Geological carbon sequestration: prediction and verification

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Risks Associated with CO2 Sequestration in Deep Brine Reservoirs: Qualitative and Hybrid Bayesian/Fuzzy Risk Analysis

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When a regulator considers the risk associated with a geologic CO2 sequestration project several questions should be considered: 1) What can go wrong (what are the possible adverse outcomes)?; 2) What is the probability or likelihood of these outcomes?; 3) What would the consequences be at this site?; and 4) In view of the uncertainty in the data used, how confident are we about the answers to these first three questions? Answers to these questions can be an important in gaining public acceptance of geologic CO_2 sequestration. Risk assessments of geologic sequestration projects should facilitate more robust and transparent decisions. All large industrial projects bring with them operational risks. These risks for CCS projects include: (1) the risks of capturing, compressing, transporting, and injecting CO2; (2) the risk of blowouts or very rapid CO2 release from wells or faults; (3) the risks that leakage from the containment zone will contaminate drinking water or energy resources (as well as environmental and ecosystem impacts); and (4) That sequestered CO2 (and possibly associated methane gas) will leak into the atmosphere reversing the climate change benefits of sequestration and perhaps requiring repayment of CO2 sequestration credits.

Although the range of potential avenues for both rapid and slow leakage during transport and injection (as well as the spectrum of leakage pathways from the containment zone), are well known at least conceptually, a standard, widely-accepted framework for risk analysis is yet to emerge. Predicting time dependant risk profiles for real CO2 sequestration projects require a systematic exploration of plausible scenarios (including prediction of their frequency of occurrence) leading to adverse outcomes. Such scenarios will be created by combining both initiating events, chains of consequent events, and the role potential mitigating processes or events (including operator intervention or mitigation). The scenarios generated as part of the risk analysis explore the range of adverse consequences that can propagate from a specific initiating event. Such scenarios can be viewed as coherent, causal event-chains that are conceptually similar to a linked series of FEP's (Features, Events, Processes). We will review a number of such possible event chains for site specific examples where we have been involved in risk assessments such as the Texas FutureGen sites.

Risk is composed of two elements, the likelihood (probability) of an adverse outcome (hazardous event) and the magnitude of its consequences that is: *Risk = Likelihood x Consequences.* Geologic sequestration of CO_2 in deep brine reservoirs is an appropriate application of this approach as it is a process-driven system that will exist for long times.

The risks resulting from events that have significant consequences but small probabilities of occurrence are difficult to estimate in the absence of large datasets.

The risks of CO_2 storage in a geological reservoir should be seen in the context of an engineered reservoir. The subsurface engineering technology that will form the basis of a new sequestration industry is in large based on equipment and approaches developed over the last 37 years for CO_2-EOR. Apart from possible ruptures of CO_2 pipelines the next most plausible risk to public safety comes from the “blow out” or loss of control of a CO_2 injection well. Blowouts do occur rarely in association with CO_2-EOR injection activity and understanding the nature and consequences of these events can help us predict the risk of such events occurring in association with future CO_2 sequestration. There are currently 4,700 injector wells operating in the Permian Basin amounting to 40% of the CO_2 EOR wells currently operating, the other 60% of wells being production wells. The total CO_2 injected into the Permian Basin amounts to approximately 1,200 million tons of CO_2. Almost certainly the number of injection wells that will be used for CO_2 sequestration in brine reservoirs to inject an equivalent amount of CO_2 will be far fewer. We are examining the record of blowouts associated with the CO_2 EOR industry. This study is in its initial phases. So far four blowouts associated with CO_2 injection wells have been identified and another twelve are being evaluated. Although this study is incomplete the preliminary conclusion is that the incident rate is small.

The next most likely risk associated with CO_2 sequestration is probably related to leakage into groundwater (USDW) from well bore failures (corrosion, cracked casing etc). From 20,271 cumulative site-years of underground natural gas storage experience, the IEA in 2006 identified eight leakage incidents that appeared to fit this category for a frequency of occurrence of 3.95×10^{-4} significant leaks/site-year. They found that the frequency of significant leakage from all underground mechanisms (sixteen incidents) was estimated at 7.89×10^{-4} significant leaks/site-year for all types of underground natural gas storage facilities. Because this estimate included both salt caverns, and aquifers storage, this data probably significantly overestimates the likelihood of such phenomena associated with CO_2 sequestration.

The risk that we have the least factual basis to constrain the likelihood of is that of leakage through the seal or containment zone of the sequestration reservoirs, ultimately leading to pollution of drinking water. Leakage may be diffuse but most likely would be focused by transmissive faults or fracture zones. These issues are the subject of considerable current research effort that has resulted in a consistent picture. First numerical modeling results support the assertion that the chances of catastrophic leakage through the seal are extremely small. In well chosen sites we believe that such a risk is effectively non-existent. The main impact of leakage through the seal (should it occur) will be on groundwater quality. The likelihood of such leakage and the consequences that would results from it are site specific. Some sites are more likely to leak than others. At some sites there are negligible quantities of drinking quality water and therefore the consequences are limited. We argue that careful site selection is the key to controlling risk from slow (long term leakage). This type of risk will dominate the long term (post-closure) risk.

Scientists and engineers have a good understanding of the risks associated with CO_2 sequestration in brine reservoirs in terms of the spectrum of risk elements. However, a consensus is lacking in the published literature as to the relative (and absolute)

probabilities of adverse outcomes. There is a particular concern for the long-term risk in the post closure period of injection projects. The risk during the operational phase of CO2 sequestration projects is arguably relatively well understood can be adequately addressed through and existing financial risk management frameworks or straight forward modifications thereof.

In developing a quantitative framework to analyze risks associated with CO2 sequestration in deep brine reservoirs, where relevant data on adverse impacts are scarce (or absent) and experience is extremely limited, a common approach is to use Bayesian inference. Bayesian analysis is a tool that has been in use for over half a century. Bayesian modeling facilitates combining of results of measurement (such as monitoring a CO2 sequestration site) with other relevant information (domain knowledge), and provides a methodology to deal with missing data. Bayesian analysis enables inferences of expected values for model parameters and prediction of credible intervals for such parameters that are analogous to, but not identical to, the confidence intervals of classical or ‘‘frequentist’’ statistics. These parameters can be used to project credible intervals or bounds for risk in terms of the future behavior of the system. The Bayesian approach can be used to identify the best decision that can be made based on the uncertainty and the available information. The best decision can be defined as one that “maximizes the expected value of one or more performance indices”. Bayesian analysis can be used to evaluate the degree to which additional information can change the decision we would be made and thus improve estimation of the risk. This enables the ‘‘expected value of imperfect information’’ to be quantified. An application would be evaluating the cost effectiveness of various monitoring strategies. This requires establishing the sampling density or strategies necessary to assure a high likelihood of leak detection.

Bayesian networks were first used to model expert knowledge where such knowledge is uncertain, ambiguous, and/or incomplete. Bayesian networks with causal dependence relationships are called referred to as causal belief (or probabilistic) networks or Bayesian causal maps. Such networks or maps can be used to model the uncertainty associated with mapped variables. Probabilistic inference in a Bayesian network can be achieved by calculating the posterior marginal probability distributions for variables associated with the outcomes of interest by evidence propagation algorithms. These can be used to assess the sensitivity of variables related to specific outcomes to various inputs. Fuzzy logic/set theory has been applied to subsurface contamination risk assessment problems. Fuzzy logic based modeling approaches can be combined with probabilistic (including Bayesian) approaches. Such hybrid approaches are capable of using fuzzy logic to characterize model imprecision while using stochastic methods to model irreducible uncertainty.

Risk management is concerned with implementing processes and policies to both prevent and control risks. Risk mitigation strategies attempt to either intercept leaking CO2 before it leads to adverse consequences or to neutralize the effects. Although many researchers in CO2 sequestration use the terms mitigation and remediation as equivalents there are good reasons for treating them as distinct issues. Two alternative terms can be defined, corrective action and preventive action. Preventive action involves strategies to decrease the rate of leakage or to decrease the negative consequences of such leakage. Corrective action (remediation) is repairing the damage to drinking water resource. With early detection of leakage at depth, preventive action may be initiated perhaps decades

before corrective action is relevant. The most likely source of leakage is well failure (breaches of the well casings, defective cementing jobs and other mechanical flaws in the injection system). Preventive action strategies include: (1) conducting targeted well testing and repair of leaking injection well by replacing the injection tubing and packers and/or by reworking well by performing a cement "squeeze" to plug leaks behind the well casing; (2) plugging leaking abandoned wells; (3) reduction of injection pressure; and (4) lowering the relative permeability for CO2 of faults, fracture zones or any other feature identified as the leakage pathway. A significant pressure reduction could be accomplished by producing brine from a well that accesses the zone of anomalously pressure. Another possibility is to manipulate the relative permeability of CO2 using technologies developed by the CO2-EOR industry such as creating "gel plugs" (by injecting two separate reactants in sequence with an intermediate water slugs), and increasing the viscosity of CO2 in faults or fracture zones by injecting thickening agents.

A key question is what circumstances should trigger preventive action? It has been suggested that mitigation should be employed in the event of "unanticipated leakage at unacceptable rates". The size of an "unacceptable rate" has not been defined. Going from detecting leakage to quantification of leakage rate presents a technical challenge and will require multi-phase flow modeling. Preventive action may be mandatory if there is substantial evidence that the leak will inevitably result in the contamination of USDW. Kuuskraa has recently suggested the importance of establishing a "Ready-to-Use" contingency plan for corrective action, a suggestion with considerable merit.

The legitimate safety and environmental concerns of local communities near potential sequestration sites are not being adequately addressed by many of the published papers on risk. Unfortunately some authors have been intemperate in their use of language. One widely referenced paper in 2004 suggested that the "acute hazards" related to geologic CO2 sequestration are "wellhead failure [blowouts], seismic hazard during injection, accumulation and explosion in lakes, and massive efflux in soils". Another paper in 2003 suggested that the "most obvious local [associated with the surface release of CO2] risk" is related to "catastrophic leaks such as well blowouts or pipeline ruptures". Similarly a 2005 paper suggests that "the most frightening scenario [related to risks associated with geologic CO2 sequestration] would be a large, sudden, catastrophic leak. This kind of leak could be caused by a well blowout or pipeline rupture". Both these papers apparently ignored (or were unaware of) the excellent safety record off the CO2-EOR industry in transporting and injecting CO2. A 2005 paper asserts that of 20 seismic events attributed to injection of fluids, 13 were "caused by the injection of CO2 for the enhancement of oil recovery". Although these events may be spatially and temporarily related to water flooding operations at oil fields it has not been established that these earthquakes were triggered by the injection operations and they do not appear to be associated with CO2 injection. In fact an earlier published study noted that thousands of injection sites within Texas were aseismic even though the injection pressures were in theory sufficiently high to induce an earthquake.

Risk assessments and analysis will likely play an increasing role in the design, permitting, and monitoring of CO2 sequestration projects. Case studies of the proposed injections sites for the Texas FutureGen will demonstrate the application of the proposed framework and outline potential applications to monitoring.