A Comparative Analysis of Risk Assessment Methodologies for the Geologic Storage of Carbon Dioxide

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Abstract

This paper offers a broad summary of the most common risk assessment methodologies for the geologic storage of carbon dioxide. We believe it is valuable to compare these methodologies, particularly in the areas where they lead to similar conclusions. The objective of this paper is to provide a better understanding of the current similarities and differences of these proposed methodologies.

Since CCS was proposed as a mitigation option for reducing anthropogenic CO2 emissions, several attempts have been made to study the potential risks of long-term storage of CO2 in geological formations. Various worldwide projects have tried different industrial methods adapted to GSC. In spite of these efforts, currently there is no standardised method or set of methods for evaluating risk and/or uncertainty for GSC projects. Application or adaptation of advanced industrial quantitative risk assessment methods seems not convenient at this point because of lack of specific data. The development of frameworks and qualitative methods looks the most trustable for current projects.

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Keywords: geologic storage; risk management; risk assessment; risk analysis; uncertainty

1. Introduction

Risk assessment (RA) for long-term performance related to geological storage of CO2 (GSC) requires a strong and consistent framework in order to facilitate the deployment of the Carbon Capture and Storage (CCS) technologies. A
safe storage site, with enough capacity of storing large volumes of Carbon Dioxide, for centuries or millennia, is indispensable as a contribution to GHG reductions and to gain public acceptance through assurances of storage integrity.

Existing industries have vast experience dealing with risk assessment methodologies, but the GSC is a new technology with no accident and/or track records. The only one experience -listed as natural disaster- is related to the limnic eruption in the Lake Nyos in Cameroon in 1986 causing the death of more than 1,700 people and numerous animals (Tazieff 1989, Cotel 1999). Although the Nyos’ case was entirely unrelated to geological storage, it was an extreme situation and its consequences have altered dramatically every discussion related to the risks of geological storage of CO2.

In safety engineering, the concept of risk is generally accepted as the product of probability that an event will occur and the consequences of the event if it does occur. This concept is generally applicable to well-defined systems, however, that is not the case for GSC because most of its components are not well known. In other words, there is “uncertainty” in the system. Estimating risk is highly dependent in the level of knowledge of a system: The better known a system, the better understanding of the implied risks. For the GSC, at the early stages of the project, the level of risk is higher. In 2007, Sally Benson depicted the risk evolution for a GSC in the Figure 1 (Benson 2007). Figure 2 illustrates the influence of uncertainty in the value of risk (DNV 2009)

The main issue for risk in health, safety and environment (HSE) in GSC projects is related to leakage. Leakage from the targeted storage formation could occur through several pathways, such as (abandoned) wells, cap rock, and faults. Impacts from CO2 seepage at the surface may be notable on a local scale, even in a short time frame.

A key activity in Risk Assessment (RA) is to develop methodologies and tools to evaluate HSE risks and to develop monitoring tools that allow early detection and remediation. RA aims at identifying and quantifying potential risks originating from storage sites. Because CO2 storage is a rather recent area of investigation, new RA methods are being proposed and no well established method for this purpose exists. However, many of the proposed RA methods and models were originally developed for the oil and gas industry (Pitblado, Moosemiller 2004).
2. Common Risk Assessment Methodologies

RA methodologies are generally classified in two main groups: qualitative and quantitative. Qualitative Risk Assessment does not provide concrete or numerical results. When there is a lack of data and/or specified knowledge, time and expertise, qualitative risk assessment may be sufficient and more effective. Among the most common quantitative methods are the features, events, and processes (FEP), and the Vulnerability Evaluation Framework (VEF).

The quantitative methods are used in well-known systems where the level of uncertainty is relatively low. Two main kinds of methods belong to this group: Deterministic Risk Assessment (DRA) and Probabilistic Risk Assessment (PRA). DRA does not deal with uncertainty, but it is useful in determining trends due to its single parameter variation. It gives very accurate results if the input parameters are known exactly. PRA, on the other hand, can statistically quantify the uncertainty associated with parameters describing the processes in deterministic models. PRA is the most preferable method of assessing long-term risk in complex systems. By using PRA models, a range of input values (e.g. PDF/probability density function) for each input parameter gives a range of outcomes. Values for PDFs are obtained from Monte Carlo analysis, derived from measured data, or assigned by expert judgments. PRA may provide a holistic assessment of the uncertainties associated with CO2 storage.

Based on the above description, a set of examples are given as part of the available methods for assessing risk in GSC projects. Table 1 summarizes the main characteristics of these methods.

The Features, Events and Processes (FEP) method consist of a list of relevant factors that describe the current state and possible future evolution of a site. Features include specific on-site parameters such as cap rock porosity, number of wells, reservoir permeability, etc. Events are processes like seismic and well-blowouts. Processes can be physical and/or chemical such as geomechanical or geochemical processes and multi-phase flow behaviour (Condor 2009). The analysis can be employed in two ways, bottom-up or top-down (Figure 4). The bottom-up approach uses

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2 There are several methods that were not considered in this paper due to limited amount of literature related to GSC. Among the most important methods, they are: Preliminary Hazard Analysis (PHA), Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Fuzzy Logic (Pitblado, Moosemiller 2004, Goodden 2000)
the database directly to develop the assessment models. In the top-down approach the database is used as an audit tool to ensure all relevant FEPs are included in the models and to document why others have not been considered. The FEP analysis is useful in the licensing and certification stages of project development. It provides qualitative risk assessment of various plausible scenarios. As a disadvantage, it is a time consuming method which requires considerable site specific information.

The Vulnerability Evaluation Framework (VEF) is a qualitative method which systematically identifies conditions that could increase or decrease the potential for adverse impacts (susceptibility to consequences). The conceptual method has three main components, i.e. columns in the Figure 5, (EPA 2008). The VEF is not designed as a site selection tool, establish performance standards, or to specify data requirements. The VEF is a conceptual framework designed to help regulators and technical experts for framing specific considerations and identifying areas that require design evaluation, specific risk assessment, monitoring, and management. VEF has some similarities to the Certification Framework Approach (CFA) developed at the Lawrence Berkeley National Laboratory (Oldenburg, Nicot & Bryant 2009).

The Structured What-If Technique (SWIFT) is a form of Delphi risk analysis used by DNV for qualitative hazard identification. This method was developed as an efficient alternative to the Hazard and Operability (HAZOP) technique and to the Failure Modes and Effects Analysis (FMEA) for providing highly effective hazard identification in situations and systems where none of them were convenient. It consists of a series of questions "what-ifs…?" or "How could…?" to identify situations or issues or threats with potential for causing harm. There is no single standard approach to SWIFT. Hence it is flexible and can be modified to suit each individual application (Vendrig et al. 2003).

The Multi-Criteria Assessment (MCA) covers a variety of non-monetary evaluation techniques sharing a basic framework under which a number of alternatives can be scored against a series of defined or fixed criteria. This list of criteria is proposed according to the fundamental goals of the GSC. These criteria can then be categorized in groups (Gough, Shackley 2006). This method delivers a rich profile of the views and preferences of participants and thus enables 'mapping' key issues that will affect the prospects for further development. A similar method is the Multi-Attribute Utility Theory (MAUT). The main difference between MAUT and MCA is that MAUT assumes a dependency of preferences of criteria, enabling the inclusion of subjective elements (Scholz, Tietje 2002).

The Evidence Support Logic (ESL) is designed to identify the amount of uncertainty or conflict involved in a decision. This involves systematically breaking down the question under consideration into a logical hypothesis model whose elements expose basic judgements and opinions related to the quality of evidence associated with a particular interpretation or proposition (Metcalfe et al. 2009). The evidence may correspond to quantitative or
qualitative information. Each item of qualitative or quantitative information is then mapped to two values on a numerical scale of 0 to 1. This representation of evidence is a type of Interval Probability Theory, which employs three-value logic. Experts assign values to each hypothesis representing the amount of supporting evidence, the amount of refuting evidence and the amount of uncertainty or conflict in the evidence. Figure 7 illustrates the ESL three-value logic (Quintessa Limited 2008).

The Risk Identification and Strategy using Quantitative Evaluation (RISQUE) was used in the GEODISC program in Australia. This is a systematic process that uses expert panel judgments to evaluate the specific characteristics of a GSC site. It uses an event-tree method, which can be interpreted as a FEP list. RISQUE uses logarithmic square matrixes to evaluate the acceptability criteria based on six performance indicators: containment, effectiveness, self-funding potential, wider community benefits, community safety, and community amenity. Figure 8 gives an example of the acceptability criteria between containment and effectiveness. The validation of this methodology took place in four Australian sites: Dongara, Petrel, Gippsland, and Carnarvon (Bowden, Rigg 2004).

The Method Organized for a Systematic Analysis of Risk (MOSAR) is designed for analyzing the technical risks of a system and for identifying prevention means to neutralize them. It consists of 10 steps where the system is divided in interacting subcomponents. The first step “A” allows the realisation of analysis of major risks. The second step “B” makes a detailed analysis of project implementation and specifically defines the safety tools related to the technical dysfunction. The MOSAR method relies on a step by step method, where no step can be neglected. This does not prevent flexibility, because if an unexpected event arises or a new danger source appears, it is possible to include it at the beginning of the method without calling all the rest into question. It is based on site observations and facts and not just on complicated mathematical models (Cherkaoui, Lopez 2009).

The Certification Framework Approach (CFA) is similar to the VEF, but it adds values for the leakage probability. For quantification of risk, the system is divided into compartments. These compartments can be subsurface.

Figure 6 The MCA concept (after Grataloup et al. 2009)

Figure 7 Comparison between two and three-value logic in defining risk (Quintessa Limited 2008)

Figure 8 Containment and Effectiveness Risk Matrix (after Bowden, Rigg 2004)

Figure 9 The MOSAR concept (Cherkaoui, Lopez 2009)
(hydrocarbon reservoirs or underground sources of drinking water) or at surface (local sites where leakage occurs),
and distant sites. Conduits for leakage from source to compartments or from one compartment to another may be
wells or faults. The total probability (called CO₂ leakage risk, CLR) is the product of all identified probabilities of
the system (Oldenburg 2008, Kumar, Bryant & Nicot 2009). A similar method to CFA is the Screening and Ranking
Framework (SRF) which is based in the assumption that if the primary seal or containment leaks, then the second
seal will act. If the second seal fails, then the leakage will be attenuated or dispersed (e.g., by mixing in the
atmosphere or by uptake and mixing by groundwater or surface water) (Oldenburg 2008).

The Performance and Risk (P&R) assessment for well integrity was developed by Schlumberger and OXAND, and
is based on the classical definition of risk (likelihood versus consequence). The uncertainties of the system are
converted into the notion of probability and the quantity of CO₂ leakage mass assessed into the notion of severity. It
also includes the definition of a Risk Acceptance Limit (RAL), which brings forward the criteria of unacceptable

The System Modelling Approach (SMA) is part of the CO₂-PENS and was developed in Los Alamos National
Laboratory and originally designed to perform probabilistic simulations for the whole CCS chain. The long-term
fate of the injected CO₂, including possible migration patterns out of the target formation, is simulated through
probability distributions (Stauffer et al. 2009)

![Figure 10](image1.png)  
**Figure 10** Generic cross section with CFA source and compartments overlaid (Oldenburg 2008)

![Figure 11](image2.png)  
**Figure 11** P&R assessment for well integrity (after (Le Guen et al. 2008))
Table 1. RA Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Goal</th>
<th>Data needed</th>
<th>Industrial application</th>
<th>Application for GSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRA</td>
<td>Analytical point estimate calculations</td>
<td>Numerical and qualitative expert estimation for scenario development and model development</td>
<td>Safety engineering (sensitivity analysis)</td>
<td>Initial risk assessment. No uncertainty estimations</td>
</tr>
<tr>
<td>PRA</td>
<td>Predict the probability of safety failures of complex systems</td>
<td>Numerical qualitative expert estimation for scenario development, model development, quantifying PDFs</td>
<td>Safety engineering</td>
<td>Detailed risk assessment. Uncertainty estimation</td>
</tr>
<tr>
<td>FEP</td>
<td>Scenario development</td>
<td>Qualitative expert estimation for scenario development</td>
<td>Scenario analysis</td>
<td>Screening and Site selection</td>
</tr>
<tr>
<td>VEF</td>
<td>Conceptual framework for regulators and technical experts</td>
<td>Qualitative expert estimation to identify which areas should be in-depth studied</td>
<td>Hazard identification and potential consequences</td>
<td>Framework for site selection and regulator guidance</td>
</tr>
<tr>
<td>SWIFT</td>
<td>Elaborate hypothesis</td>
<td>Qualitative expert estimation to identify hazards</td>
<td>Hazard identification in engineering</td>
<td>Hazard and consequence mapping</td>
</tr>
<tr>
<td>MCA / MAUT</td>
<td>Evaluation of alternatives in multiple objective</td>
<td>Qualitative and numerical expert estimation for data input utility</td>
<td>Decision making</td>
<td>Framework for screening and site selection</td>
</tr>
<tr>
<td>RISQUE</td>
<td>Systemic process with participation of expert panels</td>
<td>Qualitative and numerical expert estimation in event-tree approach</td>
<td>Hazard identification and potential consequences</td>
<td>Hazard and consequence mapping</td>
</tr>
<tr>
<td>CFA / SRF</td>
<td>Estimation of risk based on probabilities of occurrence in individual features</td>
<td>Qualitative and quantitative estimation of risk and uncertainty</td>
<td>Development of simple probabilistic models</td>
<td>Managing risks in GSC sites</td>
</tr>
<tr>
<td>MOSAR</td>
<td>Identifying and preventing risks</td>
<td>Qualitative and quantitative data for a well-known system</td>
<td>Risk reduction in complex systems</td>
<td>Systematic risk analysis for well-known sites</td>
</tr>
<tr>
<td>ESL</td>
<td>Identification of uncertainties in decisions</td>
<td>Qualitative and quantitative understanding of uncertainties</td>
<td>Reduction of uncertainties in well-known systems</td>
<td>Detailed PRA and dealing with uncertainties</td>
</tr>
<tr>
<td>P&amp;R</td>
<td>Risk mapping in wellbores under the criteria of degradation scenarios</td>
<td>Qualitative and quantitative data for wellbores</td>
<td>Risk evaluation under the concept of ALARP</td>
<td>Long-term well integrity</td>
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<tr>
<td>SMA</td>
<td>Estimation of risk based on probabilities</td>
<td>Quantitative estimation of risk and PDFs</td>
<td>Development of complex models in well-known systems</td>
<td>PRA for the whole CCS chain</td>
</tr>
</tbody>
</table>

3. Discussion

Since CCS was proposed as a mitigation option for reducing anthropogenic CO₂ emissions, several attempts have been made to study the potential risks of long-term storage of CO₂ in geological formations. Various worldwide projects have tried different industrial methods adapted to GSC. In spite of these efforts, currently there is no standardised method or set of methods for evaluating risk and/or uncertainty for GSC projects. Application or adaptation of advanced industrial quantitative risk assessment methods seems not convenient at this point because of lack of specific data. The development of frameworks and qualitative methods looks the most trustable for current projects.

A common approach being used by some research groups involves four general steps of: FEP analysis, scenario analysis, process modelling, and consequence analysis. This approach still leaves some room for uncertainty. It should be understood that the original risks in a GSC project may be higher at the early stages of project, but it is expected to reduce when more specific information is available. This should not be a limitation for deploying CCS projects. For the Weyburn project, all above mentioned methodologies were applied to assess geosphere migration of CO₂ and a single well performance. It was found that the primary variability in the geosphere model is the heterogeneities in CO₂ distributions and rock properties in the reservoir. As for the abandoned wells, their variability of characteristics necessitated a stochastic approach.
4. References


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