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Containment risk management for CO_2 storage in the Goldeneye depleted gas field, UK North Sea

DRAFT – extension granted

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Abstract

To ensure secure permanent underground storage of CO_2 we must characterise, understand, and manage the storage site. This is essential for regulatory assurance, for liability transfer negotiation and public acceptance. The Goldeneye CO_2 storage site, based on a depleted gas field, is used as a worked example. Two techniques for assessing the suitability and containment risks of a potential storage site were employed. The TESLA methodology and tool (centred on Evidence Supported Logic – ESL) is used to assess the suitability of the site, while the specific containment risk is assessed using the Bow-tie risk assessment methodology.

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Keywords: CO_2 sequestration; Risk assessment; Bowtie; TESLA; Goldeneye; Containment

1. Introduction

Hydrocarbon extraction requires the removal of fluids or gasses from the subsurface – at times we inject water or gas to maintain pressure or improve sweep – but the process generally reduces pressures, removes the product, and finally ends up at a stable minimum.

Geological storage of CO_2 requires the injection of CO_2 into the subsurface – this increases both the fluid pressures and volume of product in the subsurface. The injected CO_2 therefore has potential to migrate over a period of time and can be thought of as a divergent system.

The challenge for CO_2 storage projects is to show that we understand this new divergent system and that the CO_2 will stay where we expect it to for over 1000 years. We have to demonstrate that we are

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confident of containment – and we have developed a way to do this is via a structured risk assessment.

In evaluating the suitability of the Goldeneye store, Shell used two techniques for the containment risks. The TESLA methodology and tool (centred on Evidence Supported Logic – ESL) was used to assess the suitability of the site, while the specific containment risk was assessed using the Bow-tie risk assessment methodology.

This paper examines the process followed to determine the suitability of the Goldeneye CO_2 store.

2. Background to the Goldeneye CO_2 store

After significant work spanning a number of years, it can be argued that the Goldeneye potential storage complex in the Central North Sea is the most mature CO_2 storage candidate in the UK. The site has additional advantages as it demonstrates the re-use of existing oil and gas infrastructure. This existing infrastructure also paves the way for cost-effective future appraisal and expansion into massive saline aquifer systems that are either laterally connected to the Goldeneye field or that overlie the field.

This paper describes the UK Demonstration 1 competition, a project that was cancelled by the UK Government, however, the Goldeneye store has been selected by another CCS project: the Peterhead to Goldeneye post combustion gas-fired power station project. At the time of writing it is not known if this project will receive UK Government and EU funding, however, by the time of the conference this should be known.

The UK Demo 1 proposed scheme was based on capture and storage of ca 20 million tonnes of CO_2 over a period of 10-15 years – so notionally two million tonnes per annum. Flue gas from the ScottishPower owned Longannet coal fired power station was to be captured by an Aker Clean Carbon amine-based process. The resultant 99% purity CO_2 stream would then be compressed to 30 bar (still in gaseous/vapour phase) and transported via an onshore National Grid pipeline to the Blackhill compressor station, next to the Shell St Fergus plant in the north east of Scotland. There it would be further compressed to 120 bar into dense phase. The capture, transport and storage system is shown in Fig 1.

The depleted Goldeneye gas/condensate field 100km offshore was identified as an ideal CO_2 store.

- It came to the end of its production life in 2011.
- The facilities are young, having been installed in 2004, and are normally unmanned.
- The platform is tied back to shore with a dedicated pipeline.
- Geologically the formation is of excellent Darcy quality sandstone, and is well connected – even tank like.
- Evidence supporting containment is excellent:
  - The field has held gas (with a percentage of CO_2) for an estimated 55 million years and there is no evidence of escape features like gas chimneys.
  - The field at approximately 2500m depth is topped by a competent caprock, then chalk formations, then secondary storage formations (sequestration targets in their own right), additional caprocks and finally a sequence of sands, shales and muds.
  - There are very few well penetrations – that could provide man-made leak paths – and the current production wells can be converted into injectors.
- Finally monitoring the field in 120m of water is feasible and so are corrective measures on wells should they be necessary.

The geological details of the storage complex and site are discussed in the companion paper, Development of an offshore monitoring plan for a commercial CO_2 storage pilot, also presented at this conference and will not be repeated here.

Fig 1. The Longannet to Goldeneye CO_2 capture, transport and storage scheme

3. Risk assessment techniques

There are many different methods of assessing risk, however, they may be divided into Quantitative and Qualitative groups. To perform a robust quantitative risk assessment, historical performance data are required to provide empirical evidence for the occurrence frequency of rare events. Although CO_2 has been used in miscible gas flooding for decades, and underground hydrocarbon gas storage is a proven technology, underground storage of CO_2 is new and currently lacks the body of empirical evidence required. This means that it is not possible to perform a rigorous quantitative risk assessment.

Instead, Shell employs two techniques for assessing the suitability and containment risks of a potential storage site. The suitability of a storage site is assessed using the TESLA tool, which is essentially a structured evidence-based screening and assessment tool. The containment risk assessment employs the bow-tie risk assessment technique which is widely used in the assessment of facilities risks and an integral part of the process used to demonstrate that risks are As Low As Reasonably Practicable (ALARP).

4. TESLA assessment

It is key to ensure that all risks in a sequestration project have been identified and subsequently addressed. One technique regularly used in waste disposal is to compare the project against a Features, Events and Processes (FEP) database (Savage et al. [1]). Comparing the project parameters against standard FEP databases for CO_2 storage reduces the likelihood that the project *'misses'* something material.

When large volumes of information are combined from multiple sources there might be disputed or contradictory interpretations. Some evidence might be from hard quantitative data, while other evidence might arise from analogue reasoning or expert judgment. Therefore, in order to provide a justified interpretation of the available evidence it is necessary to make visible judgments on both the quality of the data and their interpretation.

The technique of Evidence Supported Logic (ESL) involves systematically breaking down the question under consideration into a logical hypothesis model whose elements expose basic judgements and technical opinions relating to the quality of evidence relating to a particular interpretation or proposition

[2].

Shell has taken the Quintessa FEP database [3] and experience from CCS, EOR and Gas storage projects and worked with Quintessa – experts in assessing the risks associated with nuclear waste storage – to apply ESL to CO_2 storage. This is called TESLA – Technical Evidence Supported Logic Assessment.

TESLA can be viewed as an overarching storage project risk assessment and health check. It helps to ensure that all risks have been covered, and it highlights where a project's weaknesses lie by tabulating the evidence supporting the main hypotheses, the evidence against the hypotheses and the uncertainty (current level of unknowns). Repeated application through time by the same team allows monitoring of how the project is progressing in reducing the risk and uncertainty.

A cornerstone of ESL is three-value logic. Judgments based on classical probability theory follow two-value logic where evidence is either for or against and the hypothesis is either true or false. This assumes perfect knowledge about the system. Three-value logic adds a third element – uncertainty, as illustrated in Fig 2.

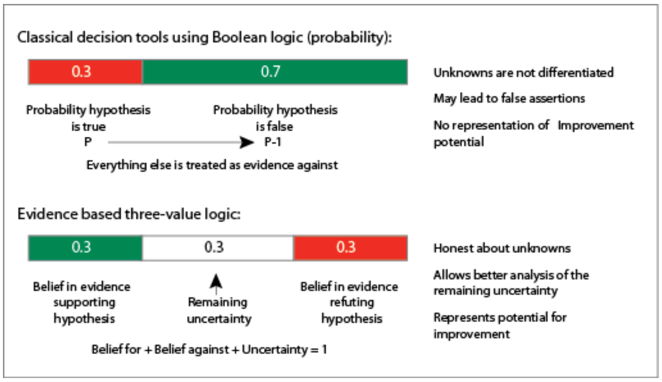


Fig 2: Classical Boolean logic compared to three-value logic

A significant advantage of the three-value logic is that evidence for and evidence against can be evaluated independently each ranging from 0 to 1 – with uncertainty taking a value from -1 to 1. An uncertainty of 1 implies that there is no evidence at all, while something less than zero indicates a conflict.

The TESLA analysis presents the assessment of CO_2 sequestration in a logical tree-based structure with top hypothesis supported by the key sub-hypotheses of CCS (Fig 3), which in turn are broken down into component parts.

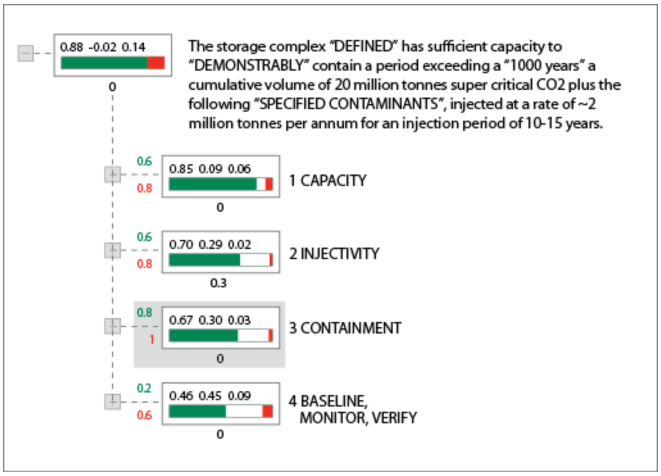


Fig 3: TESLA top level nodes

The next key element to the TESLA analysis is that the hypothesis results (the evidence for, against and the uncertainty) for each node are rolled up to give a top level assessment of evidence for the whole project. The weighting factors are shown as green and red numbers to the left of the probability bars (Fig 4).

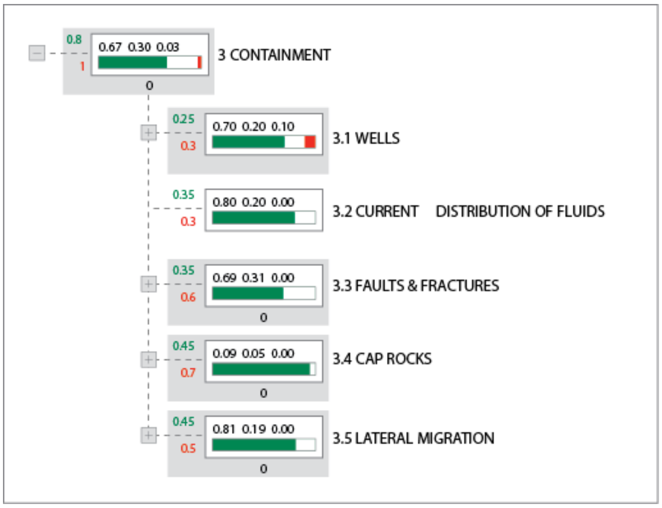


Fig 4: Expanded containment node showing subordinate hypotheses.

Note that the evidence against has stronger weighting factors than the evidence for – the system is tuned for high certainty or to emphasise negative evidence. While this top level assessment is qualitative, when the TESLA exercise is applied repeatedly and consistently during a project it provides a valuable tracking device to show if the risk and uncertainty levels in a project are decreasing as a result of the project work. It can also be applied to multiple sequestration candidates within a portfolio to establish relative maturity and security. During a project's evolution the top level node should, we hope, move upwards and towards the vertical axis (see Fig 5) - as evidence for the hypothesis increases and the uncertainty decreases. A site that does not screen will move downwards and towards the axis.

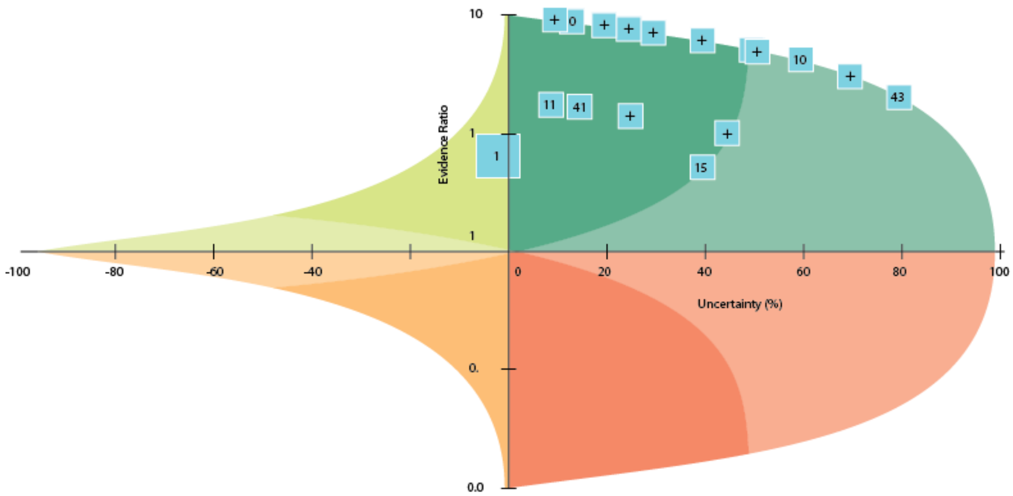


Fig 5: TESLA kite plot. 1 indicates the top level note – the rolled up result fo the tree. The other boxes are end nodes. + indicates that there is more than one node under the box.

From a project management perspective the kite plot is especially useful as it highlights areas of uncertainty or risk and thereby, areas that need more work.

5. Bow-tie risk assessment

The benefits of using bowtie analysis for risk management have been realised by organisations world-wide across a variety of business sectors and the method has been in widespread use since the mid-1990s. It provides a readily understandable representation of the relationships between the causes of unwanted events, the escalation of such events to a range of possible outcomes, the controls preventing the event from occurring and the mitigation measures in place to limit the consequences. It is regularly used in facilities engineering.

Illustrating the preventive and mitigation controls against their respective causes and consequences in such a structured way demonstrates that risks are understood and are being controlled, and can highlight gaps in risk control which should be a focus for remedial action. The bowtie diagram provides a simple visual demonstration of the way in which risks are managed. This allows understanding at all levels, including non-risk specialists, giving everyone the opportunity to review the existing controls in place and to identify any potential improvements.

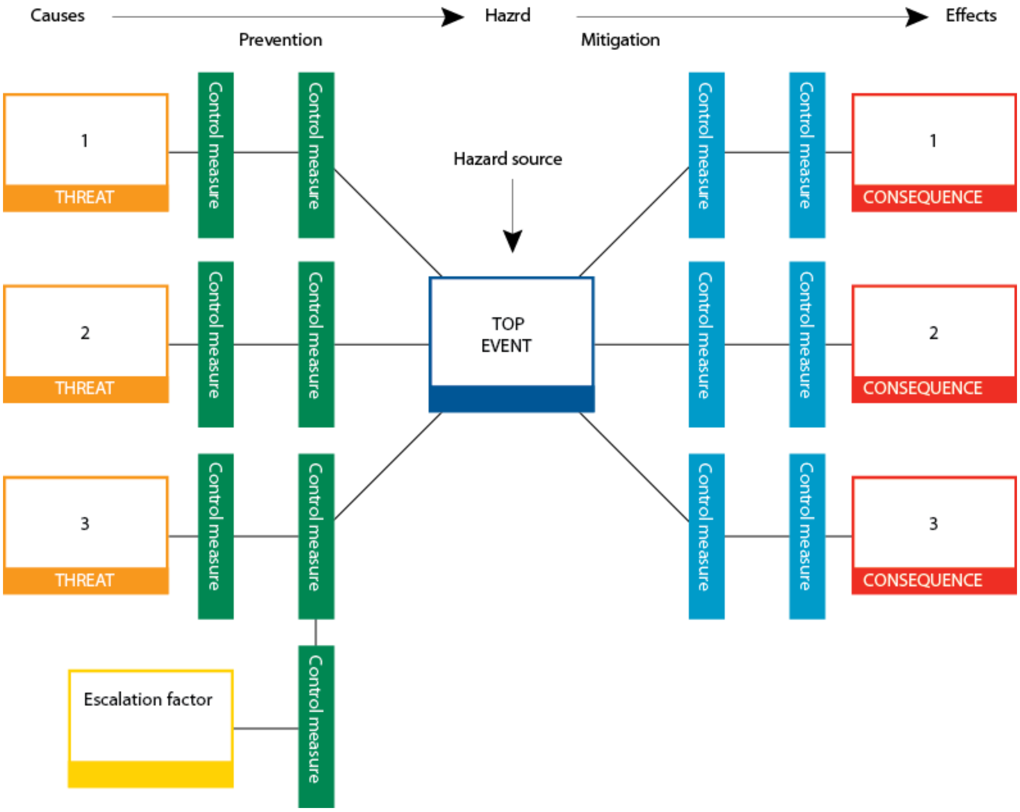


Fig 6: Bowtie diagram schematic

The bowtie method entails building a bowtie diagram (Fig 6), step-by-step, to produce a qualitative risk assessment of the hazard under consideration.

For the Goldeneye CCS project, the hazard is CO_2. It has the potential to cause harm (e.g. by its toxicity to people who are engulfed by a cloud of CO_2, by acidic corrosion or pH modification when CO_2 is dissolved in water or by contributing to greenhouse gas induced environmental damage).

Hazards normally do not cause harm because they are kept under control. However, if control of the hazard is lost, an initial incident will occur – this is the top event and is shown at the centre of the bowtie diagram. For the Goldeneye CCS project, the top event is movement of CO_2 outside the confines of the storage complex.

The causes (sometimes called 'threats') illustrate the various ways in which the hazard could be released i.e. what could cause loss of control of the hazard? Examples of causes which could result in movement of CO_2 outside the Goldeneye storage complex include, but are not limited to, leakage through existing faults or fractures which cross the primary and secondary seal, injection induced stress causing new faults or fractures or re-opening existing faults or fractures, and flow of CO_2 up through abandoned wellbores.

Once control is lost and the top event occurs, there may be a number of ways in which the event can develop to the ultimate consequence. Each consequence will result in a specific extent of harm i.e. severity of impact. The impact might be on people, the environment, physical assets or the reputation of the company, or all of these. Examples of potential consequences relevant to the Goldeneye project are release of CO_2 at the seabed or platform release into the shallow subsurface, or a deeper release just above the storage complex seal.

There are barriers in place which can prevent the release of the hazard (i.e. prevent the threat leading to the top event). These barriers are shown on the left side of the bowtie diagram and can be items of equipment or actions taken in accordance with training and procedures. They also include natural barriers such as impermeable geological layers. No control can be 100% effective, so if the preventive measures fail to maintain control and the top event occurs, further mitigation measures are in place to interrupt development of the event and limit, or recover from, the consequences.

Circumstances may arise which undermine a preventive or mitigation control and reduce its effectiveness; these are recorded on the diagram as escalation factors (i.e. they allow the event to escalate). Escalation factors are, in turn, managed by further control measures.

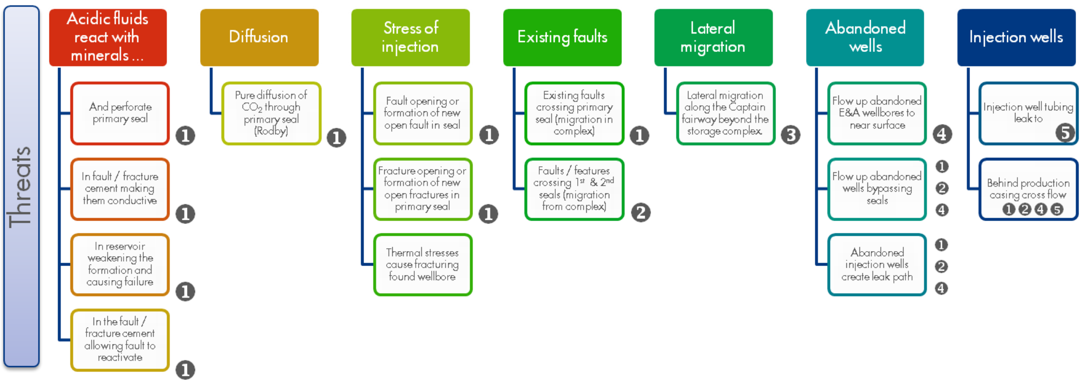
During bowtie analysis, the effectiveness of each control is assessed and recorded. Some types of control are more effective than others. For example, eliminating the hazard altogether or substituting it for a less hazardous one is the most effective type of control. Obviously eliminating or substituting the CO_2 in this CCS project is not an option, where sequestration of CO_2 is the whole purpose of the project. However there are control measures other than elimination which are included in the project design, occur naturally at the storage complex or will be part of the future injection and monitoring procedures and systems.

The bowtie analysis does not stop once the currently planned controls have been recorded; the following questions are also asked:

- “Do we comply with company and industry standards?” ;
- “Can we improve the effectiveness of the existing controls?”;
- “Are there any more controls that can be implemented?”; and
- “Is it reasonably practicable to do so?”.

The analysis therefore identifies additional controls, over and above those currently planned, which can reduce the risk still further. These new risk reduction measures are recorded during the bowtie analysis and actions are raised to evaluate whether or not they should be implemented. In this way, the bowtie analysis can be used to demonstrate that the risks are reduced to levels which are As Low As Reasonably Practicable (ALARP).

Shell’s three main operated CO_2 storage projects to date have all employed bow-tie containment risk assessments.



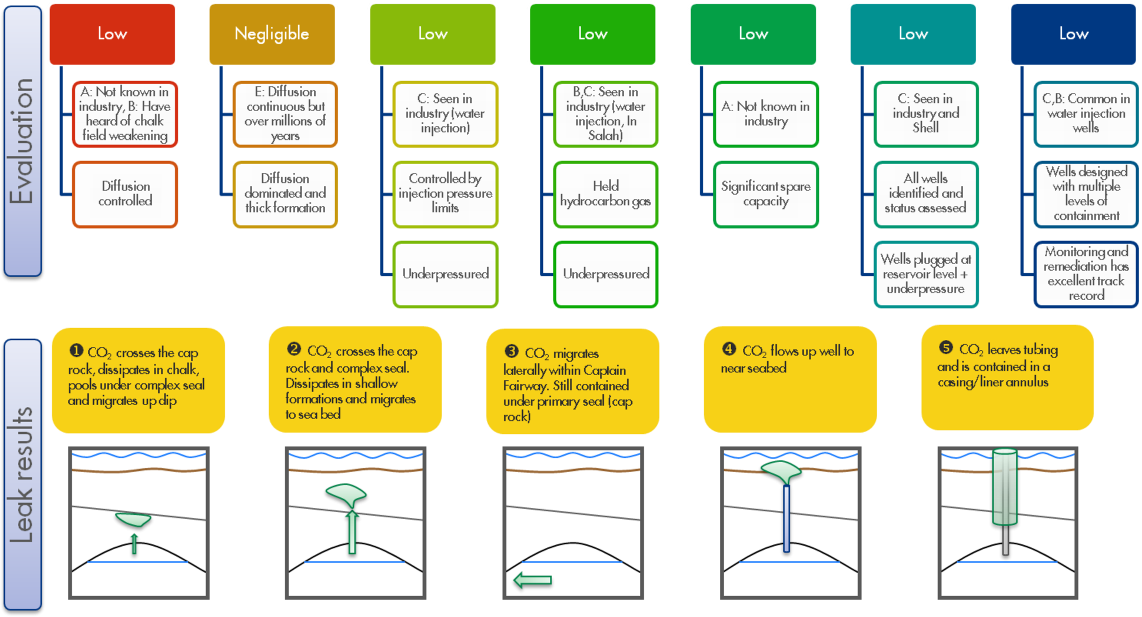


Fig 7: Schematic representation of the Goldeneye containment bow-tie risk assessment and potential leak scenarios (consequences).

The identified threats and consequences analysed using the bow-tie method for Goldeneye are shown in Figures 7 and 8.

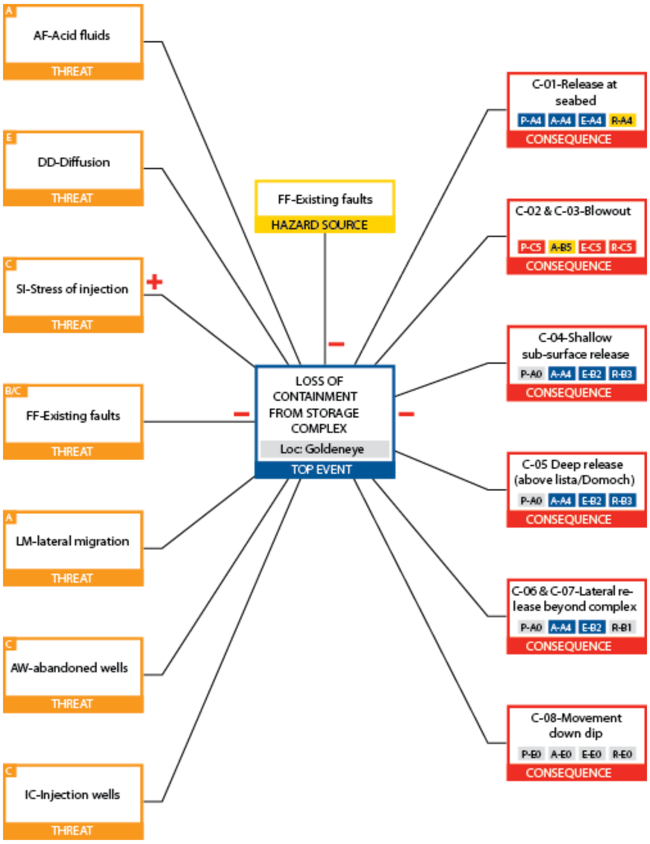


Fig 8: Top level bow-tie for Goldeneye

A birds-eye view of the full bow-tie developed including escalation factors and controls is shown in Fig. 9 to give an impression of the overall analysis and the number of barriers identified.

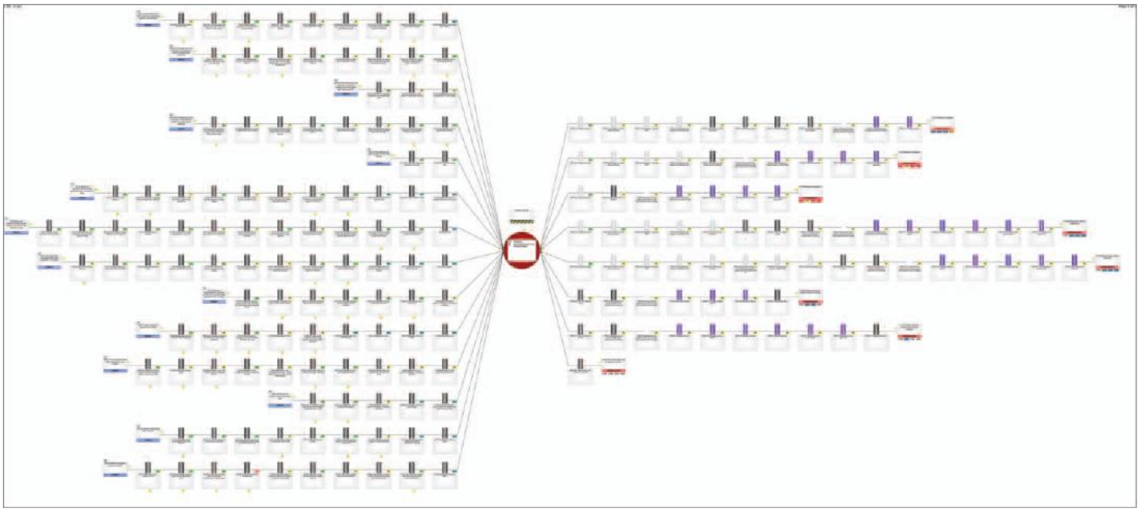


Fig 9: Birds-eye view of the full Goldeneye bow-tie (though even this excludes escalation factors and controls on these)

The threats in the bow-tie are listed in Table 1, and are cross referenced to each CCS stage. A detailed analysis underlies the evaluation of each barrier in the system. It is this analysis that forms the majority of the work involved in proving a CO_2 store. The likelihood criteria are:

A: Never heard of in the industry
B: Heard of in the industry
C: Has happened in the organisation or more than once per year in the industry
D: Has happened at the location or more than once per year in the organisation
E: Has happened more than once per year at the location

Table 1 Summary of threats to CO_2 containment

Threats		Likelihood	Relevant CCS Stage
AF	Acid fluids		
AF-01	Acid fluids perforate primary seal (Rødby)	A	Post-closure at hydrostatic
AF-02	Acid fluids react with minerals in existing fault / fracture cement making them conductive / open	A	Injection, post-closure below hydrostatic and post-closure at hydrostatic
AF-03	Acid fluids react with minerals in the reservoir weakening the formation and causing failure (geomechanical failure).	B	Injection, post-closure below hydrostatic and post-closure at hydrostatic
AF-04	Acid fluids react with minerals in the fault / fracture cement allowing fault to reactivate (reactive transport)	A	Injection, post-closure below hydrostatic and post-closure at hydrostatic
DD	Diffusion		
DD-01	Pure diffusion of CO_2 through primary seal (Rødby) (without permeability)	E (happens continuously but at extremely slow rates)	Injection, post-closure below hydrostatic and post-closure at hydrostatic
SI	Stress of injection		
SI-01	Stress of injection / refilling causes fault opening	C	Injection

Threats		Likelihood	Relevant CCS Stage
	or formation of new open fault in seal		
SI-02	Stress of injection / refilling causes tensile / shear fracture opening or formation of new open fractures in primary seal / cap rock	C	Injection
FF	Faults, fractures and features		
FF-01	Existing faults, mapped / unmapped crossing primary seal (not secondary seal)	B	Injection (local effects) and post-closure at hydrostatic
FF-02	Existing faults / features that cross primary and secondary seal	C	Injection and post-closure at hydrostatic
LM	Lateral migration		
LM-01	Lateral migration beyond the storage complex.	A	Injection
AW	Abandoned wells		
AW-01	Low up abandoned exploration and appraisal wellbores to near surface	C	Injection, post-closure below hydrostatic and (particularly) post-closure at hydrostatic
AW-02	Abandoned injection wells create leak path	C	Post-closure below hydrostatic and (particularly) post-closure at hydrostatic
IW	Injection wells		
IW-01	Injection well tubing leak to annuli	C	Injection
IW-02	Behind production casing cross flow	B	Injection, post-closure below hydrostatic and post-closure at hydrostatic

In order to better understand the relative risks and to prioritise areas for further investigation the likelihood of each threat and the severity of each consequence was assessed using the Shell risk assessment matrix (RAM).

The bow-tie diagram visually shows where there are insufficient barriers/safeguards and where active safeguards are required. This then informs the development of the monitoring programme and corrective measures plan. Once all barriers/ safeguards are taken into account a judgement can be made, in conjunction with regulators and stakeholders, of the containment risk and if the project should progress.

5.1. Potential further risk reduction (preventive)

During analysis of each threat branch, the technical team considered whether any further risk reduction measures could possibly be adopted, over and above those already planned [4]. A total of 20 risk reduction measures were identified across all threat branches, with some occurring on more than one branch resulting in 13 unique risk reduction measures.

The potential benefits of each risk reduction measure were assessed by the team, together with a qualitative assessment of the effort (e.g. cost, practical difficulties) involved in implementing the measure. A decision was then made to either:

- retain the risk reduction measure and consider it further and/or subject it to further analysis during the detailed design stage of the project (8 measures);
- reject the measure at this point in time, but reserve the option to re-consider the measure if a catastrophic problem was encountered (i.e. as part of the intervention / mitigation plan) (3 measures); or
- reject the measure given its cost, environmental impact and practical difficulties (2 measures).

The most commonly occurring risk reduction measures were:

- **N-STN Sidetrack or drill new injection wells** (instead of converting current producing wells to injection wells). The advantages of this are that a completely new injection well design can be adopted and, if the existing wells are given over to monitoring, additional monitoring points are provided. However, this option would entail extremely high cost / effort and there are practical difficulties (e.g. unavailability of extra slots on platform). It also introduces additional potential leak paths from the storage complex.
- **N-STD Side track or recomplete existing wells deeper.** This would increase the distance of the injection points from the cap rock (so reducing thermal cooling effects on the cap rock) and would allow more efficient refilling of the reservoir. Again this measure entails extremely high cost / effort, and also makes injection more difficult (due to relative permeability effects).

Given these advantages and disadvantages, the technical team decided that neither of these two measures should be adopted at present, but they should be retained as part of the potential intervention / mitigation plan.

5.2. Consequences

On the right hand side of the bowtie diagram, eight consequences were identified, with some sub-divided into variations (Table 2). The consequences can be grouped into five leak paths as shown in Fig 9.

The vast majority of the consequences were assessed to have either low or very low risk. A large release at the seabed with a short duration was judged to pose a medium risk to the company's reputation, but only low or very low risk to people and the environment. The highest risk scenario was a blowout, with high risks to people, the environment and reputation and medium risk to the asset.

It should be noted that these risk ratings are based on the assessment team's experience and understanding of previous incidents in the CCS and analogous industries. The rating does not take account of the Goldeneye-specific mitigation measures in place to reduce the severity of each consequence, but instead reflects the generic, inherent industry risk.

Table 2: Summary of consequences of CO_2 release from storage complex

Consequence		Potential Risk[1]			
		P	A	E	R
C-01	Release at seabed				
	Large release, short duration (1 year), point source	A4	A4	B2	A5
	Large release, short duration, diffuse	A1	A4	A4	B4
	Large release, long duration (100 years), point source	A0	A3	A2	A4
	Large release, long duration, diffuse	A0	A3	A3	A4
	Small release, time independent, point source	A0	A4	A3	B3
	Small release, time independent, diffuse	A0	A4	A3	B3
C-02 & C-03	Blowout				
C-02	Subsea blowout	B5/C5	B5	B4/C5	B5/C5
C-03	Platform blowout	B5/C5	B5	B4/C5	B5/C5
C-04	Shallow subsurface release				

Consequence		Potential Risk[1]			
		P	A	E	R
	Pock mark creation / reactivation	A0	A4	B2	B3
	Local diffuse area of blanking	A0	A4	B2	B3
	Pool under shallow mud formation	A0	A4	B2	B3
C-05	Deep release				
	Release above Lista / Dornoch, migration of CO_2 in overburden formations, might not reach sea bed, moves up to shallow release	A0	A4	B2	B3
C-06 & C-07	Lateral release				
C-06	Release laterally beyond complex				
	Might enter At/Crom, field abandoned, might interact with abandoned wells	A0	A4	B2	B1
	Might interact with BG well 14/28 B4 and other wells or faults, could become a near surface leak	A0	A4	B2	B1
	Might reach seabed near Captain field	A0	A4	B2	B1
C-07	Release laterally below Lista but beyond complex				
	Might interact with other wells and leak paths to near surface, seabed outcrop nearer spatially so might become shallow release	A0	A3	A0	A1
C-08	Movement down dip				
C-08	CO_2 moves down dip in aqueous solution	E0	E0	E0	E0

Notes:

1. P = risk to people, A = risk to asset, E = risk to environment, R = risk to reputation. The numbers denote increasing severity, 0 being the lowest, and 5 the highest.

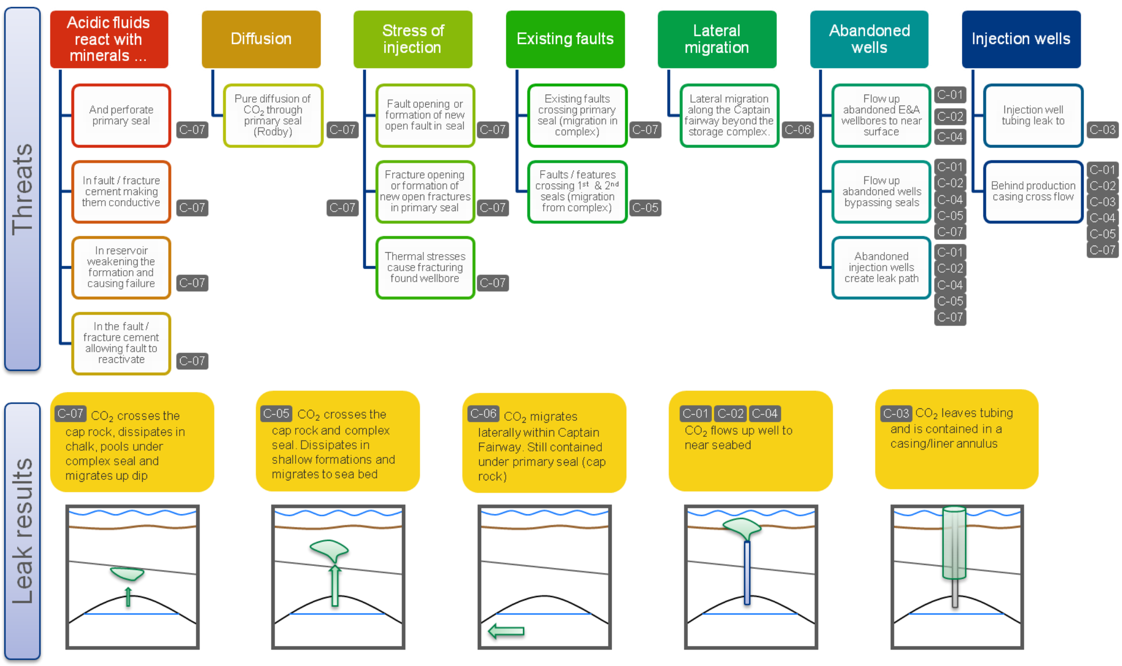


Fig 9: Link between threats and consequences. These should also be cross-referenced with Table 2.

5.3. Requirement for ALARP Demonstration

The risk management framework described in Guidance Document 1 [5] on the implementation of CCS Directive [5], requires that: "*for every risk identified, with its associated uncertainty, the aim is to reduce both the risk and uncertainty to acceptable levels*"

The guidance goes on to explain that: "*In practice this is a matter of identifying the options for reducing the risk and uncertainty, their costs and their consequences for risk and uncertainty reduction*".

While there is no explicit requirement in the framework to demonstrate that the risk has been reduced to As Low As Reasonably Practicable (ALARP) levels, the spirit of the directive, as described in the guidance, aligns with the recognised approach of demonstrating ALARP and hence this part of the bowtie analysis report provides a documented ALARP demonstration.

5.3.1. Definition of As Low As Reasonably Practicable (ALARP)

ALARP is defined as the point where, when objectively assessed, the time, cost and difficulty of further risk reduction measures becomes grossly disproportionate to the risk reduction achieved.

A risk cannot be demonstrated as ALARP until consideration has been given to

1. means of further reducing the risk; and
2. reasons why these further means have not been adopted.

5.3.2. Achieving ALARP risk levels

The first step in the process is to ensure that the facility meets certain standards (otherwise the risk levels cannot be claimed to be ALARP). For example, the CCS project must comply with the CCS Directive [6].

Once such minimum standards are met, there is still a requirement to demonstrate that the remaining risks are reduced to ALARP levels. This is achieved by identifying measures which, if implemented, could bring about a reduction in risk levels. The added benefit of each risk reduction measure is assessed to determine the benefit gained and the effort (whether in money, time or practical difficulty) involved in implementing the measure.

The process is not one of balancing the costs and benefits of measures but, rather, of adopting measures except where they are ruled out because they involve grossly disproportionate effort. ALARP has been achieved when the resources required for the implementation of additional measures which may further reduce risk are unreasonably large when compared to the potential benefit to be gained. Resources would be better applied to reduce risk in another area.

Once all risk reduction measures have been considered and the justification for acceptance or rejection on the grounds of gross disproportion documented, it has been demonstrated that risks have been reduced to the lowest level that is reasonably practicable.

As part of the assessment process the technical team went beyond the assessment of the effectiveness of the currently planned preventive and mitigation measures to consider whether there are additional steps that can be taken to reduce the risk still further. For each threat / consequence scenario, the technical team was asked:

- "C*an we improve the effectiveness of the existing controls?*"; and
- "A*re there any more controls that can be implemented?"*

The options for further reducing risk generated during the process were evaluated in terms of the associated effort (i.e. cost, practical difficulties) and benefit (i.e. risk reduction) and, as a result, a number of options have been carried forward either as part of the Intervention / Mitigation Plan, or for further analysis during detailed design.

By challenging the design (i.e. by asking “can we make the controls more effective?” and “is there anything more we can do?”), the technical team therefore confirmed, using qualitative assessment and based on the *collective experience and judgment of the bowtie analysis teams*, that the risk of CO_2 release from the storage complex is reduced to ALARP levels.

6. Conclusions

The early stages of evaluation of a CO_2 store are ideally suited to the TESLA methodology as this facilitates the comparison of different storage sites, and the tracking of the progress of a single storage site during the technical assessment. By using three-value logic the TESLA methodology explicitly acknowledges and exposes the uncertainty inherent in any geoscience based analysis and is therefore a significant improvement on Boolean logic based approaches.

Once the site assessment is mature it is necessary to perform a more structured analysis to show evidence of containment, and to highlight areas where risks must be managed through engineered solutions (such as monitoring and remediation). This task is performed using a structured bowtie risk assessment approach. The result of this is an explicit assessment, which is open to challenge by regulatory authorities and stakeholders, of whether the risks to loss of containment have been reduced to as low as reasonably practicable (ALARP).

The Goldeneye storage site in the UK has used both of these techniques and, in our opinion, has shown that the risk of containment breach has been reduced to ALARP.

Acknowledgements

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