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Risk Based and Proportionate Measurement, Monitoring, and Verification (MMV) Plans that Meet Key Regulations

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Abstract

Carbon Capture and Storage (CCS) is a technology that can help to reduce greenhouse gas emissions. However, there are risks associated with CCS; for the storage element, this includes the risk that the storage site is not technically suitable for long-term storage of large volumes of CO_2. Key risk factors include insufficient capacity for the anticipated injectate volume, poor injectivity quality, and loss of containment risk including the potential for measurable CO_2 leaks.

It is important for storage project developers to understand that CO_2 storage is not the same as hydrocarbon production in reverse. CO_2 is a different fluid, both chemically and thermodynamically, with variable properties under surface and subsurface conditions, and particularly as pressurization occurs over time.

There are both international and country-specific regulatory frameworks and requirements in place for CO_2 storage which are separate to those directed at Enhanced Hydrocarbon Recovery (EHR) or waterflooding. These regulations are based on site-specific risk elements of a project and focus on how risk assessments must be conducted and managed, ensuring that other natural resources, human health, and the environment are not harmed.

A Containment Risk Assessment (CRA) is an important part of the CO_2 storage site selection process. The CRA identifies potential leak-paths and evaluates the likelihood and severity of any leakage. The CRA also helps to focus the design of a Measure, Monitoring and Verification (MMV) plan.

The MMV plan includes both a technology selection and implementation plan, and a response plan including proportionate corrective measures in case of (suspected) leakage. A holistic CRA includes a multi-disciplinary analysis of the geological storage complex, incorporating legacy wells and future injector and monitor wells. The behavior of injected CO_2 is simulated, resulting in the expected maximum

extent of the CO_2 plume and possible displaced fluids. All potential leak-paths, regardless of their perceived likelihood, are evaluated. Barriers physically preventing CO_2 from leaving the storage complex, as well as mitigating measures that can either prevent and/or minimize the severity of any leakage, are mapped, and compiled into bowtie diagrams.

A key benefit of the bowtie method is the easy identification of the potential need for procedural barriers to further minimize the likelihood and/or severity of a specific leak. These procedural barriers are associated with early identification (monitoring) and implementation of corrective measures, which result in a *site-specific* and *proportionate* MMV plan.

Introduction & Definitions

There are several established regulatory guidelines and requirements for geological CO_2 storage. Some good examples are the EU Directive 2009/31/EC, US EPA Class VI rules, Australia OPGGS Act (2006), and ISO Standards 27914:2017. These regulations have a common denominator: they focus on how risk assessments must be conducted and managed, ensuring that other natural resources, human health, and the environment are not harmed.

These regulations require an assessment of the risk of leakage for subsurface CO_2 storage. For example, the European Directive 2009/31/EC and the ISO 27914 standards define leakage as any CO_2 released or migrating outside the predefined storage complex. This includes small proportions of CO_2 that move into geological strata or areas outside the pre-determined storage complex, even if it would not reach the water column or atmosphere and/or have any associated environmental or economic consequences. If CO_2 ever reaches the water column or the atmosphere, this is defined as *emissions*.

Each regulatory framework uses slightly different terminology to define each element of a storage project, but in general, the following definitions can be applied and should be considered when discussing CO_2 movement in the subsurface to ensure clarity on whether migration or leakage is inferred.

For example, the European Directive 2009/31/EC and the ISO 27914 standards define a *geological storage complex* as the storage location and the geological surroundings that may be of significance for the security of the storage.

A *storage location* is defined as a certain area within a geological formation that is used for geological storage of CO_2, and associated surface and injection facilities, including the structure of injector and monitor wells.

Storage units are defined as the reservoirs (geological formations) where CO_2 is intended to be injected and stored.

Migration is defined as the movement of CO_2 within in the storage complex. Containment is defined as retention of CO_2 within the storage complex.

A key requirement for subsurface CO_2 storage is that the injected CO_2 remains contained within the defined geological storage complex. The purpose of a Containment Risk Assessment (CRA) is to assess the safety and containment integrity of the geological storage of CO_2 to confirm that there is no significant risk of leakage and thus no relevant risk that could affect human health, the environment, or other industrial activity.

The CRA is an important input to an Environmental Impact Assessment as well as to a cost-effective and risk-based Measure, Monitoring and Verification (MMV) plan.

Integrated Containment Risk Assessments– The workflow

The Containment Risk Analysis (CRA) workflow is shown in Figure 1. A holistic CRA includes a multi-disciplinary analysis of the geological storage complex, incorporating legacy wells and future injector and monitor wells. The analysis should include a forward prediction of the maximum plume extension over the anticipated injection and post-injection periods, through activities such as identification and characterization of reservoir (storage), seal and other barrier units and faults based on seismic data, well logs, as well as geomechanical and drilling parameters.

Interpretations of the available data define the subsurface geometry and spatial property distribution built into subsurface models. The behaviour and impact of injected CO_2 is then simulated, resulting in the expected maximum extent of the CO_2 plume and associated dynamic changes to the storage complex. Special attention is given to all potential leak-paths, regardless of their perceived likelihood. Once identified all plausible pathways where CO_2 can possibly leave the storage complex, a detailed barrier assessment is carried out.

- Barriers physically preventing CO_2 from leaving the storage complex through geological failure mechanisms or through wells, as well as mitigating measures that can either prevent and/or minimize its severity, are mapped.
- All information on the identified preventive or corrective (reactive) measures, for each leakage-path, is compiled into bowtie diagrams.

To ensure that the risk is at a level which is As Low As Reasonably Practical (ALARP) at any time, the ALARP principle is applied in which the benefit of identified additional barrier or risk reducing measures versus the cost or effort of their implementation are assessed.

Update and review of risk-reducing measures is an ongoing effort. During bowtie workshops, actions to improve the quality of the barrier definition, as well as data acquisition and de-risking opportunities, are identified and measures considered to have a risk reducing effect that is in proportion with the cost or effort to implement it, and therefore are recommended to be implemented.

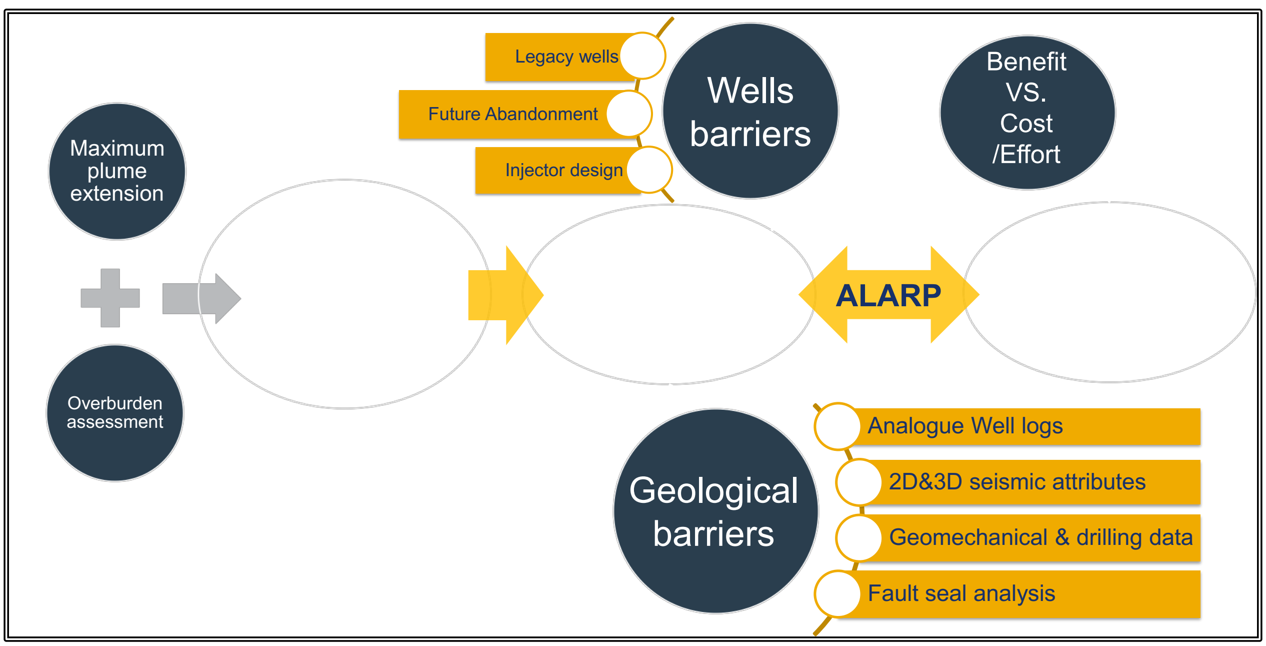

Figure 1. The Containment Risk Analysis process (modified from Vebenstad et al. 2021)

The CRA process can be summarized in the following steps:

- Identification of possible leakage or failure pathways.
- Barrier assessment.

- Identify Steps to improve Effectiveness/Uncertainty of active physical barrier.
- Estimate Likelihood for each barrier to fail.
- Agree on the "Consequence" in terms of Leak-rates and duration for each leak path.
- Identify additional procedural barriers (incl. monitoring) and possible response plan.
- Risk Register per leakage path in terms of Likelihood VS. Consequence (Leak-rates and duration).

Bowtie analysis: Leak-path specific implementation

The bowtie analysis is a risk assessment methodology that has been used in several CO_2 storage projects with relevant publications such as van Eijs et al. (2011), Tucker et al. (2013), Bourne et al. (2016), the White Rose project report (2016) and Vebenstand et al. (2021).

A leak-path specific implementation of the bowtie analysis enables a detailed understanding of the more likely and/or most severe potential events of loss of containment and how these could be mitigated. This type of implementations of a bowtie analysis result in a very site-specific analysis, including the measures in place to manage each plausible leak-path that might be present within the geology of the Under this workflow, bowtie analysis is intended to be time specific, and therefore requires constant updates as new data is acquired. Bowties are recommended to be kept “live” during each phase of a CO_2 storage project. The hazard in geological storage of CO_2 is the CO_2 itself, as its mere presence has the potential to cause unwanted consequences.

Figure 2 illustrates the key elements of the methodology. The unwanted (top) event sits in the centre of the diagram, with threats (causes) on the left-hand side and potential consequences (outcomes) on the right-hand side.

The top event is defined as the release of CO_2 from where it is intended to be, i.e., movement out of the storage complex.

The barriers (preventative and corrective) may be geological features (such as impermeable layers), well barriers, operational constraints (e.g., limits on injection pressures and volumes) or monitoring barriers that allow for corrective actions to be taken. The ultimate site-specific unwanted consequences or potential outcomes are usually shown on the right-hand side of the bowtie. These may be containment in strata outside the pre-defined storage complex, emission to the surface or water column, or contamination of assets, e.g., aquifers or nearby hydrocarbon fields, etc.

The bowties are there to support a project’s risk management efforts, by allowing for more informed decisions to be made.

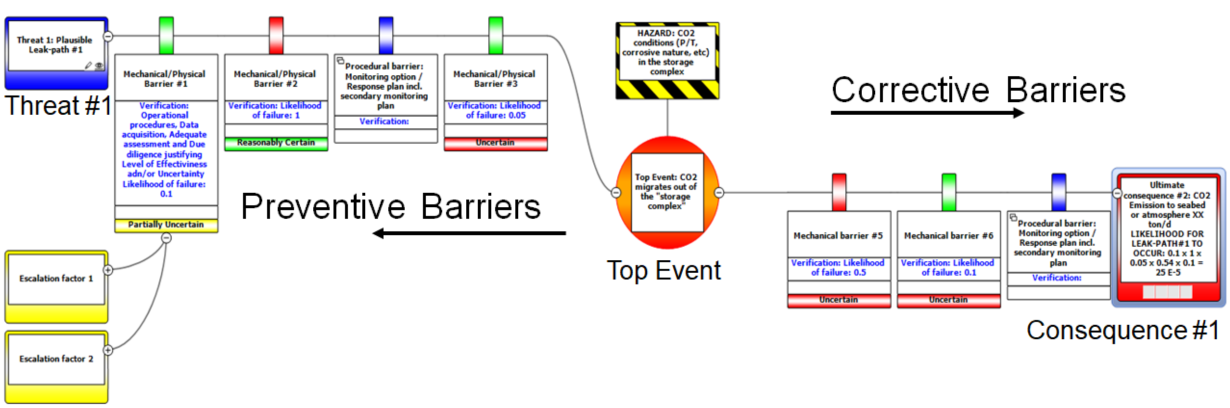

Figure 2. Example of a Leak-path specific implementation of the bowtie analysis

A key benefit of the bowtie method focusing on each potential leak-path, either geological, well-specific or hybrid, is the easy identification of the potential need for more detailed studies to reduce uncertainty on the risks identified. Furthermore, it provides structure to facilitate multidisciplinary understanding and communication amongst all subsurface and wells disciplines.

Containment Risk Matrices

A bowtie analysis may involve a semi-quantitative risk analysis (SQRA) or a quantitative risk analysis (QRA) to estimate the likelihood and possible rates of different leak paths.

The SQRA uses a simplified Layers of Protection Analysis (LOPA) approach, which is a commonly used method for assessing risks quantitatively (CCPS, 2001).In the LOPA approach, the likelihood of initiating events is adjusted by considering the risk reduction provided by protection layers, or barriers, to determine the frequency of adverse consequences. This frequency can then be compared to a predefined target, which considers the magnitude of the consequence, to determine if the risk is acceptable or if additional risk reduction measures are needed.

It is important to note that although the SQRA generates numerical values, these values rely heavily on the judgement of subject matter experts due to the limited data available for long term geological CO_2 storage. Therefore, the results should be viewed as indicative values that are most suitable for comparing relative risks rather than deriving absolute values.

			Consequence (Release Rate & Duration Combined)				
			Very Small < 0.01%	Small < 0.1%	Medium < 1%	Large < 10%	Catastrophic > 10%
Likelihood	Very Remote	≤ 1.00E-6		W5			
	Remote	≤ 1.00E-5					
	Highly unlikely	≤ 1.00E-4					
	Unlikely	≤ 1.00E-3	G3	G2			
	Possible	≤ 1.00E-2			G1	W3	
	Probable	≤ 0.1					
	Likely	≤ 1			W1 W2		

		Consequence Severity (release rate)			
		Small ≤ 10 t/day	Medium ≤ 100 t/day	Large ≤ 1000 t/day	Catastrophic > 1000 t/day
Duration	Short (≤ 1 year)	W5 G3	W4	W3	
	Medium (≤ 10 years)	G2			
	Long (≤ 100 years)		G1		
	Extended (<1000 years)		W1 W2		

Figure 3. The Containment Risk Analysis process (Vebenstand et al. 2021)

After completing the SQRA, the results are plotted on Containment Risk matrices (Figure 3). In the generic example presented in the top matrix, leak-paths W1 to W5 are Wells related and G1 to G3 are geological leak-paths. These leak-paths are plotted against their estimated likelihood (Y-axis) and their estimated leak-rate in terms of percentage (%) of the total amount of CO_2 injected (X-axis).

To account for the impact of the duration of a leak, regardless of its rate, another matrix is used, as depicted in the lower matrix (Figure 3). When these two matrices are combined—the one assessing leak-rates and the other focusing on leak duration—they provide a comprehensive evaluation of the potential risks of loss of containment.

It is worth mentioning that this approach has certain disadvantages, such as creating an impression of accuracy and certainty. While the values used in the analysis were derived through consultation with the project team and subject matter experts, they are still estimates. It is crucial to understand the underlying assumptions and not to present the resulting risk numbers as precise and certain values.

Proportionate Measure, Monitoring, and Verification (MMV) plans

The implementation of a comprehensive monitoring, measurement, and verification (MMV) plan is essential to ensure the safe and effective storage of CO_2. This plan should encompass all stages of the CO_2 injection operation, including pre-injection, injection, and post-injection and is a fundamental requirement of all established CO_2 storage regulatory and permitting bodies

The conceptual philosophy behind MMV involves the use of procedural barriers and various options to identify any anomalies that may arise during the storage process. These anomalies serve as indicators for implementing appropriate corrective measures that are proportionate to the identified issues. The objectives of the MMV plan include:

- Containment Assurance: Demonstrating the safety of the storage facility by ensuring that the CO_2 is contained within the intended storage reservoir.
- Conformance Verification: Validating that the actual performance of the storage matches the predicted behavior in terms of injectivity, resources, and the behavior of the CO_2 within the storage complex.
- Provision of Safeguards and Early Warning Signals: Establishing mechanisms to prompt timely corrective actions by providing early warnings of any deviations from expected performance.
- Facilitating Liability Handover: Ensuring a smooth transition of ownership and responsibility for the storage facility.

To address the potential leakage paths specific to individual wells and subsurface conditions, various alternative technologies are being considered. These technologies can include instruments located near or on the seabed, such as tiltmeters and active seismic devices, as well as those included in the well surveillance plan for ongoing monitoring and evaluation.

Figure 4 provides a general illustration of the assessment of various identified leak paths (G1 to G3 and W1 to W5) in relation to the available technologies and their respective implementation potential. These technologies can be deployed either from the surface or seabed, or they can be installed specifically in observation and injection wells.

Concentrating on the leak-paths with the highest likelihood or potential impact, as determined by their leak-rates, enables quick recognition of the technologies that ought to be included in the Monitoring, Measurement, and Verification (MMV) strategy.

This method meets the systematic requirements for risk assessments as stipulated by international standards and regulations for CO_2 storage. Additionally, the devised MMV concept is tailored specifically to the CO_2 storage site since it targets the identified leak-paths and areas of vulnerability. This approach also guarantees the selection of the most cost-effective solutions by balancing risks against their potential benefits.

Monitoring Options		Well specific Leak-Paths					Geological Leak-paths		
		W1	W2	W3	W4	W5	G1	G2	G3
Surface	Technology #1	X	X	X	X	X	✓	✓	✓
Surface	Technology #2	-	-	-	-	-	✓	-	-
Surface	Technology #3	✓	✓	✓	✓	✓	X	X	X
Injection / Monitor Wells	Technology #A	X	X	✓	✓	✓	✓	✓	✓
Injection / Monitor Wells	Technology #B	✓✓	✓✓	-	-	X	-	-	-
Injection / Monitor Wells	Technology #C	X	X	✓	✓	✓	✓	X	X

LEGEND

✓✓	Optimal	Optimal in context of technology maturity
✓	Useful	Recommended in context of technology maturity
-	Marginal	Requires further evaluation / value currently uncertain
x	Non - Applicable	

Figure 4. Example of assessment of leak-paths VS. technology implementation potential

Conclusions

Regulatory standards, guidelines and requirements for CO_2 storage worldwide stipulate a structured approach to risk assessment for carbon capture and storage (CCS) projects. Compliance with these guidelines, such as the EU Directive 2009/31/EC, US EPA Class VI rules, Australia's OPGGS Act, and ISO Standards 27914:2017, is non-negotiable.

The core of these regulations is the requirement for a rigorous and methodical risk assessment, concentrating on the safety and integrity of CO_2 storage, to prevent leakage and ensuing harm to human health, the environment, or other nearby resources.

Containment Risk Assessment (CRA) plays a vital role in evaluating the feasibility and security of geological CO_2 storage locations. This involves analyzing potential leakage or failure pathways, both geological and those involving wells, and incorporating multi-disciplinary approaches to ensure CO_2 remains within the defined storage complex. Barriers - both physical, such as geological features, and procedural, including monitoring and emergency response plans - are scrutinized for their effectiveness. The bowtie analysis method serves as a central tool in this process by breaking down and addressing risks at each potential leak-path.

The CRA process is advanced and dynamic, requiring constant updating as new data come to light. All findings inform the development of MMV plans, which underpin containment assurance, conformance verification, provision of early warning systems, and the smooth handover of liability where necessary.

Overall, the practice of CCS risk assessment revolves around identifying and minimizing the risks of CO_2 leakage. A focus on the most critical pathways enables the prioritization of technology implementation within an MMV strategy, ensuring effective monitoring while meeting stringent international regulatory requirements.

In the realm of developing a MMV plan for CO_2 storage, the emphasis should be on designing solutions that are necessary, well-executed, and cost-effective. It's vital to avoid "gold-plating," which refers to the practice of adding unnecessary features or excessively engineering a system, leading to increased complexity and costs.

The key to achieving proportionate and cost-efficient storage development and MMV plans is to adopt an integrated and structured approach to risk assessments. By focusing on leak paths, developers can create site-specific plans that address the unique characteristics and risks of each storage site. This ensures that efforts and resources are directed towards mitigating the most significant risks. Doing what is essential and doing it well is preferable to implementing every conceivable solution, thereby optimizing the balance between safety, effectiveness, and financial investment.

References

Bourne S, Crouch S, Smith M. **A risk-based framework for measurement, monitoring and verification of the Quest CCS Project, Alberta, Canada**. International J of Greenhouse Gas Control 2014; 26, 109-126.

Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers. **Layer of Protection Analysis: Simplified Process Risk Assessment Wiley**, ISBN 978-0-8169-0811-0, 2001.

Tucker O, Holleya M, Metcalfe R, Hurst S. **Containment risk management for CO_2 storage in a depleted gas field, UK North Sea**. Energy Procedia 2013; 37, 4804 – 4817.

UK Department of Energy and Climate Change (DECC). **CO_2 Storage Liabilities in the North Sea An Assessment of Risks and Financial Consequences**. 2012.

van Eijs R, Kuijper M, Bisschop R. **Containment demonstration for the Barendrecht CO2 Storage Project**. Energy Procedia 2011; 4, 4092-4099.

Vebenstad K., Vazquez Anzola D. A., Lidstone A., and Zweigel P., 2021. **Containment risk assessment of the Northern Lights Aurora CO_2 storage site**. 15th Greenhouse Gas Control Technologies Conference. Abu Dhabi 15-18 March 2021 (GHGT-15).

White Rose. **White Rose Carbon Capture and Storage Project**. K.01 Full Chain FEED Summary Report. 2016. [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/531384/K01_Full_chain_FEED_summary_report.pdf]