Risks Associated with CO2 Sequestration in Deep Brine Reservoirs: Potential advantages of Hybrid Bayesian/Fuzzy Risk Analysis

Ian J. Duncan, Jean-Philippe Nicot, Svetlana Ikonnikova, and Jong-Won Choi

Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX

When the risks associated with a geologic CO2 sequestration project are being evaluated 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 step in gaining public acceptance. Risk assessments of geologic sequestration projects should facilitate more robust, and transparent decisions. All large industrial projects carry risks. These risks for CCS projects include: (1) operational 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) the risk 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.

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. Unfortunately, very few risk studies may made quantitative estimates of the dollar value of potential consequences.

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 CO2-EOR. Apart from possible ruptures of CO2 pipelines the next most plausible risk to public safety comes from the "blow out" or loss of control of a CO2 injection well. Blowouts do occur rarely in association with CO2-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 CO2 sequestration. There are currently 4,700 injector wells operating in the Permian Basin amounting to 40% of the CO2 EOR wells currently operating, the other 60% of wells being production wells. The total CO2 injected into the Permian Basin amounts to approximately 1,200 million tons of CO2. Almost certainly the number of injection wells that will be used for CO2 sequestration in brine reservoirs to inject an equivalent amount of CO2 will be far fewer. We are examining the record of blowouts associated with the CO2 EOR industry. This study is in its initial phases. So far four blowouts associated with CO2 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 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 contamination 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. The next most likely risk associated with CO2 sequestration is probably related to leakage of CO2 (or more likely brine/brackish water driven by CO2 injection) into groundwater (USDW) from well bore failures (corrosion, cracked casing etc). Some researchers have suggested that future leakage rates from well bore failure for CO2 sequestration sites can be inferred from data from natural gas storage sites, however this approach is fraught with problems.

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. 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 can 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.

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 CO_2 before it leads to adverse consequences or to neutralize the effects. Although many researchers in CO_2 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 CO_2 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 high? pressure. Another possibility is to manipulate the relative permeability of CO_2 using technologies developed by the CO_2-EOR industry such as creating "gel plugs" (by injecting two separate reactants in sequence with an intermediate water slugs), and increasing the viscosity of CO_2 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 flow modeling. Preventive action may be mandatory if there is substantial evidence that the leak will inevitably result in the contamination of USDW.

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 CO_2 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 CO_2] 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 CO_2 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 CO_2 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 CO_2 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.

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 CO_2 sequestration projects is arguably relatively well understood can be adequately addressed through and existing financial risk management frameworks or straight forward modifications thereof. Risk assessments and analysis will likely play an increasing role in the design, permitting, and monitoring of CO_2 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.