has not been conducted based on ISO 27914:2017 Section 4.1, but has some weaknesses or areas of omission.

*Dispersion Modelling*

4) Atmospheric dispersion modelling is not capable of simulating fluid dispersion in multiple scenarios and at a low resolution ([define resolution]) to enable some comparison with operational data and has been carried out based on ISO 27914:2017 Section 5.5, but has some weaknesses or areas of omission.
Figure 52: SECURE -02 Consequence 7 – Full Context

Please refer to Table 19 for Geological Barrier: Geological Properties: Extent to which geological layers / formation seals well and prevents / slows down release of natural gas
Please refer to Table 33 for Geological Barrier: Geological Properties: Separation of shale formation from potential receptors
Please refer to Table 34 for Engineering Barrier: Site Engineering: Extent to which site selection minimises the presence of local populations
### Table 35: SECURE -02 Consequence 7 – Geological Barrier 3

#### Uncertainty Descriptors

- Site Selection Studies and Site Surveys
  1. Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site surveys have provided data on the location of radiological / toxic hazards.
  2. Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5.

#### Effectiveness Descriptors

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geological Properties: Site characterisation identifies potential for radiological / toxic hazards</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Geological Properties
  1. There are no radiological / toxic hazards in the vicinity of the site or all radiological / toxic hazards have not been fully identified for remedial action in the event of a leak | N/A |  |  |
| **Variable Parameters** |  |  |  |
| - Presence of radiological / toxic hazards |  |  |  |

---

**Geological Properties**

1. There are radiological / toxic hazards in the vicinity of the site and/or all radiological / toxic hazards have not been fully identified for remedial action in the event of a leak
Figure 53: SECURE-03 High Level Bow-tie

- SECURE-03: Fracturing Fluid / Flowback Water (under Pressure)
- Fracturing Fluid in well annulus (Annulus A)
- Leak along / through cement (external leak) - Failure of cement bond and/or casing / production liner
- Release from Well (during Fracturing / between Fracturing / after Fracturing)
- Groundwater / Soil contamination from fracturing fluid released from well - impact to ecosystems (flora & fauna) and / or people
Figure 54: SECURe-03 Threat 1 – Full Context

Please refer to Table 11 for Engineering Barrier: Well Engineering - Primary Barrier Envelope: Prevents flow of hydrocarbons into annulus from tubing or production zone.

Please refer to Table 12 for Engineering Barrier: Well Engineering: Secondary Well Barrier Envelope: Prevents flow of hydrocarbons into annulus from production zone or into environment (subsurface or atmospheric) from annulus.

Please refer to Table 13 for Engineering Barrier: Well Engineering: Extent to which tubing and casing design adopts good practice, e.g., three casing strings (Surface, Intermediate, and Production) - Production casings extending below the aquifer level.
Figure 55: SECURE -03 Threat 1 Barrier 1 Degradation Factors (1 of 2)
Figure 56: SECURe-03 Threat 1 Barrier 1 Degradation Factors (2 of 2)
Please refer to Table 13 for Engineering Barrier: Well Engineering: Extent to which tubing and casing design adopts good practice, e.g., three casing strings (Surface, Intermediate, and Production) - Production casings extending below the aquifer level.
Figure 59: SECURE -03 Threat 2 Barrier 1 Degradation Factors

- Leak along / through cement (external leak) - failure of cement bond and/or casing / production liner
- Well engineering - primary barrier longevity (integrity of cement and its interfaces with casing and surrounding geology)
- Well engineering and design 101
- Cement design criteria 101
- Liner Cement design and integrity
- Casing / Production Liner design and integrity

- Pre-fracturing injection tests
- Define Operational Strategy
- Strategy correction based on monitoring
- Costing and repair between fracturing stages
- Volume of injected fluid
- Volume of flowback fluid
- Injection rate
- Flowback rate / recovery time
- Seismicity
- Well design and integrity

- Well engineering: Stimulation resistant cement formulations
- Well engineering and design 101
- Cement bond log 101
- Well design and integrity

- Concrete (mechanical and chemical) degradation over time leads to development of cracks and potential for leakage
- Hydraulic fracturing takes place during the early stages of a well / project lifecycle

- Well examinations: Well records examined by an "independent and competent person" (well examiner) and defects corrected
- Well examinations 101
- Pressure testing of well casing 101
- Cement bond log 101
- Well design and integrity

- Monitoring - Monitoring of cementation through crosslinked cement bond logs (CBL) and / or fluoroscopy
- Cement bond log 101
- Nflouoscopy Monitoring 101
- Well design and integrity

- Poor quality cement / cement bond logs identify defects in cementation / cement improper placed / cement shrinkage
- Hydraulic fracturing takes place during the early stages of a well / project lifecycle
- Well engineering: Identification of poor quality cementation and remedial cement job before subsequent sections are drilled
- Well engineering and design 101
- Cement quality additves 101
- Cement quality test 101
- Cement bond log 101
- Well design and integrity

- Release from well during fracturing / between fracturing / fracturing
Figure 60: SECURE -03 Consequence 1 – Full Context

Please refer to Table 19 for Geological Barrier: Geological Properties: Extent to which geological layers / formation seals well and prevents / slows down release of fracturing fluid
Please refer to Table 20 for Geological Barrier: Geological Properties: Extent to which geological layers above the production zone / between the production zone and receptors slow down movement of fracturing fluids
Please refer to Table 23 for Engineering Barrier: Well Engineering: Positioning of wells / location of hydraulic fracturing in relation to known receptors
Table 36: SECURE -03 Consequence 1 – Engineering Barrier 1

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Selection Studies and Site Surveys</td>
</tr>
<tr>
<td>1) Site surveys have been undertaken to characterise nearby leakage pathways. Site Selection Studies and Site Surveys has provided data on the location, composition and behaviour of known receptors.</td>
</tr>
<tr>
<td>Selection of Fracturing Fluid 102</td>
</tr>
<tr>
<td>2) Fracturing fluid selection has been carried out based on accepted good practice. The composition of the fracturing fluid selected is fully known and understood. The fracturing fluid has been provided by a reputable supplier, whom has been appropriately vetted in accordance with an approved supplier scheme, and successfully subject to repeated audit of quality management systems.</td>
</tr>
</tbody>
</table>

Variable Parameters

- Composition / Properties of Fracturing Fluid

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection of Fracturing Fluid: Non-hazardous fracturing fluid</td>
<td>Good</td>
</tr>
<tr>
<td>Design and Installation</td>
<td>1) Composition / properties of fracturing fluid selected to minimise potential harm to the environment. Fracturing fluid is non-hazardous.</td>
</tr>
<tr>
<td></td>
<td>Design and Installation</td>
</tr>
<tr>
<td></td>
<td>Design and Installation</td>
</tr>
<tr>
<td>Site Selection Studies and Site Surveys</td>
<td></td>
</tr>
<tr>
<td>1) Site surveys have been undertaken to characterise nearby leakage pathways. Site Selection Studies and Site Surveys has provided data on the location, composition and behaviour of known receptors, however, this is based on legacy data, in excess of ten years old.</td>
<td></td>
</tr>
<tr>
<td>Selection of Fracturing Fluid 102</td>
<td></td>
</tr>
<tr>
<td>2) Fracturing fluid selection has NOT been carried out based on accepted good practice. The composition of the fracturing fluid selected is not fully known and understood.</td>
<td></td>
</tr>
</tbody>
</table>
Figure 61: SECURE-04 High Level Bow-tie

- Existing/legacy wells
- Presence of fracture network/fault
- Fracture propagation beyond target production zone
- Natural seismicity fracture development or fault reactivation
- Lateral migration
- Displacement of formation fluid

- SECURE-04: Fracturing Fluid/Flowback (and Formation Water) (in formation)
- Groundwater contamination from fracturing fluid injected into production zone and/or formation water/gas pressurised by injected fluid
- Groundwater contamination with liberated contaminants, e.g., NORM, H2S
- Contamination of neighbouring formations (used for storage or production)
Figure 62: SECURe -04 Threat 1 – Full Context

Please refer to Table 24 for Engineering Barrier: Site Engineering: Positioning of wells / location of hydraulic fracturing in relation to known leak pathways.
Please refer to Table 25 for Geological Barrier: Geological Properties: Extent to which degree of fault development and location of significant faults and fractures reduces likelihood of release.

Please refer to Table 26 for Geological Barrier: Geological Properties: Properties of fault / fracture network constrains flow along fault / fracture network.

Please refer to Table 27 for Engineering Barrier: Site Engineering: Positioning of wells / location of hydraulic fracturing in relation to known faults / fracture networks.
Please refer to Table 28 for Geological Barrier: Geological Properties: Extent to which shale constrains fracture growth / seals induced fracture networks
Please refer to Table 26 for Geological Barrier: Geological Properties: Properties of fault / fracture network constrains flow along fault / fracture network
Please refer to Table 29 for Geological Barrier: Geological Properties: Thickness of shale formation / additional confining strata above the Production Zone
Figure 65: SECURe-04 Threat 4 – Full Context

Please refer to Table 30 for Engineering Barrier: Site Selection: Selection of site based on seismic event history
Please refer to Table 31 for Geological Barrier: Geological Properties: Geometry and features of production zone, e.g. faults that act as barriers to lateral migration

Please refer to Table 32 for Engineering Barrier: Site Engineering: Positioning of wells / location of hydraulic fracturing with consideration to geometry and features of production zone and in relation to known/potential locations of leak paths e.g. existing wells
Figure 67: SECURe -04 Threat 6 – Full Context

- SECURE-04: Fracturing Fluid / Flowback (and Formation) Water (in Formation)
- Release from Shale Production Zone
- Displacement of formation fluid

Geological Properties:
- Extent to which hydraulic properties of the production zone / other strata prevent the displacement of formation fluid
- Hydraulic properties (production zone and other geological layers)
- Formation fluid properties
### Table 37: SECURe -04 Threat 6 – Geological Barrier 1

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geological Properties: Extent to which hydraulic properties of the production zone / other strata prevents the displacement of formation fluid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Variable Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic properties (production zone and other geological layers)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation fluid properties</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Geological Properties**
1. Hydraulic properties (production zone / confining strata) retain or terminate the flow of fluid in formation
2. Formation fluid properties are sufficient to trap injected fluid in formation and have no negative effect on well

Note from semi-quantitative workshop: Degree to which you displace formation fluid is a function of volume injected.

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Selection Studies and Site Surveys</td>
</tr>
</tbody>
</table>
1. Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site surveys have provided data on the geometry and features of production zone in terms of the ability to prevent the displacement of formation fluid.
2. Diffusion rates have been calculated based on fracturing fluid / flowback water properties, permeability, porosity and the predicted the biogeochemical processes.
3. Prediction of fluid flow through the production zone has been studied based on the complex interplay between the geometrical and chemical heterogeneity of the production zone, and the coupling of fluid flow and effective stress.
4. Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5

<table>
<thead>
<tr>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Selection Studies and Site Surveys</td>
</tr>
</tbody>
</table>
1. Site selection studies have not been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site surveys have NOT provided data on the geometry and features of production zone in terms of the ability to prevent the displacement of formation fluid.
2. Diffusion rates have NOT been calculated based on fracturing fluid / flowback water properties, permeability, porosity and the predicted the biogeochemical processes.
3. Prediction of fluid flow through the production zone has NOT been studied based on the complex interplay between the geometrical and chemical heterogeneity of the production zone, and the coupling of fluid flow and effective stress.
4. And / or geomechanical analysis, geochemical analysis and geological analysis has not been conducted based on ISO 27914:2017 Section 5

<table>
<thead>
<tr>
<th>Hydraulic properties (production zone and other geological layers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hydraulic properties of the production zone / confining strata retain or terminate the flow of fluid in formation, however this may change with time/operation</td>
</tr>
<tr>
<td>2. Formation fluid properties are sufficient to trap injected fluid in formation and have no negative effect on well, but this may change with time/operation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Formation fluid properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hydraulic properties of the production zone / confining strata do not retain or terminate the flow of fluid in formation</td>
</tr>
<tr>
<td>2. Formation fluid properties are not sufficient to trap injected fluid in formation</td>
</tr>
</tbody>
</table>

| Low |
| Medium |
| High |
Please refer to Table 33 for Geological Barrier: Geological Properties: Separation of shale formation from potential receptors
Please refer to Table 20 for Geological Properties: Extent to which geological layers above the production zone / between the production zone and receptors slow down movement of contaminants
Please refer to Table 36 for Engineering Barrier: Selection of Fracturing Fluid: Non-hazardous fracturing fluid
Please refer to Table 19 for Geological Barrier: Geological Properties: Extent to which geological layers / formation seals well and prevents / slows down release of contaminants
Please refer to Table 33 for Geological Barrier: Geological Properties: Separation of shale formation from potential receptors
Please refer to Table 35 for Geological Barrier: Geological Properties: Site characterisation identifies potential for radiological / toxic hazards
Please refer to Table 33 for Geological Barrier: Geological Properties: Separation of shale formation from potential receptors.

Please refer to Table 20 for Geological Barrier: Geological Properties: Extent to which geological layers / formation seals well and prevents / slows down release of natural gas.
Figure 71: SECURE-05 High Level Bow-tie

- **Societal inconvenience / Nuisance seismicity engendering fear and concern**
- **Damage to Well Integrity / Disruption to production**
- **Damage to buildings / local infrastructure**
- **Triggered seismic event - potentially remote spatially or temporarily**
- **Seismic event above regulatory threshold halts production - economic impact**

**SECURE-05: Seismicity / Earth Movement (Hydraulic Fracturing)**

- **Hydraulic Fracturing - increase in pore pressure**
- **Wastewater Disposal - increase in pore pressure**
- **(Critically) pre-stressed fault present**
Figure 72: SECURe-05 Threat 1 – Full Context

Hydraulic Fracturing – increase in pore pressure

For when a pre-stressed fault is present, see (Critically) pre-stressed fault present

Where a fault is not reactivated only microseismic events will occur - such events cannot lead to the consequences identified on the RHS of this bow-tie

Geological Properties: Extent to which rock formation resists seismic events [SSS & SS] Geomechanical Modelling

Pre-existing Stress States – Normal and Shear

Depth of Production Zone

Ductility (other geological layers / formation)

Monitoring: Advanced Traffic Light System (TLS) monitoring of micro seismicity (magnitude and location e.g. unexpected fault activation) and comparison against predictive models to determine whether more significant seismic events would be likely to occur

Operational Strategy: Modification of operational strategy based upon the results of Advanced TLS and prediction of more significant seismic events

Strategy Correction based on Monitoring

Advanced TLS Predictive Modelling

Volume of injected fluid

Volume of flowback fluid

Injection rate

Flowback rate / Recovery time

Composition / properties of injected fluid

Seismicity

Location of faults and fracture networks

Induced / Triggered Seismicity

Inaccurate / wrong data for geomechanical model
### Table 38: SECURe -05 Threat 1 – Geological Barrier 1

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>Fair</td>
</tr>
<tr>
<td><strong>Geological Properties:</strong> Extent to which rock formation resists seismic events</td>
<td></td>
</tr>
<tr>
<td><strong>Variable Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>- Pre-existing Stress States – Normal and Shear</td>
<td></td>
</tr>
<tr>
<td>- Depth of Production Zone</td>
<td></td>
</tr>
<tr>
<td>- Ductility (other geological layers / formation)</td>
<td></td>
</tr>
</tbody>
</table>

#### Uncertainty Descriptors

- **Low**
  - Site Selection Studies and Site Surveys
    1) Site Selection Studies and Site surveys have provided data on production zone properties including ductility and resistance to induced seismicity.
    2) Mechanical response of the production zone to fluid pressure has been determined from the intrinsic production zone properties and the in-situ stress conditions.
    3) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5.
  - Geomechanical Modelling
    4) Geomechanical modelling is capable of simulating the subsurface mechanical behaviour in multiple scenarios at a high computational efficiency at a high resolution (stress = 1 bar, strain = 0.001m) and to enable accurate comparison with operational data and has been carried out based on ISO 27914:2017 Section 5.5.

- **Medium**
  - Site Selection Studies and Site Surveys
    1) Site Selection Studies and Site surveys have provided data on production zone properties including ductility.
    2) Mechanical response of the production zone to fluid pressure has not been determined from the intrinsic production zone properties and the in-situ stress conditions.
    3) And / or geomechanical analysis, geochemical analysis and geological analysis has not been conducted based on ISO 27914:2017 Section 5.
  - Geomechanical Modelling
    4) Geomechanical modelling is capable of simulating the subsurface mechanical behaviour in multiple scenarios at a low resolution based on ISO 27914:2017 Section 5.

- **High**
  - Site Selection Studies and Site Surveys
    1) Site Selection Studies and Site surveys have not provided data on production zone properties including ductility.
    2) Mechanical response of the production zone to fluid pressure has not been determined from the intrinsic production zone properties and the in-situ stress conditions.
    3) And / or geomechanical analysis, geochemical analysis and geological analysis has not been conducted based on ISO 27914:2017 Section 5.
  - Geomechanical Modelling
    4) Geomechanical modelling is not capable of simulating the subsurface mechanical behaviour in multiple scenarios and / or has not been carried out based on ISO 27914:2017 Section 5.5.

#### Variable Parameters

- **Pre-existing Stress States – Normal and Shear**
- **Depth of Production Zone**
- **Ductility (other geological layers / formation)**

#### Geological Properties

- **Good**
  - Ductility of geological layers / formation is sufficient to seal well, resist induced / triggered seismicity above regulatory thresholds and prevent release of fluids from formation.
- **Fair**
  - Ductility of geological layers / formation is sufficient to seal well, resist induced / triggered seismicity above regulatory thresholds and prevent release of fluids from formation, however this may change with time/operation.
- **Poor**
  - Ductility of geological layers / formation is not sufficient to seal well, resist induced / triggered seismicity above regulatory thresholds and prevent release of fluids from formation.
Figure 73: SECURe-05 Threat 2 – Full Context

Please refer to Table 38 for Geological Barrier: Geological Properties: Extent to which rock formation resists seismic events
### Table 39: SECURE -05 Threat 2 – Geological Barrier 2

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
<th>Uncertainty Descriptors</th>
</tr>
</thead>
</table>

#### Good
- **Geological Properties:** Extent to which rock formation resists seismic events
  1) Good injectivity of store: The ability of the reservoir to transmit fluids and the pore pressure of the store is sufficient to prevent induced / triggered seismicity above regulatory thresholds.
  2) The variation and quality of variation in properties of the reservoir in different directions results in the reservoir remaining largely homogeneous during and immediately following injection. However, a

#### Fair
- **Geological Properties:** Extent to which injectivity / permeability of formation distributes the injection pressure throughout the complex preventing localised build-up of pressure
  1) Fair injectivity of store: The ability of the reservoir to transmit fluids and the pore pressure of the store is sufficient to prevent induced / triggered seismicity above regulatory thresholds, however this may change with time / operation.
  2) The variation and quality of variation in properties of the reservoir in different directions results in the reservoir pressure not remaining homogeneous. Multiple areas may be susceptible to proportionally greater pressure increases during injection.

#### Poor
- **Geological Properties:** Extent to which rock formation resists seismic events
  1) Poor injectivity of store: The ability of the reservoir to transmit fluids and the pore pressure of the store is not sufficient to prevent induced / triggered seismicity above regulatory thresholds.
  2) The variation and quality of variation in properties of the reservoir in different directions results in the reservoir pressure not remaining homogeneous. Multiple areas may be susceptible to proportionally greater pressure increases during injection.

- **Site Selection Studies and Site Surveys:**
  1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site Surveys have provided data on reservoir properties including: permeability, porosity, reservoir thickness, areal extent, pressure, temperature, brine salinity, geologic architecture, and heterogeneity.
  2) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5.

- **Reservoir Modelling:**
  3) Reservoir modelling is capable of simulating fluid interaction with reservoir based on geology, fluid content and behaviour of reservoir in multiple scenarios at a high resolution to enable accurate comparison with operational data and has been carried out based on ISO 27914:2017 Section 5.5.

- **Barrier Description**
  - Wastewater Disposal: increase in pore pressure
  - Geological Properties: Extent to which rock formation resists seismic events
  - Geomechanical Modelling
  - Pre-existing Stress States – Normal and Shear
  - Depth of Production Zone
  - Ductility (other geological layers / formation)
  - Reservoir Modelling
  - Permeability and Porosity (Reservoir)
  - Heterogeneity and Anisotropy

- **Induced / Triggered Seismicity**
- **Low**
  - Site Selection Studies and Site Surveys
  1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site Surveys have provided data on reservoir properties including: permeability, porosity, reservoir thickness, areal extent, pressure, temperature, brine salinity, geologic architecture, and heterogeneity.
  2) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5.

- **Medium**
  - Site Selection Studies and Site Surveys
  1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site Surveys have provided data on reservoir properties including: permeability, porosity, reservoir thickness, areal extent, pressure, temperature, brine salinity, geologic architecture, and heterogeneity.
  2) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a low resolution based on ISO 27914:2017 Section 5.

- **High**
  - Site Selection Studies and Site Surveys
  1) Site selection studies have not been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site Surveys have NOT provided data on reservoir properties including: permeability, porosity, reservoir thickness, areal extent, pressure, temperature, brine salinity, geologic architecture, and heterogeneity.
  2) And / or geomechanical analysis, geochemical analysis and geological analysis has not been conducted based on ISO 27914:2017 Section 5.
<table>
<thead>
<tr>
<th>Variable Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure remaining largely homogeneous during and immediately following injection 3) The rate and pressure at which wastewater is pumped into the store does not fracture the formation</td>
<td>Few small areas may be susceptible to proportionally greater pressure increases during injection, potentially leading to additional pressure applied to the primary seal. However, this will not achieve the fracture pressure of the primary seal. 3) The rate and pressure at which wastewater is pumped into the store does not fracture the formation, however this may change with time/operation</td>
</tr>
<tr>
<td>Reservoir Modelling 3) Reservoir modelling is not capable of simulating fluid interaction with reservoir based on geology, fluid content and behaviour of reservoir in multiple scenarios and / or has not been carried out based on ISO 27914:2017 Section 5.5</td>
<td></td>
</tr>
</tbody>
</table>
Figure 75: SECURe -05 Threat 3 Barrier 2 Degradation Factors

- **Well Engineering:** Positioning of wells / location of fracking / disposal in relation to known faults / fracture networks
- **Seismic Survey**
- **Sub-surface Fault Modelling**
- **Wellbore imaging logs, mud logs, wellbore core**
- **Site Engineering 108** Location of faults and fracture networks

- **Well only sample formation locally and may not intersect the most seismically important fault**
- **Geological Properties:** Formations containing large faults frequently have large numbers of faults, which will be detected in wellbore - detailed seismic surveys carried out during site survey
- **Degree of fault / fracture development**

- **Limitations of seismic reflection survey - may not detect small faults**
- **Faults that cannot be detected tend to have relatively small surface areas so are less likely to lead to seismic events that can be felt at the surface**
- **Geological Properties:** Formations containing large faults frequently have large numbers of faults, which will be detected in wellbore - detailed seismic surveys carried out during site survey

- **Seismic survey target zone definition may result in non-identification of significant faults, (for example top basement may not be the target zone)**
- **Good practice to be aware of the seismic limitations in the identification of fault orientation, fault throw and the definition of target zones**

- **Local resistance to seismic monitoring on private/public property in vicinity of target areas**
- **Social site characterisation, engaging members of the public with proposed subsurface activities**

**Induced / Triggered Seismicity**
Figure 76: SECURe-05 Threat 3 Barriers 3 and 5 Degradation Factors
Table 40: SECURE-05 Threat 3 – Geological Barrier 1

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Selection Studies and Site Surveys</td>
</tr>
<tr>
<td>- Site Selection Studies and Site surveys have provided data on the significance of pre-stressed fault / fracture network in terms of its likelihood to be triggered by operational activities resulting in seismicity above regulatory requirements.</td>
</tr>
<tr>
<td>- The location of faults and fracture networks in and around the production zone are known and mapped to a high level of detail/resolution</td>
</tr>
<tr>
<td>- Mechanical response of fault / fracture network to fluid pressure has been determined from the intrinsic fracture properties and the in-situ stress conditions [as detailed in March et al. - Numerical computation of stress-permeability relationships of fracture networks in a shale rock, Ref. 47].</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Seismic Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>- The degree of fault / fracture development in and around the production zone is well understood.</td>
</tr>
<tr>
<td>- The seismic survey was carried out recently (e.g. within the last two years), using modern techniques, methods, and technology to a high seismic resolution</td>
</tr>
<tr>
<td>- Seismic survey reports acknowledge the limitations of the technology in the identification of fault orientation, fault throw and the definition of target zones and provide conclusions within acknowledged error bounds, supported by risk assessment – noted that sub-seismic faults are unlikely to have a fracture network above percolation threshold.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sub-surface Fault Modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Sub-surface fault modelling has been carried out capable of predicting the presence of sub-surface faults (through detailed surface mapping, development of validated geological models, and the data from seismic reflection surveys) at a high resolution to enable accurate comparison with operational data. Exemption available (Medium descriptor applies) where Seismic Surveys have fully mapped the entire primary seal to a high level of detail/resolution.</td>
</tr>
<tr>
<td>- Site Selection Studies and Site Surveys have provided data on the significance of pre-stressed fault / fracture network in terms of its likelihood to be triggered by operational activities resulting in seismicity above regulatory requirements.</td>
</tr>
<tr>
<td>- The location of faults and fracture networks in and around the production zone are known and mapped to a sufficient level of detail/resolution</td>
</tr>
<tr>
<td>- Mechanical response of fault / fracture network to fluid pressure has been determined from the intrinsic fracture properties and the in-situ stress conditions [as detailed in March et al. - Numerical computation of stress-permeability relationships of fracture networks in a shale rock, Ref. 47].</td>
</tr>
<tr>
<td>- Significant faults and fracture networks have been identified, but the degree of fault / fracture development in and around the production zone is not well understood at a detail level</td>
</tr>
<tr>
<td>- The seismic survey was carried out within the last five years</td>
</tr>
<tr>
<td>- Sub-surface fault modelling has been carried out capable of predicting the presence of sub-surface faults (through detailed surface mapping, development of validated geological models, and the data from seismic reflection surveys) at a low resolution to enable some comparison with operational data and has been carried out based on accepted good practice, but has some weaknesses or areas of omission. Exemption available where Seismic Surveys achieve the descriptor for low level of uncertainty.</td>
</tr>
</tbody>
</table>
### Barrier Description

<table>
<thead>
<tr>
<th>Variable Parameters</th>
<th>Geological Properties: Degree of fault zone development and nature of faults reduces likelihood of significant seismicity</th>
</tr>
</thead>
</table>

#### Variable Parameters
- Degree of fault / Fracture development
- Fault frictional properties and stability, and orientation
- Size (Faults) – Length and Surface Area
- Pre-existing Stress States – Normal and Shear

#### Geological Properties
1. There are **no** faults in or near the production zone. The degree of fault / fracture development across site is not sufficient for seismicity to be triggered / faults to be reactivated as a result of stresses of hydraulic fracturing or wastewater injection.

### Effectiveness Descriptors

<table>
<thead>
<tr>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
</table>

#### Geological Properties
1. There are **no** significant faults (as characterised based on length and surface area against analogues to other sites where triggered seismicity has occurred) in and around the production zone that are expected to be reactivated by the stresses of hydraulic fracturing or wastewater injection.

2. For faults in or around the production zone geology, pre-existing stress states, frictional properties, stability, orientation are **not** conducive to reactivation by the stresses of hydraulic fracturing or wastewater injection resulting in triggered seismic events based on analogues to other sites where triggered seismic events have occurred.

3. For faults in the storage complex geology, pre-existing stress states, frictional properties, stability, orientation are **potentially** conducive to reactivation by the stresses of CO2 injection resulting in triggered seismic events based on analogues to other sites where triggered seismic events have occurred.

### Site Selection Studies and Site Surveys
- Site Selection Studies and Site surveys have **not** provided data on the significance of pre-stressed fault / fracture network in terms of its likelihood to be triggered by operational activities resulting in seismicity above regulatory requirements.
- The location of faults and fracture networks in and around the production zone are **not well** known and mapped to a sufficient level of detail/resolution.

### Seismic Survey
- Seismic surveys have not been carried out, or surveys which have been carried out have significant shortcomings against good practice.
- The seismic survey may be more than ten years old.

### Sub-surface Fault Modelling
- Sub-surface fault modelling has **not** been carried out or is not capable of predicting the presence of sub-surface faults and / or there are significant shortcomings against accepted good practice.
Table 41: SECURE -05 Threat 3 – Engineering Barrier 1

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
<th>Site Selection Studies and Site Surveys</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Site Selection Studies and Site surveys have provided data on the significance of pre-stressed fault / fracture network in terms of its likelihood to be triggered by operational activities resulting in seismicity above regulatory requirements.</td>
</tr>
<tr>
<td></td>
<td>- The location of faults and fracture networks in and around the production zone are known and mapped to a high level of detail/resolution</td>
</tr>
<tr>
<td></td>
<td>- Mechanical response of fault / fracture network to fluid pressure has been determined from the intrinsic fracture properties and the in-situ stress conditions [as detailed in March et al. - Numerical computation of stress-permeability relationships of fracture networks in a shale rock, Ref. 47].</td>
</tr>
</tbody>
</table>

Seismic Survey
- The degree of fault / fracture development in and around the production zone is well understood.
- The seismic survey was carried out recently, within the last two years, using modern techniques, methods, and technology
- Seismic survey reports acknowledge the limitations of the technology in the identification of fault orientation, fault throw and the definition of target zones and provide conclusions within acknowledged error bounds, supported by risk assessment

Sub-surface Fault Modelling
- Sub-surface fault modelling has been carried out capable of predicting the presence of sub-surface faults (through detailed surface mapping, development of validated geological models, and the data from seismic reflection surveys) at a high resolution to enable accurate comparison with operational data. Exemption available (Medium descriptor applies) where Seismic Surveys have fully mapped the entire primary seal to a high level of detail/resolution.
- Wellbore imaging logs, mud logs, and (if practical) wellbore core can be used to characterize the degree of fault development observed at the Wellbore [Ref. 4] Imaging logs can identify large features, and core and mud logs can be used to identify the presence of cataclasite. These have been carried out and provide an input into site characterisation.

Site Selection Studies and Site Surveys
- Decision making for positioning of injection wells, takes into consideration outputs from wellbore imaging logs, mud logs, or wellbore core, the presence and criticality of pre-stressed faults and fracture networks in and around the production zone. This process is supported by risk assessment, which provides a high confidence regarding the conclusions of the decision making process.

Sub-surface Fault Modelling
- Sub-surface fault modelling has been carried out capable of predicting the presence of sub-surface faults (through detailed surface mapping, development of validated geological models, and the data from seismic reflection surveys) at a low resolution to enable some comparison with operational data and has been carried out based on accepted good practice, but has some weaknesses or areas of omission. Exemption available where Seismic Surveys achieve the descriptor for low level of uncertainty.
- Wellbore imaging logs, mud logs, and (if practical) wellbore core can be used to characterize the degree of fault development observed at the Wellbore [Ref. 4] Imaging logs can identify large features, and core and mud logs can be used to identify the presence of cataclasite. These have been carried out and provide an input into site characterisation.

Site Engineering 102
- Decision making for positioning of injection wells, takes into consideration outputs from wellbore imaging logs, mud logs, or wellbore core, the presence and criticality of pre-stressed faults and fracture networks in and around the production zone. This process is supported by risk assessment, which provides a sufficient confidence regarding the conclusions of the decision making process.
### Site Selection Studies and Site Surveys
- Site Selection Studies and Site surveys have not provided data on the significance of pre-stressed fault / fracture network in terms of its likelihood to be triggered by operational activities resulting in seismicity above regulatory requirements.
- The location of faults and fracture networks in and around the production zone are not well known and mapped to a sufficient level of detail/resolution.

### Seismic Survey
- Seismic surveys have not been carried out, or surveys which have been carried out have significant shortcomings against good practice.
- The seismic survey may be more than ten years old.

### Sub-surface Fault Modelling
- Sub-surface fault modelling has not been carried out or is not capable of predicting the presence of sub-surface faults and / or there are significant shortcomings against accepted good practice.

### Wellbore imaging logs, mud logs, wellbore core
- Wellbore imaging logs, mud logs, and wellbore core have not been carried out, or have been carried out without producing usable data for consideration in the site characterisation process.

### Site Engineering 102
- Decision making for positioning of injection wells, does not take into consideration outputs from wellbore imaging logs, mud logs, and wellbore core, the presence and criticality of pre-stressed faults and fracture networks in and around the production zone. This process may be supported by risk assessment, but this risk assessment is not considered to be suitable and sufficient.

### Barrier Description

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Good</strong></td>
<td><strong>Fair</strong></td>
</tr>
<tr>
<td><strong>Well Engineering:</strong> Positioning of wells / location of fracking / disposal in relation to known faults / fracture networks</td>
<td></td>
</tr>
<tr>
<td><strong>Variable Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Location of faults and fracture networks</td>
<td></td>
</tr>
</tbody>
</table>

**Design and Installation**

1. Well location(s) are selected such that all identified pre-stressed faults and fracture networks are a significant lateral distance beyond that which fracking pressure or injected wastewater is expected to reach - see barrier for extent of fault and fracture development.
2. There is no potential for the injection pressure front to affect identified pre-stressed faults and fracture networks.

**Note from semi-quantitative workshop:** Only significant relocations would have an effect on pressure front and difficult to predict what effect that would be.

### Effectiveness Descriptors

<table>
<thead>
<tr>
<th><strong>Design and Installation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Well location(s) are selected such that critical pre-stressed faults and fracture networks are a significant lateral distance beyond that which fracking pressure or injected wastewater is expected to reach - see barrier for extent of fault and fracture development.</td>
</tr>
<tr>
<td>2. Well location(s) are selected such that all other pre-stressed faults and fracture networks are at the lateral limits at which fracking pressure or injected wastewater is expected to reach - see barrier for extent of fault and fracture development.</td>
</tr>
</tbody>
</table>

**Design and Installation**

1. Injection well location(s) are not selected such that identified pre-stressed faults and fracture networks are beyond or equal to that which fracking fluid or injected wastewater is expected to reach - see barrier for extent of fault and fracture development. Fracking pressure or injected wastewater is expected to reach pre-stressed faults, which may lead to reactivation of the faults resulting in potential seismic activity.
Figure 77: SECURE -05 Consequence 1 – Full Context

- Induced / Triggered Seismicity
- Depth of induced seismic activity will limit intensity (peak partial velocity) of movement at surface. BGS research indicates that geomechanical properties of shallow geology is more a determining factor on the extent of ground movement than depth.
- Monitoring: Accurate monitoring of seismicity and comparison against accurate baseline seismicity to alleviate concerns of local population.
- EBA
- Social Engagement: Site social characterisation, and early engagement and partnership development with publics, including participatory monitoring.

- Increased likelihood of existing fault networks at greater depths (e.g., in basement) leads to the potential for triggering a seismic event of greater magnitude.

- SSS&SS
  - Depth of Production Zone
  - Separation (horizontal or vertical) of Production Zone from Receptors

- See left hand side barriers for pre-stressed fault.
Table 42: SECURe -05 Consequence 1 – Geological Barrier 1

<table>
<thead>
<tr>
<th>Uncertainty Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
</tr>
<tr>
<td>Site Selection Studies and Site Surveys</td>
</tr>
<tr>
<td>1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site surveys have provided data on the location of induced seismicity from operations.</td>
</tr>
<tr>
<td>2) The mechanical response of the rock formations to fluid pressure has been determined from the intrinsic rock formation properties and the in-situ stress conditions.</td>
</tr>
<tr>
<td>3) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5.</td>
</tr>
</tbody>
</table>

| Medium                  |
| Site Selection Studies and Site Surveys |
| 1) Site selection studies have been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site surveys have provided data on the location of induced seismicity from operations. |
| 2) The mechanical response of the rock formations to fluid pressure has been determined from the intrinsic rock formation properties and the in-situ stress conditions. |
| 3) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a low resolution based on ISO 27914:2017 Section 5, but has some weaknesses or areas of omission. |

| High                    |
| Site Selection Studies and Site Surveys |
| 1) Site selection studies have not been undertaken prior to operation to characterise nearby leakage pathways. Site Selection Studies and Site surveys have NOT provided data on the location of induced seismicity from operations. |
| 2) The mechanical response of the rock formations to fluid pressure has NOT been determined from the intrinsic rock formation properties and the in-situ stress conditions. |
| 3) And / or geomechanical analysis, geochemical analysis and geological analysis has not been conducted based on ISO 27914:2017 Section 5. |

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>Fair</td>
</tr>
<tr>
<td>Depth of induced seismic activity will limit intensity (peak partial velocity) of movement at surface - BGS research indicates that geomechanical properties of shallow geology is more a determining factor on the extent of ground movement than depth</td>
<td></td>
</tr>
</tbody>
</table>

**Geological Properties**
1) The vertical distance from the surface to the production zone results in the intensity of movement at the surface due to seismicity below regulatory thresholds |
2) The relative distances between the production zone and potential receptors results in the intensity (peak partial velocity) of the movement near the identified receptors due to seismic activity below regulatory thresholds, however this may change with time / operation |

**Variable Parameters**
- Depth of Storage Reservoir |
- Separation (horizontal or vertical) of Storage Complex from Receptors
Figure 78: SECURE-05 Consequence 2 – Full Context

- Induced / Triggered Seismicity
- Monitoring: Seismicity Monitoring
  - Seismic Monitoring 101
- Operational Strategy: Hydraulic Fracturing Strategy - prevents damage to well and includes testing and any necessary repair following each fracturing stage
- Well Engineering: Positioning of wells / location in relation to other active wells - minimum separation distance adhered to
  - Site Location and Design
  - Location of other active wells
- Corrective Action: Repair well / replace components, e.g. tubing, liner, remediation fluid
  - Remediation of well
- Damage to Well Integrity / Disruption to production
- See SECURE-01 and SECURE-03 consequences and right hand side barriers

Pre-fracturing Injection Tests
Define Operational Strategy
Strategy Correction based on Monitoring
Casing test and repair between fracturing stages
Volume of injected fluid
Volume of flow back fluid
Injection rate
Flow back rate / Recovery time
Seismicity
Well Design and Integrity
Table 43: SECURE-05 Consequence 2 – Engineering Barrier 1

<table>
<thead>
<tr>
<th>Barrier Description</th>
<th>Effectiveness Descriptors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Good</td>
</tr>
</tbody>
</table>
| Well Engineering: Positioning of wells / location in relation to other active wells - minimum separation distance adhered to | Design and Installation | 1) The positioning of wells / location in relation to other active wells is such that damage to existing well by induced / triggered seismicity is unlikely to occur Site Selection Studies and Site Surveys
2) Site engineering to position wells is not based on modelling of fluid behaviour in the storage complex
3) And / or geomechanical analysis, geochemical analysis and geological analysis has not been conducted based on ISO 27914:2017 Section 5 | |
| Site Location and Design Location of other active wells | Design and Installation | 1) Site surveys have been undertaken to characterise nearby operations and receptors. Site Selection Studies and Site Surveys have provided data on the location and vulnerability of operations and receptors, including active wells. 2) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5 | |
| Variable Parameters | Design and Installation | 1) Site surveys have been undertaken to characterise nearby operations and receptors. Site Selection Studies and Site Surveys have provided data on the location and vulnerability of operations and receptors, including active wells. 2) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a low resolution based on ISO 27914:2017 Section 5 | |

Uncertainty Descriptors

Site Selection Studies and Site Surveys
1) Site surveys have been undertaken to characterise nearby operations and receptors. Site Selection Studies and Site Surveys have provided data on the location and vulnerability of operations and receptors, including active wells.
2) Geomechanical analysis, geochemical analysis and geological analysis has characterised subsurface features at a high resolution based on ISO 27914:2017 Section 5

Site Engineering 105
3) Positioning of wells / location of hydraulic fracturing / gas production in relation to potential operations and active wells has been carried out based on detailed environmental impact assessment, including detailed subsurface source-pathway-receptor models.

Low

Medium

High
Please refer to Table 42 for Geological Barrier: Depth of induced seismic activity will limit intensity (peak partial velocity) of movement at surface - BGS research indicates that geomechanical properties of shallow geology is more a determining factor on the extent of ground movement than depth.
Please refer to Table 40 for Geological Barrier: Geological Properties: Degree of fault zone development and nature of faults reduces likelihood of significant seismicity
Figure 81: SECURE-05 Consequence 5 – Full Context

- Induced / Triggered Seismicity
- Monitoring: Advanced Traffic Light System (TLS) monitoring of micro seismicity (magnitude and location e.g. unexpected fault activation) and comparison against predictive models to determine whether more significant seismic events would be likely to occur.
- Social Engagement: Site social characterisation, and early engagement and partnership development with public, including participatory monitoring.
- Seismic event above regulatory threshold halts production - economic impact.
- Liaison with Regulator.
- EBA: Seismic Monitoring 101, Advanced TLS, Predictive Modelling, Location of faults and fracture networks, Seismicity.
Appendix B  BOWTIE METHODOLOGY

Bowtie analysis is a recognised risk assessment tool [Ref. 44] that involves building a bowtie diagram, usually in a workshop environment. It is used to depict the relationships between the causes of unwanted events, the escalation of such events to a range of possible outcomes, the measures preventing the event from occurring and the measures in place to mitigate the consequences. Figure 82 presents a representation of a bowtie diagram to illustrate the various elements along with definitions of the key elements and terms.

The unwanted event is shown in the centre of the diagram, with causes on the left and outcomes, or ultimate consequences, on the right. Prevention measures sit on the left of the diagram between causes and the (top) event; they can either prevent the cause in its entirety, or prevent the cause from resulting in the central event. Mitigation measures sit on the right of the diagram between the event and the consequences and only come into play once the unwanted event has occurred. Mitigation measures can either prevent the specific consequence from occurring all together or reduce the severity (frequency and/or consequence) of its impact in some way [Ref. 11].

Figure 82 illustrates the logical progression of the bowtie representation from left to right; threats lead to the top event, which leads to consequences. Notwithstanding this logical basis, reviewers should not apply this too strictly or literally. For example, it is possible for prevention barriers to prevent a threat from occurring, as well as preventing a top event. It is also possible for mitigation barriers to reduce the severity of a consequence, without preventing it from occurring altogether.

When analysing subsurface unconventional hydrocarbon production, the shale gas, fracturing fluid and flowback water are categorised as a hazard (i.e. something with the potential to cause harm). If the shale gas is released, it has the potential to cause harm (e.g. by asphyxiating people who are engulfed by a cloud of shale gas, exposure to NORM / toxic effects of additional substances in the shale gas, contamination groundwater sources and potential ignition of hydrocarbon release can lead to fire/explosion).

Hazards normally do not cause harm because they are kept under control. However, if control of the hazard is lost, an initial incident will occur – this is the unwanted event shown at the centre of the bowtie diagram. Preventive controls to this release are located on the left side of the bowtie diagram and mitigation controls (e.g. to the environmental damage) are located on the right. Controls can be, for example, natural geological barriers, engineered barriers, operating strategies, monitoring, and intervention strategies. For subsurface unconventional hydrocarbon production, the unwanted event in the centre of the diagram may be shale gas release from the shale production zone, such that barriers associated with the presence of fault and fractures that prevent release from the production zone are considered on the left hand side of the bowtie and geological layers above the production are considered on the right hand side of the bowtie.

Circumstances may arise which undermine a preventive or mitigation control and reduce its effectiveness; these are recorded on the diagram as degradation factors (also sometimes called escalation factors). Degradation factors are, in turn, managed by further control measures.

Once a bowtie diagram has been constructed, additional data can be included on the diagram elements to increase the understanding or to provide specific information to differing groups of users. Such additional information is referred to as meta-data and may, for example, include the effectiveness or uncertainty of a barrier, the likelihood of a cause or the magnitude of a consequence.
Figure 82: Bowtie Diagram Schematic and Definitions

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazard</td>
<td>Something that has the potential to cause harm to something of concern.</td>
</tr>
<tr>
<td>Top Event</td>
<td>The ‘release’ of the hazard. The initial consequence that occurs when control of the hazard is lost. Also known as the ‘zero consequence event’.</td>
</tr>
<tr>
<td>Threat</td>
<td>Causes of loss of control of the hazard, which can lead to the top event.</td>
</tr>
<tr>
<td>Consequence</td>
<td>An event or chain of events that result from the release of a hazard i.e. what happens when the top event progresses.</td>
</tr>
<tr>
<td>Prevention Barrier</td>
<td>The protective measures that are existing or put in place to prevent threats from releasing a hazard.</td>
</tr>
<tr>
<td>Mitigation Barrier</td>
<td>The measures that limit the chain of consequences arising from a top event.</td>
</tr>
<tr>
<td>Degradation Factor</td>
<td>Specific conditions that can result in the failure or impairment (reduction in effectiveness) of a prevention or mitigation barrier. These in turn may be prevented or mitigated by degradation factor barriers.</td>
</tr>
<tr>
<td>Degradation Factor Barrier</td>
<td>The measures put in place which contribute to maintaining barrier effectiveness by preventing degradation of a barrier.</td>
</tr>
</tbody>
</table>
Bowtie Analysis - Unconventionals

SECURe Project

Barriers interrupt the progression from threat to top event (preventive barriers) or top event to consequence (mitigation barriers). In this way, bowties are related to the Swiss Cheese Model of Accidents Causation [Ref. 45] as shown in Figure 83. The holes in the Swiss Cheese represent weaknesses or potential failures of the barriers and these holes can be related to degradation factors in the bowtie model. The size of the holes relate to the significance of the degradation factors and the effectiveness of degradation factor barriers [Ref. 44]. Degradation factors can result in failure or impairment (reduction in effectiveness) of prevention or mitigation barriers. There are also degradation barriers in place, which are controls against the realisation of a degradation factor, noting that these may not always meet the criteria of a barrier (effective, independent, auditable).

Figure 83: Swiss Cheese Model [Ref. 45]

Objectives, Benefits and Uses of Bowtie Analysis

Bowtie analysis provides a means of analysing the possible causes of a release from a hydrocarbon production zone and the potential consequences should such a release occur in a qualitative and in-depth manner. It allows evaluation of the individual prevention and mitigation barriers planned to be in place to either prevent such a release from occurring, or to minimise the extent of the consequences of such a release.

The bowtie diagram provides a simple, visual demonstration of the way in which risks are managed, illustrating the preventive and mitigation barriers against their respective threats and consequences in a structured way. This highlights any areas where there is a gap or weakness in risk control which should be a focus for further analysis and/or action to improve the effectiveness of the barriers/control measures, or to provide additional barriers over and above those currently planned.

The diagram can be understood at all levels, including by non-risk specialists. It is a useful tool for communicating the various aspects of a particular hazard and the means by which it is managed in a clear, logical, and substantiated manner. This is especially useful in an emerging field such as sub-surface unconventional hydrocarbon production, where the level of risk perceived by the public can be significant, and the nature of the risks and how they are managed can be highly technical.

The process of developing the bowtie diagram also brings significant benefits, as the bowtie workshop provides an opportunity for all parties involved in the unconventional hydrocarbon production project to air potential problems and allows each discipline to appreciate how their decisions and plans can impact on planned risk controls and other areas of the project.

The bowtie workshop gives everyone the opportunity to review the existing barriers in place and to collectively identify any potential improvements. By aiding a clearer understanding of all aspects of how a particular risk scenario can occur and is managed, the bowtie directly contributes to more informed, and better, decisions being made.
The Center for Chemical Process Safety (CCPS) Concept Book for Bowtie Analysis [Ref. 44] states the following:

The development and appropriate use of bowtie barrier diagrams have the potential to significantly improve process safety. They do this by focussing on the operational aspects, clearly highlighting all important safety barriers, helping in the assessment of barrier adequacy, communicating this visually to all staff and contractors, and providing a framework to continually monitor the effectiveness of these barriers.

In this way bowtie diagrams encourage and facilitate the scrutiny of identified barriers; in effect, each bowtie barrier is a risk assessment in its own right. CCPS Concept Book for Bowtie Analysis [Ref. 44] continues:

Once constructed, the bowtie purpose is best used to support risk management and risk communication. The bowtie diagram can provide a clear graphical representation of the output of the risk assessment and management process (threats, consequences, barriers, and degradation controls) which is readily understood by people at all levels – from operational personnel and senior managers, to regulators and members of the public.

Therefore, the bowtie analysis technique provides benefits, both in the process of developing a bowtie (and the advantages afforded for barrier scrutiny) and the use of the complete, constructed bowtie as a communication tool. The bowtie provides a framework against which individual barrier analysis risk assessments can be addressed in context, facilitating both scrutiny and communication.

History of Bowtie Analysis

It is generally accepted that bowties were developed by Imperial Chemical Industries (ICI) in the 1970s, however, the exact origin of the technique is unclear. Shell is an example of an organisation that has integrated bowtie analysis into the analysis of Major Accident Hazards (MAHs) during the development of safety cases for both upstream and downstream facilities, and is widely acknowledged as being the first major company to do so [Ref. 44]. The CCPS has developed a Concept Book for bowties and process safety [Ref. 44]; CCPS Concept Books ‘address newer techniques in process safety that have not yet become accepted standard practice or where there is not yet industry consensus on the approach.’

The barrier concept, as depicted by the bowtie diagram, is becoming more common in regulatory regimes, and standards and guidance, provided by regulators and standards organisations, such as the American Petroleum Institute (API), the UK Health and Safety Executive (HSE), International Association of Drilling Contractors (IADC) and the Petroleum Safety Authority (PSA) in Norway [Ref. 44]. Bowties have been used extensively within CCS projects, for example, the Goldeneye, White Rose, Quest, Northern Lights and Acorn projects have all used bowties to aid in their understanding and demonstration of how project risks are being managed.

Bowtie Analysis and ALARP Demonstration

In addition to building the basic bowtie diagram, the analysis can be used to consider whether the controls’ effectiveness can be improved, or if there are additional controls that can be implemented, over and above those currently planned. Typically, the workshop team will be asked:

- Are company and industry standards and regulatory requirements complied with?
- Can the effectiveness of the existing controls be improved?
- Are there any more controls or risk reduction measures that can be implemented?

The analysis may go on to evaluate additional risk reduction measures in terms of the sacrifice (e.g. time, cost, difficulty) involved in implementing them and the benefit (e.g. from reduced consequences) gained by their implementation. On this basis, additional measures are rejected, recommended for implementation or carried forward for further analysis, and hence the bowtie analysis helps assure that the risk of unconventional hydrocarbon production is at levels which are ALARP.

The optimum number of controls on each bowtie branch is a balance between too many controls (which could incur excessive time and / or high costs to implement, or could cause operational difficulties), and too few controls (which could result in a relatively high risk of harm). When this balance has been reached, the risks associated with the hazard are reduced to ALARP levels.
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