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

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Abstract

In order to show that a CO_2 offshore storage site is secure, it must be effectively characterized and a full understanding of any risks, and their management, must be in place. The Goldeneye candidate CO_2 storage site, centred 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. A methodology based on Evidence Support Logic (ESL), as implemented in the TESLA software, 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; Bow-tie; TESLA; offshoreContainment; ESL

1. Introduction

Hydrocarbon extraction requires the removal of fluids or gasses from the subsurface – at times water or gas are injected to maintain pressure or improve the 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 disturbed system.

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The challenge for CO_2 storage projects is to show that we understand this new disturbed system. We have to demonstrate that we are confident of containment – and we have developed a way to do this via a structured risk assessment.

In evaluating the suitability of the Goldeneye candidate store, Shell used two techniques for the containment risks. The Evidence Supported Logic (ESL) methodology, implemented using the TESLA software tool, was used to assess the suitability of the site, while the site 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 candidate CO_2 store.

2. Background to the Goldeneye candidate CO_2 store

After significant work spanning a number of years, it can be argued that the Goldeneye candidate storage complex in the Central North Sea is the most mature in the UK. The site has the additional advantage of demonstrating 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.

The store has been selected by a Shell CCS (Carbon Capture and Storage) project that is being actively progressed for a post combustion gas-fired power station project. The depleted *offshore* field was identified as an ideal CO_2 store:

- It recently came to the end of its production life.
- 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.
    - The field is topped, at approximately 2500m depth, 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* [1], also presented at this conference and will not be repeated here.

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 a structured evidence-based screening and assessment tool based on Evidence Support Logic (ESL) as implemented in the TESLA software. The containment risk assessment employs the bow-tie risk assessment technique which is widely used in the assessment of facilities risks and is 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. [2]). 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 [3].

Shell has taken the Quintessa FEP database [4] and experience from CCS, EOR (Enhanced Oil Recovery) and Gas storage projects and worked with Quintessa[†] to apply ESL to CO_2 storage. The resulting tool is implemented in software called TESLA – The Evidence Support Logic Application. The ESL based tool 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). The TESLA software allows users to embed within it explanations of the judgments made and the supporting evidence base (e.g. reports, web links), thereby building an audit trail. 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 of hypotheses based on classical probability theory follow two-value logic where evidence for or against the hypothesis is either true or false. This assumes perfect knowledge about the system. Three-value logic adds a third element (Fig. 1) – uncertainty due to unknowns or uncertainty due to "overcommitted belief", whereby the evidence for and against a hypothesis, when judged independently, implies probabilities of truth and falsehood that sum to a value different from 1.

[†] Experts in assessing the risks associated with varied underground activities, including CO_2 storage, natural gas storage, cavern stabilization and nuclear waste management

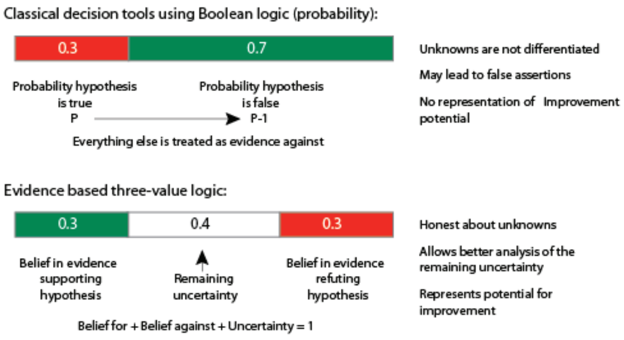

Fig 1: Classical Boolean logic compared to three-value logic

The TESLA analysis presents the assessment of CO_2 sequestration in a logical tree-based structure with the top hypothesis supported by the key sub-hypotheses of CCS (Fig. 2 and Fig.3), which in turn are broken down into further sub-hypotheses component parts.

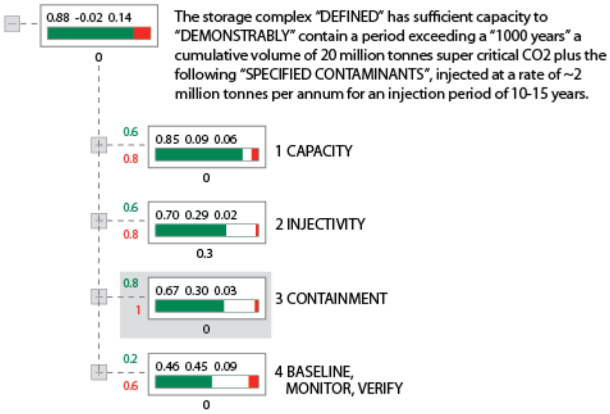

Fig 2: Decision tree developed in TESLA for the project, showing top-level hypotheses. Red and green numbers to the left of the hypotheses are weighting factors that control propagation of confidence for (green bars) and against (red bars) hypotheses.

The next key element to the TESLA analysis is that the hypothesis results (the evidence for, against and the remaining uncertainty) for each node are rolled up to give a top level assessment of evidence for the whole project. Two weighting factors are used, one for supporting evidence the other for refuting. These factors are, by their nature, subjective however, what is key is to maintain the same factors for all the assessments in a project. Note (see Fig. 2) that the evidence against has stronger weighting factors than the supporting evidence – the system is tuned for high certainty or to emphasise negative evidence. While this top level assessment is qualitative, when the ESL 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.

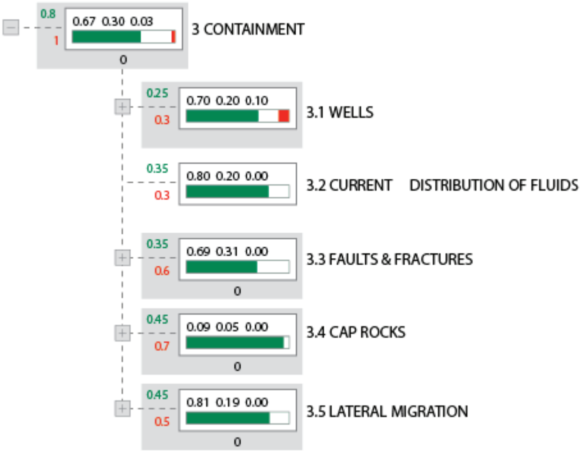

Fig 3: Expanded containment hypothesis showing subordinate hypotheses.

One of the analysis tools that TESLA provides is a *ratio* or *kite* plot, which provides a measure of the ratio of evidence for to evidence against on the y-axis and residual uncertainty on the x-axis (Fig. 4.) On such a plot, during a project's evolution the top level node should, we hope, move upwards and towards the vertical axis – as evidence for the hypothesis increases and the uncertainty decreases. A site that does not screen will move downwards and towards the axis.

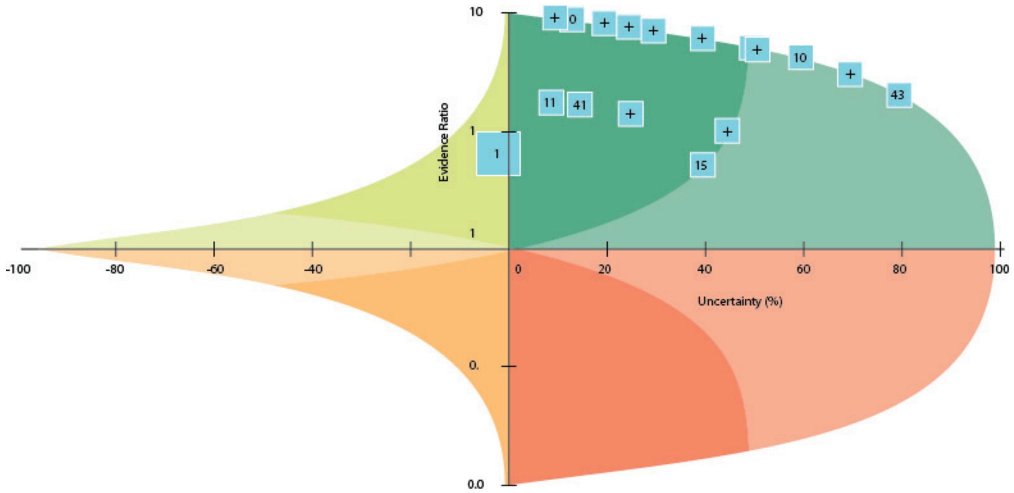

Fig 4: TESLA ratio plot. 1 indicates the top level node – the rolled up result for the tree. The other boxes are end nodes. + indicates that there is more than one node under the box.

From a project management perspective the ratio plot is especially useful as it highlights areas of uncertainty or risk and thereby, areas that need more work. More detail can be found in [3].

5. Bow-tie risk assessment

The benefits of using bow-tie 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 bow-tie 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.

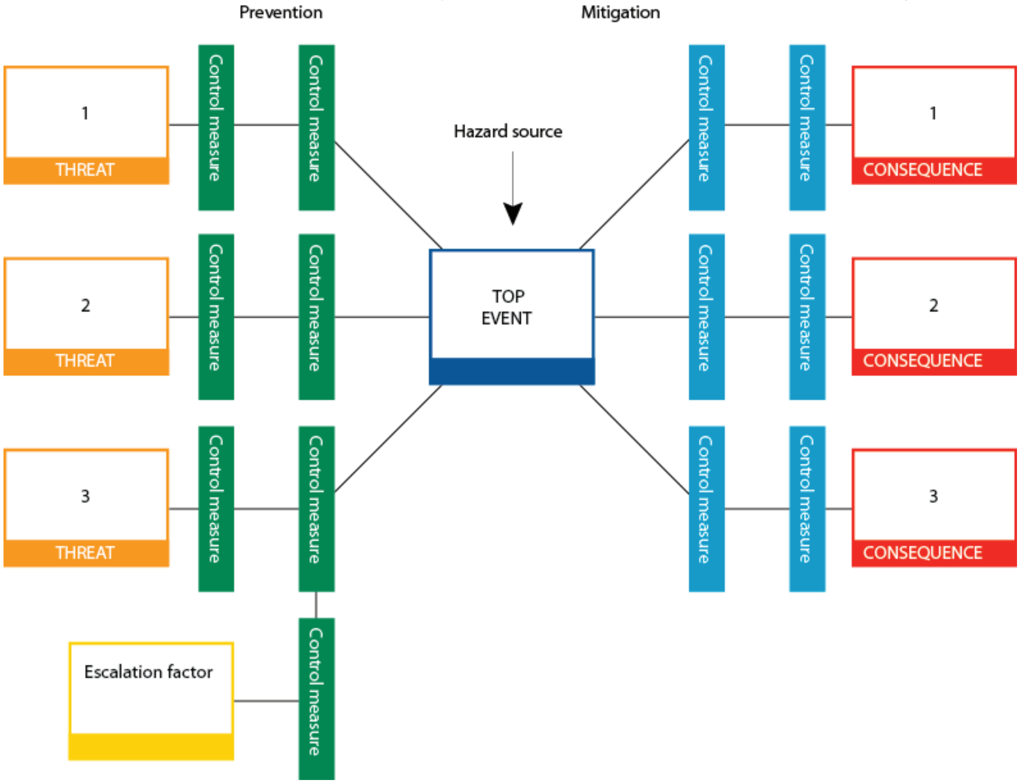

Fig 5: Bow-tie diagram schematic

The bow-tie method entails building a bow-tie diagram (Fig. 5), 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 bow-tie 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 the release of CO_2 at the seabed or platform; a 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 bow-tie 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 mitigative 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 bow-tie 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.

The bow-tie 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 so to do?".

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 bow-tie analysis and actions are raised to evaluate whether or not they should be implemented. In this way, the bow-tie analysis can be used to demonstrate that the risks are reduced to levels which are As Low As Reasonably Practicable (ALARP). ALARP risk is reached when the effort involved in implementing any new risk reduction measures is grossly disproportionate to the benefit (i.e. risk reduction) gained.

Shell's three main operated CO_2 storage projects to date have all employed bow-tie containment risk assessments. For the Goldeneye CCS project the bow-tie analysis was conducted during a series of multi-disciplinary workshops over a period of several months, facilitated by an independent bow-tie practitioner.

The identified threats and consequences analysed using the bow-tie method for Goldeneye are shown in Figures 6 and 7. The likelihood of each threat was evaluated by the analysis team. The likelihood criteria are:

A: Never heard of in the industry
B: Heard of in the (hydrocarbon) 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

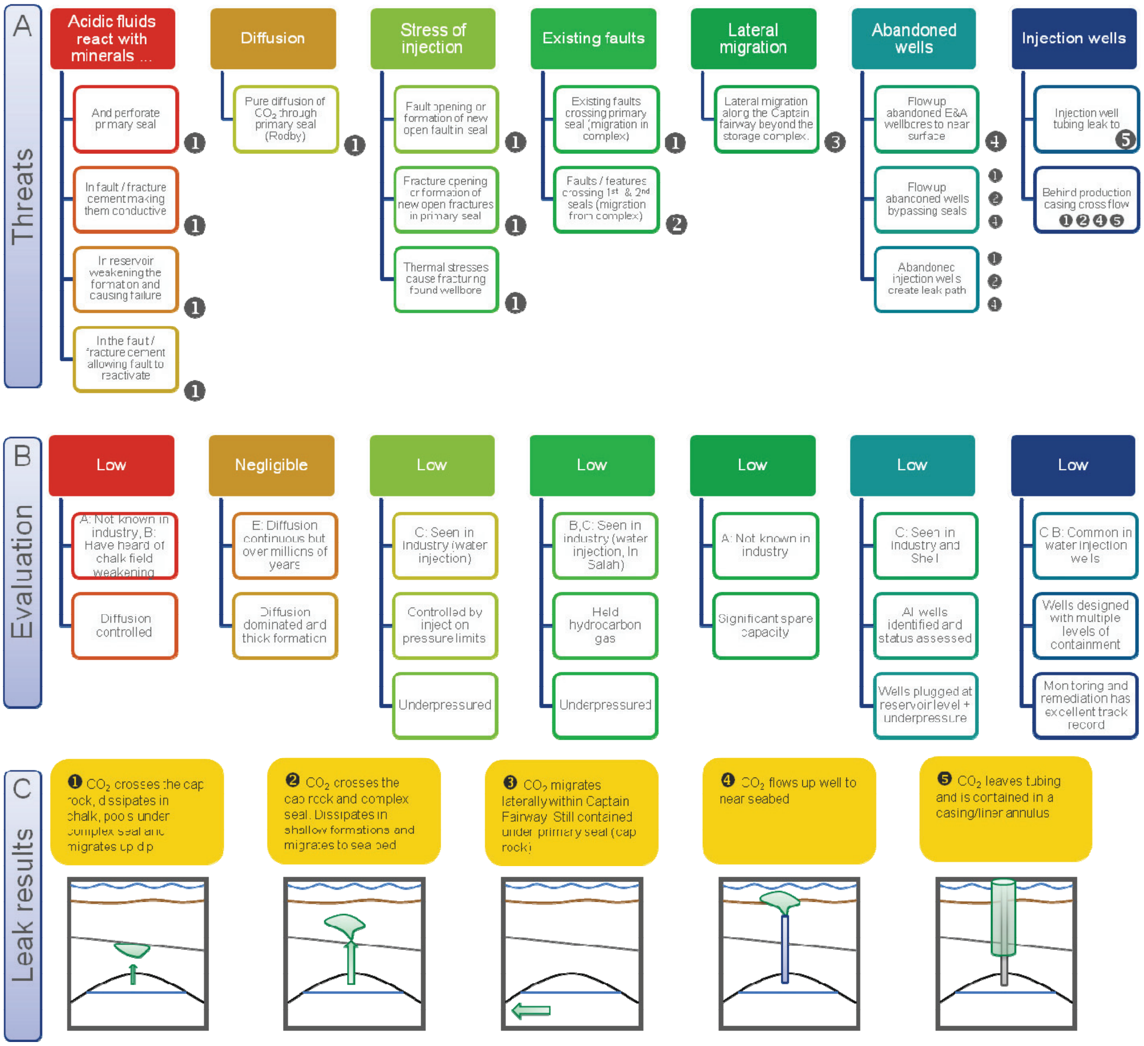

Fig 6: Schematic representation of the Goldeneye containment bow-tie risk assessment showing A: threats, B: evaluation showing that the risk of having a top level event is low, and C: potential leak scenarios that could take place were natural and engineered barriers to fail .

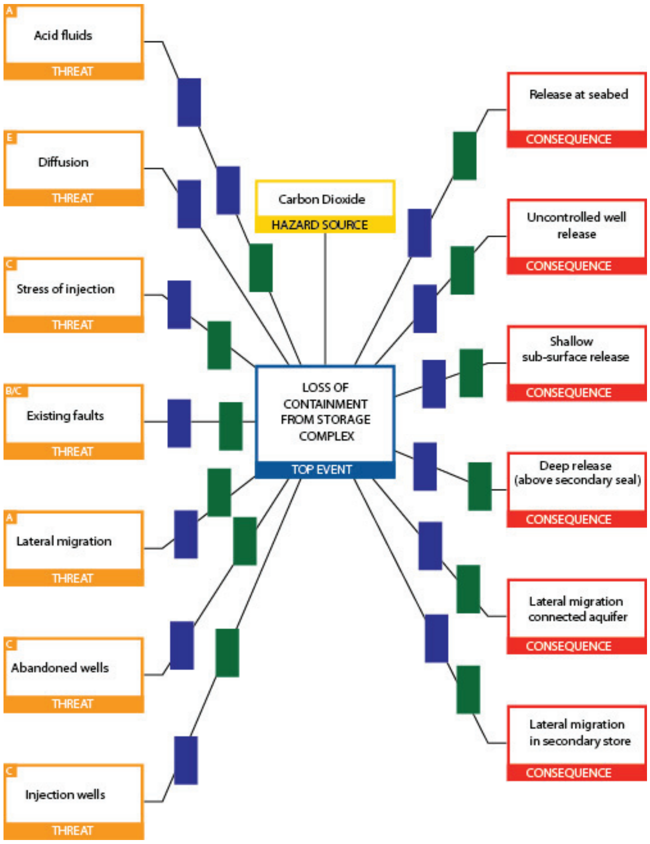

Fig 7: Top level bow-tie for Goldeneye. The right hand side shows the potential consequences of a top level event. It is worth noting that these consequences are shared by all offshore CCS projects.

A birds-eye view of the full bow-tie developed is shown in Fig. 8 to give an impression of the overall analysis and the number of barriers identified.

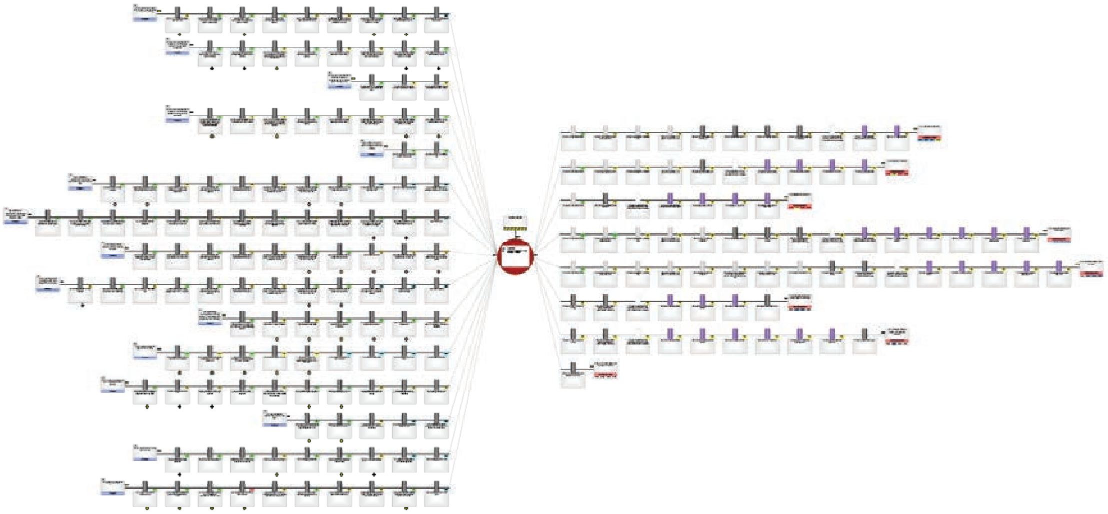

Fig 8: Birds-eye view of the full Goldeneye bow-tie (excluding escalation factors and controls on these for size reasons)

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. For fully effective barriers, the control is continuously in place, functions properly when tested, and requires only infrequent repair. For controls relying on the actions of people, the individuals are deemed competent and their training is up to date. It is this analysis that forms the majority of the work involved in proving a CO_2 store.

Table 1 Summary of threats to CO_2 containment

Threats	**Relevant CCS Stage**
Acid fluids	
Acid fluids perforate primary seal (Rødby)	Post-closure at hydrostatic
Acid fluids react with minerals in existing fault / fracture cement making them conductive / open	Injection, post-closure below hydrostatic and post-closure at hydrostatic
Acid fluids react with minerals in the reservoir weakening the formation and causing failure (geomechanical failure).	Injection, post-closure below hydrostatic and post-closure at hydrostatic
Acid fluids react with minerals in the fault / fracture cement allowing fault to reactivate (reactive transport)	Injection, post-closure below hydrostatic and post-closure at hydrostatic
Diffusion	
Pure diffusion of CO_2 through primary seal (Rødby)	Injection, post-closure below hydrostatic and post-closure at hydrostatic
Stress of injection	
Stress of injection / refilling causes fault opening or formation of new open fault in seal	Injection
Stress of injection / refilling causes tensile / shear fracture opening or formation of new open fractures in primary seal / cap rock	Injection
Faults, fractures and features	
Existing faults, mapped / unmapped crossing primary seal (not secondary	Injection (local effects) and post-closure at

Threats	**Relevant CCS Stage**
seal) create leak path	hydrostatic
Existing faults / features that cross primary and secondary seal	Injection and post-closure at hydrostatic
Lateral migration	
Lateral migration beyond the storage complex.	Injection
Abandoned wells	
Flow up abandoned exploration and appraisal wellbores to near surface	Injection, post-closure below hydrostatic and (particularly) post-closure at hydrostatic
Abandoned injection wells create leak path	Post-closure below hydrostatic and (particularly) post-closure at hydrostatic
Injection wells	
Injection well tubing leak to annuli	Injection
Behind production casing cross flow	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).

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. 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:

- **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. It also introduces additional potential leak paths from the storage complex.
- **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

Consequences have the potential to take place if all barriers and mitigative actions should fail. This should never happen, but as in all human activity, it is important to understand what could happen should all barriers and mitigative actions fail. On the right hand side of the bow-tie diagram in Fig. 7, eight consequences were identified.

Consequences in CCS are all variations on the potential for a release of CO_2 from the storage complex. Not all releases get to surface, and even if a release were to reach the surface the volumes and rates are such that it is unlikely to cause harm to people or the environment. Onshore this is evidenced by photographs of people standing next to Chrystal Geyser, Utah [5], and as reported by Roberts [6] in her study of the health risks of natural CO_2 seeps in Italy. In an offshore environment many of consequences for people are further mitigated by the sea water. Consequences are therefore assessed according to their effects on people, assets, the environment and the reputation of the company and industry.

The vast majority of the consequences were assessed to have either low or very low risk of any effect on people, infrastructure or the environment. A large release at the seabed with a short duration was judged to pose only low or very low likelihood of any effect to people and the environment. The highest threat to people would be if well control was lost and CO_2 was to flow up the well to the surface and there were people on the platform at the time. All consequences have mitigation measures in place to stop them talking place. These are detailed in the corrective measures plan that is required as part of the EU directive.

5.3. ALARP Demonstration

The risk management framework described in Guidance Document 1 [8] on the implementation of CCS Directive [9] 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 the bow-tie analysis was used to provide a documented ALARP demonstration for the Goldeneye CCS project.

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.

5.3.1. Achieving ALARP risk levels

The first step in the process is to ensure that the facility meets certain standards.

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.

By examining and challenging the design (i.e. by asking “can we make the controls more effective?” and “is there anything more we can do?”), it is possible to make the conjecture that the risk of CO_2 release from the storage complex is reduced to ALARP levels. This can then be checked and validated by the regulatory authorities prior to storage permit award.

6. Conclusions

The early stages of evaluation of a CO_2 store are ideally suited to the ESL methodology as implemented in TESLA. 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 ESL 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 bow-tie 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 candidate 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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