Practical Approaches to CO_2 Subsurface Storage Risk Assessment

6th International Workshop on Offshore Geologic CO_2 Storage

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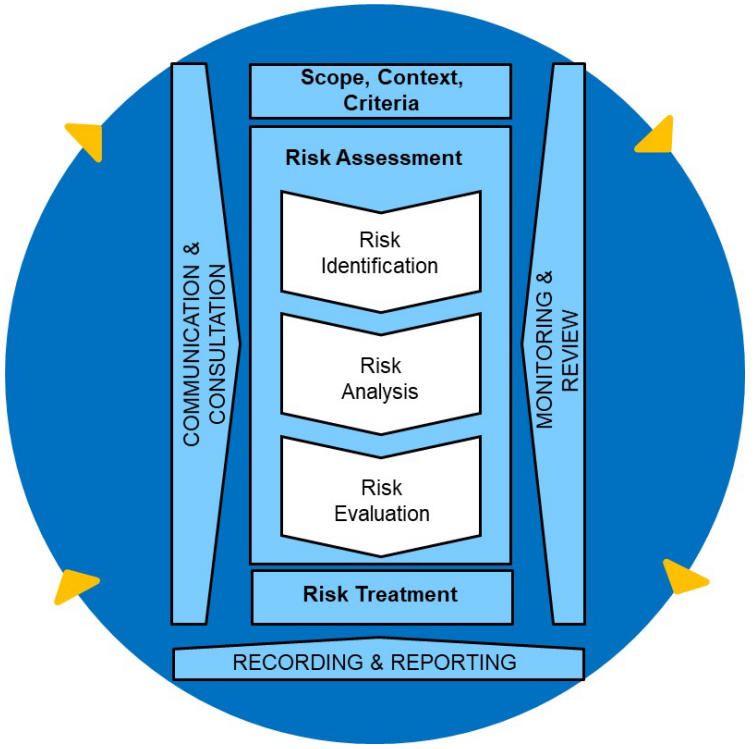
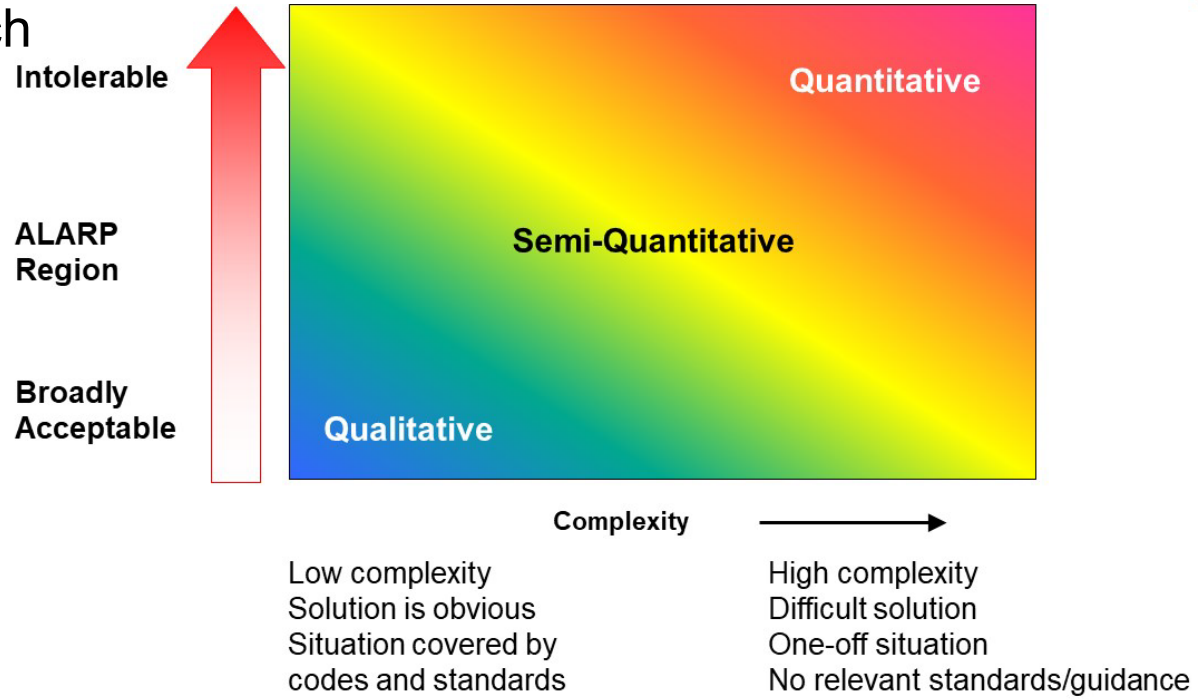
Risk Management Concepts

Successful risk management requires:

- A structured approach
  - Identification
  - Analysis
  - Evaluation
- A proportionate approach



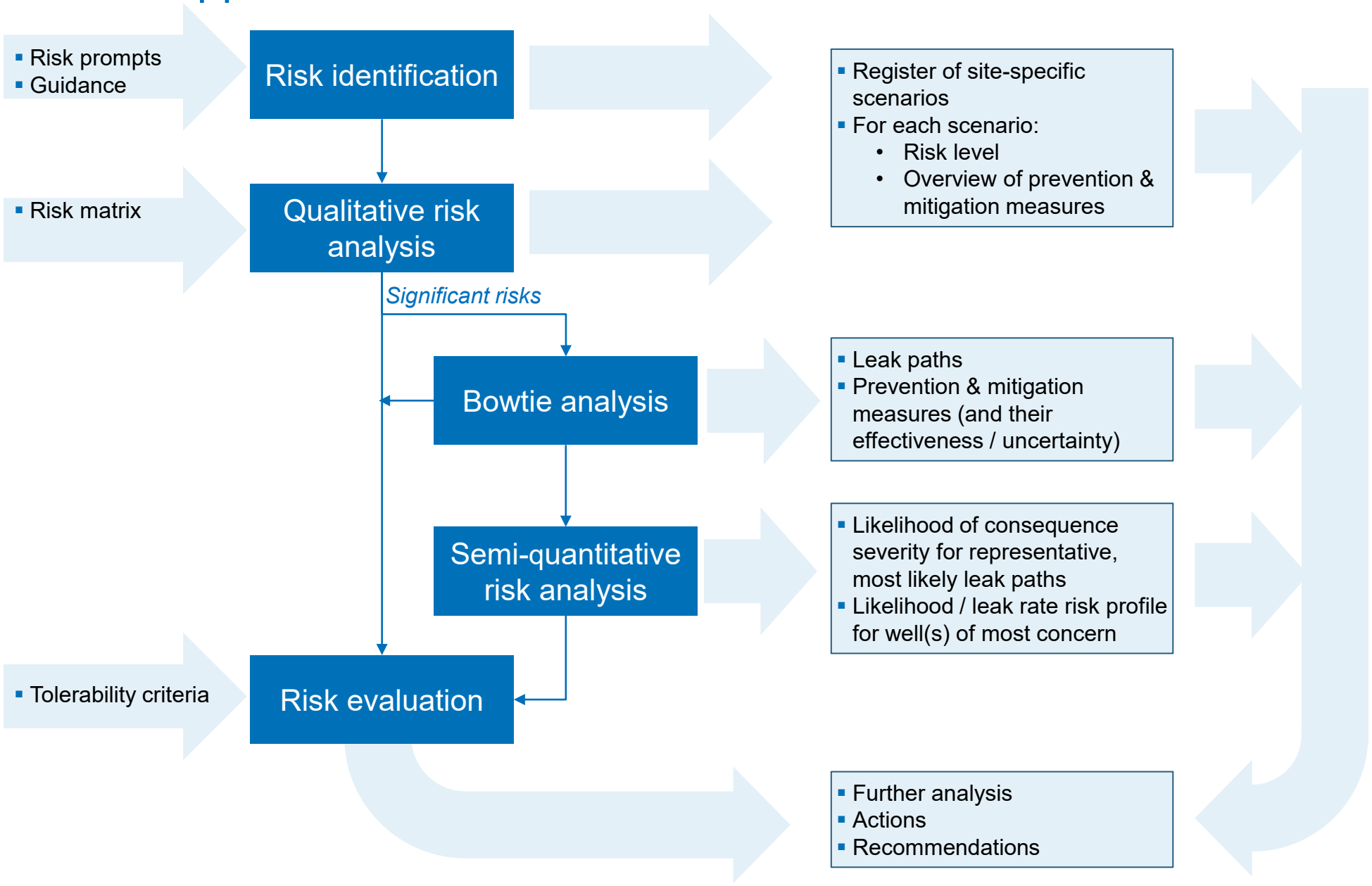
From ISO 31000:2018



After: Guidance on Risk Assessment for Offshore Industries HSE 3/2006

What helps you reach a decision?

Outline Approach



Risks to Consider

- Scope of assessment
- Loss of containment
- Injectivity
- Capacity
- Induced seismicity
- Effects to
  - Environment
  - Health
  - Reputation
  - Financial

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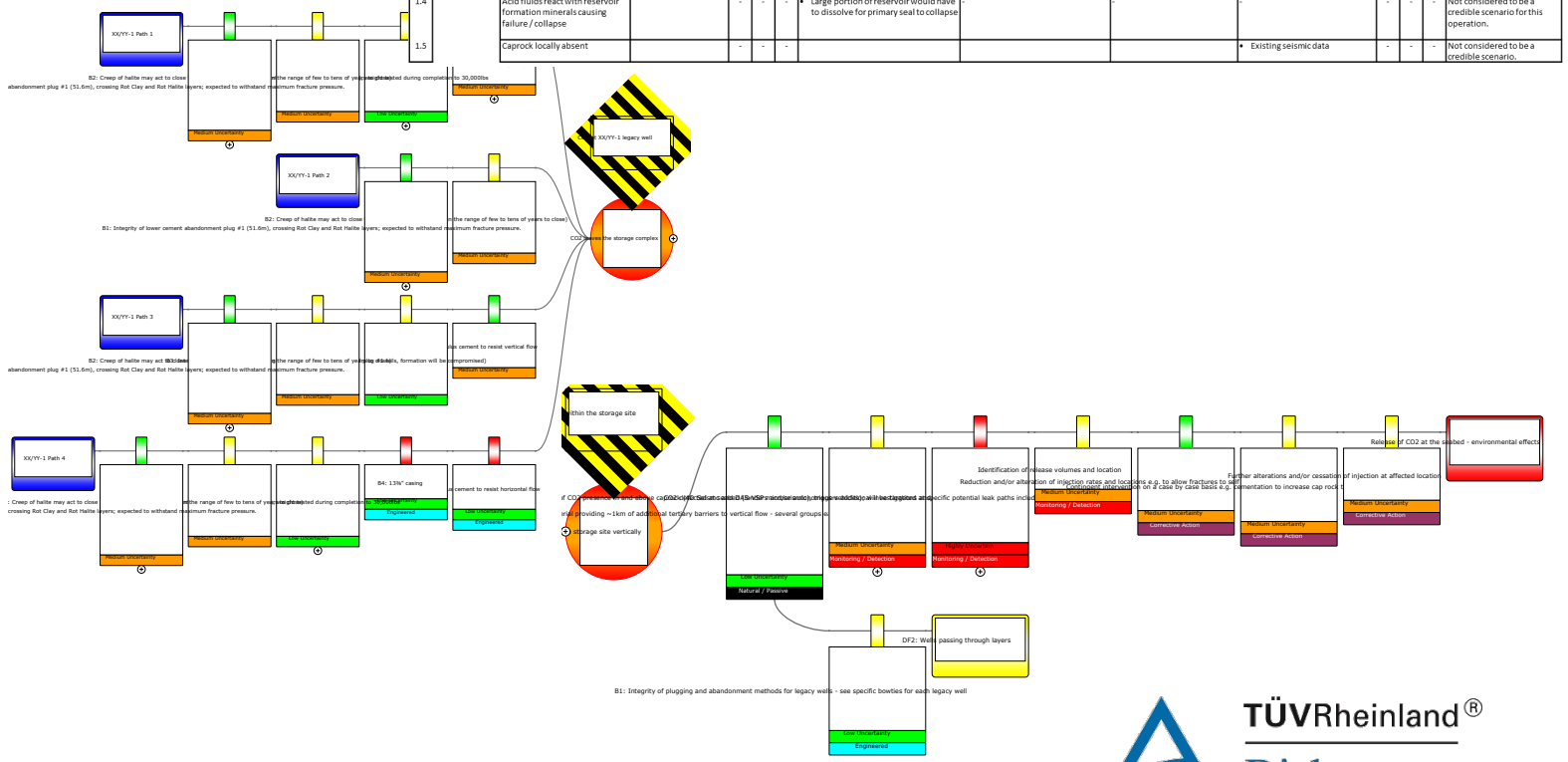
Structured Qualitative Approaches

- Potential applications
  - Scenario identification and ranking
  - Review and communication of risks
- Considerations
  - Can account for uncertainty
  - Very reliant on consensus judgement
  - Difficult to compare options

	Prompt Note 1	Risk scenario	Consequence	Unmitigated Risk Notes 2 & 3 E Note 4	R	A	Risk Controls (Prevention & Mitigation)	Monitoring	Corrective Actions	Data, Modelling, Analyses	Residual Risk Notes 2 & 3 E Note 4	R	A	Notes
Geological														
1.1	Primary Seal	Acid fluids react with primary seal and penetrates it (Chemical alteration of caprock)	CO_2 release to seabed	B3	B5	B5	**See bowtie 1** • Properties of primary seal to resist acid • Secondary seal acts as part of primary caprock with different geomechanical / geochemical characteristics • Multiple low and impermeable layers above primary caprock	**See bowtie 1** • 4D seismic monitoring (will detect changes in primary seal thickness) • Pressure transient analysis • Micro-seismic monitoring detect CO2 plume in overburden • CO2 monitoring at seabed (AUV, landers, etc.)	• Identification of leak location and volume • Contingent intervention/ cementation to increase cap rock thickness • Alterations to injection rates	• Storage and Primary Seal interaction with CO2 • Geochemical modelling • Analogues with other operations e.g. Green River	B3	B5	B5	If close to well, could undermine seal / cement around well (see well-related leak paths below)
1.2		Diffusion / vertical migration through primary seal	CO_2 release to seabed	B2	B3	B1	**See bowtie 1** • Properties of primary seals to resist diffusion (capillary entry pressure, very thick) – diffusion is very slow • Modelling suggests timescales >10,000 years to occur • Multiple low and impermeable layers above primary caprock	**See bowtie 1** • 4D seismic monitoring • Micro-seismic monitoring detect CO2 plume in overburden • CO2 monitoring at seabed (AUV, landers, etc.)	• Identification of leak location and volume • Contingent intervention/ cementation to increase cap rock thickness • Alterations to injection rates	• Analogues with other operations e.g. Green River	B2	B3	B1	
1.3		Migration via existing fracture network in primary seal - existing fracture network - chemical alteration of fracture properties	CO_2 release to seabed	C2	C3	C1	**See bowtie 1** • No evidence of permeable / connected fracture networks in the primary seal • Fractures in overburden do not penetrate primary seal • Secondary seal is self-sealing • Multiple low and impermeable layers above primary caprock	**See bowtie 1** • 4D seismic monitoring • Micro-seismic monitoring detect CO2 plume in overburden • CO2 monitoring at seabed (AUV, landers, etc.)	• Identification of leak location and volume • Contingent intervention • Alterations to injection rates	• Fault Seal analysis • Dynamic modelling • Geochemical modelling • Baseline seismic surveys	B2	B3	B1	
1.4		Acid fluids react with reservoir formation minerals causing failure / collapse		-	-	-	• Large portion of reservoir would have to dissolve for primary seal to collapse	-	-	-	-	-	-	Not considered to be a credible scenario for this operation.
1.5		Caprock locally absent		-	-	-				• Existing seismic data	-	-	-	Not considered to be a credible scenario.



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Risk Identification and Ranking

- Structured brainstorming
  - Geological leakage pathways e.g.
    - Via caprock
    - Via natural/induced faults/fractures
    - Lateral migration
  - Manmade leakage pathways
  - Other scenarios
- Risk assessment matrix
  - Limited operating experience
  - Predictive rather than historical approach?
- Uncertainty
  - In ranking?
  - In control?
- Acceptability

Consequence					Increasing Likelihood of Occurrence				
					A	B	C	D	E
					Practically non-credible occurrence	Rare occurrence < 1 in 1,000 chance of occurring	Unlikely occurrence 1 in 1000 chance of occuring	Credible occurrence I in a 100 chance of	Probable occurrence >I in 10 chance of occurring
Severity	People	Environment	Asset	Reputation	Practically non-credible occurrence	Less than 1 in 1,000 chance of occuring within the project per year.	Expected to occur between once every 100 years and once every 1000 years per year within project.	Expected to occur between once every 10 years and once every 100 years per year within project.	Expected to occur between more frequently than once every 10 years within project.
1	Slight health effect / injury	Slight effect	Slight damage	Slight impact					
2	Minor health effect / injury	Minor effect	Minor damage	Minor impact					
3	Major health effect / injury	Local effect	Local damage	Local impact					
4	PTD or 1 fatality	Major effect	Major damage	National impact					
5	Multiple fatalities	Extensive effect	Extensive damage	International impact					

From EU Guidance Document 1

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Example Risk Register Extract

	Prompt Note 1	Risk scenario	Consequence	Unmitigated Risk Notes 2 & 3			Risk Controls (Prevention & Mitigation)	Monitoring	Corrective Actions	Data, Modelling, Analyses	Residual Risk Notes 2 & 3			Notes
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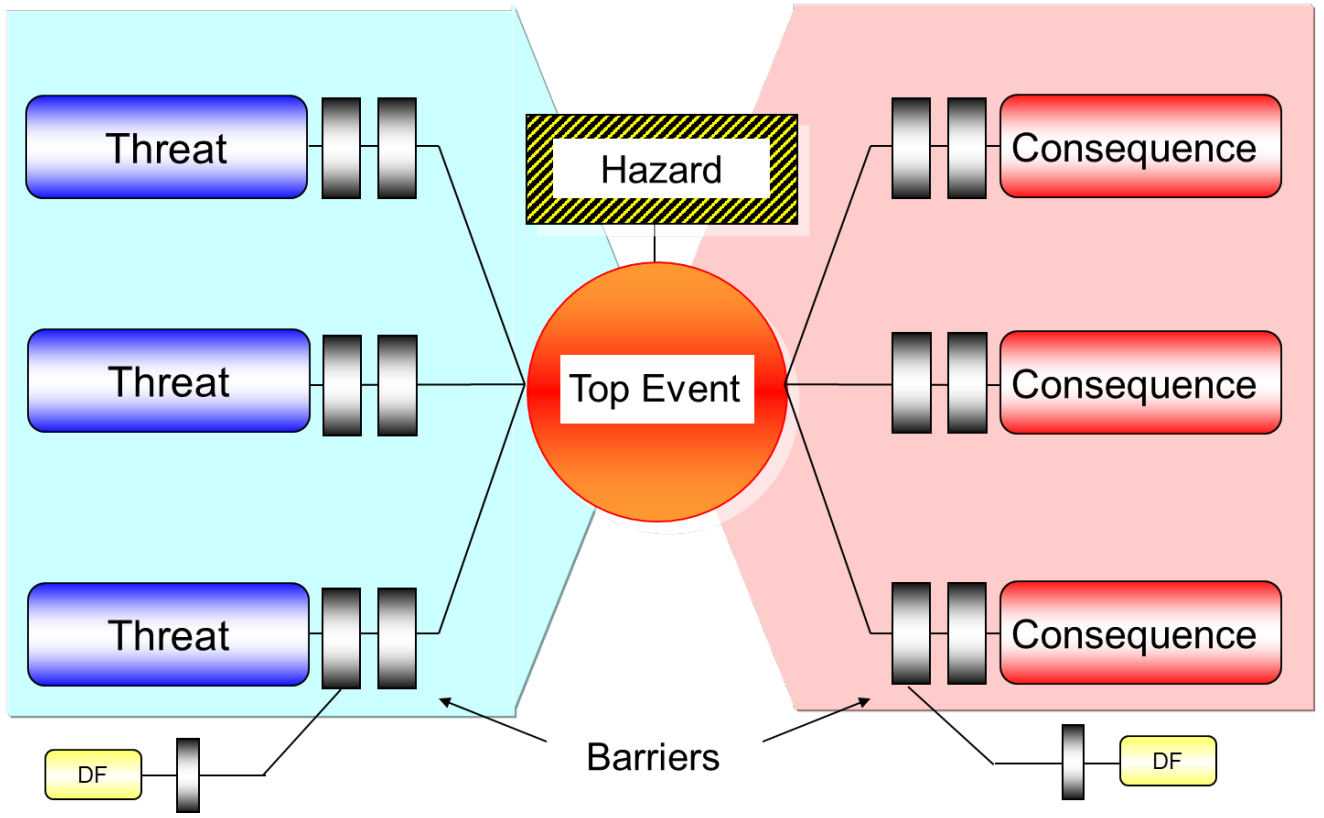
Risk Analysis & Evaluation

- What controls exist?
  - Geological
  - Modelling
  - Operational
  - Engineering
  - Measurement, monitoring
  - Intervention
- How good are the controls?
- What is known/unknown?
- What uncertainties exist?
- What more could we do?



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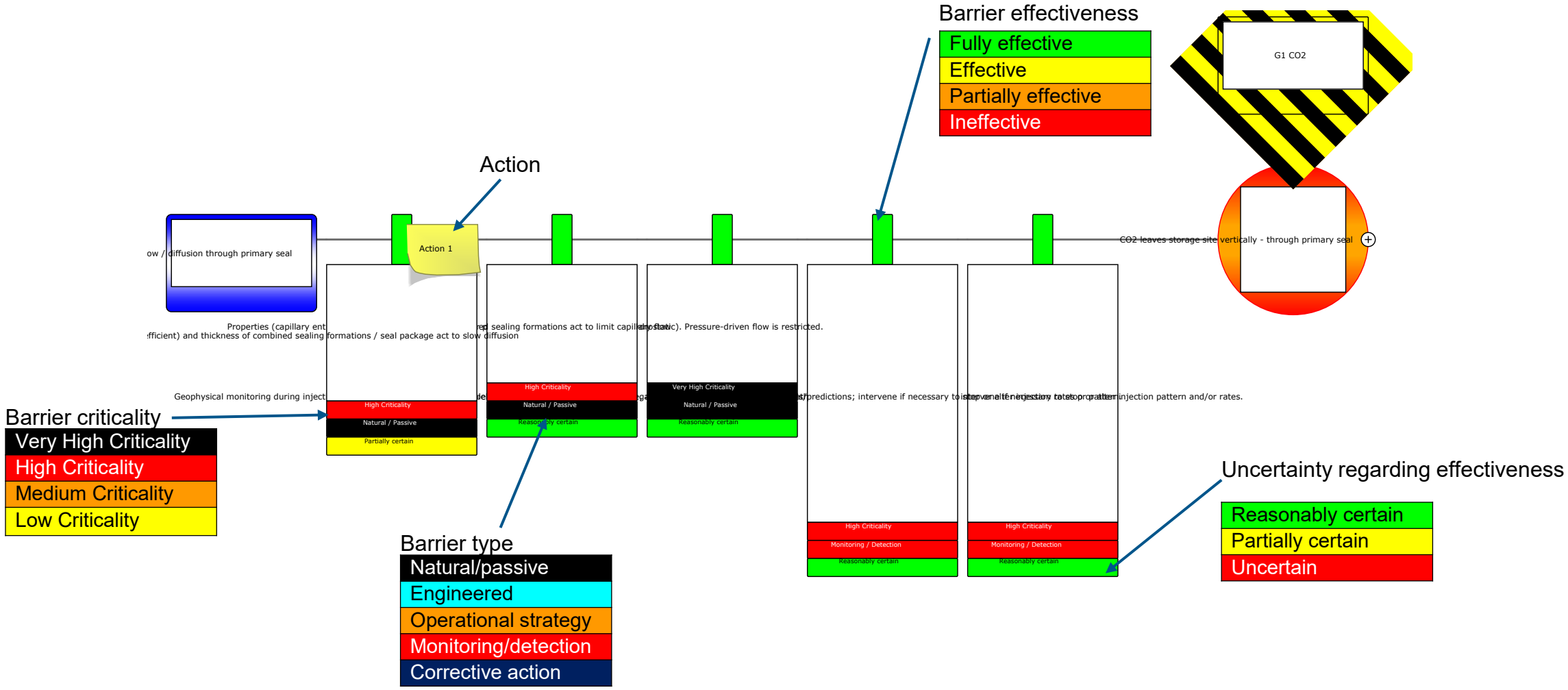
Example Populated Bowtie



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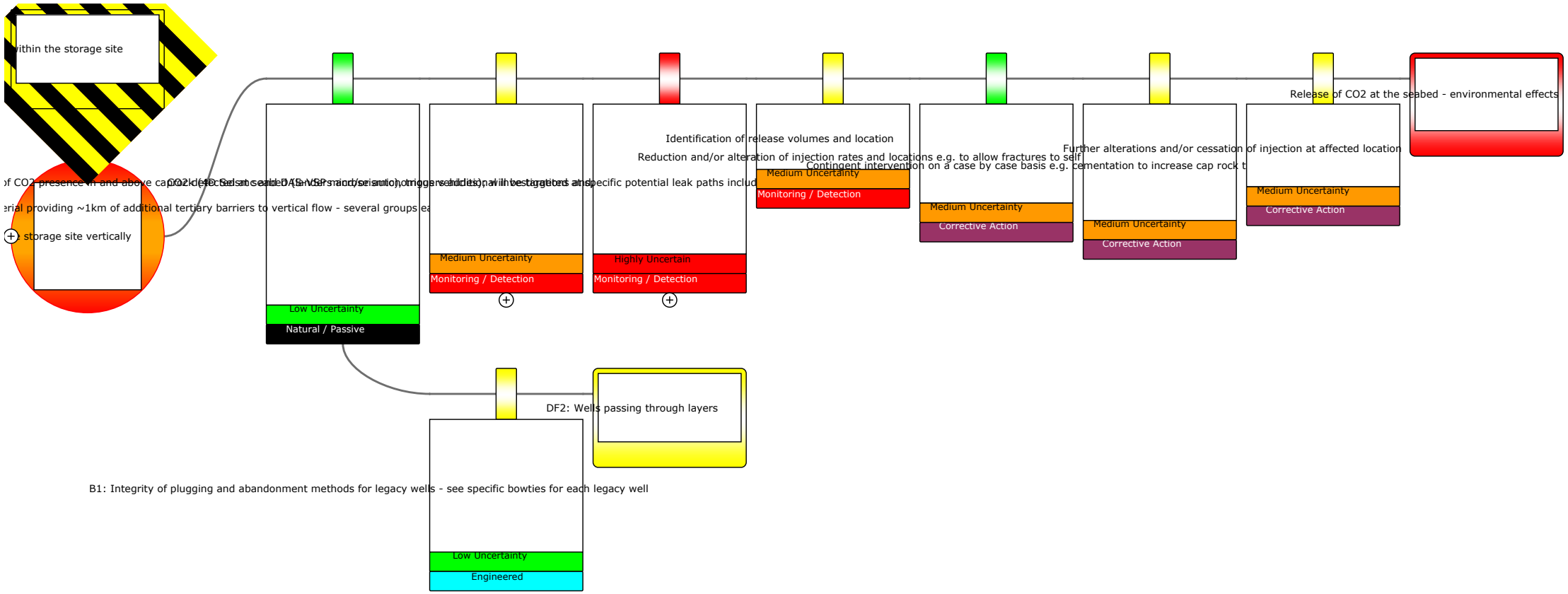
Example Populated Bowtie



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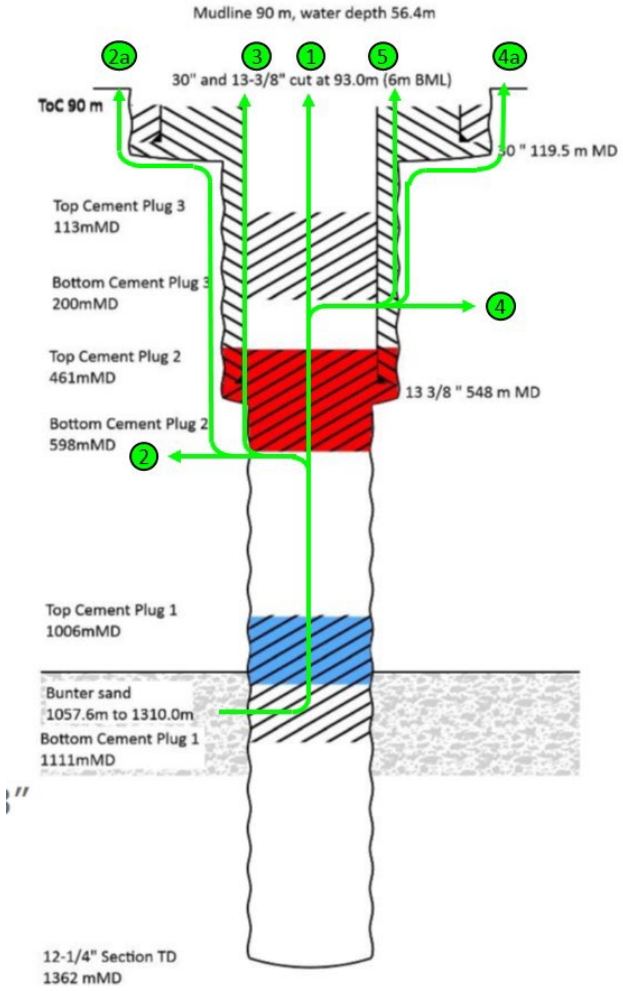
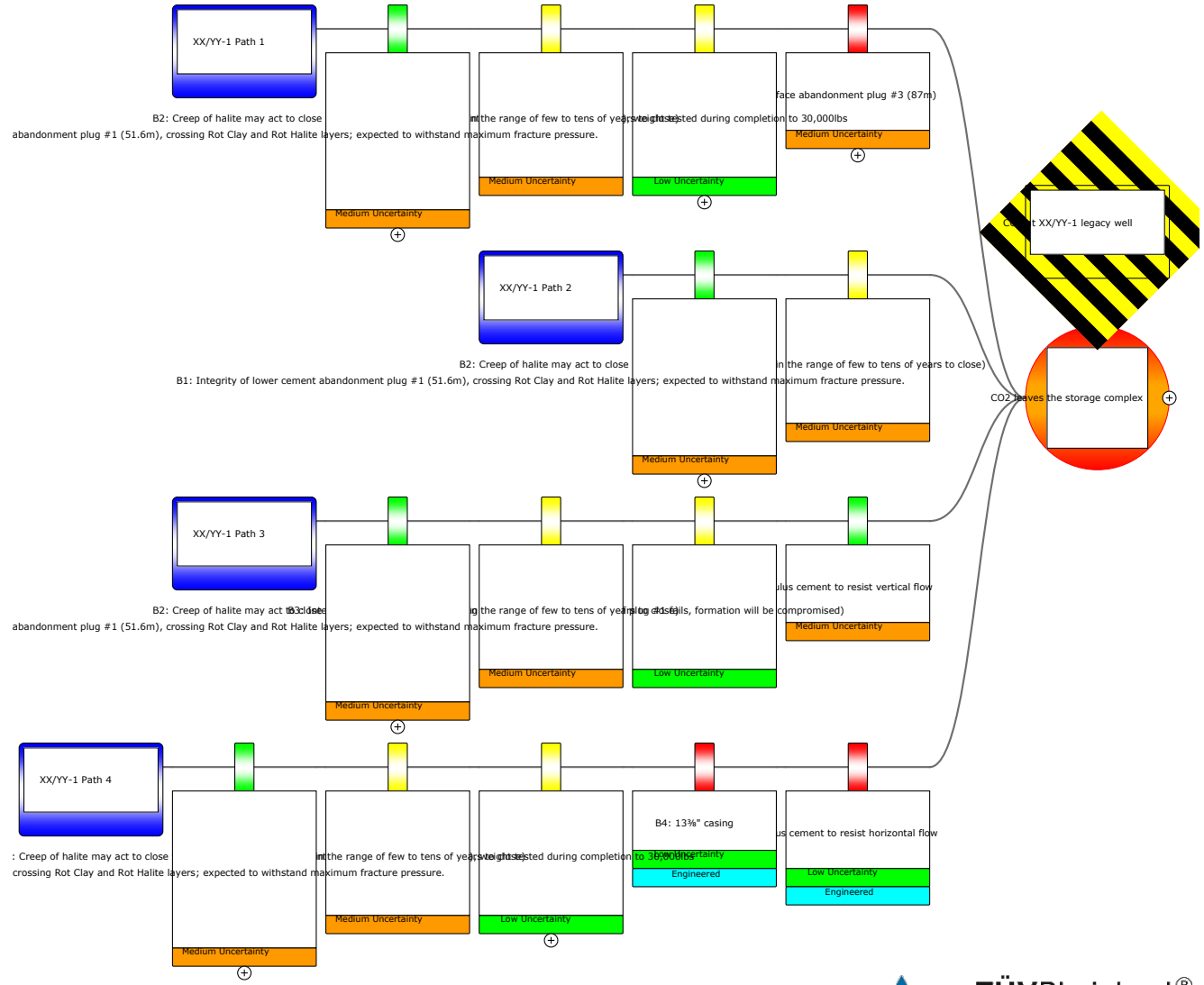
Example bowtie extract - Wells

- Injection wells during/post injection
- Legacy wells





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Quantitative Approaches

- Potential applications
  - Estimation of maximum release rates e.g. for input to environmental assessments, intervention planning
  - Insurance liabilities
  - Meeting targets
- Considerations
  - Provides ‘objective’ values to compare e.g. options, against targets
  - Sensitivities can account for uncertainty
  - Paucity of data
  - Still relies on expert judgement for assigning inputs
  - Easy to infer greater accuracy than may be warranted

Quantitative Methods – Example Data

- Engineering judgement
  - e.g. RISQUE
- Industry databases
  - e.g. OGP Risk Assessment Data Directory
- CO_2 Storage Safety in the North Sea: Implications of the CO_2 Storage Directive
  https://zeroemissionsplatform.eu/co2-storage-safety-in-the-north-sea-implications-of-the-co2-storage-directive/
- Deep Geological Storage of CO_2 on the UK Continental Shelf
  https://www.gov.uk/government/publications/deep-geological-storage-of-carbon-dioxide-co2-offshore-uk-containment-certainty

Saline Aquifer		Geological Pathway	Leak Category	Probability of occurrence per storage complex		Leak Rate t/d	
				Min	Max	Min	Max
Through caprock	1	Diffusion	Seep	Neglible	Neglible	2.74E-08	2.74E-06
	2	Capilliary flow through intact caprock	Seep	Neglible	Neglible	2.74E-09	2.74E-05
	3	Lateral variability in seal quality	Minor	5.00E-04	5.00E-03	4.3	43
Faults and fractures	4	Major active fault zone	Major/Minor	Neglible	Neglible	27.4	5480
	5	Large block bounding fault zone	Minor	5.00E-04	1.00E-03	2.74	1370
	6a	Map-scale faults	Seep	5.23E-03	1.00E-02	0.274	1
	6b		Minor	1.00E-03	5.23E-03	1	27.4
	7a	Sub-seismic faults and fracture networks	Seep	3.35E-03	1.25E-02	2.74E-02	1
	7b		Minor	1.00E-03	3.35E-03	1	27.4
Induced faulting/ fracturing	8a	Reactivation of pre-existing faults	Seep	5.23E-03	1.00E-02	0.274	1
	8b		Minor	1.00E-03	5.23E-03	1	27.4
	9a	Initiation of new faults/fractures	Seep	5.23E-03	1.00E-02	0.274	1

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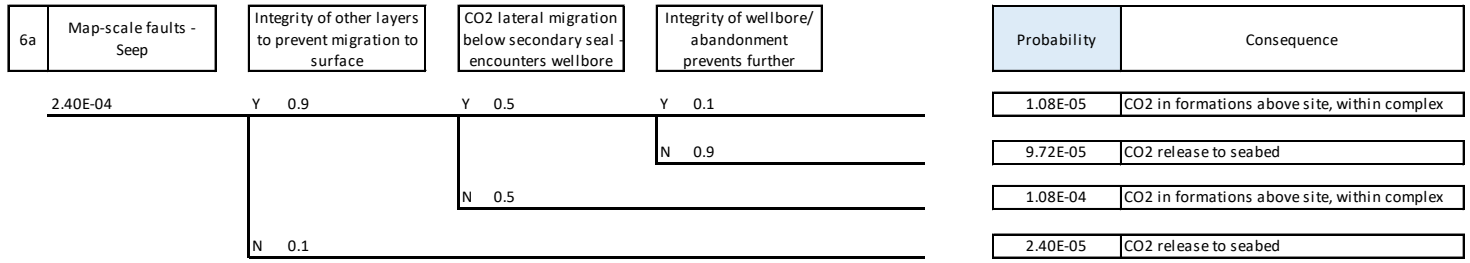
Quantitative Approach

- Simple event trees

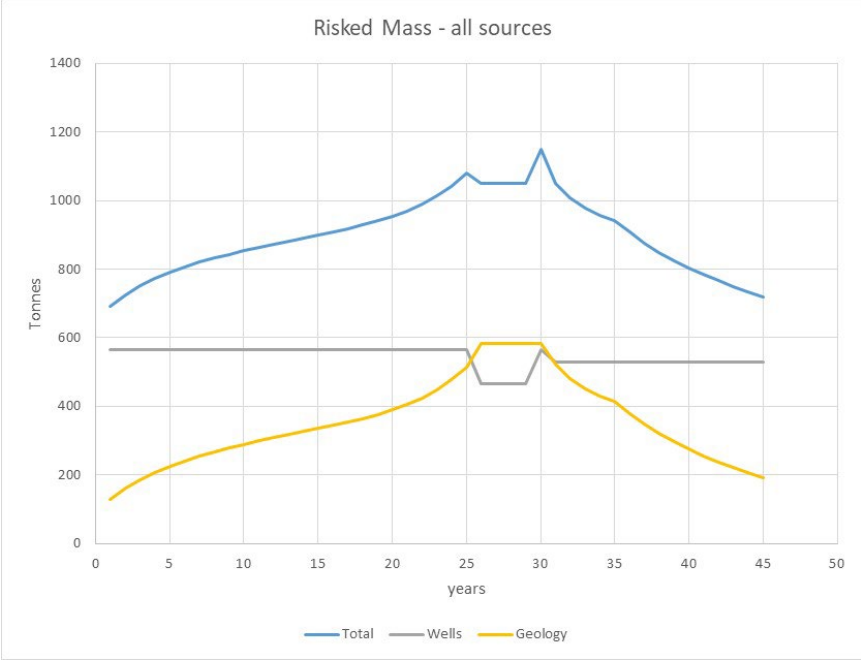


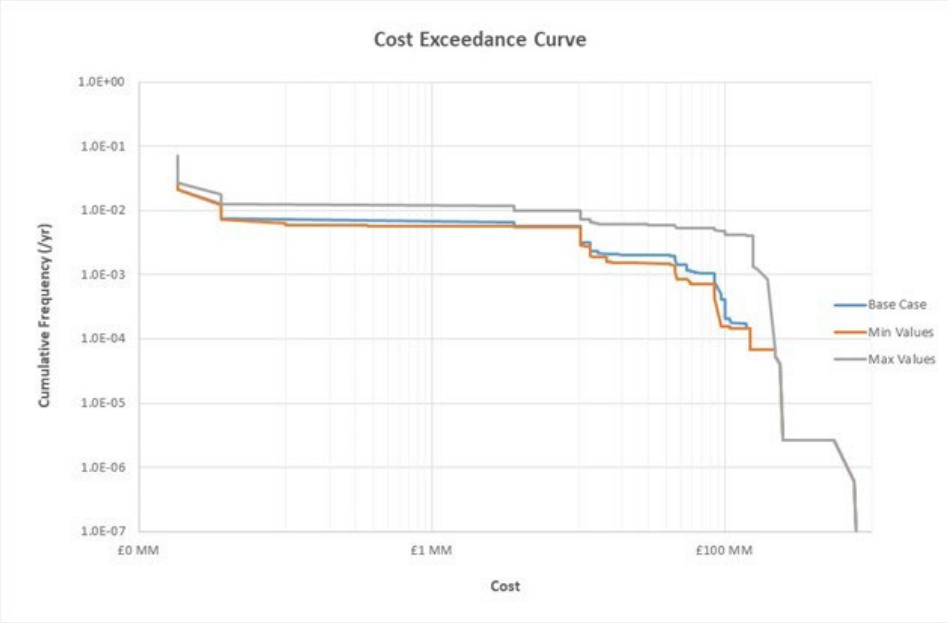
Probability	Consequence
1.08E-05	CO2 in formations above site, within complex
9.72E-05	CO2 release to seabed
1.08E-04	CO2 in formations above site, within complex
2.40E-05	CO2 release to seabed

Physical Consequences

Financial Costs

- Calculation of Risked Mass and Risked Cost





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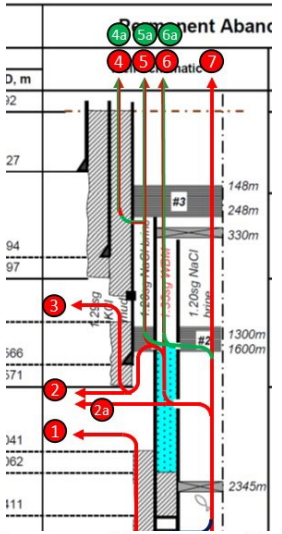
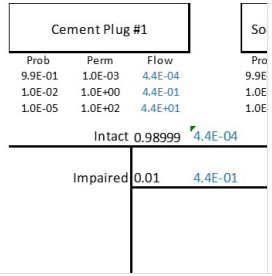
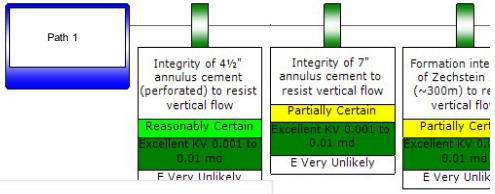
Quantitative - wells

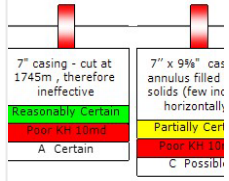
- Based on well specific bowtie
- For each barrier estimation of permeability and probability of failure
  - Intact
  - Impaired
  - Failed
- Estimation of leakage rate
- Event tree analysis for each leak path
- Summation of results

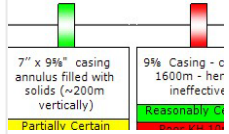
	<1.0E-9	<1.0E-6	<1.0E-4	<1.0E-3	<1.0E-2	<1.0E-1	<1.0E+0
Loss of ≤0.0001% of injection volume over 1000yrs	445	119	37	0	7	0	13
Loss of ≤0.001% of injection volume over 1000yrs	138	21	7	0	3	0	0
Loss of ≤0.01% of injection volume over 1000yrs	144	5	0	0	0	0	0
Loss of ≤0.1% of injection volume over 1000yrs	38	1	1	0	0	0	0
Loss of ≤0.2% of injection volume over 1000yrs	0	0	0				
Loss of ≤1% of injection volume over 1000yrs	0	0	0				
Loss of >1% of injection volume over 1000yrs	0	0	0				

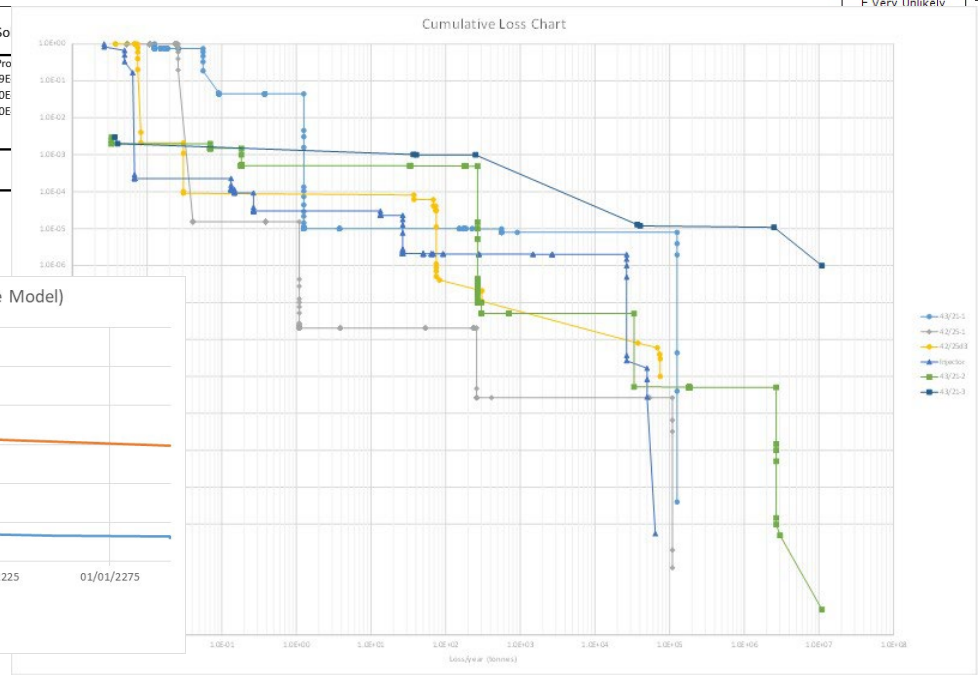


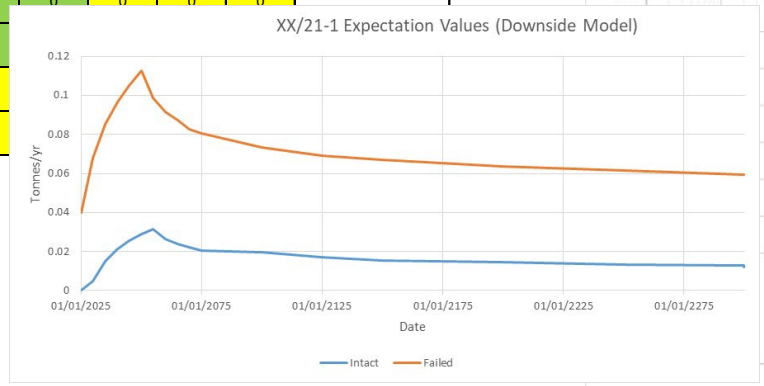












Summary

- A structured risk assessment approach is required
- Many different stakeholders
- Most appropriate tools / techniques depend on:
  - Level of risk (generally low)
  - Complexity / uncertainty
  - Available information
  - End use / audience for the assessment
- Bowties provide an easily understood representation of how risks are managed
  - Applicable at all stages of project – updated as more information becomes available
  - Detail can be varied to aid communication to specific groups
  - Can accommodate uncertainty
- Quantitative approaches can be used
  - Scarcity of data
  - Indicative only
  - Comparative rather than absolute
  - Infers a degree of accuracy

Thank you

Have a safe day!

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