D5.2

Methodology for quantitative modelling of CO2 storage containment risks

Organisation(s)	Risktec Solutions B.V.
Author(s)	Steve Pearson; Michael Kupoluyi
Reviewer	Andy Lidstone; David Cooper; Tine Larsen; Elin Skurtveit
Type of deliverable	Methodology
Dissemination level	Public
WP	5
Issue date	06/06/2022
Document version	3.0

Keywords:

Assessment, CO_2, Containment, Quantitative, Risk

Abstract

The current state-of-the-art for assessing CO_2 containment risk relies on qualitative or semi-quantitative methods using bowtie analysis or Layers Of Protection Analysis (LOPA). Whilst these are more than adequate for screening of sites, a fully quantitative method is desirable to support licensing and ongoing management of risk. Such a method would focus on the probabilistic failure of geological features; and would necessarily take full account of dependent failure of geological barriers, which is a failing of current methods, as well as consider explicitly the uncertainty in supporting failure and consequences data. Building on previous Carbon Capture and Storage (CCS) work and established techniques in the nuclear industry for the quantitative risk modelling of fission product release from containment and, separately, seismic hazards, the aim of this task is to develop and trial a suitable fully quantitative CO_2 containment risk evaluation method. This first issue provides an outline of the proposed methodology, which will be trialled, further developed and finalised during the course of the project.

TÜVRheinland®

Risktec

Report

Work Package 5, Task 5.3 Methodology for quantitative modelling of CO_2 storage containment risks

Prepared for – SHARP Project: Stress history and reservoir pressure for improved quantification of CO_2 storage containment risks

Document Number: RVO-02-R-01

Issue: 3.0

Date: 06th June 2022

risktec.tuv.com

Certificate Number 9783
ISO 9001

ISSUE RECORD

Issue	Date	Author Name	Reviewer Name	Approver Name	Revision History
1.0	28-Mar-22	Steve Pearson Michael Kupoluyi	Andy Lidstone David Cooper	BertJan Haitsma	First issue to the SHARP Project (WP5)
2.0	11-Apr-22	Michael Kupoluyi	Tine Larsen Elin Skurtveit Steve Pearson	BertJan Haitsma	Second issue to the SHARP Project, incorporating comments
3.0	06-Apr-22	Michael Kupoluyi	Elin Skurtveit Steve Pearson	BertJan Haitsma	Third issue to the SHARP Project, incorporating comments

DISTRIBUTION

Client Name	SHARP Project
File	Risktec Solutions Limited, Warrington, United Kingdom

CONTENTS

Distribution....3
Contents....4
Tables....4
Figures....5
Abbreviations....6
1 Introduction....8
1.1 Background....8
1.2 Objectives....11
1.3 Scope....11
2 Overview of Method....13
2.1 Introduction to CO_2 Release Risk....13
2.2 Overall Approach....13
2.3 Key Inputs....17
2.4 Deliverables....17
3 Literature Review....19
3.1 Approach....19
3.2 Summary of Main Findings....19
3.3 Implications for Proposed Methodology....19
4 Phase 1....21
4.1 Derivation of generic releases diagrams....21
4.2 Development of Generic Event Tree (ET) Modules....24
4.3 Refining Generic Releases Diagrams For Specific Case Studies....29
4.4 Adapting Generic Event Tree Modelling....30
4.5 Identification of Specific Data Requirements....30
4.6 Interim Reporting....30
5 Phase 2....32
5.1 Introduction....32
5.2 Data preparation....32
5.3 Population of model with data....33
5.4 Quantification of geological containment risks....34
5.5 Reporting....34
5.6 Updating of methodology....34
5.7 Production of supporting guidance....35
6 References....36
Appendix A Literature Review – Initial Sift....A.1
Appendix B Literature Review....B.1
B.1 Inputs....B.1
B.2 Current CCS Quantification Methods....B.3
B.3 Mitigation and Remediation....B.9

TABLES

Table 1: Deliverables....18
Table 2: Proposed Record of Generic Releases....24
Table 3: Example of Release Categories....27

Table 4: Example of Reduced Release Categories 27
Table 5: Derivation of Release Bands (Climate Change) 28
Table 6: Indicative Release Band Targets (Climate Change) 29

FIGURES

Figure 1: Overview of SHARP Consortium 8
Figure 2: Overview of work packages and their interdependency 9
Figure 3: Workflow for WP5, showing the interaction with other WPs 10
Figure 4: Generic Bowtie for the SHARP Project 11
Figure 5: Example of a Generic Releases Diagram 14
Figure 6: Example of a Containment Event Tree from the Nuclear Industry 15
Figure 7: Task 5.3 Subtasks 17
Figure 8: Examples of Schematic Releases Diagrams 22
Figure 9: North Sea cross-section examples 23
Figure 10: Proposed ET Module Structure 26
Figure 11: Examples from Gerstenberger et al (2009) of probability distributions for (a) CO_2 concentration in seawater and (b) CO_2 release into the atmosphere for a well leakage scenario B.4
Figure 12: Example from Hurst and Lidstone (2020) of Clay Swelling Effects Bowtie and Logic Tree B.5
Figure 13: Korre et al (2017) Polymer-gel injection technique: (a) success probability; (b) spider chart B.14

ABBREVIATIONS

Abbreviation	Description	Abbreviation	Description
AEAT	AEA Technology	MNA	Monitored Natural Attenuation
BBN	Bayesian Belief Networks	NGCL	National Grid Carbon Limited
AES	Alternative Evolution Scenarios	NRC	Nuclear Regulatory Commission
BS	British Standards	NUREG	US Nuclear Regulatory Commission Regulation
CBR	Center, Body, and Range	PCE	Polynomial Chaos Expansion
CCS	Carbon Capture and Storage	PDF	Probability Density Function
CPT	Conditional Probability Tables	PFD	Probability of Failure on Demand
CO_2	Carbon Dioxide	PGA	Peak Ground Acceleration
DECC	Department of Energy and Climate Change	PRES	Pressure
DETECT	Determining the risk of CO_2 leakage along fractures in caprocks using an integrated monitoring and hydro-mechanical-chemical approach	PROBAN	Probability Analysis
EC	European Commission	PS	Primary Seal
EN	European Standards	PSA	Probabilistic Safety Assessment
ET	Event Tree	PSHA	Probabilistic Seismic Hazard Analysis
ETA	Event Tree Analysis	RVO	Rijksdienst voor Ondernemend Nederland
ESL	Evidence Support Logic	RWB	Reliability Workbench
FEED	Front End Engineering Design	SHARP	Stress History and Reservoir Pressure
FEP	Features Events and Processes	SIL	Safety Integrity Level
FMEA	Failure Modes and Effects Analysis	SORM	Second Order Reliability Methods
FORM	Second Order Reliability Methods	SPSA	Seismic Probabilistic Safety Assessment
FTA	Fault Tree Analysis	SSC	Structures Systems and Components
FR	Fracture	SSE	Safe Shutdown Earthquake
GCS	Geologic Carbon Sequestration	SSHAC	Senior Seismic Hazard Analysis Committee
HEP	Human Error Probability	SVE	Soil Vapour Extraction
IAEA	International Atomic Energy Agency	TDI	Technically Defensible Interpretations
IE	Initiating Event	TE	Top Event
IEC	International Electrotechnical Commission	UK	United Kingdom
ISO	International Organization for Standardization	U.S.	United States of America
LOPA	Layers Of Protection Analysis	yr	Year
MAJ	Major	WP	Work Package
MCMC	Markov Chain Monte Carlo	ZEP	Zero Emissions Platform

MMV	Monitoring, Measurement and Verification

1 INTRODUCTION

1.1 Background

1.1.1 SHARP Project Overview

Carbon Capture and Storage (CCS) is now maturing in Europe and worldwide with several projects emerging. Hence, the need for safe and reliable CO_2 storage sites is accelerating and the assessment of largescale storage options is critical.

The SHARP project aims to develop and integrate models for subsurface stress, rock mechanical failure and seismicity to increase technical understanding and mature the technology for quantification of subsurface deformation, thereby leading to cost-efficient CO_2 subsurface risk assessment, monitoring and management. Work will be informed by case studies drawn from the Horda area (Norway), the Greater Bunter Sandstone area (UK), the Lisa formation (Denmark) and depleted oil and gas fields Nini (Denmark) and Aramis (Netherlands), but will also feed into emergent CO_2 injection and storage projects in India.

The project is being delivered by a multidisciplinary, transnational consortium of 16 partners from 6 countries (Figure 1). The key activities of the SHARP project include:

WP1 Developing basin-scale geomechanical models that incorporate tectonic and deglaciation effects, and use newly developed constitutive models of rock/sediment deformation;

WP2 Improving knowledge of the present-day stress field in the North Sea from integrated earthquake catalogues and a comprehensive database of earthquake focal mechanisms;

WP3 Quantifying rock strain and identify failure attributes suitable for monitoring and risk assessment using experimental data;

WP4 Developing intelligent methods for in situ monitoring of rock strain and failure, and fluid pressure and movement;

WP5 Quantifying containment risk using geomechanical models and observations from the field and laboratory;

WP6 Communicating technology development on containment risk to industry and regulators.

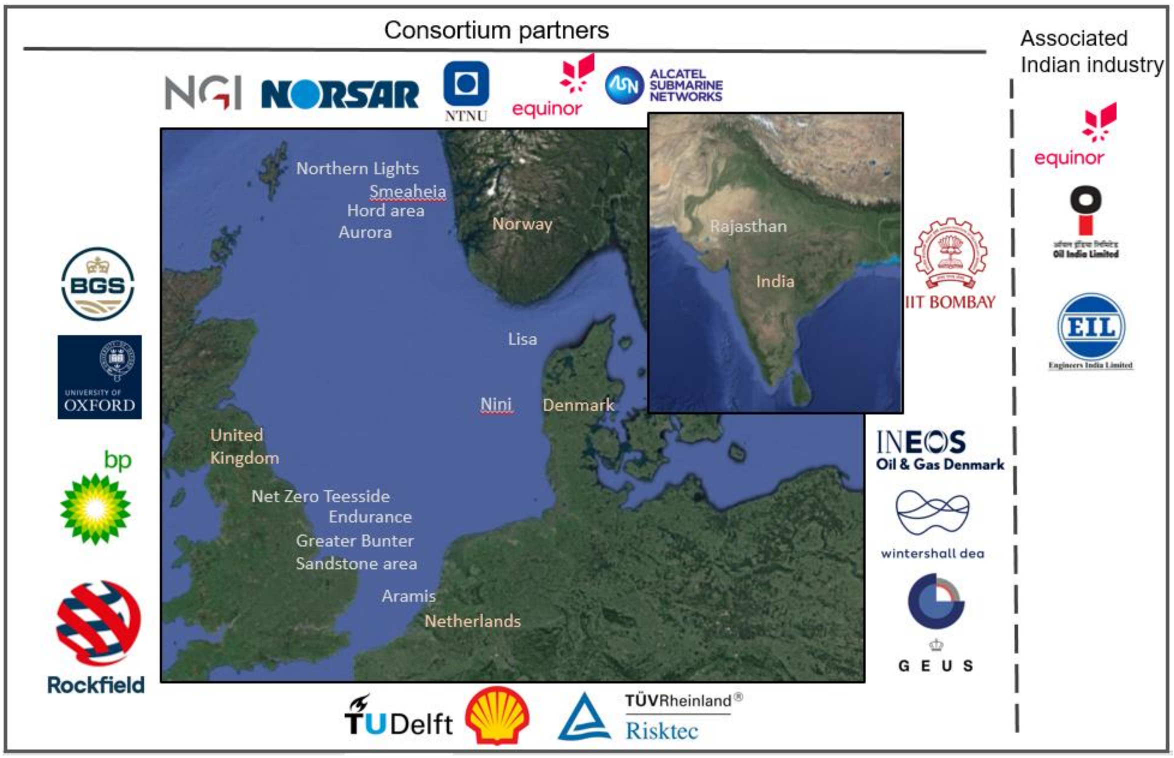


Figure 1: Overview of SHARP Consortium

1.1.2 Project Scope

The project consists of five strongly dependent work packages (WP1-5) and a project management and dissemination work package (WP6) (Figure 2). The subsurface stress state model will be improved by implementing tectonic, glacial and sediment compaction data (WP1) and define fault slip using new integrated earthquake catalogues (WP2). New experimental data will be combined with existing rock rheology site data to define rock strain and identify failure attributes suitable for monitoring and risk assessment (WP3). Finally, monitoring design will be "sharpened" based in the updated rock failure models providing input for right time and place monitoring systems (WP4) and containment risk quantified based on updated stress and failure models (WP5). The results of the project will be communicated to industrial stakeholders and regulators to foster impact creation (WP6).

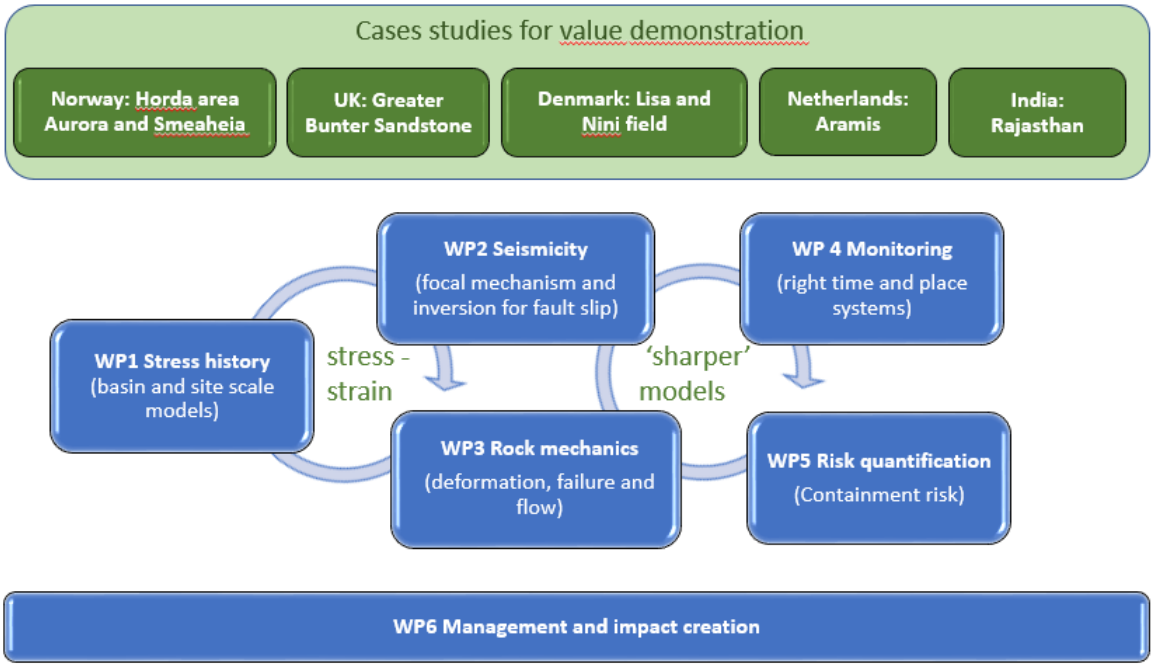


Figure 2: Overview of work packages and their interdependency

1.1.3 Work Package 5 Summary

In WP5, the knowledge and concepts developed throughout the project will converge and be integrated into a new interdisciplinary, quantitative methodology (Figure 3). The main objective of WP5 is to develop a new innovative approach to evaluate quantitatively the containment leakage risks associated with CO_2 sequestering, using interdisciplinary state-of-the art knowledge and experience to develop the methods. The results and methods developed in WP1 to WP4 will be implemented, as well as know-how from relevant projects and literature. The new methodology will include the uncertainty of all modelled parameters explicitly in the quantitative risk analysis and will be validated using site-specific case studies. For the Horda area (Aurora and Smeaheia) and Greater Bunter Sandstone, site containment risk will be addressed combining both geomechanical models and seismicity data. For the Lisa, Nini and Aramis cases, the focus will be on seismic containment risk, with an option for evaluation of geomechanical based risks for the Nini field.

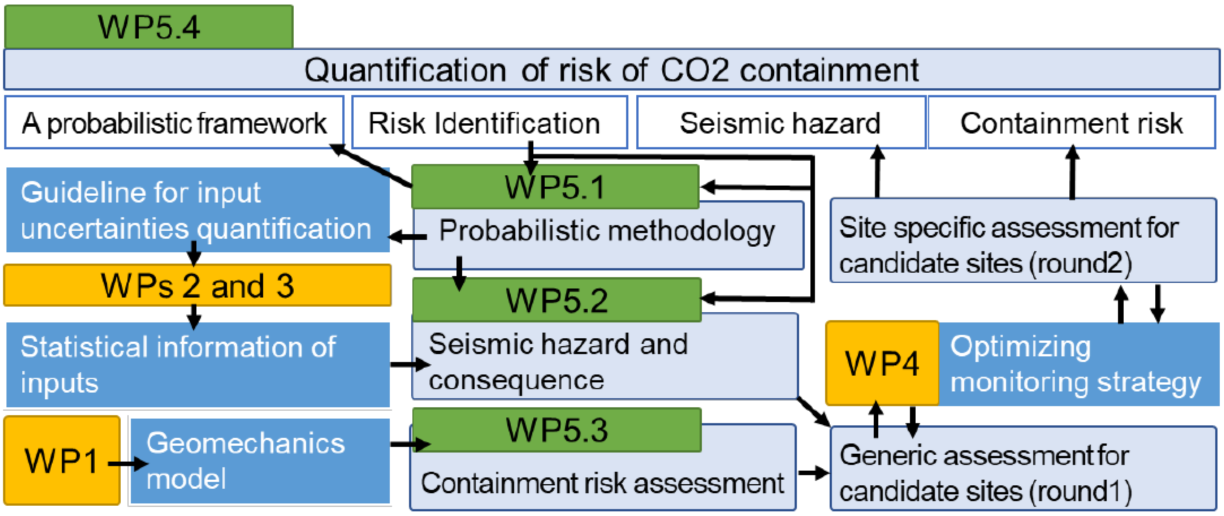


Figure 3: Workflow for WP5, showing the interaction with other WPs

WP5 Tasks 5.1 and 5.2 are summarised below for context, noting that Task 5.3 is the subject of this method statement and is introduced in the next sub-section.

Task 5.1: Probabilistic description of stress-field related containment integrity

A probabilistic methodology that can stochastically describe the containment integrity associated with the stress field (e.g. caprock integrity, fault stability, etc.) will be developed to include the uncertainties in the in-situ stress conditions, both actual and as modelled. A probabilistic framework using a reliability-based approach will be developed to quantify the impact of the uncertainties involved in stress modelling and mechanical properties on the integrity of the CO_2 sequestration site. The outcomes of an initial analysis will be used to re-evaluate the key stress modelling inputs/uncertainties and their influence on subsequent predictions. Understanding how potential risks develop as a result of specific modelling outcomes should help to identify and communicate parameters/techniques that should be accorded greater importance in the further work. A robust response surface method that can approximate reliably the implicit responses developed in WP1 to WP4 as explicit responses will be used.

Task 5.2: Seismic hazard and induced seismicity (U. Oxford, GEUS, NGI)

A systematic study of induced seismicity will be used to assess key controls on fault reactivation. Probabilistic seismic hazard analysis (PSHA) will be performed on the improved natural seismicity data from WP2. A method for evaluating the risk for induced seismicity will be developed based on natural seismicity, known/suspected induced seismicity, state of stress, rock rheology and known faults. Mohr-Coulomb stress modelling and fluid flow modelling will be carried out to assess controls on seismicity. Ground motion prediction equations will also be developed for sites.

A Bayesian change point approach is proposed to model changes in temporal rates, paralleling other similar studies in Oklahoma using induced seismicity due to waste water injection. This method can then be extended to develop a hazard informed traffic light scheme based on monitoring to allow operators a simple and effective way to manage risk due to induced seismicity.

1.1.4 Introduction to WP5 Task 5.3 - Quantitative modelling of C02 storage containment risks

The current state-of-the-art for assessing CO_2 containment risk relies on qualitative or semi-quantitative methods using bowtie analysis or Layers Of Protection Analysis (LOPA) (see for example, the summary of methods collated in support of the DETECT project, Hurst & Lidstone 2020). Whilst these are more than adequate for screening of sites, a fully quantitative method is desirable to support licensing and ongoing management of risk. Such a method would focus on the probabilistic failure of geological features; and would necessarily take full account of dependent failure of geological barriers, which is a failing of current methods, as well as consider explicitly the uncertainty in supporting failure and consequences data. Building on previous CCSU work and established techniques in the nuclear industry for the quantitative risk modelling of fission product release from containment and, separately, seismic hazards (e.g. IAEA 2010 and IAEA

2020), the aim of this task is to develop and trial a suitable fully quantitative CO_2 containment risk evaluation method.

1.2 Objectives

The overall WP5 objective is to develop a new innovative approach to evaluate quantitatively the containment leakage risks associated with CO_2 sequestering. Within this, the narrower objective of Task 5.3 is to develop and trial (using real case studies) a suitable fully quantitative CO_2 containment risk evaluation method.

1.3 Scope

1.3.1 Scope of Methodology

The scope of the methodology and associated containment risk modelling will cover the wholly geological aspects of the generic bowtie developed by the DETECT project, as depicted in Figure 4, which for illustration purposes assumes ideal barriers and an offshore location. This will include consideration of CO_2 leaks caused by stress/pressure, faults and fractures, induced seismicity and natural seismicity. The potential variation in geological features and their interplay will be informed by the case studies. As a minimum, one case study area will be modelled for each of the four types of causes.

The uncertainty in leak frequency and leak rate will be explicitly modelled, noting that the method for release categorisation of modelled leaks will, necessarily, remain flexible so that it can accommodate the range of consequence analysis available for the different sites. In practice, this may vary considerably in nature from judgement-based expert elicitation to 3D leak modelling.

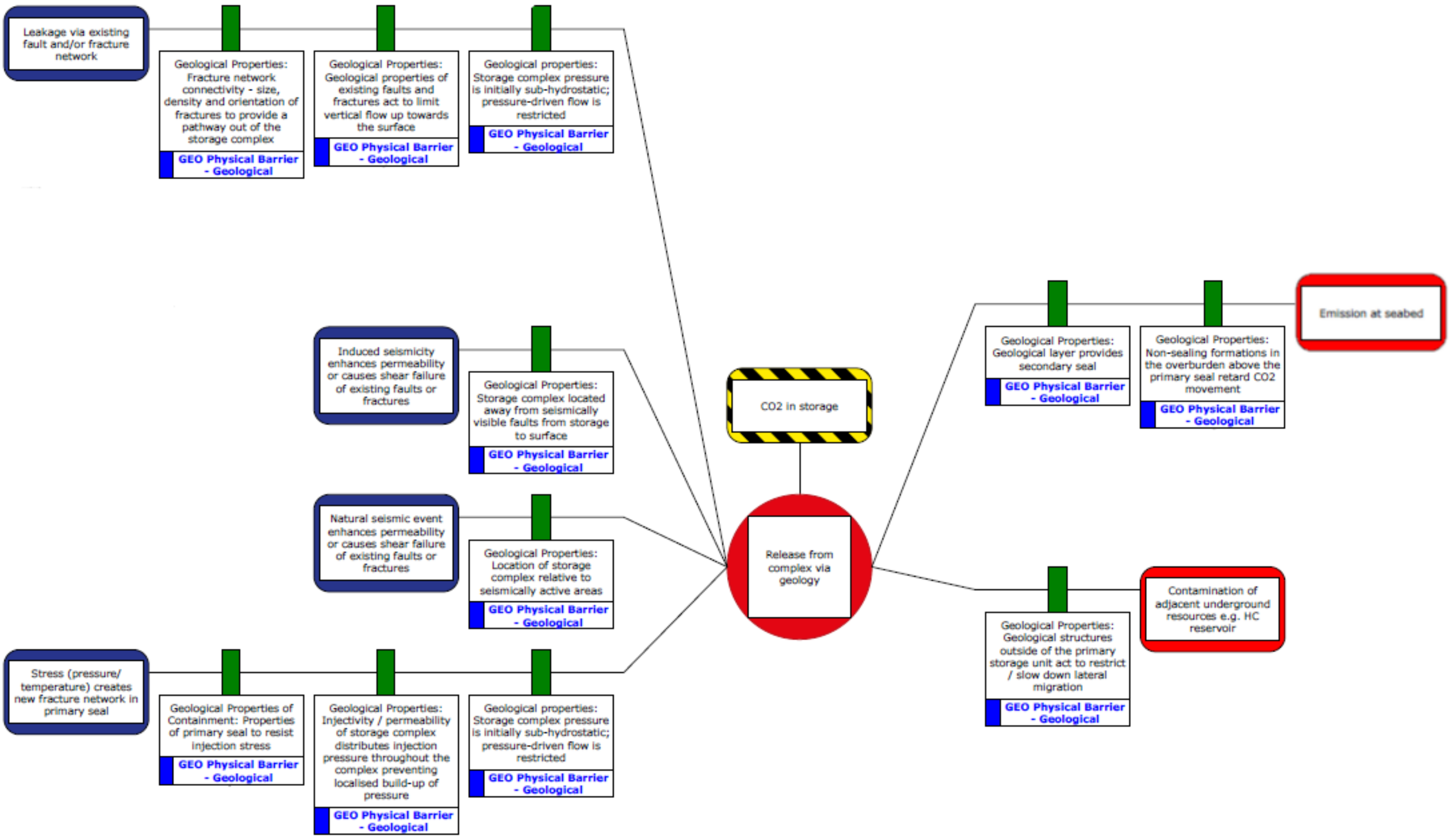


Figure 4: Generic Bowtie for the SHARP Project

1.3.2 Limitations and Exclusions

The scope of work is, by definition, limited to considering geological causes for loss of containment (noting that in principle, the methodology and tools could form the basis for a developing an integrated, quantified containment risk assessment that addresses all CO_2 leak risks).

Hazards considered are limited to those associated with CO_2 leaks from the storage reservoir (and do not include, for example, hazards from brine release). Modelling is terminated at predefined release bands, which act as a surrogate for classifying the ultimate consequences (with respect to the potential harm to the climate, people, marine life, aquifers etc.).

Whilst case studies will be used to 'road test' relevant aspects of the methodology (e.g. modelling techniques and data derivation), a complete geological containment risk model for each site will not be produced. Rather, modules will address well-defined site-specific aspects founded on the output of other work packages. For example, seismicity risk modelling may be covered in one case study, whereas pressure/stress failure modelling may be the subject of a separate case study for a separate site. (Note, however, that the resulting modules would provide a natural starting point for developing complete risk models.)

This first issue provides an outline of the proposed methodology, which will be trialled, further developed and finalised during the course of the project.

2 OVERVIEW OF METHOD

2.1 Introduction to CO_2 Release Risk

Risk[1] is a combination of the likelihood of an event and the severity of its consequences, both elements of which can be defined either qualitatively or quantitatively. In the case of CO_2 leaks from geological storage, the concept of risk can be explained by referring to the bowtie in Figure 4.

CO_2 leakage from the storage unit (i.e. the storage reservoir)[2] is the event at the centre of the bowtie. The cause branches on the left of the bowtie show ways by which CO_2 might leak from the storage unit (e.g. leakage along existing faults which cross the caprock (also known as the primary seal), injection-induced stress causing new fractures in the caprock or re-opening existing fractures). Each cause is denoted by a blue-framed box. Once the leak has occurred, the right side branches,show how the event could progress to reach the ultimate consequences (e.g. CO_2 released at the seabed, CO_2 emitted to atmosphere (not shown) or CO_2 contamination of an adjacent hydrocarbon reservoir or aquifer), denoted by red-framed boxes.

Each bowtie branch on the left may have a number of prevention controls, which for this work (which is confined in scope to geological causes) will be geological barriers, such as the ability of the primary seal (caprock) to withstand the pressure of injection, the (lower) storage pressure in the longterm or the effects of earthquake. Similarly, each branch on the right may have mitigation controls that will prevent or slow the release, such as a secondary seal or a low permeability geological layer, respectively. There may also be actions (not shown) that can be taken to limit a leak or its impact if it is detected (e.g. pressure relief).

Evidently, the frequency of any given leak pathway leading to its defined consequences depends on the successive failure of each barrier[3] from cause to ultimate consequence, each of which will have an associated probability of failure (and uncertainty). The associated rate of leakage beyond the storage complex also depends on the specific accident sequence and may be characterised by varying leak sizes (with associated uncertainties) according to the nature and severity of successive failures. Hence, in principle, we can quantify leak frequency versus leak size (with uncertainties) from both the storage unit and the storage complex to provide a 'Level 1' and 'Level 2' risk picture[4], respectively. Of course, we can go further and characterise the ultimate effects of varying magnitudes of leakage from the storage complex, which may be quite different in respect of their severity for people's wellbeing, marine life, ground water or climate change.

The proposed methodolgy, however, stops short of this 'Level 3' risk assessment, which relies on site-specific environmental impact assessment. In all cases (Level 1, 2 or 3), risk results would (ideally) be assessed against predefined acceptance criteria (i.e. frequency versus risk thresholds). Whilst of interest, this topic is also outside the scope of methodology.

2.2 Overall Approach

Work will be split broadly into two phases. During Phase 1, for each of the four fundamental causes relevant to the SHARP project (stress/pressure, faults and fractures, induced seismicity, natural seismicity), a generic CO_2 releases diagram will be derived that's consistent with geological aspects of the generic DETECT bowtie and suitably representative of key geological features (similar to Figure 5 below, which applies to faults, from Wu et al, 2021). Each diagram will be informed by relevant case studies and verified/refined by workshop, which will also consider common cause failures that might affect multiple release paths.

---

[1] This is in contrast to the term *hazard* which is the potential to do harm (e.g. to people or the environment).

[2] CCS terms used throughout are consistent with BS ISO 27914:2017. In this case, the term storage unit means the defined geological stratum into which CO2 is injected for storage, also referred to the storage reservoir). The term storage complex means the subsurface geological system extending laterally and vertically to encompass the storage unit and identified seals.

[3] This statement is strictly only true if barriers are independent, whereas in practice partial or wholly dependent failure of barriers may occur in some cases (e.g. primary and secondary seals may both be affected by induced or natural seismicity).

[4] This terminology is borrowed from the nuclear industry (e.g. IAEA, 2010). In this context Level 1 refers to releases from the storage unit, Level 2 is releases from the storage complex and Level 3 describes the ultimate impact.

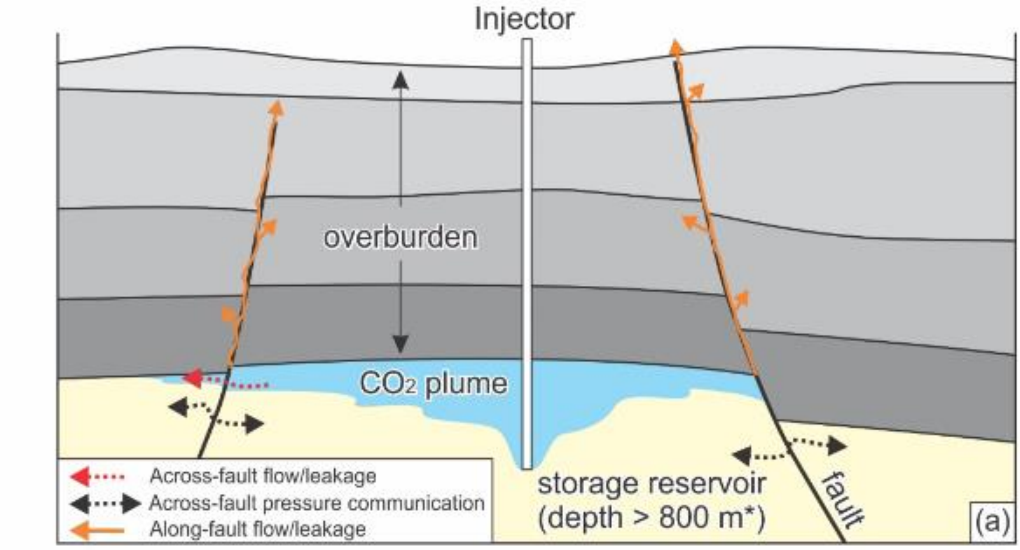


Figure 5: Example of a Generic Releases Diagram

By considering the possible variation in geology (e.g. extent/direction/number of faults, overburden stratification), the possible geomechanical failures and common cause failures, each diagram will be transposed into an event tree module[5]. Each module will include generic releases logic spanning (or where sensible, bounding) the possible combinations, with placeholders (events) for failures (including common causes) and release categories (consequences) (with data to be provided by Task 5.1, Task 5.2, and WP3, for example). This approach is similar to Level 2 Probabilistic Safety Assessment (PSA) used in the nuclear industry for fission product release modelling, which is a similar problem (IAEA, 2010). Figure 6 illustrates a typical containment event tree for a reactor design, courtesy of Cho et al, 2018.

---

[5] An event tree model comprises many event tree modules. Each module may comprise one or more ETs.

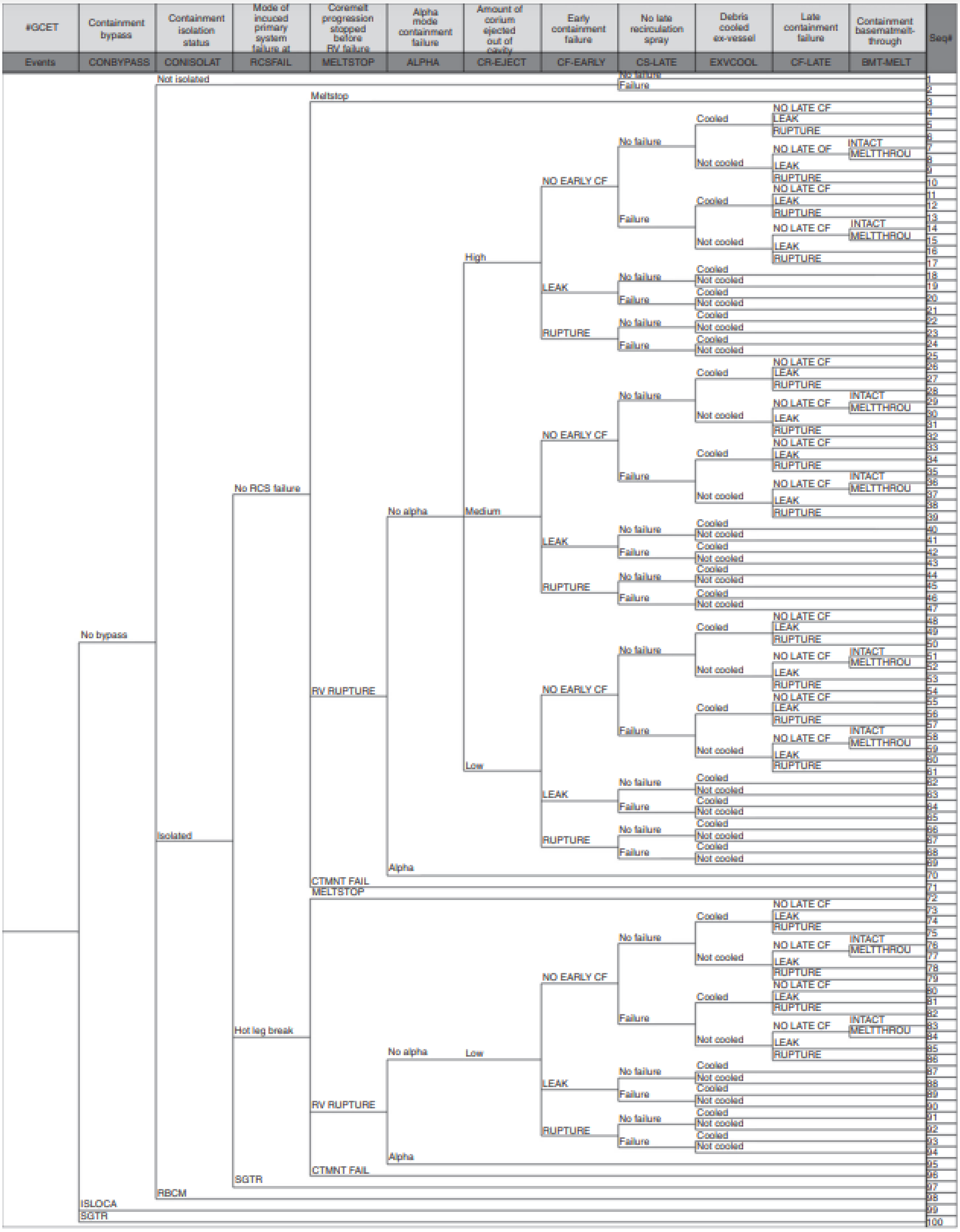


Figure 6: Example of a Containment Event Tree from the Nuclear Industry

Once the generic output of the risk model (minimal cut-sets[6]) has been validated, specific case studies will be used for trialling each module. For each specific case study, the relevant generic releases diagram(s) would be refined accordingly and verified by workshop to reflect critical geological failures. Corresponding generic event trees would be adapted to suit. This work will allow all specific best estimate and uncertainty data requirements for Phase 2 to be specified and agreed (e.g. geomechanical failure data, seismic hazard curve and fragilities, release categories requiring consequence analysis, treatment of uncertainty).

In Phase 2, the event tree modules would be populated with event and consequences data, including uncertainties, refining/manipulating supporting data as necessary (e.g. chopping up the seismic hazard curve, calculating seismic fragilities using stress vs capacity). Following validation of best estimate cases, Monte Carlo simulation would be used to evaluate the uncertainty.

As well as predicting the geological containment risk (and uncertainty) in terms of frequency vs defined CO_2 release bands, results will also allow the importance of geological features and failure modes to be quantified (e.g. as a percentage contribution to specific release categories), together with the sensitivity of importances to uncertainty. As such, results will inform WP4 concerning the risk-based benefit of different monitoring strategies. More generally, the proven methodology and associated user guidance will provide sites with a practical handbook for quantifying geological containment risk.

Specific sub-tasks necessary to support Task 5.3 are described in Figure 7 and detailed in subsequent sections.

---

[6] A cut-set (or accident sequence) is a series of successive event failures and successes leading to a defined consequence state. During the evaluation process, the model produces sets of cut-sets for each consequence state and minimises these using the laws of Boolean algebra to produce minimal cut-sets in each case.

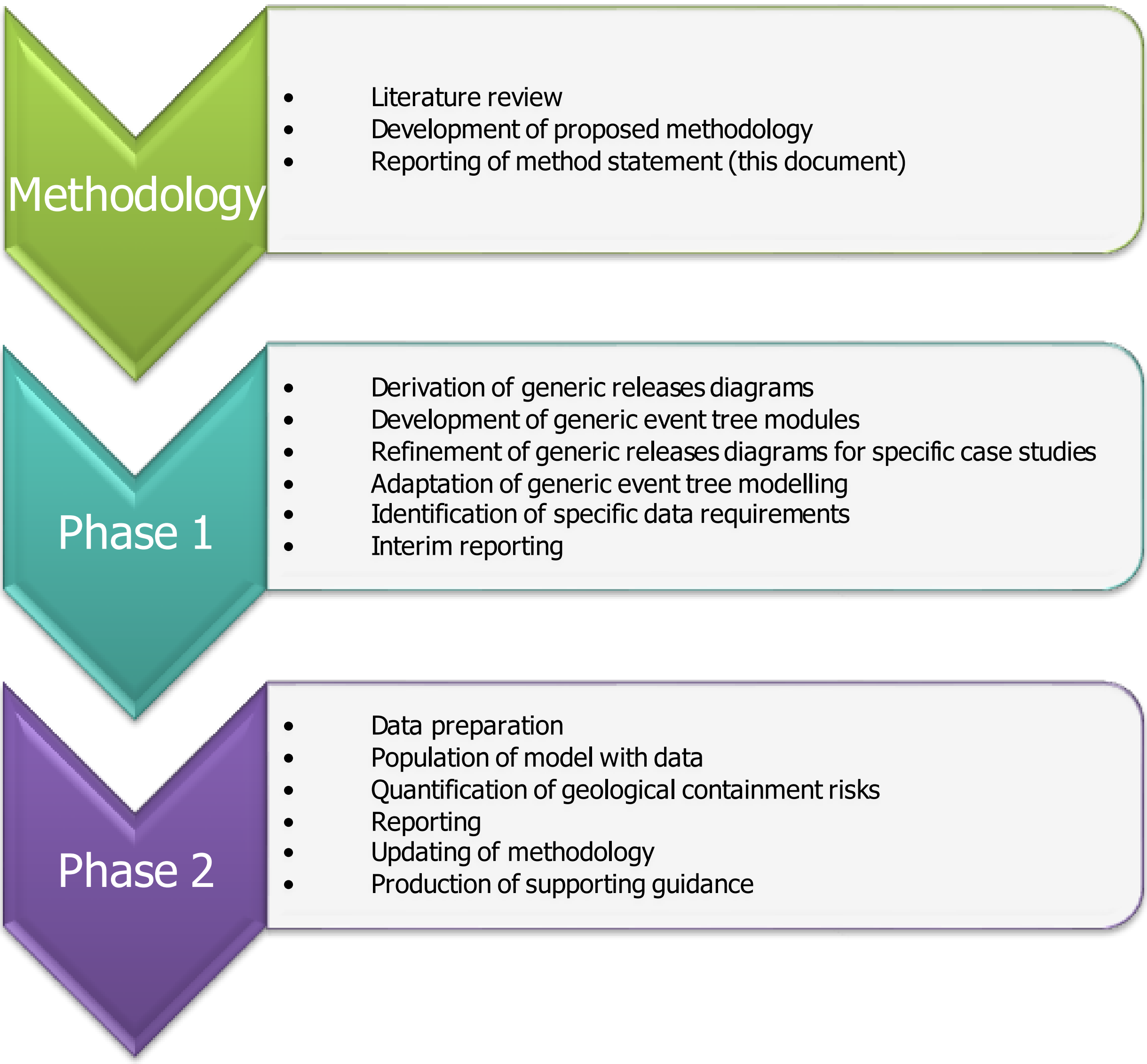


Figure 7: Task 5.3 Subtasks

2.3 Key Inputs

Key inputs needed to support this task from others in the project are:

- Refinement and acceptance of generic and site-specific release diagrams.
- Provision of failure and uncertainty data relating to site-specific geological barriers to release.
- Provision of seismic hazard curve(s), seismic fragilities for geological barriers and their associated uncertainty.
- Characterisation of bounding leak pathways in terms of CO_2 flow rates to inform release categorisation.

The specific data requirements are considered further in Section 4.5.

2.4 Deliverables

The key outputs from this task are summarised in the table below.

Table 1: Deliverables

ID	Description	Type of deliverable	Responsible partner
D5.2	Methodology for quantified CO_2 containment risk assessment (initial)	Report	Risktec/Equinor
D5.6	Quantified containment risk assessment Phase 1 (interim) Report	Report	Risktec
D5.7	Methodology for quantified CO_2 containment risk assessment (final); Quantified containment risk assessment Phase 2 (final); Guidance for quantified containment risk assessment.	Report	Risktec/Equinor

3 LITERATURE REVIEW

3.1 Approach

The DETECT project undertook a comprehensive literature survey in 2018, considering a total of 265 papers, many of which cover topics relating to CCS containment risk assessment. Hence, this was a natural starting point for Task 5.3's literature survey. In addition, the search was extended and narrowed to identify further sources of potential interest, including those more recently published, and those concerning the quantification of containment risk and its uncertainty. The results of this initial sift are presented in Appendix A, which summarises each paper and its relevance (if any) to Task 5.3 and the wider SHARP project. Papers of topical interest were reviewed in more detail and are discussed in Appendix B.

3.2 Summary of Main Findings

Based on its literature survey and the expertise of the assessors, the DETECT project summarises potential approaches to quantifying CCS geological containment risk as quantified bowties and Layers of Protection Analysis (LOPA) (Hurst & Lidstone 2020). The extended literature survey confirms that this is the case in the mainstream, but identifies two additional methods: namely Bayesian Belief Networks (BBN) and Markov Chain Monte Carlo simulation (MCMC).

BBN is a probabilistic graphical modelling tool that has been used to model the complex system interdependencies of CCS to determine containment risk (Gerstenberger et al., 2015; Gerstenberger et al., 2013). However, it was found that BBN could quickly become overly complex and intractable, especially for modelling seismicity (Gerstenberger et al, 2015). Neither does the output lend itself to effective communication with stakeholders and the general public (Gerstenberger et al., 2013).

Augustin (2014) proposes the use of Markov Chain Monte Carlo (MCMC) simulation for determining the average amount of surface leakage that a stakeholder could expect if they engaged in CCS. This involved the use of a Bayesian modelling technique to forecast leakage incidents, but relies on baseline data from industry, which is generally lacking.

The literature survey as a whole confirms that whilst event tree modelling[7] (and supporting approaches for obtaining data) is well established in the nuclear industry for containment risk assessment, where it is referred to as Level 2 PSA (see for example, IAEA, 2010), the technique has not yet been applied to model geological containment of CO_2, as is proposed here. A similar conclusion is drawn for the application of seismic PSA techniques (as exemplified by IAEA, 2010 for example). There are, however, a number of examples of event trees, decision trees and logic trees in the literature being applied in the context of CCS containment risk assessment (refer to Appendix B for further detail), albeit not in a fully integrated and quantitative manner in terms of risk evaluation. As such, the evidence supports the contention that the proposed methodology is innovative.

Unsurprisingly, the treatment of uncertainty features heavily in many papers reviewed, some of which may hold insights for detailed data analysis, noting that this aspect of quantification is the focus of Task 5.1 (refer to Appendix B for further detail), whereas Task 5.3 deals mainly with the question of how best to represent uncertainty in the risk model. Interestingly in this regard, Gerstenberger et al (2009) considers incorporating Monte Carlo simulation in logic trees to evaluate uncertainty, which is the approach used in modern PSA codes.

There are also potentially useful papers on mitigation options should a CO_2 leak occur (e.g. Manceau et al (2014) and Korre et al., 2017), which may augment project expertise on this subject and provide avenues for mitigation modelling. Allied to this are techniques for estimating the failure probability of leak detection for varying CO_2 surface fluxes (Yang et al, 2011).

3.3 Implications for Proposed Methodology

Currently there is no widely accepted standard for quantitative risk assessment of geological storage of CO_2. However, given the maturity of PSA techniques in the nuclear industry and associated software codes (notwithstanding the differences in setting), having surveyed the alternatives, a logical next step is to trial and adapt their use for quantitative risk assessment of geological CCS (essentially as originally envisaged).

---

[7] This includes linked fault tree-event tree modelling where the initiating events and top events of the event trees are modelled using fault trees – an approach that may be used in this work.

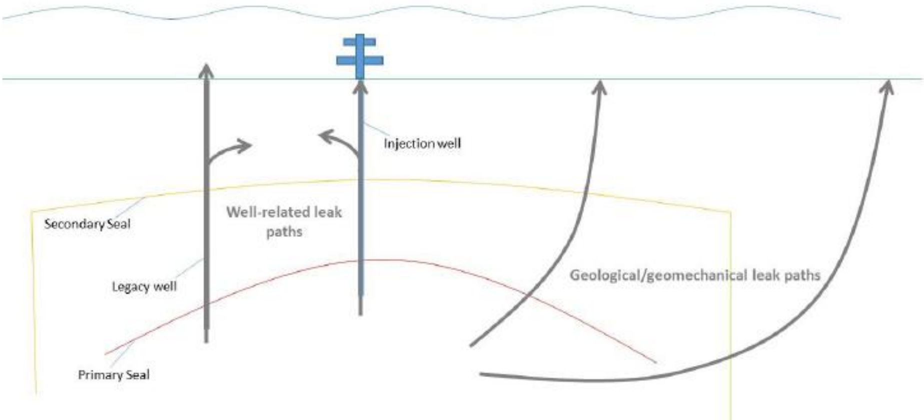
In terms of detailed implementation, however, regarding release diagrams, data analysis, treatment of uncertainty, detection and mitigation modelling, some of the literature reviewed in Appendix B may be useful in selecting specific approaches. Where this is the case, specific reference is made in text.

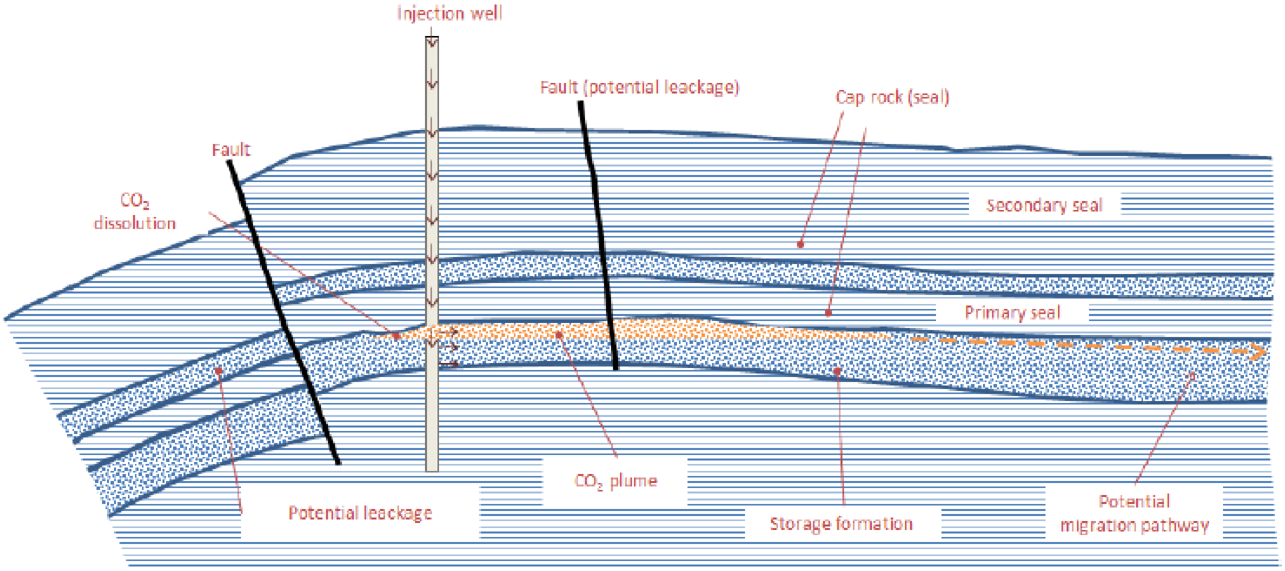
4 PHASE 1

4.1 Derivation of generic releases diagrams

4.1.1 Development of standard notation for release diagrams

For consistency and clarity throughout this work, it is proposed that a simple, standard notation will be developed to portray release diagrams. These will use standard colours, symbols and other features to denote the geology of an area in a 2D cross-section, differentiating between geological features such as strata of varying composition and permeability (highlighting those that act as primary and secondary seals, for example), and faults and fracture networks. Also clearly marked will be the injection well, the normal location of the CO_2 plume and for each scenario the potential leak path. Where a scenario is dynamic, such as fault slip, the diagram will clearly show the before and after condition. Figure 5 provides one example of a releases diagram (Wu et al, 2021). Other examples from the literature are captured below (Hurst & Lidstone, 2020; ZEP, 2019; unpublished Risktec source; Capture Power and National Grid, 2016).





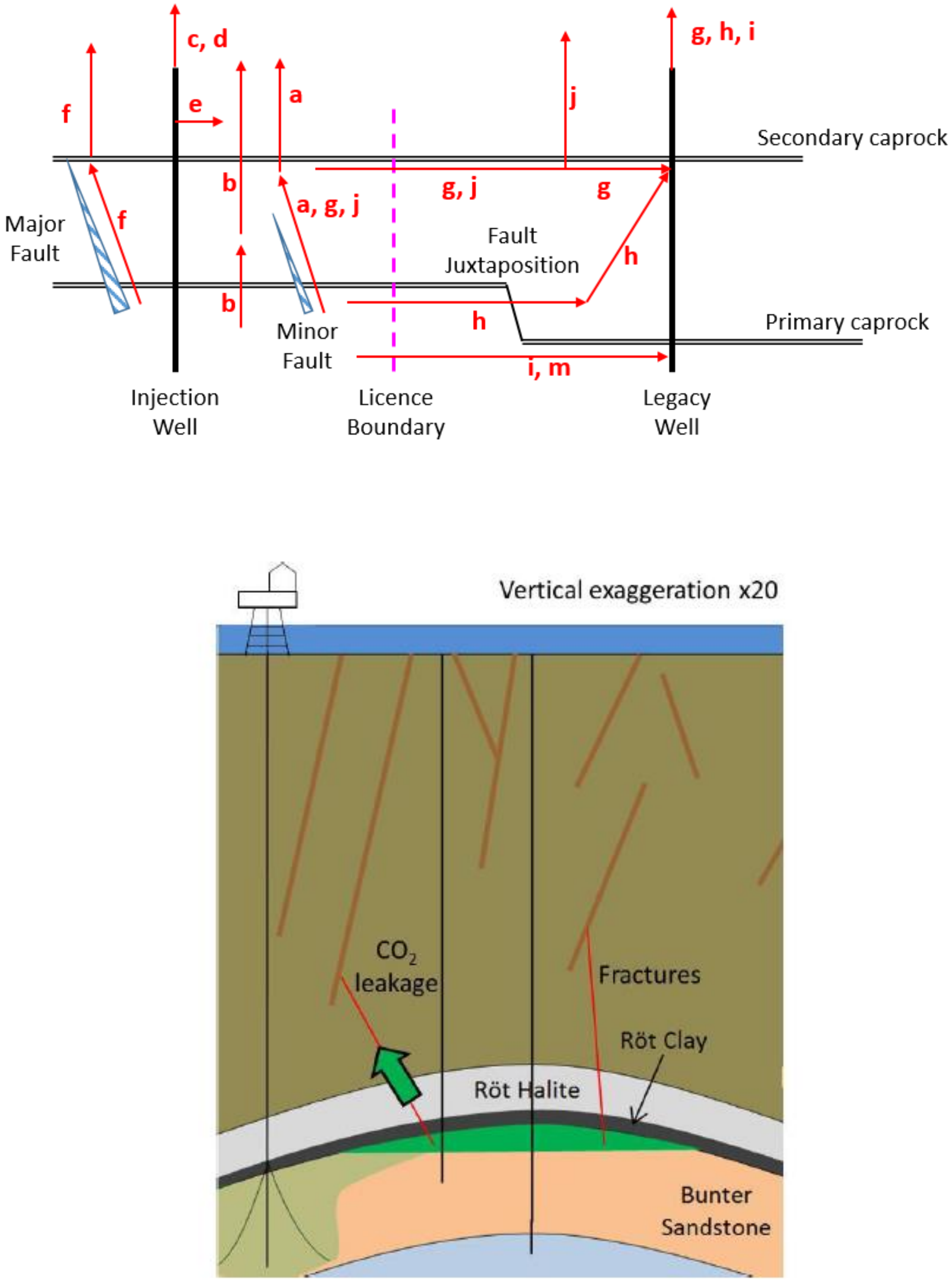


Figure 8: Examples of Schematic Releases Diagrams

4.1.2 Review and conversion of generic bowtie diagram from DETECT project

Generic release diagrams will be initially derived by considering the generic bowtie developed as part of the DETECT project (and illustrated in Figure 4). Separate release diagrams will be drawn for the normal condition in both the injection and storage phases of operation and then for each generic cause of an accident condition (stress/pressure, fault and fractures, induced seismicity and natural seismicity), which may be split into multiple diagrams (as required).

Each barrier in the bowtie will be associated with a specific geological feature (or features), and added to the release diagram to define the normal condition. The potential variation in geological features in terms of geometry and arrangement will be considered and where this might influence leak pathways significantly addition variants will be constructed.

The effect of each cause on CO_2 containment will be considered to derive the possible leak pathways, each of which will be uniquely labelled. Where dynamic effects may have varying extents geometrically speaking (such as fault slip), this will also be represented (either on the same diagram if practicable or using a separate version).

4.1.3 *Review of case studies to inform the derivation of idealised and representative geological features*

The derivation of generic release diagrams described above will also consider the specific geologies of the case study sites to help inform the scope for variation. Representative cross-sections from each area will be reviewed against each of the normal condition diagrams to confirm that they adequately cover the range of geological variation. If not, normal condition diagrams will be modified or supplemented accordingly, before using them to describe leak paths.). Examples from literature of the North Sea are captured below (Wu et al, 2021; Baig et al, 2019).

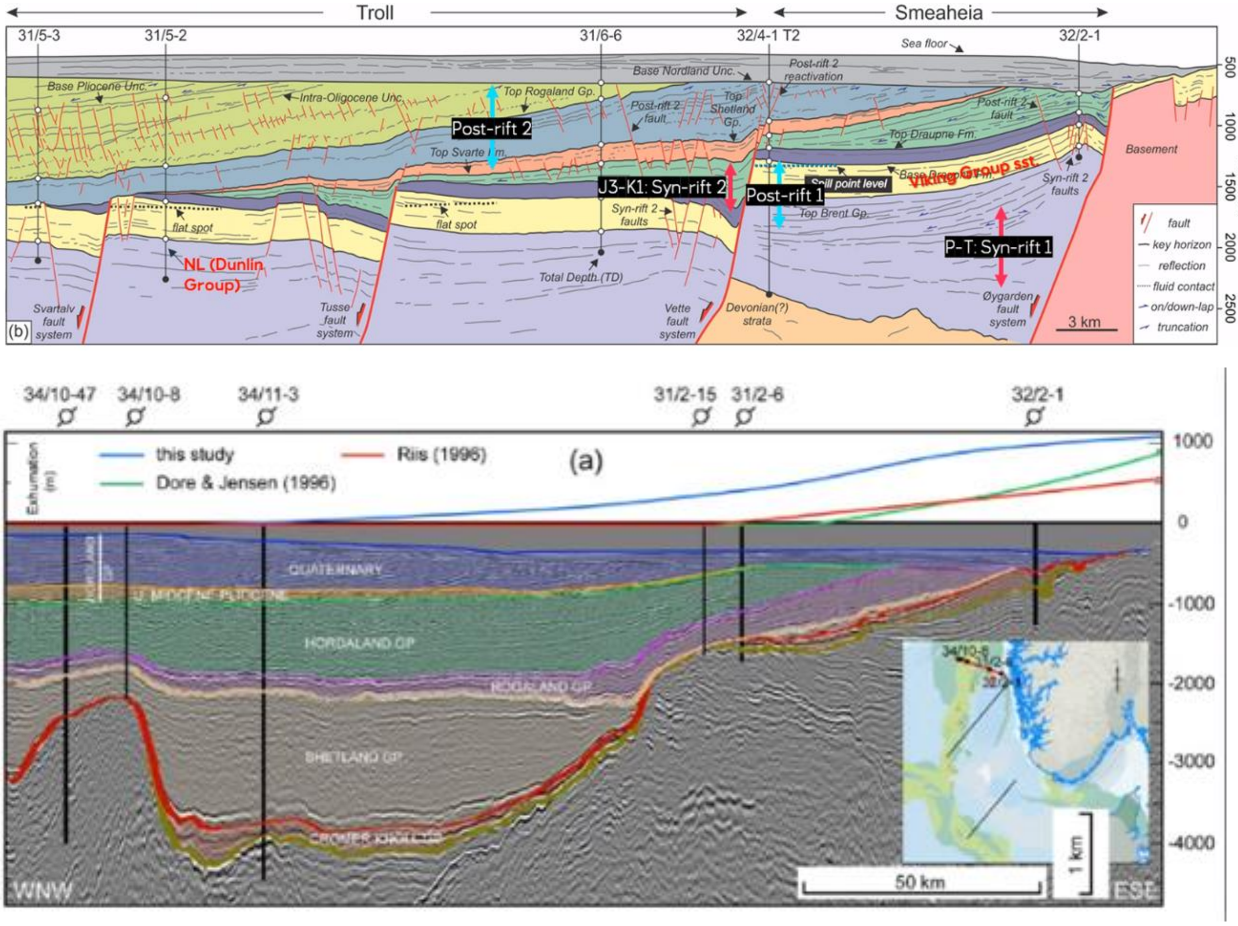


Figure 9: North Sea cross-section examples

4.1.4 *Workshop to refine and agree generic releases diagrams, and monitoring and leak mitigation options*

Once the set of initial release diagrams has been derived, they will be reviewed by relevant specialists from the project (with expertise in seismology, geomechanics, monitoring, leak mitigation) in a collaborative workshop setting to:

- Review all identified leak causes and confirm their completeness, or otherwise identifying (and agreeing) further causes or sub-causes for subsequent consideration;
- Identify/confirm all critical failure modes, together with a qualitative description of their nature and severity;

- Identify/confirm all subsequent barriers to environmental release, with a qualitative description of their possible failure modes, the nature of failure and its severity;
- Identify the potential for common cause or common mode failure of subsequent geological barriers;
- Refine and agree each normal and releases diagram as generically representative, both in terms of geology and critical leaks paths;
- Identify monitoring and leak mitigation strategies (if any) for each critical leak pathway identified.

With respect to the latter, WP4, which is examining monitoring strategies, will feed in here. In terms of leak mitigation strategies, literature review (in particular, Mancea et al, 2014, which presents a comprehensive overview) identifies a number of potentially available options[8], including:

- Pressure relief in the storage formation (e.g. stopping injection if active, or brine extract);
- Hydraulic barriers (e.g. injecting brine into an overlying aquifer);
- In situ CO_2 plume dissolution and residual trapping (e.g. by brine injection);
- Ex situ CO_2 disolution and re-injection of saturated brine;
- CO_2 back production (which may be preferable to an uncontrolled leak to the seabed, for example);
- Breathrough technologies, such as injected gels, nanoparticles and biofilms, to block leak paths.

The finalised and agreed set of generic releases diagrams will, against each release path, identify any viable monitoring and mitigation strategies. As well as the diagrams themselves, the following tabularised information will be recorded as an output from the workshop:

Table 2: Proposed Record of Generic Releases

ID	Containment Feature	Cause	Failure Mode	Direct Effects of Failure	Description of Release	Diagram & Release Path Ref	Other Barriers to Release (& Failure Modes)	Potential For CCF/CMF

This is similar in many ways to Failure Modes and Effects Analysis (FMEA) (e.g. as per BS EN IEC 60812:2018), which is often used as a pre-cursor to PSA, except that, in this case, it also includes consideration of common cause and common mode failure of subsequent geological barriers. This aspect is intended to identify whether the IE might also cause failure of further barriers, and if so what failure modes would apply.

4.2 Development of Generic Event Tree (ET) Modules

4.2.1 Proposed computer code

The risk model(s) will be developed using Reliability Workbench (RWB) software (Version 15) developed by Isograph, who are accredited under ISO9001 for the design, development, sales and support of software products. This is an industry-standard commercial off-the-shelf software package which is used widely in the nuclear industry and other high hazard industries such as the chemical processing, aero, rail and oil and gas sectors.

---

[8] The focus is on mitigation strategies that arrest or reduce CO_2 leakage, rather than treat the consequences (e.g. contaminated soil or groundwater).

4.2.2 General form for ET modules

Accident sequences will be modelled by representing each CO_2 leak (from the storage unit) as an initiating event (IE), with the success and failure of subsequent barriers to environmental release represented as top events (TEs) in an ET, so that each potential accident sequence is a pathway through the ET (as illustrated in Figure 6, albeit for fission product release from a reactor).

It is envisaged that separate ET modules will be produced for each generic cause, as depicted in Figure 10. Each module may comprise a number of separate initiating events (IEs) spanning the range of failure modes, severities and locations (where applicable). In this respect, the most obvious example is natural seismicity, for which the seismic hazard curve (produced by WP5.2) will be discretised into frequency bands (in common with best practice in the nuclear industry, IAEA, 2020). A similar approach may also be warranted in other cases if there are step changes in storage complex response (e.g. minor fault re-activation vs fault slip) at different frequencies.

Where the response to IEs is similar (e.g. the same barriers to release, albeit perhaps with varying probabilities of failure), these may be defined as disjoint events[9] and combined under a fault tree (initiating gate) and linked to a single ET for modelling efficiency. Downstream ET modelling will take into account any differences by including disjoint event logic in top event gates[10].

Barriers to release will be modelled successively from left to right, so that the resulting accident sequences represent the chronological (as well as logical) progression of the leak (and are therefore straightforward to interpret).

IEs will be modelled in primary ETs, so that the total leak frequency from the storage unit (irrespective of size[11]) can be evaluated by assigning the outgoing ET branch to a corresponding consequence state (representing storage unit leaks). As well as modelling the IE, the primary ET will also capture any potential to arrest the accident sequence before a leak occurs from the storage unit. This aspect only applies to slowly developing geological processes where monitoring (e.g. of rock strain) is able to act as an early warning system and where there is an effective strategy available (e.g. pressure relief) to arrest the failure process.

The primary ET will transfer to a secondary ET to model subsequent geological barriers to wider CO_2 release from the storage complex, and then leak detection (e.g. via pressure monitoring or a network of CO_2 detectors on the near-surface) and finally leak mitigation (e.g. pressure relief by back-producing). The latter will be capable of being enabled or disabled, so that the sensitivity to mitigation measures can be determined. In some cases, it may be that secondary ETs will be common (i.e. shared across IEs or modules) if leak outcomes at the primary/secondary or secondary/secondary transfer point are sufficiently similar.

ET branches (success or failure) will terminate at predefined release categories (considered in more detail below), which, based on their magnitude of release, will be binned to higher level release bands ranging from nominal release (the maximum normal level assumed, also coinciding with the level above which leaks can be detected if monitoring is in place) to gross release (the maximum release feasible).

---

[9] Disjoint events are mutually exclusive and cannot appear together in accident sequences.

[10] The specific events representing failure of each barrier at each level of IE are ANDed with their corresponding IE and collected under an OR gate.

[11] This approach is analogous to Level 1 PSA in the nuclear industry where the frequency of severe core damage (core melt) is evaluated and compared to a simple frequency target, with the emphasis, therefore, on prevention. A similar frequency target for CO_2 leakage from the storage unit could also be envisaged.

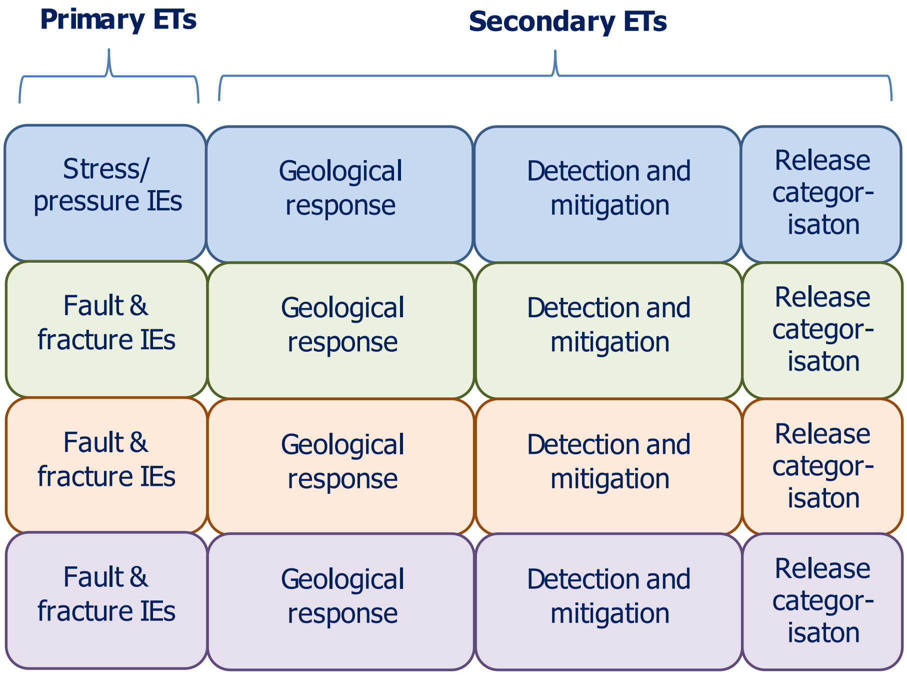


Figure 10: Proposed ET Module Structure

4.2.3 Rules for transposing generic releases diagrams into ETs

The general principles for modelling failures of layers of defence (in this case geological barriers to release and mitigating options following a release) by ETs are firmly established, being a logical consequence of the method itself. Following the initial failure (the IE):

- Independent layers of defence are represented by linking failure branches to subsequent success and failure (such that ultimate failure requires failure of all barriers);
- Where a barrier relies on a number of separate elements, these can either be represented explicitly in the ET by linking success branches to subsequent success and failure, such that overall success of the barrier relies on success of all elements; or, the barrier can be represented by a fault tree (an OR gate with all elemental failures beneath it);
- Wholly dependent failures (such as an earthquake or fault slip that fails or bypasses multiple barriers) can be represented explicitly in the ET by omitting dependently failed top events (i.e. the failure branch does not bifurcate until it reaches a top event that can prevent or reduce the release);
- Partly dependent failures, where there is a conditional probability of dependent failure less than unity, given the initial event, can either be modelled explicitly in the ET as an additional top event; or implicitly by associating all affected events with a beta factor (the proportion of dependent failures, normally applied to the lowest probability event in the CCF group);
- Where a range of consequences may result from a single event, either from the IE or subsequent failure or partial failure of barriers, these can be represented by multiple failure branches, each with a different failure probability (so that the success branch and all failure branches sum to unity).

These general rules will be refined and expanded to reflect the practical experience of transposing release diagrams and in particular recommend preferred strategies for modelling.

4.2.4 Defining release categories

The magnitude of CO_2 release to the environment will depend on the severity of the IE, the nature of subsequent failure of geological barriers and the release path. In modelling terms, this means that in principle every single path through the ET may have a different magnitude of release. In practice, it is usually possible to bound similar cases (e.g. IAEA, 2010) so that the number of release categories, while still quite large, is tractable (e.g. tens rather than thousands). This will rely on the characterisation and naming of containment failures so that like consequences can be assigned the same release categorisation. For example, an earthquake that causes a minor fracture of the primary and secondary seal may be similar in consequences to a pressure/stress related minor fracture of the primary seal during long-term storage, with an independent subsequent minor fracture of the secondary seal.

Release categories will be defined by considering the combinations of failure modes of the IE and subsequent barriers to release identified during Task 4.1.4. For instance, for a simple two seal geology (neglecting mitigation), the release categories for pressure-induced failure might be:

Table 3: Example of Release Categories

ID	Phase	Cause	Primary Seal	Secondary Seal	Release Category
1	Injection	Pressure/stress	Nominal	-	IPN
2			Minor	Nominal	IPMN
3			Gross	Nominal	IPGN
4			Minor	Minor	IPMM
5			Gross	Minor	IPGM
6			Minor	Gross	IPGG
7			Gross	Gross	IPGG

In principle, each release category represents a geological configuration for which CO_2 release modelling is required to determine the magnitude of the leak to the environment. In practice, however, the number of cases can be reduced by firstly, choosing bounding cases, and secondly, considering the frequency of each release category when the model is evaluated. For example, gross leakage of the primary seal together with nominal leakage of the secondary seal bounds minor leakage. If the associated conservatism is small release categories could be reduced to:

Table 4: Example of Reduced Release Categories

ID	Phase	Cause	Primary Seal	Secondary Seal	Release Category
1	Injection	Pressure/stress	Nominal	-	IPN
2			Minor	Nominal	IPM/GN
			Gross	Nominal	
3			Minor	Minor	IPMM
4			Gross	Minor	IPGM
5			Minor	Gross	IPMG
6			Gross	Gross	IPGG

If when the model is evaluated, it is found that the frequency of a release category is negligibly small, it may be decided that there is no merit in modelling the consequences. Nuclear PSA typically uses an initiating event frequency cut-off of 1E-8 /yr, for example, although model evaluation cut-offs are typically lower than this. In this case, a threshold of 1E-8 /yr is proposed, with the opportunity to revisit this decision when results are available.

For reasonably simple ETs (as is envisaged here), release categories can be assigned by inspection of the preceding accident sequence modelling.

Once leak modelling has been completed (as part of other work packages), each release category can be mapped to one or more defined release bands. As the name suggests, these consequence end states each represent a defined range of leak rates over specified durations (e.g. per year, 10 years, 100 years, 1000 years) and can be expressed in absolute units (e.g. kg/s) or relative terms (e.g. % of total stored CO_2). In defining release bands, it is important that they address regulatory criteria (if any), cover the range of predicted releases and are subdivided in a way that describes (as a surrogate) the spectrum of associated risk (when the impact of CO_2 releases on people and the environment is taken into account as it applies to each release category). This could well mean that multiple sets of release bands are required covering the varying effects on people, ecology and climate change.

Another potential complication is that the level of harm may also depend on the nature of release. A point source-type release at the sea bed with higher CO_2 concentrations may well cause more harm to marine life than a diffuse release over a larger area with the same release rate (Navamony, 2011). The overall extent of harm is then a function of release rate, CO_2 concentration and duration. In practice, this means that the use of release bands as a surrogate for risk has its limitations (since it doesn't explicitly address CO_2 concentration), which should be recognised. Of course, this limitation disappears in a Level 3 PSA, where release categories are mapped to defined levels of harm, noting that this is beyond the scope of this study.

As a proof of principle, it is suggested that the definition of release bands is restricted to a single dimension (e.g. climate change[12]), noting that it is a straightforward matter to accommodate other factors (e.g. people, marine ecology, aquifer contamination) in the same way.

In the absence of quantitative regulatory criteria, Navamony, 2011 suggests that acceptable leakage might be less than 0.01 to 0.1% per year and 1% per 1000 years[13], which would certainly appear reasonable from a climate change perspective, although it isn't necessarily clear that the two criteria are compatible, since the latter implies a constant leak rate of less than 0.001% per year, implying some degree of self-sealing behaviour or the acceptance of higher leakage rates during the injection phases when pressures are higher.

As an example, if we assume that an average leakage rate of 1% per 1000 years is acceptable (for climate change), release bands versus frequency targets can be derived by attempting to apportion this equally across frequency decade bands.

Table 5: Derivation of Release Bands (Climate Change)

Frequency /1000 yrs	Release Magnitude	Expected Release	Comments
1	0.25%	0.25%	Nominal release
10^{-1}	2.5%	0.25%	
10^{-2}	25%	0.25%	
10^{-3}	100%	0.1%	The scheme breaks down at this point, since releases are limited to 100%.

Evidently, we will meet our overall target of 1% leakage per 1000 years if the following frequency criteria are met in each release band:

---

[12] It is perhaps worth noting that whilst climate change is used as a proof of principle to define release bands, it is unlikely to be associated with the most onerous regulatory criteria, especially for very large storage reservoirs with the potential for catastrophic damage to the biosphere.

[13] It might be argued that targets should be absolute rather than relative to storage capacity, since the potential consequences of a release from a large capacity storage reservoir depend on its size. However, with respect to climate change, if the risk budget is apportioned according to capacity (with larger reservoirs afforded larger risk budgets), the use of relative targets is appropriate.

Table 6: Indicative Release Band Targets (Climate Change)

1000 yr Release Band (R)	Frequency Target /1000 yrs	Comments
R1 ≤ 0.25%	≤ 1	Nominal release
0.25%< R2 ≤ 2.5%	≤ 10^{-1}	
2.5% < R3 ≤ 25%	≤ 10^{-2}	
R4 > 25%	≤ 10^{-3}	Gross release

With risk acceptance criteria defined, it is an obvious matter to define corresponding release bands in the model for binning each category of release. Their evaluated frequency can then be compared against the frequency targets.

So far discussion has implicitly concerned the use of mean values of leak rate (as evaluated by appropriate leak calculations, 2D or 3D models). In practice, such evaluations should also consider uncertainty and typically predict leak rates at varying confidence intervals (e.g. Bradbury & Bloodworth, 2020). Approaches for building this into the risk model are considered in the Section 5.3.1.

4.2.5 Transposing generic releases diagrams into ETs

Following the ET module structure described in Section 4.2.1, each ET will be developed by considering the associated release diagram using the transposition rules described in Section 4.2.3 (noting that these may develop further as they are implemented).

All events will be named using a standard convention that will be developed in parallel to facilitate easy identification (e.g. when reviewing results) and avoid duplication. The naming convention will include elements separated by '-' to identify an initiating event (e.g. prefix IE), the item concerned (e.g. PS – primary seal), the cause (e.g. PRES for pressure), the failure mode (e.g. FR for fracture) and where relevant the magnitude of failure (e.g. MAJ for major) if these vary. Hence, the initiating event concerning a major pressure related fracture of caprock would be named IE-PS-PRES-FR-MAJ.

At this stage ET branches will be terminated at release categories (as defined according to Section 4.2.4), since they cannot be binned to release bands until specific release rate analysis (or failing that the results of expert elicitation) is available.

4.2.6 Testing and validating resulting ETs

Once completed, each ET module will be technically reviewed and then tested and validated by evaluation. Since there are no data assigned at this stage, validation will consist of reviewing all cut-sets (all sequences of success and failures leading to each release category) for logical and physical consistency against the corresponding release diagrams and definitions of release category. If cut-sets are especially numerous, success states may be post-processed (i.e. removed) so that only failure sequences remain (which greatly compacts cut-sets and reduces their number).

4.3 Refining Generic Releases Diagrams For Specific Case Studies

4.3.1 Workshop with case study experts

The generic release diagrams will be revisited to reflect the specific geology of relevant case study areas. Comparison will be made against 2D cross-sections to identify key features to be retained or added and residual features to be omitted.

The resulting draft diagrams will be reviewed and refined in a workshop setting similar to that proposed in Section 4.1.4, but with participation by case study experts. The output would also be similar – i.e. an agreed set of case-specific release diagrams and a tabular record of each release path (similar to Table 2).

4.4 Adapting Generic Event Tree Modelling

4.4.1 ET modification

All substantive changes to generic release diagrams and supporting information will be transposed into ET changes, using a consistent approach to Section 4.2.

4.4.2 Testing and validating resulting ETs

Once completed, each ET module will be technically reviewed and then tested and validated by evaluation using the approach described in Section 4.2.6.

4.5 Identification of Specific Data Requirements

4.5.1 Review of ET events and consequences

Failure data will be required for all defined events in the risk model(s), distinguishing between:

- Initiating events, which are characterised by their frequency of failure and;
- Enabler events, which follow initiating events and are characterised by their probability of failure on demand;
- Initiator/enabler events, which can be either initiators or enablers (but are not envisaged for this work).

Hence, all events will be exported, suitably grouped and reviewed, ensuring that event descriptions convey sufficient context. Where necessary, additional commentary will be provided.

Failure data needed for each event will comprise the mean failure frequency or probability (as applicable), the standard deviation and an associated probability distribution. RWB supports the normal, lognormal, log-triangular and log-uniform distributions for Monte Carlo simulation. Hence, uncertainty data is limited to the most appropriate of these choices (which may vary from event to event).

As discussed in connection with defining release categories, leak rates will need to be assessed for each release category. These will necessarily have to bound all contributing accident sequences (cut-sets). Hence, these will be described in each case (by exporting cut-sets and their descriptions). As with failure data, it is desirable to obtain both the best estimate (e.g. mean leak rate) and uncertainty data. However, since Monte Carlo is not available for consequence specification in RWB (since these are predefined end states not data) a less sophisticated approach is advocated (described in Section 5.3.1). To support this a 3-point estimate of release rate (over 1,000 years) is required for each release category – i.e. the mean and the maximum and minimum corresponding to an agreed confidence level (e.g. 95% or 99%).

Events relating to monitoring and mitigation strategies may relate to phenomenology (e.g. the probability of detectors being in the right location and being sufficiently sensitive), engineering (e.g. the probability of detectors functioning on demand) and human error. If required, the latter two types of data will be generated as part of this task, as described in more detail in Section 5.2.

4.5.2 Specification of data

For all data described above, a draft data specification will be produced listing the requirements for all specific events and release categories for agreement with identified data suppliers from within the project. Initially, it will be circulated with proposed data suppliers (or gaps where this may be uncertain) to gain agreement. Where necessary, elaboration of data requirements will be provided (as required). In some cases, post processing of data may be needed to convert it into the pre-requisite form, in which case this will be noted. If there are gaps that prove to be outside the scope of the project, this will also be noted, together with its impact and any workarounds.

The output will be a data specification that is agreed by identified data suppliers.

4.6 Interim Reporting

4.6.1 Draft Phase 1 report

On completion of the data specification, the output generated during Phase 1 will be summarised in a formal interim report, broadly in the order presented in Section 4. Any significant departures from this methodology will also be reported.

4.6.2 Updating report for internal comments

The draft report will be circulated to internal stakeholders for comment and update prior to release.

5 PHASE 2

5.1 Introduction

Phase 2 builds on the framework risk model(s) provided in Phase 1 by incorporating the data requested.

5.2 Data preparation

As data is supplied, it will be reviewed to confirm its suitability and if necessary clarification will be sought from the data provider, which may require some iteration. Should manipulation of data be required to convert it into a suitable form for use, this will be completed at this stage.

One example of where this might prove necessary is seismicity, where hazard characterisation is normally in the form of a seismic hazard curve (e.g. peak ground motion verses frequency). For modelling purposes this curve is discretised into separate events of increasing frequency (IAEA, 2020). Pragmatically, this will use one event per decade and use the mean frequency (either the logarithmic midpoint or the geometric mean). Each event is associated with a mean magnitude, which is then used to calculate the fragility of each barrier, typically by assuming a lognormal distribution of failure probability versus stress (or equivalently, ground motion).

For pressure induced failures, the probability of caprock failure through tensile fracturing (for example) is described by the probability distribution of the pressure demand and the probability distribution of tensile strength.

Depending on the scope of Tasks 5.1 & 5.2, for example, such event failure data may be evaluated outside this task (5.3) and, therefore, provide a direct input or may need to be derived from supplied data. This will become clear once the data specification is completed and agreed.

5.2.1 Engineering failure data analysis

Since the causes of CO_2 leakage and the barriers to its release from the storage complex are geological, engineering failures are limited to those associated with monitoring and mitigation. However, since the timescales for mitigation are very long (many weeks or more), it is reasonable to assume that the probability of engineering failures will be very small in comparison to other factors (such as leak detection or the inherent failure probability of the mitigation method itself). Hence, it is reasonable to assume success and not model such failures explicitly.

For estimating the reliability of engineered monitoring systems (as opposed to the inherent probability of detection assuming the detector works, which will also need to be considered), the preferred approach is to use (as appropriate):

- Operational experience;
- Existing reliability modelling of systems (if available);
- Experience-based judgement to determine reasonable system unavailability targets (as described below);
- Bespoke modelling of systems using FTA and basic event failure probabilities.

Where data is lacking, a simple set of rules will be used based on experience, which suggests that the failure probability of system, or group of components, depends on several factors, specifically:

- The type of failure/failure mode (e.g. electrical, electronic, mechanical, structural)
- The minimum level of redundancy within the system;
- The control and instrumentation logic;
- The potential for common cause failure due, amongst others, to:
  - The lack of adequate separation/segregation between similar components;
  - The maintenance practices followed;
  - The organisational safety culture.

Failure data assignment is guided by the following generalisations:

- A realistic, but still conservative, estimate for the failure probability of a single train of active equipment (given periodic testing) can be taken as ~0.1 pfd (noting that individual components of the train will be much less).
- The likelihood of a redundant equipment failing is limited by the potential for common mode/cause failure, AEAT, 1996 suggests that, as first pass, for:
  - A system with only two 100% duty trains of equipment, approximately 10% of the above (single train) failures will fail the system;
  - A highly redundant system, i.e. with a minimum of three trains of equipment, approximately 5% of the above (single train) failures will fail the system.

The above assumes that the system will be of a proven, and simple, design conforming to national/international standards, and will be thoroughly tested during commissioning, maintained and tested periodically throughout its life (and replaced before the end of its design life) and operated by suitably qualified and experienced personnel.

In determining failure data for specific events, engineering judgement may be applied in addition to the guidance above to reflect specific circumstances (e.g. type of failure, failure mode, operational experience of similar failures, environment, duration of design life).

Where components or major assemblies of components are known (or specified), suitable generic data will be used (e.g. Non-Electronic Parts Data Publication).

In the absence of data, embedded software or firmware will be assumed to attract a Safety Integrity Level (SIL) of 1 in accordance with BS EN IEC 61508 (i.e. with a failure frequency or 0.1 per year or a probability of failure on demand of 0.1, as applicable).

5.2.2 Human reliability analysis

Since operator intervention is only expected over very long timescales (e.g. many days or more) in response to monitoring, the contribution to human error is expected to be very small in comparison to other factors (e.g. the reliability of monitoring and subsequent mitigation techniques). As such, success is assumed and human error will not be modelled explicitly. Should this assumption prove invalid (for example, if scenarios are identified where operator action is required in short timescales, or where there is a significant potential for ambiguous monitoring data which could be interpreted in error), human error probabilities will be derived using standard techniques and this methodology will be updated accordingly.

5.2.3 Consequences data

Ideally, leak rate evaluation would be undertaken for each release category (as it relates to the case study in question), so that a 3-point estimate is supplied characterising the leak over 1,000 years as a percentage of storage capacity. However, in some cases, the generation of such data may be beyond the scope of the project. Instead, expert elicitation will be used to generate a 3-point estimate. This will draw on the knowledge and experience of relevant experts as well as taking into account leak rate results that are known (both for this project and other similar projects). The source of all data will be clearly identified.

5.3 Population of model with data

5.3.1 Adding failure and consequences data

Populating the model with failure data is a matter of selecting an appropriate failure model for each event and completing the data fields with mean, standard deviation and probability distribution type.

The source and derivation of all data used will be referenced within the risk model (in each defined failure model) for ease of review and update and to provide an integrated audit trail.

Consequences data will allow each release category to be binned to its designated release band. With respect to modelling uncertainty of release quantities, two separate schemes will be considered:

- Three separate sets of release band will be defined – high, best estimate and low – and release categories will be binned to each according to their high, best estimate and low release rates;
- A single set of release bands will be used, but release categories will be assigned probabilistically. For instance, if high and low release rates represent the 95% confidence level, we might weight each high and low value with a probability of 0.05 and the best estimate value with a probability of 0.9, reflecting a simple, discretised probability distribution function. In the model this can be achieved using three

partial failure branches, each assigned with a separate event (with the corresponding failure probability) and each transferring to the relevant release band. It is also worth noting that if consequence analysis produces a probability density function of the release rate (or equivalently, the cumulative probability distribution), this could be discretised as finely as desired to refine this approach.

The advantage of the first approach is that it will produce overall upper and lower bounds for all releases, whereas the second approach provides a best estimate taking uncertainty into account.

5.3.2 Validating results

Once all data changes have been completed, the populated model will be checked (including item-by-item checking of data) and then validated by initial quantification. For each release category and release band, cut-sets, initiating event importances and top event importances will be reviewed to confirm that results appear to be sensible – i.e. initiating events and accident sequences that are expected to be influential appear prominently and any that appear to be missing can be explained.

If evaluation cut-offs are necessary (to reduce runtime or prevent out-of-memory errors), these will be optimised by parametric survey, balancing convergence, approximation error and runtime.

5.4 Quantification of geological containment risks

5.4.1 Best estimate analysis (single valued)

The risk model(s) will be evaluated both with and without monitoring and mitigation strategies enabled, so that their sensitivity to these aspects can be gauged. Level 2 results will be analysed, focusing on headline values of release bands versus frequency (compared to the indicative criteria derived in Section 4.2.4, for example), and dominant initiating event and top event importances and cut-sets in each case.

Results will be used to provide insights into the overall suitability of case study areas for geological containment of CO_2; as well as the significance of and sensitivity to geological features and monitoring and mitigation strategies. Results will be used to consider whether refinements to modelling are warranted (to reduce pessimism or provide more detailed insights) and whether potential improvements could be considered in monitoring or mitigation (e.g. areas that might benefit from enhancement).

5.4.2 Monte Carlo analysis (uncertainty quantification)

Monte Carlo analysis of the model will provide confidence limits for the best estimate headline results discussed above, as well as an associated probability distribution function. Note that this addresses only the frequency aspects of uncertainty.

Depending on how consequences uncertainty is modelled, upper and lower bound headline results (for consequences) may also be available.

The implications of uncertainty analysis results on best estimate conclusions will be considered.

5.5 Reporting

5.5.1 Draft Phase 2 report

On completion of Phase 2, the output generated during Phase 1 will be summarised in a formal report, broadly in the order presented herein. Significant departures from this methodology will also be summarised (noting that the methodology itself will be updated as a separate deliverable).

5.5.2 Update of report for internal comments

The draft report will be circulated to internal stakeholders for comment and updated prior to release.

5.6 Updating of methodology

Once Phase 2 is complete, this methodology will be updated to reflect the outcome of its testing using case studies, as well as incorporating any lessons learnt from Phase 1.

5.7 Production of supporting guidance

Supporting guidance will be produced to accompany the methodology, generic releases diagrams and generic risk model (i.e. unpopulated). This will provide implementation guidance and examples (using the case studies) on how to:

- Tailor the generic risk model for a specific site;
- Specify data;
- Validate and use the risk model;
- Interpret results.

6 REFERENCES

AEA Technology plc, 1996. SRDA-R13, UPM 3.1: A Pragmatic Approach to Dependent Failures Assessment for Standard Systems.

Augustin, C., 2014. A MCMC Simulation of CCS site leaks-design and implications. In IIE Annual Conference. Proceedings (p. 1149). Institute of Industrial and Systems Engineers (IISE).

Baig, I., Faleide, J.I., Mondol, N.H. and Jahren, J., 2019. Burial and exhumation history controls on shale compaction and thermal maturity along the Norwegian North Sea basin margin areas. Marine and Petroleum Geology, 104, pp.61-85.

Bradbury, J., and Bloodworth, C., 2020. SGSI-12-R-05, Issue 2, DETECT: Integrated CO_2 Leakage Risk Assessment – Quantitative Model Methodology and Validation. Risktec Solutions BV.

Capture Power and National Grid, 2016. White Rose Project FEED K42: Storage Risk Assessment, Monitoring and Corrective Measures Reports Category: Storage. Capture Power and National Grid.

Carlton, B., Skurtveit, E., Atakan, K., Kaynia, A.M., 2019. Probabilistic Seismic Hazard Analysis of A CO_2 Storage Prospect Using the NGA East Ground Motion Models. SECED 2019 Conference: Earthquake risk and engineering towards a resilient world, 9-11 September, 2019, London.

Cho, J. et al, 2018. Multi-unit Level 2 probabilistic safety assessment: Approaches and their application to a six-unit nuclear power plant site, Nuclear Engineering and Technology, Volume 50, Issue 8, pp. 1234-1245.

Clarke, H., Verdon, J.P., Kettlety, T., Baird, A.F. and Kendall, J.M., 2019. Real-time imaging, forecasting, and management of human-induced seismicity at Preston New Road, Lancashire, England. Seismological Research Letters, 90(5), pp.1902-1915.

Gerstenberger, M., Nicol, A., Stenhouse, M., Allinson, G., Berryman, K., Doody, B., Ho, M., McCurdy, M., Neal, P., Stirling, M. and Webb, T., 2009. Opportunities for underground geological storage of CO_2 in New Zealand-Report CCS-08/10-Risk assessment methodologies. GNS Science Report, 63.

Gerstenberger, M.C., Christophersen, A., Buxton, R., Allinson, G., Hou, W., Leamon, G. and Nicol, A., 2013. Integrated risk assessment for CCS. Energy Procedia, 37, pp.2775-2782.

Gerstenberger, M.C., Christophersen, A., Buxton, R. and Nicol, A., 2015. Bi-directional risk assessment in carbon capture and storage with Bayesian Networks. International Journal of Greenhouse Gas Control, 35, pp.150-159.

Goitom, B., Werner, M.J., Goda, K., Kendall, J.M., Hammond, J.O., Ogubazghi, G., Oppenheimer, C., Helmstetter, A., Keir, D. and Illsley-Kemp, F., 2017. Probabilistic seismic-hazard assessment for Eritrea. Bulletin of the Seismological Society of America, 107(3), pp.1478-1494.

Hurst, S. & Lidstone, A., 2020. DETECT: Integrated CO_2 Leakage Risk Assessment – Bowtie Analysis Report, SGSI-12-R-07, Issue 1, Risktec Solutions B.V.

IAEA, 2010. Development and Application of Level 2 Probabilistic Safety Assessment for Nuclear Power Plants Specific Safety Guide. International Atomic Energy Agency. SSG-4, Vienna.

IAEA, 2020. Probabilistic Safety Assessment for Seismic Events. International Atomic Energy Agency. IAEA-TECDOC-1937, Vienna.

Jewel, S. and Senior, B., 2012. CO_2 storage liabilities in the North Sea: an assessment of risks and financial consequences. Summary report for DECC.

Kettlety, T., Verdon, J.P., Werner, M.J., Kendall, J.M. and Budge, J., 2019. Investigating the role of elastostatic stress transfer during hydraulic fracturing-induced fault activation. Geophysical Journal International, 217(2), pp.1200-1216.

Kettlety, T., Verdon, J.P., Werner, M.J. and Kendall, J.M., 2020. Stress transfer from opening hydraulic fractures controls the distribution of induced seismicity. Journal of Geophysical Research: Solid Earth, 125(1), p.e2019JB018794.

Korre, A., Govindan, R., Mosleh, M.H., Durucan, S., Heinemann, N. and Wilkinson, M., 2017. Report on individual remediation techniques scoring method and classification/ranking results. MiReCOL Project, D11.2.

Lacasse, S., 2016. Hazard, reliability and risk assessment-research and practice for increased safety. In Proceedings of the 17th Nordic Geotechnical Meeting Challenges in Nordic Geotechnic 25th – 28th of May. Reykjavik.

Manceau, J.C., Hatzignatiou, D.G., De Lary, L., Jensen, N.B. and Réveillère, A., 2014. Mitigation and remediation technologies and practices in case of undesired migration of CO_2 from a geological storage unit—Current status. International Journal of Greenhouse Gas Control, 22, pp.272-290.

Oladyshkin, S., Class, H., Helmig, R. and Nowak, W., 2011. A concept for data-driven uncertainty quantification and its application to carbon dioxide storage in geological formations. Advances in Water Resources, 34(11), pp.1508-1518.

Rahman, M.J., Choi, J.C., Fawad, M. and Mondol, N.H., 2021. Probabilistic analysis of Vette fault stability in potential CO_2 storage site Smeaheia, offshore Norway. International Journal of Greenhouse Gas Control, 108, p.103315.

Rohmer, J. and Bouc, O., 2010. A response surface methodology to address uncertainties in cap rock failure assessment for CO_2 geological storage in deep aquifers. International Journal of Greenhouse Gas Control, 4(2), pp.198-208.

Navamony, R., 2011. A Semi-Quantitative Risk Assessment of the Goldeneye Carbon Dioxide Geological Storage Project. University of Aberdeen.

Solomon, S., Flach, T.A., Carpenter, M. and Selmer-Olsen, S., 2009. A simplified, semi-analytical method to handle uncertainty in long-term containment in geologic CO_2 storage sites. Energy Procedia, 1(1), pp.2533-2540.

van Thienen-Visser, K., Hendriks, D., Marsman, A., Nepveu, M., Groenenberg, R., Wildenborg, T., van Duijne, H., den Hartogh, M. and Pinkse, T., 2014. Bow-tie risk assessment combining causes and effects applied to gas oil storage in an abandoned salt cavern. Engineering geology, 168, pp.149-166.

Wu, L., Thorsen, R., Ottesen, S., Meneguolo, R., Hartvedt, K., Ringrose, P. and Nazarian, B., 2021. Significance of fault seal in assessing CO_2 storage capacity and containment risks–an example from the Horda Platform, northern North Sea. Petroleum Geoscience, 27(3).

Yang, Y.M., Small, M.J., Ogretim, E.O., Gray, D.D., Bromhal, G.S., Strazisar, B.R. and Wells, A.W., 2011. Probabilistic design of a near-surface CO_2 leak detection system. Environmental science & technology, 45(15), pp.6380-6387.

ZEP 2019. CO2 Storage Safety in the North Sea: Implications of the CO2 Storage Directive. Zero Emissions Platform.

Zhang, Y., Oldenburg, C.M., Finsterle, S., Jordan, P. and Zhang, K., 2009. Probability estimation of CO_2 leakage through faults at geologic carbon sequestration sites. Energy Procedia, 1(1), pp.41-46.

Appendix A LITERATURE REVIEW – INITIAL SIFT

ID No.	Title	Author(s)	Document URL	Full Doc Available?	Reviewed by (Risktec)	Paper Date
D015	Integrated Risk Assessment for CCS	M C Gerstenberger et al	http://www.sciencedirect.com/science/article/pii/S1876610213004050	Yes	MT, AL	2013
Abstract/Summary: Using a suite of risk assessment tools across the lifecycle of a project will provide the best estimates of the risk and enable communicating this knowledge in the most effective manner. Recommends a staged suite of risk assessment tools.			**Methods / Ideas Relevant to WP5, Task 5.3:** Good general paper on principles of risk assessment and communication. Talks about bowties for communication and Bayesian Belief Networks for quantification. May be worth following up on BBN as a possible alternative to Event Tree Analysis (ETA).			
D047	Mitigation and Remediation Technologies and Practices in Case of Undesired Migration of CO_2 from a Geological Storage Unit – Current Status	J-C Manceau	http://www.sciencedirect.com/science/article/pii/S1750583614000085	Y	MT/AL	Feb 2014
Abstract/Summary: This paper reviews the status of knowledge with regards to the mitigation and remediation technologies, from mature techniques adapted from other fields, such as oil and gas industry and environmental clean-up, to research topics offering potential new possibilities. Highlights the status of knowledge with regards to the mitigation and remediation technologies, reviews the actual practices in the emerging field of CO_2 geological storage and concludes on important best practices and on future challenges stemming from this review.			**Methods / Ideas Relevant to WP5, Task 5.3:** Provides a useful summary of the techniques available (existing and developing) for physical mitigation of risks if they occur e.g. well capping, re-cementing, and groundwater treatment.			
D057	A Semi-Quantitative Risk Assessment of the Goldeneye Carbon Dioxide Geological Storage Project	R Navamony	Not available online	Yes	MT, FH	Sep 2011
Abstract/Summary: Study of the Goldeneye geological storage project as the UK's first commercial-scale CCS program. Quantifies risks of the project to in terms of human, environmental and investment/asset risks.			**Methods / Ideas Relevant to WP5, Task 5.3:** Presents a semi-quantitative method of assessing risks to people, environment and investment/asset. Threats, barriers and consequences considered are based on Shell UK's bowtie analysis. Failure probabilities are assessed using fault tree analysis of the bowties, with a quantitative descriptor (with associated failure probability) assigned to element. Leak rates from previous quantitative studies have been used together with event tree analysis to qualitatively assess a range of different leakage scenarios.			

<table>
<tr><td>D102</td><td>A Simplified, Semi-Analytical Method to Handle Uncertainty in Long-Term Containment in Geologic CO_2 Storage Sites</td><td>S Solomon et al</td><td>http://www.sciencedirect.com/science/article/pii/S1876610209006602</td><td>Yes</td><td>MT,FH</td><td>Feb 2009</td></tr>
<tr><td colspan="3">Abstract/Summary:
This paper gives a brief introduction and description of the mathematics of the reliability method and how it can be applied to analyse the failure probability of CO_2 geologic storage using commercially available software.</td><td colspan="4">Methods / Ideas Relevant to WP5, Task 5.3:
Discussion of the semi-quantitative FORM/SORM methods (first/second order reliability methods) and an example of their application to CO_2 geological storage. The method is presented as a potential alternative to techniques such as Monte Carlo in situations where a large number of low probability failures can lead to slow numerical convergence. The focus of the paper is the analysis of vertical flow of CO_2 through a fault plane using the commercial software package PROBAN. The problem is formulated using a 'limit state' function as the basis of determining whether the flow exceeds certain thresholds, dependent on several probabilistic variables. In addition to presenting the results of the analysis, the importance of uncertainty of each of the probabilistic variables on the results is presented.</td></tr>
<tr><td>D222</td><td>Opportunities for underground geological storage of CO_2 in New Zealand - Report CCS -08/10 - Risk assessment methodologies</td><td>M. Gerstenberger, A Nicol et al</td><td>http://www.mbie.govt.nz/info-services/sectors-industries/energy/energy-efficiency-environment/documents-library/ccs-docs/2009-63-CCS-Risk-assessment%20-PDF%20963%20KB.pdf</td><td>Yes</td><td>AL</td><td>December 2009</td></tr>
<tr><td colspan="3">Abstract/Summary:
The purpose of this report is to outline the risk assessment methods best suited to potential future CO_2 sequestration projects in New Zealand and to recommend tasks that, if completed, would either reduce the risk or enable the likelihood of these risks to be constrained better.</td><td colspan="4">Methods / Ideas Relevant to WP5, Task 5.3:
Good general overview of whole 'risk picture' associated with CCS, including public perception. Discusses the use of 'logic trees', which are part event trees and part decision trees, for options assessment.</td></tr>
<tr><td>D233</td><td>Probabilistic Design of a Near-Surface CO_2 Leak Detection System</td><td>Y-M Yang at al</td><td>http://pubs.acs.org/doi/pdf/10.1021/es104379m</td><td>Y</td><td>AL</td><td>2011</td></tr>
<tr><td colspan="3">Abstract/Summary:
A methodology is developed for predicting the performance of near-surface CO_2 leak detection systems at geologic sequestration sites. The methodology integrates site characterization and modelling to predict the statistical properties of natural CO_2 fluxes, the transport of CO_2 from potential subsurface leakage points, and the detection of CO_2 surface fluxes by the monitoring network. The probability of leak detection is computed as the probability that the leakage signal is sufficient to increase the total flux beyond a statistically determined threshold.</td><td colspan="4">Methods / Ideas Relevant to WP5, Task 5.3:
Relevant for determining the probability of detection of CO_2 leaks.</td></tr>
</table>

<table>
<tr><td>D245</td><td>A response surface methodology to address uncertainties in cap rock failure assessment for CO_2 geological storage in deep aquifers</td><td>Jeremy Rohmer, Olivier Bouc</td><td>http://www.sciencedirect.com/science/article/pii/S1750583609001534</td><td>Y</td><td>AL</td><td>Jan 2010</td></tr>
<tr><td colspan="3">Abstract/Summary:
Cap rock failure assessment, either tensile fracturing or shear slip reactivation of pre-existing fault, is a key issue for preventing CO_2 leakage from deep aquifer reservoirs up to the surface. For an appropriate use in risk management, the uncertainties associated with such studies should be investigated. Nevertheless, uncertainty analysis requires multiple simulations and a direct use of conventional numerical approaches might be too computer time consuming. An alternative is to use conventional analytical models, but their assumptions appear to be too conservative. An intermediate approach is proposed based on the response surface methodology, consisting in estimating the effective stress state after CO_2 injection as a linear combination of the most influential site properties based on a limited number of numerical simulations. Decision maker is provided with three levels of information: (1) the identification of the most important site properties; (2) an analytical model for a quick assessment of the maximal sustainable overpressure and (3) a simplified model to be used in a computationally intensive uncertainty analysis framework.</td><td colspan="4">Methods / Ideas Relevant to WP5, Task 5.3:
Could be useful as a methodology for predicting the probability of cap rock failures, utilising as it does the response surface approach.</td></tr>
<tr><td>248</td><td>A Markov Chain Monte Carlo Simulation of CCS site leaks – design and implications</td><td>C Augustin</td><td>https://search.proquest.com/docview/1622299124/fulltextPDF/27C298631F084816PQ/1?accountid=12118</td><td>Y</td><td>AL</td><td>2014</td></tr>
<tr><td colspan="3">Abstract/Summary:
CCS technology features prominently in international and intergovernmental proposals to reduce atmospheric CO_2 levels. Despite overwhelming implementation support, considerable uncertainty regarding CCS exists, not only around regulating injection processes but also concerning the likelihood of potential leakage post-injection. The most pressing CCS issue is whether stored CO_2 will leak to the surface. With CCS, it is not feasible to collect enough comprehensive CO_2 leak data in order to perform a risk assessment based on frequentist statistics. Alternatively, we present a Markov Chain Monte Carlo (MCMC) simulation using information from natural CO_2 leaks—which follow a leak pattern demonstrated in man-made low-probability, high consequence material releases—to inform a Gamma prior distribution for a compound Poisson predictive Bayesian model. These leakage simulations provide a vital look at the long –term storage implications of CCS and frame key recommendations for policy-makers. Localized leakage effects are outlined and project extensions are also discussed.</td><td colspan="4">Methods / Ideas Relevant to WP5, Task 5.3:
Derives the probability of leaks from CCS based on historical statistics concerning natural CO_2 leaks, so probability/size of leak appears to be independent of properties of the actual location itself; but the method may be worth looking at in more detail, since it applies to situations where data is limited. This uses Bayesian statistics and Markov Chain Monte Carlo simulation to predict the probability of varying leak sizes.</td></tr>
</table>

<table>
<tr><td>D256</td><td>A concept for data-driven uncertainty quantification and its application to carbon dioxide storage in geological formations.</td><td>Oladyshkin S, Class H, Helmig R, Nowak W</td><td>http://www.sciencedirect.com/science/article/pii/S0309170811001540?showall%3Dtrue%26via%3Dihub</td><td>N</td><td>FH</td><td>2011</td></tr>
<tr><td colspan="3">Abstract/Summary:

Model-based uncertainty analysis can help to judge the potentials and hazard in many engineering applications better. This requires to specify the probability distributions of all model parameters, posing a huge demand on data availability or requiring highly subjective assumptions on distribution shapes to compensate for missing data. We present a minimally subjective approach for uncertainty quantification in data-sparse situations, based on a new and purely data-driven version of polynomial chaos expansion (PCE). It avoids the subjectivity that is otherwise introduced when choosing among a small limited number of theoretical distribution shapes to represent natural phenomena: we only demand the existence of a finite number of statistical moments, and do not require knowledge or even the existence of probability density functions for input parameters. In a small fictitious example with independent experts, otherwise, we demonstrate that this subjectivity can easily lead to substantial prediction bias, and that the subjective choice of distribution shapes has a similar relevance as uncertainties due to physical conceptualization, numerical codes and parameter uncertainty. With our approach we can directly and most flexibly use raw data sets available from global databases or soft information from experts in the form of arbitrary distributions or statistical moments. We illustrate and validate our proposed approach by a comparison with a Monte Carlo simulation using a common 3D benchmark problem for CO_2 injection, which is a low-parametric homogeneous system. We obtain a significant computational speed-up compared with Monte Carlo as well as high accuracy even for small orders of expansion, and show how our novel approach helps overcome subjectivity.</td><td colspan="4">Methods / Ideas Relevant to WP5, Task 5.3:

The paper focuses on the representation of uncertainty in modelling, in particular in cases where there is limited or no information relating to the distribution of parameters. The approach of arbitrary polynomial chaos is used, with statistical moments of the raw data associated with a system parameter used to define the orthogonal polynomial basis. The key feature of this method is that it uses what limited data is available regarding a parameter to derive these polynomials rather than requiring the use of assumed/fitted probability distribution functions. A ‘response surface’ representing how a system responds to variations in input parameters is constructed and a benchmark comparison made with a Monte Carlo model of CO_2 leakage into overlying formations through a leaky well to demonstrate the accuracy and rate of convergence. The impact of subjectivity is explored by outlining the results obtained when asking experts to select and fit distributions to data sets and examining the subsequent variations in results.

The approach taken for uncertainty analysis may be worth considering further.</td></tr>
<tr><td>D261</td><td>Probability estimation of CO_2 leakage through faults at geologic carbon sequestration sites</td><td>Zhang, Y.Q., Oldenburg, C.M., Finsterle, S., Jordan, P., Zhang, K</td><td>https://www.sciencedirect.com/science/article/pii/S1876610209000095</td><td>Yes</td><td>AL</td><td>Feb 2009</td></tr>
<tr><td colspan="3">Abstract/Summary:

Leakage of CO_2 and brine along faults at geologic carbon sequestration (GCS) sites is a primary concern for storage integrity. The focus of this study is on the estimation of the probability of leakage along faults or fractures. This leakage probability is controlled by the probability of a connected network of conduits existing at a given site, the probability of this network encountering the CO_2 plume, and the probability of this network intersecting environmental resources that may be impacted by leakage. This work is designed to fit into a risk assessment and certification framework that uses compartments to represent vulnerable resources such as potable groundwater, health and safety, and the near-surface environment. The method we propose includes using percolation theory to estimate the connectivity of the faults, and generating fuzzy rules</td><td colspan="4">Methods / Ideas Relevant to WP5, Task 5.3:

Proposes a method for evaluating the CO_2 leakage probability through faults or fractures at geologic sequestration sites.

The proposed approach includes four steps:

(1) estimate a critical value (a_c) for the parameter a, which is related to the density of conduits (faults and fractures), such that when this critical value is reached, the system is onaverage connected between the storage formation and a compartment;</td></tr>
</table>

<table>
<tr><td colspan="3">from discrete fracture network simulations to estimate leakage probability. By this approach, the probability of CO_2 escaping into a compartment for a given system can be inferred from the fuzzy rules. The proposed method provides a quick way of estimating the probability of CO_2 or brine leaking into a compartment. In addition, it provides the uncertainty range of the estimated probability.</td><td colspan="4">(2) estimate the probability that the CO_2 plume will encounter the connected conduits for a system with a $>a_c$, for various distributions of conduits, system sizes and CO_2 plume sizes;
(3) construct fuzzy rules that relate information about the conduit system and CO_2 plume size to leakage probability; and
(4) for given system characteristics, predict the probability that a CO_2 plume will escape from the storage formation to a compartment through connected conduits.
Worth coming back to.</td></tr>
<tr><td>S01</td><td>DETECT: Integrated CO_2 Leakage Risk Assessment – Bowtie Analysis Report</td><td>Hurst, S. & Lidstone, A.</td><td>https://risktec.tuv.com/wp-content/uploads/2021/01/SGSI-12-R-07-Bowtie-Analysis-i1.pdf</td><td>Yes</td><td>MK</td><td>Dec 2020</td></tr>
<tr><td colspan="3">Abstract/Summary:
DETECT Work Pack 5 (WP5) is a detailed, integrated risk assessment, using the established bowtie method to describe the various leak paths and the prevention and mitigation measures expected to be in place. It is critically important to be able to communicate about leakage risks for CO_2 storage operations in a clear, logical and substantiated manner to all stakeholders – bowtie diagrams provide a proven vehicle for such communication. Creating template bowties for use as a starting point in future risk assessments for CO_2 storage allows industry to improve the efficiency of these risk assessments, while maintaining the highest safety standards expected by society.
The objectives of DETECT WP5 are to:
- develop bowtie diagrams depicting the natural pathways for CO_2 release from subsurface storage and the measures in place to prevent/mitigate the risk;
- develop a quantitative risk assessment model aligned to the bowtie, using output from the other WPs to determine prevention/mitigation measure effectiveness; and
- calculate relative risks of CO_2 leaking through caprock fractures, enabling the model to be used for comparison purposes.
This Bowtie Analysis Report deals with the first of the above three objectives.</td><td colspan="4">Methods / Ideas Relevant to SHARP WP5, Task 5.3:
The generic bow-ties developed for the DETECT project and presented herein are the proposed starting point for the SHARP containment risk assessment methodology. In addition, the reference provides an overview of the state-of-the-art of quantitative risk modelling for CCS.</td></tr>
<tr><td>S07</td><td>Probabilistic Seismic Hazard Analysis of A CO_2 Storage Prospect Using the NGA East Ground Motion Models</td><td>Carlton, B., Skurtveit, E., Atakan, K. and Kaynia, A.M.</td><td>https://ngi.brage.unit.no/ngi-xmlui/bitstream/handle/11250/2620174/Carlton_etal%25282019%2529.pdf?sequence=2</td><td>Yes</td><td>MK</td><td>2019</td></tr>
<tr><td colspan="3">Abstract/Summary:
The Smeaheia fault block in the North Sea is a site under consideration for large scale CO_2 storage. Even though the overall earthquake hazard in the North Sea is low, it is necessary to evaluate the risk related to earthquake hazard at the site to ensure safe</td><td colspan="4">Methods / Ideas Relevant to SHARP WP5, Task 5.3:
Provides the Probabilistic Seismic Hazard Analysis (PSHA) for the Smeaheaia fault block in the North Sea.</td></tr>
</table>

storage of CO_2 and to provide a baseline to be able to estimate the change in earthquake hazard due to future CO_2 injection. This paper presents a probabilistic seismic hazard analysis (PSHA) for Smeaheia using an updated earthquake catalogue, two alternate source models and the final NGA East ground motion models. Defining the specific hazard related to the Vette and Øygarden faults, which bound the site, was not feasible due to a lack of data and uncertainty in earthquake location. However, by characterizing the main fault defining the continental-oceanic crust transition as an areal source zone, the results show that this zone dominates the earthquake hazard for the site. The results also show that the main earthquake scenarios that contribute to the hazard are magnitude 5 to 6 earthquakes 20 to 120 km from the site. The calculated peak ground accelerations (PGA) for 475 year and 2475 year return periods are 0.031 g and 0.088 g, respectively, which are smaller than in past studies.			Potential inputs to the ETA would be: • Figure 6 - Annual rate of exceedance against the full range of spectral periods • Figure 8 - Mean Magnitude and distance of the deaggregation for different return periods (100, 475, 1000, 2475 and 10000 years) against the full range of spectral periods.			
S23	D11.2 Mitigation and remediation of leakage from geological storage	Korre A., Govindan R., Mosleh M., Durucan S., Heineman N. Wilkinson M.	https://www.mirecol-CO_2.eu/download/D11.2%20-%20Report%20on%20individual%20remediation%20techniques.pdf	Yes	MK	March 2017
Abstract/Summary: The objective of the task presented in this deliverable report is to synthesise the results of the modelling studies carried out in SP1, SP2 and SP3, focusing on various mitigation and remediation techniques, and carrying out an evaluation of their performance as either threat barriers (for risk reduction) or recovery and preparedness measures (for consequence benefits) that can be achieved. The issues considered were relating to technology specific issues of the techniques, including their implementation costs. A methodology was proposed to quantify the effectiveness of the techniques in a manner which allows for a comparison of the indicative performance metrics, based on the results of the scenarios that were investigated. The overall performance characterisation was based on five dimensions, as agreed during the course of the project, namely: • likelihood of success • spatial extent • longevity • response speed • cost efficiency The overarching goal is to subsequently feed the outcomes of this report into the on-line remediation selection tool which was developed in parallel under SP5.			**Methods / Ideas Relevant to SHARP WP5, Task 5.3:** Provides the following data for various mitigation and remediation measures: • likelihood of success • spatial extent • longevity • response speed • cost efficiency			
S25	Development and Application of Level 2 Probabilistic Safety Assessment for Nuclear Power Plants	International Atomic Energy Agency	https://www.iaea.org/publications/8236/development-and-application-of-level-2-	Yes	MK	2010

<table>
<tr><td></td><td></td><td></td><td>probabilistic-safety-assessment-for-nuclear-power-plants</td><td></td><td></td><td></td></tr>
<tr><td colspan="3">Abstract/Summary:
The Safety Fundamentals, Fundamental Safety Principles establish principles to ensure the protection of workers, the public and the environment, now and in the future, from harmful effects of ionizing radiation. These principles emphasize the need to assess and manage the risk posed by nuclear facilities.
Several IAEA Safety Requirements publications were developed to provide more specific requirements for risk assessment for nuclear power plants. The Safety Requirements publication on Safety Assessment for Facilities and Activities emphasizes the need for a comprehensive safety analysis. Thus, a comprehensive probabilistic safety assessment (PSA) is required to be performed to assess and verify the safety of nuclear power plants in relation to potential internal initiating events and internal and external hazards.
This Safety Guide complements the Safety Guide on Level 1 PSA, providing recommendations on what analyses need to be performed and what issues need to be addressed to ensure that the Level 2 PSA meets the requirements on safety assessment</td><td colspan="4">Methods / Ideas Relevant to SHARP WP5, Task 5.3:
Provides guidance for meeting the requirements of the IAEA Safety Standard - Assessment for Facilities and Activities, in performing or managing a Level 2 PSA project for a nuclear power plant. This Safety Guide complements the Safety Guide on Level 1 PSA and promotes a standard framework, standard terms and a standard set of documents for PSAs to facilitate regulatory and external peer review of their results.
This Safety Guide also provides a consistent, reliable means of ensuring the effective fulfilment of obligations under Article 14 of the Convention on Nuclear Safety
The guidance presented in this Safety Guide are based on internationally recognized good practices and includes all the steps in the Level 2 PSA process (which includes containment modelling) up to, and including, the determination of the detailed source terms that would be required as input into a Level 3 PSA.
The recommendations of this Safety Guide are intended to be technology neutral to the extent possible. However, the number and content of the various steps of the analysis assume the existence of some type of containment structure.</td></tr>
<tr><td>S26</td><td>Probabilistic Safety Assessment for Seismic Events</td><td>International Atomic Energy Agency</td><td>https://www.iaea.org/publications/14744/probabilistic-safety-assessment-for-seismic-events</td><td>Yes</td><td>MK</td><td>2020</td></tr>
<tr><td colspan="3">Abstract/Summary:
This publication supports the implementation of IAEA Safety Standards Series No. NS-G-2.13, Evaluation of Seismic Safety for Existing Nuclear Installations, published in 2009. It provides a detailed methodology for seismic probabilistic safety assessment in line with the current international practices for seismic safety assessment of nuclear installations.
The methodology for seismic safety evaluation presented here includes probabilistic and deterministic approaches, as well as a combination of deterministic and probabilistic approaches. Their applications typically address the impact of beyond design basis seismic events.</td><td colspan="4">Methods / Ideas Relevant to SHARP WP5, Task 5.3:
Provides details of the technical approaches used for developing Level 1 seismic PSA, consistent with SSG-3 and NS-G-2.13.
Reflects current practice in the area of seismic PSA, taking into account recommendations provided in IAEA safety standards and information reflected in internationally recognized technical standards.</td></tr>
<tr><td>S27</td><td>White Rose Project FEED K42: Storage Risk Assessment, Monitoring and Corrective Measures Reports
Category: Storage</td><td>Capture Power and National Grid</td><td>Capture Power Report Template (publishing.service.gov.uk)</td><td>Yes</td><td>MK</td><td>2016</td></tr>
</table>

This report is one of a series of reports; these 'key knowledge' reports are issued here as public information. These reports were generated as part of the Front End Engineering Design (FEED) Contract agreed with the Department of Energy and Climate Change (DECC) as part of the White Rose Project. The purpose of this document is to provide a report on the following aspects of the project. - storage risk assessment; - monitoring, measurement and verification plan; and - corrective measures plan. The storage risk assessment is a quantitative risk assessment that considers the risks associated with underground aspects of CO_2 storage throughout the lifecycle of the project. It was structured to address the risk assessment requirements identified in the European Commission (EC) CCS Directive and Guidance (EC, 2009; 2011). The assessed risks are divided into two categories: the risks to the protection of human health and the environment; and the risks to the permanent containment of CO_2 within the defined storage. The assessment covers only sub-surface aspects of the project and was undertaken by an independent mathematical and scientific consultancy.			Considers various subsurface evolution (leakage) scenarios. Use the Evidence Support Logic approach and a risk matrix to determine the level of risk for hypothesised evolution (leakage) scenarios. The TESLA tool is used to produce a tree like structure and confidence values are assigned to each hypothesis.			
S28	Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies. U.S. Nuclear Regulatory Commission NUREG-2117	U.S. Nuclear Regulatory Commission	NUREG-2117, Rev. 1, "Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies." (nrc.gov)	Yes	MK	2012
10 CFR 100.23, paragraphs (c) and (d) require that the geological, seismological, and engineering characteristics of a site and its environs be investigated in sufficient scope and detail to permit an adequate evaluation of the Safe Shutdown Earthquake (SSE) Ground Motion for the site. In addition, 10 CFR 100.23, paragraph (d)(1), "Determination of the Safe Shutdown Earthquake Ground Motion," requires that uncertainty inherent in estimates of the SSE be addressed through an appropriate analysis such as a probabilistic seismic hazard analysis (PSHA). In response to these requirements, in 1997, the U.S. Nuclear Regulatory Commission published NUREG/CR-6372, Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and the Use of Experts. Written by the Senior Seismic Hazard Analysis Committee (SSHAC), NUREG/CR-6372 provides guidance regarding the manner in which the uncertainties in PSHA should be addressed using expert judgment. In the 15 years since its publication, NUREG/CR-6372 has provided many PSHA studies with the framework and guidance that have come to be known simply as the "SSHAC Guidelines." The information in this NUREG is based on recent efforts to capture the lessons learned in the PSHA studies that have been undertaken using the SSHAC Guidelines. As a companion to NUREG/CR-6372, this NUREG provides additional practical implementation guidelines consistent with the framework and higher-level guidance of the SSHAC Guidelines.			The SSHAC guidelines defined four levels at which hazard assessment studies can be conducted, ranging from the simplest (Level 1) to the most complicated and demanding (Level 4). The SSHAC report focused a great deal of attention on the conduct of Level 4 studies but provided comparatively little guidance on the lower levels of study, particularly Level 3. This NUREG serves two primary purposes—it provides (1) additional levels of detail on topics related to the implementation of SSHAC processes beyond those provided in the original SSHAC report, particularly for Level 3 studies, and (2) additional guidance on the implementation of Level 3 and 4 studies in light of experience gained from past SSHAC projects. Over the past 15 years, several SSHAC Level 3 and 4 studies have been conducted, thus leading to an expanded "database" of experience in the intricacies of carrying out the SSHAC process in actual projects.			

<table>
<tr><td>S29</td><td>Updated Implementation Guidelines for SSHAC Hazard Studies. U.S. Nuclear Regulatory Commission NUREG-2213</td><td>U.S. Nuclear Regulatory Commission</td><td>NUREG-2213, "Updated Implementstion Guidelines for SSHAC Hazard Studies." (nrc.gov)</td><td>Yes</td><td>MK</td><td>2017</td></tr>
<tr><td colspan="3">This document contains guidance for conducting expert assessments through the structured process that is referred to as the Senior Seismic Hazard Analysis Committee (or SSHAC) process. It serves as an update to the original SSHAC guidance in NUREG/CR-6372, “Recommendation for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and the Use of Experts” (NRC, 1997) and the implementation guidance provided in NUREG–2117, “Practical Implementation Guidelines for SSHAC Level 3 and 4 (NRC, 2012c). This document builds on the framework described in the prior NUREGs and incorporates lessons learned from conducting recent SSHAC studies. This document does not invalidate the prior guidance documents or the studies conducted accordingly; however, the intent of this NUREG is to provide the most current standalone guidance. While the prior NUREGs contain useful concepts and historical context, this document should be used for conducting future SSHAC studies.
Specifically, this document: (i) clarifies terminology and key concepts that are essential for all SSHAC studies; (ii) strengthens the implementation framework for Level 3 studies, based on extensive recent experience; (iii) provides guidance on the attributes of Level 1 and 2 studies; and (iv) presents a revised and more rigorous framework for decision-making regarding the updating of existing SSHAC studies. These updated guidelines describe an acceptable framework to implement the recommendations in Regulatory Guide 1.208 (NRC, 2007) with respect to performing a probabilistic seismic hazard analysis study.</td><td colspan="4">This review included outreach to many seismic hazard practitioners who have participated in previous SSHAC studies to develop insights. Specifically, the current document: (i) elaborates on the key features that are essential for all SSHAC studies, (ii) strengthens the implementation framework for Level 3 studies based on extensive recent experience, (iii) provides guidance on the essential attributes of Level 1 and 2 studies (missing from the earlier SSHAC documents), and (iv) develops a revised and more rigorous framework for decision-making regarding the updating of existing SSHAC studies. Continued application and development of these guidelines will enhance regulatory assurance and stability. In summary, these updated guidelines describe an acceptable framework to implement the recommendations in Regulatory Guide 1.208, “A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion” (NRC, 2007) with respect to performing a Probabilistic Seismic Hazard Analysis study.</td></tr>
</table>

Appendix B LITERATURE REVIEW

B.1 Inputs

B.1.1 DETECT BowTie

Hurst and Lidstone (2020) Bowtie Analysis Report for the ACT funded DETECT project uses the established bowtie method to describe the various leak paths and the prevention and mitigation measures expected to be in place. The DETECT bowtie provides a means of analysing qualitatively and in depth, the possible causes of a release of CO_2 from the storage complex, and the potential consequences should such a release occur. It allows evaluation of the individual prevention and mitigation measures planned to be in place to either prevent such a release of CO_2 from occurring, or to minimise the extent of the consequences of such a release.

The template bowties cover a wide range of potential leak paths, consequences/outcomes and prevention and mitigation controls. The DETECT bowtie threat, consequence, control and degradation factor wording is sufficiently generic such that it can be applied to any potential CO_2 storage site. However, due to this generic nature, the DETECT bowtie diagrams are inappropriate for direct (i.e. unedited) use in risk management decisions such as permit applications without site-specific analysis being applied. For a specific project it may be that not all leak paths are relevant, not all consequences are possible and some prevention/mitigation controls are not present.

Hurst and Lidstone (2020) Bowtie Template Tool allows the user to select which threats, consequences and controls on the generic bowties developed by the DETECT project are relevant to their CCS project and enables them to generate a bowtie framework to be used as a basis for a more detailed, project-specific bowtie analysis. The tool also allows the user to apply effectiveness and uncertainty ratings to each control measure, illustrating the project's current degree of confidence in the risk prevention/mitigation measures. Once the user is satisfied with their choices, they can generate a tailored bowtie diagram to use as a starting point for their CCS project's risk management activities.

A number of options for introducing quantification into the bowties analysis process were mentioned in Hurst and Lidstone (2020) as part of future development of the proposed bowtie approach. However, the approaches are mainly focused on semi-quantification (such as van Thienen-Visser (2014) and Layers Of Protection Analysis), as it was not considered practicable for the project to integrate a fully detailed QRA approach into bowties. The main issues with quantification of the bowties were the lack of an agreed set of data for determining both the frequencies and consequences of CCS risks and the difficulties associated with modelling dependent failures.

From a frequency perspective, a set of realistic, accurate failure data for each bowtie barrier is required and any frequency calculation must also be able to account for the presence of the same barrier across multiple threat/consequence paths and also across multiple bowties. From a consequence perspective, to obtain a reasonable estimate for the leakage rate from a geological storage site, the orders of magnitude differences in physical scale and the interconnected nature of geological leakage processes must be considered.

It would therefore be necessary to perform complex simulations of flows through geology and to determine the level of uncertainty in the analysis. As this would be time consuming and expensive the analysts would have to consider the extra detail and insights that may be obtained from detailed quantitative approaches, against the cost and effort required to perform these additional assessments, to arrive at an approach that is both practicable and fit for purpose.

B.1.2 Nuclear industry PSA containment risk modelling and seismic PSA guidance

IAEA (2010) states that, "*PSA provides a methodological approach to identifying accident sequences that can follow from a broad range of initiating events and it includes a systematic and realistic determination of accident frequencies and consequences".* Internationally there are three levels of PSA:

<u>Level 1 PSA (Core Damage Frequency)</u>

Plant design and operation are analysed to identify the sequences of events that can lead to core damage and to estimate the core damage frequency. In this way, Level 1 PSA enables the determination of the preventative measures against core damage, specifically the safety related systems and procedures in place or envisaged.

Level 2 PSA (Radioactive Materials Releases)

The core damage sequences identified in the Level 1 PSA are evaluated chronologically and a quantitative assessment is undertaken of the phenomena arising from the severe damage to the reactor fuel. Different ways in which the associated releases of radioactive material from the reactor fuel can be released to the environment can then be identified, to determine the frequency, magnitude and other relevant characteristics of the release. The relative importance of accident prevention and mitigation measures can be obtained, as well as determining the physical barriers to the release of radioactive material to the environment.

Level 3 PSA (Societal Consequences)

Involves estimation of public health and other societal consequences based on release scenarios from the Level 2 PSA, such as the contamination of land or food from the accident sequences that lead to a release of radioactive material to the environment.

Seismic Probabilistic Safety Assessment (SPSA)

The general approach to conducting a Seismic Probabilistic Safety Assessment (SPSA) is well established and has been practiced in the last few decades (IAEA, 2020). The major technical elements of a SPSA are:

- Probabilistic seismic hazard assessment – This is usually expressed in terms of the frequency distribution of the ground motion parameters (e.g. PGA or spectral acceleration). An example in a CCS context is Carlton et al. (2019);
- Development of the seismic equipment list – involves a review of the existing or envisaged structures, systems and components (SSCs) of the plant;
- Seismic fragility analysis – failure modes of the SSCs listed in the seismic equipment list are used to generate seismic fragility functions of the hazard parameter (level of ground motion);
- Seismic plant response analysis – conducted using a plant logic model which includes seismic event trees that define the accident sequences triggered by seismic induced initiating events, and that are linked with the fault trees representing failure of mitigative functions (e.g. SSC failures or human errors);
- Seismic risk quantification and interpretation of results – involves integration of seismic hazard curves and families of fragility curves following the Boolean equations defined by the union of minimum cut sets.

Guidance on Seismic Hazard Analysis

NUREG-2213 Updated Implementation Guidelines for Seismic Hazard Analysis Committee (SSHAC) Hazard Studies, builds on the framework described in the prior NUREGs and incorporates lessons learned from conducting more recent SSHAC studies to update minimum requirements for SSHAC Level 1 and Level 2 studies in terms of:

(i) the size of the technical integration team and participatory peer review panel;

(ii) the nature of engagement between the technical integration team and peer review panel;

(iii) the engagement of external experts;

(iv) hazard sensitivity and feedback;

(v) documentation, and;

(vi) the potential for workshop(s) or other augmentations.

NUREG-2117 Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies serves the following primary purposes:

(1) Additional levels of detail on topics related to the implementation of SSHAC processes beyond those provided in the original SSHAC report NUREG/CR-6372, particularly for Level 3 studies, and;

(2) Additional guidance on the implementation of Level 3 and 4 studies in light of experience gained from past SSHAC projects,

(3) Highlights the differentiation in terms of complexity, cost, and schedule between the processes of Levels 1 and 2 and the more involved processes of Levels 3 and 4, required to achieve a higher level of regulatory assurance.

The essence of the SSHAC process is the structured interaction among experts to achieve a well-documented hazard study that captures the centre, body, and range of technically defensible interpretations (commonly referred to as the CBR of TDI). There are five key features that are indispensable to the SSHAC process and that distinguish all SSHAC studies from non-SSHAC projects:

(1) **Clearly defined roles** for all participants, including the responsibilities and attributes associated with each role.

(2) **Objective evaluation** of all available data, models, and methods that could be relevant to the characterization of the hazard at the site.

(3) **Integration** of the outcome of the evaluation process into models that reflect both the best estimate of each element of the hazard input with the current state of knowledge and the associated uncertainty.

(4) **Documentation** of the study with sufficient detail to allow reproduction of the hazard analyses.

(5) **Independent participatory peer review** is required to confirm that the evaluation considered relevant data, models, and methods, and that the evaluation was conducted objectively and without bias.

B.2 Current CCS Quantification Methods

Currently there is no widely accepted standard for quantitative risk assessment tools in Carbon Capture and Storage.

B.2.1 Bayesian Belief Networks

Bayesian Belief Network (BBN) is a probabilistic graphical modelling tool that has been used to model the complex system interdependencies of CCS to determine containment risk (Gerstenberger *et al.*, 2015; Gerstenberger *et al.*, 2013). BBN is used to model the components/parameters of the system of interest as nodes and the conditional dependencies between the components are represented by edges/arrows. Nodes are connected from parent to child type node and if nodes are not connected it is assumed that they are conditionally independent of each other. Each of the nodes can have two or more states which represent discrete probability ranges. These are represented by Conditional Probability Tables (CPT) attached to each node that expresses the probabilities that a node will assume a particular state given the states of all parent nodes. The effect of propagating the change of node state through a BBN is based on Bayes' theorem

This approach is heavily dependent on the involvement of geologists, fault experts, reservoir modellers, social scientists, project managers and other CCS experts to develop and populate the structure with estimates of the conditional probabilities. This means that the development of a BBN model can be both complex and time-consuming exercise. Whilst it is likely that expert judgement will be required to a certain degree for CCS risk assessments due to the lack of historical data, this method relies more on the quality of the expert elicitation procedure, specifically:

- Selection of the experts
- Selection of the elicitation procedure
- Design of the workshop

The main challenges found by Gerstenberger *et al.* (2015) of this approach were:

(1) Ensuring the experts have sufficient understanding of the information required from the BBN;

(2) Deriving definitions for the information required from each node that can be easily understood across the range of experts selected.

Another factor that has a substantial impact on the complexity of the BBN model is the number of states chosen for each node. There is a delicate balance to find between having a BBN that is too simple (resulting in less meaningful results) and being overly complex where it becomes intractable to understand the required probabilities or find the time to elicit the large number of probabilities. This is especially the case for modelling natural and induced seismicity, which was found to be difficult mechanisms to model in BBN (Gerstenberger *et al*, 2015).

Also, Gerstenberger *et al*. (2013) found that the display of the BBN results would need to be simplified in order to effectively communicate the probabilistic output to stakeholders, regulators and the public. In the work bowtie diagrams were recommended as suitable tool for external communication that could be linked with quantitative methods such as BBN.

B.2.2 Logic Trees

Logic Trees are a widely used technique that has also been used for quantitative risk assessment for CCS projects (Navamony, R., 2011; Gerstenberger *et al*, 2009). Release paths can be modelled in logic trees using a series of nodes and branches. Each node can have two or more branches that represent possible alternative occurrences/leak paths within the containment system. Each branch is assigned a weighting/probability and the total probability of all the branches emanating from a single node is equal to 1.

In this way all the possible combinations of release paths can be explored and evaluated to determine each paths specific probability of occurrence and consequence. Due to the number of potential paths to comply with the AS/NZS 4360:2004 Risk Management Standard, Gerstenberger *et al* (2009) considered incorporating Monte Carlo simulations, which would randomly select branches based on their assigned probabilities. A benefit of this method was the ability to incorporate uncertainty analysis in the calculations.

Also, Gerstenberger *et al* (2009) advises the input of probability distributions for many of the considered parameters in the logic trees, to enable sufficient prediction of the range of possible outcomes, as shown in Figure 11. Probability of occurrence distributions were found to be the best way to recognise the range of values that are possible for each parameter and that each of these values are not likely to have the same probability of occurring. This was based on well data, which demonstrated that permeabilities of the storage reservoir or seal exhibit a range of values, with some permeabilities being more common than others.

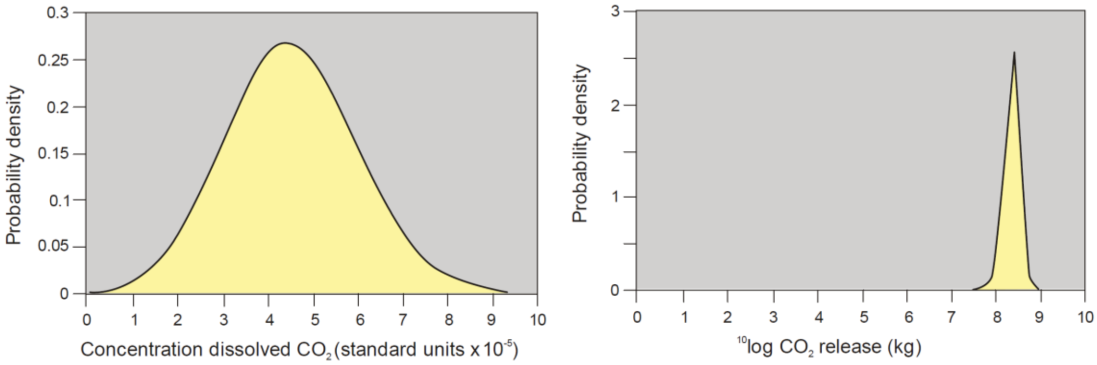


Figure 11: Examples from Gerstenberger et al (2009) of probability distributions for (a) CO_2 concentration in seawater and (b) CO_2 release into the atmosphere for a well leakage scenario

Some of the key issues identified by Gerstenberger *et al* (2009) were:

- Probability distributions for a single site may change with time positively or negatively. For example, CO_2 plume is less mobile post the injection stage compared to during injection, resulting in a reduction in the containment risk with time;
- The risk analysis is limited by the uncertainty in understanding the input parameters (such as leakage rate). This is based on the areas of focus for the research and the level of precision of the chosen methodologies for providing input data;
- Subjective input from expert elicitation is likely to be required for the risk assessment model, especially for a new site or developing site. Therefore the choice of method for expert elicitation should be considered to derive robust estimates of event probabilities;
- Acceptable risk will likely be determined by the stakeholders, who will have different views that will complicate reaching a consensus decision.

Navamony (2011) work on the Goldeneye project demonstrated determining numerical estimates for the left hand side of the Goldeneye bowtie using the fault tree method and the right hand side using the logic tree method. Frequencies and severity scales for the threat consequence branches were derived using a risk matrix and assigned based on engineering judgements and opinions from experts in Goldeneye project team.

However, the calculations would have benefited from determining how to integrate the fault tree and event trees.

Hurst and Lidstone (2020) Bowtie Analysis Report for the ACT funded DETECT project also includes logic trees. Three logic trees were constructed for three 'child' bowties including Pressure Effects, Reactive Effects and Clay Swelling Effects, as shown in Figure 12. Each node on the logic trees represent one of the parameters shown on the child bowties and for each node there are mutually exclusive branches (e.g. good/poor, yes/no values) to dictate a path through the event tree, arriving at one of a set of possible outcomes. Each logic tree is supplemented with descriptors on the effectiveness ratings, thresholds and dependencies that define the branches of each of the barriers on the logic trees.

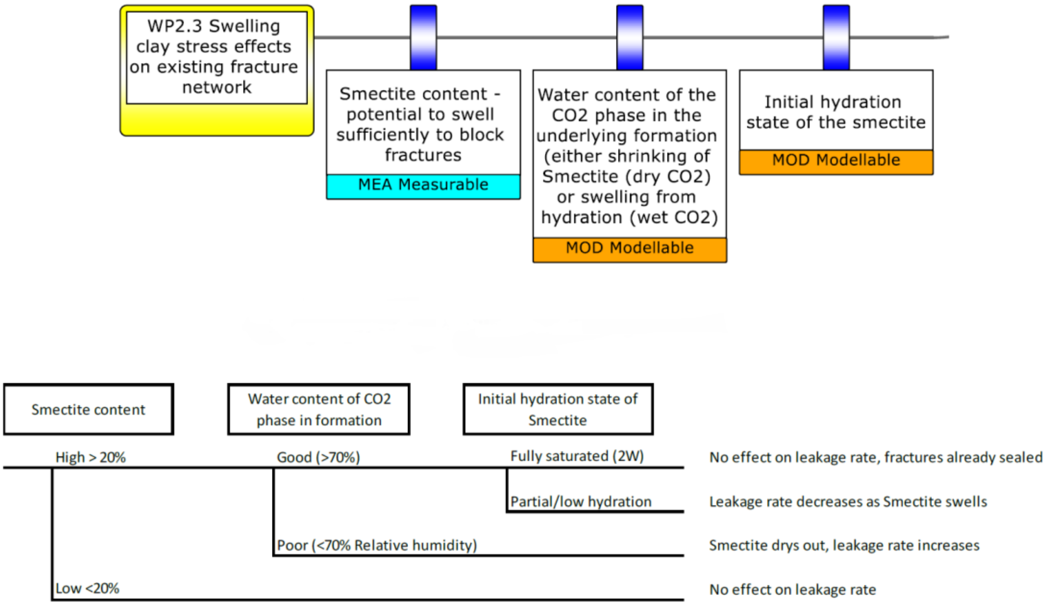


Figure 12: Example from Hurst and Lidstone (2020) of Clay Swelling Effects Bowtie and Logic Tree

Exact relationships between the parameters were found to be too complex to model (requiring simulations to reach a conclusion), therefore the logic trees only provide an indication of the relative effects of the mechanisms. As such, only the most dominant parameters are considered within the logic trees, specifically:

- Pressure Effects - Rock Properties, Fracture Roughness, Initial Effective Stress, Change in Pressure in Underlying Reservoir, Clay Content;
- Reactive Effects - Presence of calcite, dolomite and/or anhydrite/gypsum in the reservoir, Presence of calcite, dolomite and/or anhydrite/gypsum in the topseal, Residence time of brine in fracture network, CO_2 solubility in reservoir brine;
- Clay Swelling Effects - Smectite content, Water content of CO_2 phase in formation, Initial hydration state of the Smectite.

However, whilst Hurst and Lidstone (2020) demonstrate integration of bowties with logic trees, the trees do not fully explore all the mechanisms or parameters that may exist, nor are they intended to provide absolute numerical values. Probabilities have not been defined for each of the barrier branches or initial leakage rates for the logic trees. Demonstration on a CCS site, with estimates for multiple site-specific trees for a detailed assessment would be required to validate the method.

B.2.3 Uncertainty Analysis of Input Distributions

PROBAN

Solomon *et al* (2009) use the general purpose probability analysis (PROBAN) software package to apply semi-analytical reliability methods to a CO_2 storage site to analyse leakage along a single hypothetical fault. PROBAN uses first- and second-order reliability methods (FORM and SORM, respectively) to assess the probability that a given leakage from a fault exceeds a certain threshold level and to provide the sensitivity of such a probabilistic event to the basic uncertainty in the input variables.

Solomon *et al* (2009) suggested that FORM and SORM were more suitable for dealing with independent CO_2 leakage events that have a very small probability of occurrence, compared to the classical Monte Carlo simulation which would require more computational time and effort. However, further testing of FORM and SORM are required to demonstrate use of the method instead of Monte Carlo simulations. Also, the paper does not go into detail on the code used in PROBAN.

The main issues with uncertainty analysis were:

- The analysis did not consider the dependency of the parameter uncertainties on the fault permeability;
- Leakage rates along leakage pathways were difficult to determine due to lack of data on geometry and dimensions (instead probabilistic variables were used and suggestions of using a simplified model);
- The method would need to be validated for a real test case. As this was a hypothetical scenario several assumptions were made including:
    1. The fault has known dimensions and intersects the storage formation including the cap rock
    2. Constant density and viscosity of CO_2
    3. Pores in the fault zone are fully saturated by the CO_2
    4. There exists after the start of injection a pressure gradient in the fault plane that drives CO_2 upward.

Response Surface Methodology

Rohmer and Bouc (2010) suggest that response surface methodology has both the advantage of a more accurate estimation through numerical analysis (than conventional analytical approaches) with a lower computational cost for uncertainty analysis. The method was applied to assess cap failure by investigating the probability of exceeding a given threshold of horizontal effective stress and the probability of exceeding a given threshold of angle of internal friction, both at different overpressure levels. This involved:

1. Generation of training data by running a finite number of numerical simulations
2. Conducting a sensitivity analysis for selection of the most influential variables to the uncertainty in the analysis outcomes
3. Validation of the procedure by assessing the quality of the approximation using the cross-validation approach
4. Application on the Paris Basin illustrative case using the Monte Carlo method

The main issue with this methodology was determining a sufficient catalogue of analytical models to create a suitable response surface, which increases in complexity based on the number of input variables.

Polynomial Chaos Expansion (PCE)

Oladyshkin *et al.* (2011) proposed the use of Polynomial Chaos Expansion (PCE) to determine the uncertainty of a benchmark leakage problem of injected CO_2 into overlying formations. This involves approximating the dependency of model output on input parameters using a high-dimensional polynomial. This is achieved by projecting the model response surface onto a basis of polynomials which is orthogonal in the probabilistic parameter space.

The uncertainty of the reservoir absolute permeability, reservoir porosity and permeability of a leaky well, is determined through the following steps:

1. Construction of the polynomial basis according to the input data
2. Set up of the chaos expansion to obtain the required coefficients using the non-intrusive probabilistic collocation method summarized
3. Evaluation of all desired output statistics
4. Validation of the proposed approach by comparison with a benchmark Monte Carlo simulation

However, all implementations of PCE require the random variables to be statistically independent. In cases where the variables are correlated, correlation would have to be removed (or minimised) by adequate linear or nonlinear transformation. This would have to be the case for CO_2 storage model outputs, which would likely correspond to (for example) pressures in the reservoir, CO_2 saturations, amount of displaced brine or the total CO_2 leakage to the surface.

The method is suggested to provide the ability to model physical systems with unknown probability distribution functions, where data sets are very limited in size. However, if the input data set is small, direct application of the method presented becomes less robust. This is due to the sample moments being only uncertain estimates of the real moments. Therefore, expert opinion is required for data interpretation and has been incorporated in the method.

B.2.4 CO_2 Leak Detection PFD

Yang *et al* (2011) uses TOUGH2 and Bayesian statistical method to determine the probability of leak detection, which is defined as the probability that a leakage signal is sufficient to increase the total flux beyond a statistically determined threshold. TOUGH2 was the subsurface simulation code used to evaluate the relationship between leakage events and possible incremental fluxes based on:

- Chosen range of scenarios for the leakage rate;
- Leakage location (relative to monitors);
- Subsurface conditions of interest (in particular, permeability).

The Bayesian statistical method is used to fit a soil temperature-CO_2 flux relationship to calculate a (temperature-dependent) predictive distribution for observed background fluxes. However, application of the method to real sites will require more detailed site characterization data and modelling tools and adaptation of the methodology to address these complexities. Also, the simple cases considered assumed relatively dense monitoring networks (ranging from 10 to 20m, equivalent to 2500 and 10 000 surface flux monitoring points at a relatively small 1km square site) which would be impractical. Additionally, false positives would be more likely.

B.2.5 Markov Chain Monte Carlo simulation

Augustin (2014) proposed the use of Markov Chain Monte Carlo (MCMC) simulation for determining the average amount of surface leakage that a stakeholder could expect if they engaged in CCS in 2014. This involved the use of the Bayesian modelling technique to integrate analysis of the limited available data. A predictive Bayesian version of a Poisson probability distribution is used to forecast leakage incidents over 15 years. Once the simulation converged, the total leakage over the planning period was estimated by multiplying simulated values of event frequency and event size.

The main issue with the method was the lack of robust industry datasets, which instead relied on probability density functions (PDFs) of CO_2 leaks from five naturally occurring subsurface storage sites. The method relies on the following assumptions:

1. Leak events occur in discrete random intervals
2. The probability of a leak event occurring in a particular time interval is proportional to the amount of exposure in that interval
3. The entire state of the model is considered the state of the Markov chain
4. During simulation the model is able to converge.

Augustin (2014) describes MCMC simulation as a 'black box' simulation, as there are several software packages are available to test a wide variety of probability models.

B.2.6 Fuzzy-rule based prediction

Zhang *et al.* (2009) generated fuzzy rules from discrete fracture network simulations to estimate leakage probability, based on percolation theory for estimating the connectivity of the faults. The proposed approach includes four steps:

1. Estimation of the critical value for the density of conduits (faults and fractures) using percolation theory, which is the point where the system is on average connected between the storage formation and a compartment;

2. Estimation of the probability that the CO_2 plume will encounter the connected conduits for a system (at or above the critical value) for various distributions of conduits, system sizes and CO_2 plume sizes, by performing Monte Carlo simulations;
3. Construction of the fuzzy rules (based on "if then" statements) that relate information about the conduit system and CO_2 plume size to leakage probability;
4. Prediction of the probability that a CO_2 plume of various sizes will escape from the storage formation to a compartment through the connected conduits, using the Mamdani-type inference system provided by the Matlab Toolbox.

However, the prediction relies on assuming:

- The system under investigation is a square, two-dimensional (2D) cross section;
- Faults/fractures are randomly oriented, conductive and follow a power-law length distribution.

B.2.7 Evidence Support Logic Approach

Capture Power and National Grid (2016) conducted a storage risk assessment to develop a Monitoring, Measurement and Verification (MMV) plan and corrective measures plan. A risk assessment of the subsurface CO_2 storage component of the project was performed using the outputs from a number of other activities commissioned by National Grid Carbon Limited (NGCL) including:

- Data acquisition, including seismic data and information from new and legacy boreholes;
- Geological interpretations;
- Reservoir simulations;
- Geochemical investigations; and
- Geomechanical investigations.

The main purpose of the risk assessment was to analyse the risks associated with underground aspects of CO_2 storage throughout the lifecycle of the project and demonstrate that the risks are low and/or can be adequately managed by NGCL's subsurface CO_2 storage activities at the Endurance site. The assessed risks were divided into two categories:

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

The risk assessment is structured according to the derived 'scenarios' for the future evolution of the storage system. The scenarios are a structured collection of Features Events and Processes (FEPs) during and after injection, that reflect key risks to be assessed. The Alternative Evolution Scenarios (AES) identified (together with 2D illustrations, similar to the release diagram concept herein) include:

1. Reduced injectivity due to chemical changes/ reactivity
2. Reservoir pressurisation due to unexpected compartmentalisation
3. Leakage through the primary seal and secondary seals
    a. via Faults/Fractures
    b. by Diffusion
4. Increased displacement of high salinity formation waters
    a. via Fractures
    b. via Outcrop
5. Well failure
6. Lateral interaction with other hydrocarbon resources
7. Resource exploitation elsewhere affects CO_2 storage system
8. Seabed uplift/tilting
9. Human intrusion

10. Leakage as a result of seismic events
    a. Induced Seismicity
    b. Natural Seismicity
11. Sabotage
12. Accidental over-filling

Key risks associated with the scenarios were identified and divided into two categories: the risks to the protection of human health and the environment; and the risks to the permanent containment of CO_2 within the defined storage. The TESLA software tool was used to conduct the Evidence Support Logic (ESL) approach. This approach involves systematically breaking down a hypothesis under consideration into a logical hypothesis model (a 'decision tree'), the elements of which expose basic judgments and opinions about the quality of evidence associated with a particular interpretation or proposition.

A tree structure is constructed that connects some key hypothesis of interest to supporting hypotheses that can be tested using direct observations of relevant phenomena or model outputs. The key hypothesis of interest were related to containment of CO_2, displacement of formation fluids and physical effects. In practice, intermediate hypotheses will usually occur within the tree, between the readily testable hypotheses at the lowest level and the top-level hypothesis of interest.

However, this approach does not provide assurance that all risks and FEPs that may influence them have been identified and represented within a set of scenarios. The assessment scenarios also rely on developing generic timeframes into time periods of relevance to the assessment, on the basis of the key features and processes. A risk matrix is used to determine the level of risk of the scenarios qualitatively. Each hypothesis line is assigned confidence levels rather than probabilities or frequencies of occurrence.

B.3 Mitigation and Remediation

Manceau et al (2014) focuses on the risk treatment stage, which comprises mitigation and remediation techniques used to avoid an impact occurring or reduce its magnitude. This is achieved either by reducing the likelihood of failure through an action on the source of risks or by an intervention on the leakage pathway after the detection, evaluation and quantification of the leakage size, location and magnitude.

B.3.1 Fluid management practices

For some migrations cases such as caprock sealing defects including faults, fractures and high permeability areas, the leakage pathways are difficult to target directly. In these cases, the mitigation measures therefore aim at countering the forces responsible for the CO_2 migration to prevent or minimise CO_2 migration, which include:

- Temporarily or permanently arrest the pressure increase or decrease the pressure in the storage aquifer, locally or globally;
- Create a pressure barrier in the overlying geological strata to prevent or minimise CO_2 leakage;
- Back-produce injected CO_2 either locally or globally, and;
- Enhance non-structural trapping mechanisms.

<u>Pressure relief in the storage formation</u>

Natural processes of brine and rock compression, as well as dissolution of CO_2 into formation brine through density-driven convection, will naturally decrease the pressure build-up in the formation. However, the weak density difference between CO_2-saturated and unsaturated brine could hinder this process.

Stopping the CO_2 injection is effective if the resultant pressure relief in the storage formation is sufficient for reducing leakage, or preventing the CO_2 plume from reaching a leakage pathway.

Accelerated and enhanced strategies, such as drilling new injection wells, producing at the injection well or extracting brine at a distant location, can prevent or reduce CO_2 leakage outside the storage reservoir.

However, if the over-pressurization has created a new leakage pathway (e.g. through fault reactivation and hydraulic fracturing), these created cracks and reactivated faults may not totally close with the sole pressure relief.

Hydraulic barrier

Hydraulic barriers offers a preventive or corrective measure in pollution engineering by injecting (or producing) water to locally modify the hydrogeology and protect the drinking water against saline brine intrusion. For CO_2 leakage this involves injecting brine into the overlying aquifer. The pressure in the aquifer is increased just above the leakage pressure to counter-balance the CO_2 buoyancy and the storage reservoir over-pressurization that are driving this leakage.

Implementing a hydraulic barrier requires the consideration of many operational and strategic issues:

- Technical feasibility of re-using a former injection well or drilling a new one;
- Levels of induced over-pressurization to avoid reactivation of existing faults and fractures widening or even creation of new ones;
- Availability of brine;
- Efficiency of the injection;
- Rate of response.

The hydraulic barrier may be efficient if applied in the immediate vicinity of the leakage plume; however, it may be an impractical solution at long distances since it requires long injection periods to be efficient.

CO_2 plume dissolution and residual trapping

In situ enhancement of dissolution and residual trapping may be considered as a remediation option both for the injected CO_2 plume in the storage reservoir and/or a secondary accumulation in an overlying aquifer. The method relies on a brine flow over the CO_2 plume, which will enhance these two CO_2 trapping modes. However, this may require large brine injection flow rate and induce overpressure, which may negatively impact the geomechanical integrity of the reservoir.

Ex situ CO_2 dissolution and saturated brine injection can be used to store dense CO_2-saturated brine. This involves extracting the saline aquifer brine via production wells, then dissolving captured CO_2 into the extracted brine on the surface using high pressure/temperature mixing vessels and finally re-injecting the CO_2-laden brine into the storing formation. Although the extraction/CO_2-dissolution/injection process appears to be an attractive solution, it may be hampered due to the several reasons:

- Reservoir heterogeneities affecting the injected CO_2-laden brine movement into formation;
- Increased pressure regimes near the injectors;
- Decreased pressure regimes near the extractors;
- The required large number of injection/production wells to enable the process and associated costs;
- Added costs required by the surface facilities;
- Need to optimize wells location;
- Possible near-well mineralization further reducing well injectivity or mineral dissolution that may threaten the reservoir integrity;
- Deployment difficulties both onshore and offshore.

CO_2 back production

The back production of stored CO_2 is useful if the site is less suitable than anticipated. Theoretically, all stored CO_2 in the formation can be back-produced, except the CO_2 that is stored in the form of mineral trapping. However, the achievable back-production ratio in real sites is limited by the complex and heterogeneous nature of the geological storage. Moreover, partial or total back-production of the injected CO_2 has not been tested yet in CO_2 geological storage sites, and only few studies directly address this question.

B.3.2 Mitigation Technologies

Existing technologies for mitigating an undesired migration of the CO_2 plume include the use of:

- Foams and gels to reduce CO_2 mobility and isolate conductive flow paths;

- Nanoparticles and biofilms to enhance the sequestration of CO_2 and reduce/eliminate any potential risk for CO_2 leakage.

However, the potential application of some of these techniques depends strongly on the location of the undesired CO_2 migration and the leakage severity. Depending on the storage formation and leakage-path properties, some of these techniques may serve as short- to intermediate-term solutions until a more permanent one (e.g., a side tracked or new relief well is drilled in case of a major/catastrophic leakage which will serve to permanently isolate the source of leakage) can be placed to address long-term solutions.

Foams, polymer or inorganic gels have been traditionally used in the oil industry to counteract production of unwanted fluids (water and/or gas) and also divert injected fluids into formation regions which have been poorly swept, thus containing significant amounts of mobile oil. However, the selection, design and deployment of the appropriate mobility-controlled agent are type specific and require, the proper characterization of the storage site as well as the CO_2 leakage location, type and size.

Nano particles have been proposed for enhancing the mitigation technologies by:

- Increasing the strength and ease of development of foams for practical applications;
- Treating the storage reservoir to provide more uniform displacement fronts and delayed breakthroughs;
- Improving the stability and flexibility of silicate gels;
- Mixing with the injected CO_2 to reduce CO_2 leakage risks by increasing the density contrast between the CO_2-rich brine and the resident brine.

Biofilms have been proposed as means to control the spread of, and treat, a contaminant plume in subsurface formations and for helping to prevent a leakage of stored supercritical CO_2 through the caprock by enhancing:

- CO_2 structural trapping by pore clogging and CO_2 leakage reduction;
- Mineralization of carbonate minerals (i.e., mineral trapping);
- Solubilisation of CO_2 (solubility trapping).

B.3.3 Remediation measures on potential impacts

Remediation techniques for impacted groundwater

The main impacts to groundwater to be remediated are: accumulation of gaseous or dissolved CO_2; acidification of aquifers; contamination from the injected CO_2 stream, or from displaced or released species due to the CO_2–fluid–rock interactions. Remediation techniques for impacted groundwater include:

- Monitored natural attenuation (MNA)
  - Reduction of contaminants concentration: e.g. aqueous CO_2 concentration associated substances such as mobilized metals and organic compounds.
  - Transformation of contaminants into less toxic products: e.g. associated substances such as metals, organic compounds.
  - Reduction of constituent mobility and bioavailability: e.g. associated substances such as metals, organic compounds.
- Pump-and-treat - Extraction and treatment of fluids containing dissolved CO_2 or other contaminants (associated substances such as mobilized metals, organic compounds).
- Air sparging - Volatilization and extraction of dissolved CO_2 and additional contaminants.
- Permeable reactive barrier (treatment wall) - - Trapping through a permeable barrier favouring reactions of mobilized trace elements (associated substances such as metals, organic compounds)
- Injection–extraction
  - Extraction of the mobile gaseous plume.
  - Decrease of the quantity of mobile CO_2 in the groundwater aquifer.
  - Extracting the dissolved CO_2 and potential additional contaminants

- Remediation with microbes
    - Adjustment of ground water pH
    - Mineralization of dissolved CO_2
    - Co-precipitation of contaminant (heavy metals)

Remediation techniques for impacts in the unsaturated zone

The unsaturated zone is considered as the portion of the sub-surface situated above the groundwater table. Its porosity is filled with air and water. Possible impacts on the unsaturated zone in case of unexpected behaviour of a geological storage include lowering of soils pH and associated impacts, accumulation of gaseous CO_2 (and potentially associated substances) leading to asphyxiation of associated biota, leaching or mobilization of heavy metals or organic, and changes in bio-geo-chemical processes occurring in soils. This could have subsequent impacts such as damage on surface ecosystems, and damage on economic activities relying on soil such as forestry and agriculture.

Remediation techniques for impacts in the unsaturated zone:

- Monitored natural attenuation (MNA)
    - Reduction of CO_2 concentration in soil
    - Transformation or reduction of mobility of contaminants (e.g. organic compound, heavy metals)
- Soil vapour extraction (SVE) - Extraction of CO_2 (or organic compounds) from soil
- Adjustment of soil pH

Remediation techniques for impacts on surface assets

Remediation techniques for impacts on surface assets include:

- Surface water
    - Passive systems: natural attenuation - Reduction of CO_2 concentration in shallow water
    - Active venting system - Removal of dissolved CO_2 in deep stratified lakes
- Lowering of CO_2 concentrations in indoor air
    - sealing the opening
    - (de)pressurization
    - adjustment of ventilation
- Atmosphere
    - Passive system: natural mixing - Reduction of CO_2 exposure in the atmosphere
    - Air jets, helicopters or large fans - Reduction of CO_2 exposure in the atmosphere
- Ecosystem restoration - Restoration of impacted ecosystem

B.3.4 Challenges

There is a still a need for further research on how these mitigation and remediation measures could be adapted to the specific conditions of CO_2 geologic storage. In practice, the success of an intervention will be highly dependent on the knowledge of what is actually happening at the storage site. This implies knowing the location and nature of the irregularity or impact to be treated. The purpose of the measure, the time needed for implementation, the associated economic costs, the maturity or the environmental impacts of a measure are key factors that need to be assessed. In general, there is a lack of such information and extensive work is needed to fill this gap. One of the main challenges related to mitigation and remediation of leakage in the field of CO_2 storage is to choose the best possible way to intervene.

B.3.5 Probability Estimation and Performance Characterisation

Korre et al (2017) developed a methodology for quantifying the effectiveness of the mitigation and remediation techniques in a manner, which allows for a comparison of the indicative performance metrics. Based on the bow-tie analysis approach, the techniques were broadly placed under two groups. The techniques that deal with a potential threat (or risk), such as a leaky fault or injection induced over-pressure, were referred to as mitigation techniques that reduce or eliminate the threat. On the other hand, those that deal with the consequences of leakage, such as loss of CO_2 storage performance or environmental impacts, were referred to as remediation techniques that reduce the severity of the consequences.

The results obtained for the effectiveness were pooled to generate cumulative probability plots that allow for the quantification of the expected values of success of the implementation of the techniques. The overall performance characterisation was based on an ordinal classification (low, medium and high) and five dimensions, namely:

- Likelihood of success (%)
- Spatial extent (km^2)
- Longevity (years)
- Response speed (years)
- Cost efficiency (M €)

Success probability plots and performance spider charts as shown in Figure 13, were determined using the above criteria for the following mitigation and remediation techniques:

- Mitigation
    - Adaption of injection strategy to control the migration of CO_2 plume in the reservoir
    - Novel approaches to lower reservoir pressure by accelerating convective mixing between brine and CO_2
- Remediation
    - Options to enable the flow diversion of CO_2 plume
        - Foam injection
        - Polymer-based gel injection
        - Brine/Water injection
        - Brine/Water withdrawal
    - Blocking of CO_2 movement by immobilisation of CO_2 in solid reaction products
    - CO_2 back-production
    - Hydraulic barrier
    - Polymer-gel-based sealant injection
        - Well leakage remediation
        - Caprock leakage remediation

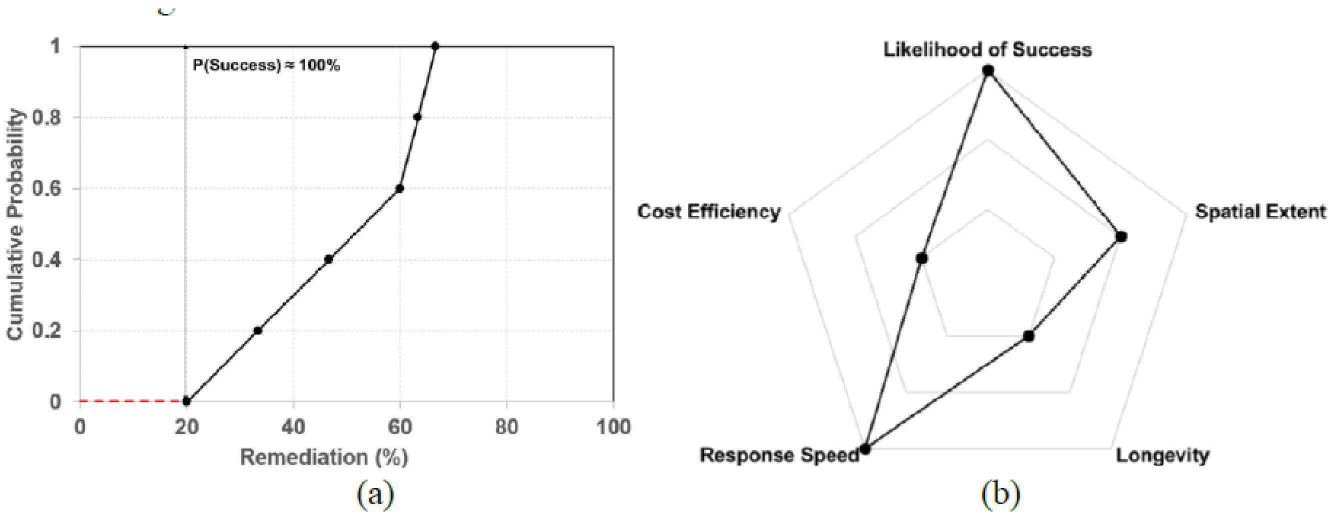


Figure 13: Korre et al (2017) Polymer-gel injection technique: (a) success probability; (b) spider chart

RISKTEC OFFICES

RISKTEC SOLUTIONS B.V.
Seven Cities
Lange Kleiweg 52C
2288 GK Rijswijk
The Netherlands

PRINCIPAL OFFICE
Risktec Solutions Ltd
Wilderspool Park
Greenall's Avenue
Warrington
WA4 6HL
United Kingdom
Tel +44 (0) 1925 611 200
enquiries@risktec.tuv.com

EUROPE
Aberdeen
Derby
Edinburgh
Glasgow
London
Nottingham
Rijswijk

MIDDLE EAST
Dubai
Muscat
Dammam

SOUTH EAST ASIA
Kuala Lumpur
Singapore

NORTH AMERICA
Calgary
Houston

TÜV RHEINLAND HEADQUARTERS
TÜV Rheinland Group
Industrial Services
Am Grauen Stein
51105 Cologne, Germany
tuv.com

risktec.tuv.com

TÜVRheinland®
Risktec