

Lawrence Berkeley National Laboratory

Lawrence Berkeley National Laboratory

Title

The consequences of failure should be considered in siting geologic carbon sequestration projects

Permalink

<https://escholarship.org/uc/item/79w744kj>

Author

Price, P.N.

Publication Date

2009-08-19

**The Consequences of Failure Should be Considered in
Siting Geologic Carbon Sequestration Projects**

Phillip N. Price¹ and Curtis M. Oldenburg²

¹Environmental Energy Technologies Division

²Earth Sciences Division

Lawrence Berkeley National Laboratory

Berkeley CA 94720

USA

February 23, 2009

Keywords: geologic carbon sequestration, site selection, risk assessment, regulation

Abstract

Geologic carbon sequestration is the injection of anthropogenic CO₂ into deep geologic formations where the CO₂ is intended to remain indefinitely. If successfully implemented, geologic carbon sequestration will have little or no impact on terrestrial ecosystems aside from the mitigation of climate change. However, failure of a geologic carbon sequestration site, such as large-scale leakage of CO₂ into a potable groundwater aquifer, could cause impacts that would require costly remediation measures. Governments are attempting to develop regulations for permitting geologic carbon sequestration sites to ensure their safety and effectiveness. At present, these regulations focus largely on decreasing the probability of failure. In this paper we propose that regulations for the siting of early geologic carbon sequestration projects should emphasize limiting the consequences of failure because consequences are easier to quantify than failure probability.

Introduction

The goal of geologic carbon sequestration (GCS) is to prevent CO₂ injected deep underground from entering the terrestrial ecosphere for centuries or millenia. Theoretical (Gunter et al., 2004; Hepple and Benson, 2005) and observational evidence (Zweigel et al., 2004; Hovorka et al., 2006; Chadwick et al., 2006) suggest that GCS, if competently performed at a well-selected site, is likely to retain the CO₂ as intended. A special report by the International Panel on Climate Change (IPCC)

says that “it is considered likely that 99% or more of the injected CO₂ will be retained for 1000 years” (IPPC, 2005). However, it is hard to assess the accuracy of this prediction: real-world experience with GCS is limited to a handful of full-scale sites, a few pilot GCS projects, and a large number of locations where CO₂ has been injected for enhanced oil recovery. The worldwide total injected mass of CO₂ and the number of injection sites are both very small relative to that needed for full-scale implementation of GCS. Experience with underground liquid waste disposal, although analogous to GCS, differs substantially because CO₂ is buoyant relative to native brines whereas most commonly injected liquid wastes are not.

Site-specific predictions are uncertain because detailed characterization of the subsurface is difficult. It is also difficult to demonstrate that all boreholes that could allow CO₂ leakage are adequately plugged and will remain so for hundreds or thousands of years (e.g., Tsang et al., 2008). One of the issues facing federal and state regulatory agencies is how to regulate GCS to ensure that selected GCS sites are safe. The choice of sites for early implementations is particularly critical as industry and government gain experience with the technology.

Failure of a GCS site to perform as expected could have serious consequences, such as:

1. Carbon dioxide could leak into an aquifer and acidify the water (by creating carbonic acid); the acidified water can dissolve minerals thereby releasing

naturally occurring elements such as arsenic, lead, or other heavy metals that can contaminate the water.

2. A fossil-fuel reservoir (such as natural gas or coal) could be contaminated by CO₂, decreasing the energy content of the fuel and thus reducing its value.
3. Leakage to the surface or the near sub-surface could harm plants, wildlife, or even people.

It is expected that every proposed GCS site will be carefully investigated, and CO₂ injection will be allowed only if there is strong evidence that there will not be substantial leakage of CO₂. However, even extremely careful site assessment cannot guarantee with 100% certainty that leakage will not occur. In fact, currently it is not possible to make an *accurate, quantitative assessment* of the probability of failure of a GCS site, either overall or in one of the specific modes enumerated above. Not until many GCS projects have been operating with careful monitoring for many years will the experience with performance be sufficient to reduce uncertainties associated with estimating failure likelihood.

The inability to make accurate quantitative predictions of failure mode probabilities may lead to two contrasting problems. Overestimating the likelihood of failure, or the consequences of failure, may lead to resistance, for example, from the public, from regulatory agencies, or from politicians, and thus might disallow sequestration even at sites that would in fact be excellent for GCS. Overestimating the failure

probability might also lead to resistance from companies that would otherwise wish to perform sequestration but are worried about public relations problems or legal entanglements. On the other hand, underestimating the likelihood of failure, or its consequences, may lead to imprudent site selection or operation that could lead to substantial damage to resources or the environment. Underestimating (and thus understating) the likelihood of failure might also lead to a loss of confidence if failure does occur, potentially leading to public or political backlash against GCS in general.

Many failure modes do not result in disastrous failure but rather affect only GCS effectiveness. For example, slow and diffuse CO₂ leaks from several abandoned wells at a GCS site may not cause any measurable damage to the environment, but they could result in an unacceptable leakage rate from the site from a climate-change mitigation perspective. These kinds of leakage risks, while tolerable from a health, safety, and environment perspective, should of course be analyzed. But our focus in this paper is on severe adverse consequences that go far beyond a GCS site merely being less effective at climate change mitigation than was planned.

In the present paper, we argue that there are at least two common-sense approaches to regulating the first generation of large-scale GCS sites that should be adopted in light of the fact that failure modes and probabilities cannot be precisely estimated. First, carry out GCS only at sites where it is most certain to be successful; and second, initially allow GCS to be sited only where the consequences of failure are

very low. These constraints may imply that initially there are only hundreds rather than thousands of acceptable GCS sites in the United States. As sites are monitored over a period of years or decades, it will become possible to more accurately predict the performance of GCS sites, and assess the limitations of these predictions. Once decision-makers become confident in the ability of geoscientists and engineers to predict failure probabilities and to identify sites that are very unlikely to fail, site restrictions based on failure consequences can be relaxed.

Current Regulations Focus on Limiting the Probability of Failure

Governments should consider the societal costs and benefits of policies. The comparison of possible regulatory policies is done by comparing each policy's benefits (such as the reduced economic and environmental consequences that are attributable to the regulations) to the policy's negatives (such the increased capital and operating expenses incurred in conforming to the policy). These negatives are collectively called "costs," even though they may include non-monetary damage. A policy whose benefits outweigh the costs is worthwhile, and regulators would prefer to develop policies that yield the greatest net benefit.

In principle, environmental regulations could be designed to allow project-specific variation in GCS project outcomes such as CO₂ leakage rates. For example, a GCS project in a highly populated area could be approved only if it meets a very strict limit on leakage to the air or to an aquifer, whereas a project in a less populated area

could face a less stringent limit. In practice, though, most environmental regulations are not set in this way. Instead, a standard is usually determined that is intended to be “safe,” for example, for ozone concentrations or automobile emissions, and regulations are promulgated that are explicitly intended (although often not demonstrated) to achieve safe conditions everywhere. As we will discuss below, this mindset causes difficulties for regulation of the nascent GCS industry, because (in contrast to, say, emissions from a car, fleet of cars, or an industrial facility) the leakage from a GCS site cannot currently be predicted precisely in advance.

In setting regulatory policy, decision-makers are generally interested in weighing the costs of a *policy* against its benefits. This is not the same as weighing costs against benefits for individual projects. Typically, once an overarching policy is set, whether informed by risk-benefit analysis or not, the policy usually leads to regulations that are uniformly applied to all projects. Of particular relevance to GCS regulation, the U.S. Environmental Protection Agency (USEPA) is charged with enforcing the Federal Safe Drinking Water Act by preventing contamination of all sources of non-saline water, including water in aquifers regardless of depth. The statutory requirement that water cannot be polluted if it could potentially be used for drinking or irrigation is independent of any cost-benefit justification. With few exceptions, a project cannot be justified on the grounds that its benefits outweigh the negative consequences of contaminating an aquifer, no matter where the aquifer is located or what its societal or environmental importance is. In other words, there is little

official difference in safety standards or characterization requirements between a project proposed for a sparsely populated region and one for a densely populated city. As a practical matter, proposals for industrial projects generate much more public comment and more careful scrutiny if they are near large population centers or important water resources, so a project in a large city might in fact face difficulties getting approved, but this is an issue of political reality rather than regulatory requirements. The same rules and regulations (on the design and construction of casings in a waste-injection well, for example) would apply in either case. Although this site-independence is true of many types of regulations, it is not universal. For example, siting of nuclear reactors has been based in part on assessments of the consequences of accidents (U.S. Nuclear Regulatory Commission, 1975).

Although policymakers are usually focused on the costs and benefits of policies rather than individual projects, policies are effective insofar as they influence each project. As Chilton and Penoyer (1981) point out, "... the efficiency of [a] policy cannot be judged without examining the individual costs and benefits of constituent elements of that policy."

Example of the Consequences of Failure

Geologic carbon sequestration is not expected to cause CO₂ to enter aquifers that might be used as groundwater resources. However, even careful application of site

characterization and underground injection methods does not guarantee success. For example, legally permitted wastewater injections in South Florida have failed in some cases, due to geologic factors that were not fully understood when the wells were permitted, and these failures have led to contamination of groundwater resources (Paula et al., 1997). The failure probability turned out to be much higher than was initially estimated for these sites. Although the reasons for these particular failures are now understood, it is clear that unexpected negative consequences can occur when injecting fluids underground.

Potential leakage of CO₂ into groundwater is one of the most worrisome consequences of the failure of a GCS site. The problem is not with the CO₂ itself, which can be removed from drinking water simply by allowing the water to sit in a reservoir for a time. Rather, the problem is the potential contamination of an aquifer with material leached from the aquifer rock due to groundwater acidification from CO₂. Wilson et al. (2007) note that “Potential risks to groundwater quality arise from CO₂’s buoyancy, its potential to mobilize organic or inorganic compounds in aquifers, and its potential to displace subsurface fluids on a regional scale.”

Contamination of groundwater by toxic compounds mobilized by aquifer acidification could be costly if the water constitutes all or part of the water supply of a city. For example, consider a large coastal metropolitan area, hereafter referred to as “City A,” whose water supply characteristics, but not geologic characteristics, are based on a specific real city in the United States. Groundwater in the city supplies

about 40% of its municipal water supply. If City A's groundwater were to become contaminated (with arsenic, for example) to the extent that it fails to meet drinking water standards by a modest margin, this will not necessarily be very costly because the water district can mix the contaminated groundwater with uncontaminated water from other sources, so that the municipal water supply will remain acceptable. But groundwater contamination that greatly exceeds the drinking water standard, to the extent that dilution with other existing water supplies will not yield an acceptably low contaminant concentration, will require much more expensive measures such as special filtration, or replacing some of the groundwater with water from other sources.

City A has a fixed supply of surface water and relies on groundwater at $d_g = \$0.0008$ per gallon for 10^{10} gallons per year, at a total groundwater cost of \$8 million annually. Suppose City A's aquifer is potentially at risk from leakage of CO_2 because the aquifer contains arsenic-bearing minerals that will dissolve if the water acidifies. Because City A has no other available drinking water sources, contamination of the aquifer would lead to additional water costs of \$5 million to \$15 million per year for filtration or for diluting contaminated groundwater with water from a new seawater desalinization plant. At a 5% discount rate, this would correspond to a Net Present Value of \$100 million to \$300 million in damage.

In contrast, consider a hypothetical GCS site in the vicinity of groundwater that is used to supply a small town. The qualitative issue may be the same as it is for City

A: operation of the site carries a small risk of contamination of the water supply. But quantitatively, the cost of failure for the small-town site is much lower because even if the groundwater becomes contaminated, replacement water (or filtration) for a small town can presumably be supplied for far less than the \$5 million to \$15 million per year that would be needed for the city.

Note that the argument discussed above does not assume that contamination is more “acceptable” in the case of a small town than in a large city: we assume the federal drinking water standards apply in both cases. It is the cost of mitigation, not the acceptable level of contamination, that differs between the hypothetical city and the small town.

Risk reduction through site selection

A standard quantitative definition of “risk” is:

$$R = \sum_i P_i C_i \quad (1)$$

where R is the risk, i indexes over the possible types of failures or accidents, P_i is the probability that failure i will occur, and C_i is the consequence or cost of failure i if it occurs.

Risk assessment and risk management experts often take it for granted that “risk,” as defined by Equation 1, is an important quantity. For instance, they may assume that the goal of a policy or regulation is to reduce or minimize risk subject to some constraints, or to ensure that the risk posed by a project is below a specified threshold, or to maximize the net societal value of the projects developed under the policy (which they may define as benefits minus known costs minus risk).

There is a connection between the cost-benefit-risk way of thinking about regulations, and the cost-independent approach of defining rules that are intended to lead to a “safe” project, no matter where the project is located or how many people it could affect. Expressed in terms of risk, the latter approach can be thought of as a way of trying to limit the probability of failure (the P values in Equation 1) to such a low level that the overall risk R is guaranteed to be low, even if the consequences C_i are very large. It is true that regulators usually do not think of the goal in this way—instead, they are usually trying to carry out a mandate such as “ensure water sources do not become contaminated”—but the effect of the regulations is to attempt to reduce the failure probabilities to very low values.

The approach of limiting risk by limiting or reducing failure probabilities P_i is appealing for many reasons: (1) it avoids many unpleasant ethical issues (such as accepting higher risk per person for rural than for urban inhabitants on the grounds that a disaster that harms thousands of people would be worse than one that harms dozens); (2) it encourages a mindset that no failure is acceptable, thereby

encouraging everyone involved in a project to strive as hard as possible to prevent failures; and (3) it eliminates the need to examine the “cost” or “consequences” terms of Equation 1, thus avoiding the often contentious problem of putting different types of losses (lives, dollars, etc.) on a common scale. But the difficulty in estimating the failure probability of GCS sites suggests that a different approach is needed for project regulation and siting, especially for the early projects in the nascent industry of GCS.

Only a few options exist to reduce the risks of a GCS project. If impacts associated with sequestration activities are unacceptable, those activities can be stopped, or injection rates can be decreased, or CO₂ or water can be produced from the formations to reduce pressure. Or a hydraulic barrier could be created by injecting fluids into or above the leakage pathway. If risks are associated with inadequately sealed boreholes, those boreholes can be re-sealed. Ventilation of structures or soils can be increased in the near-surface environment impacted by leakage. Perhaps other methods can be developed. But although control methods may work in individual instances, there is no certainty of attaining adequate control over the propagation of a CO₂ plume that is not behaving as desired. (For discussion of this issue, see California Energy Commission, 2007, Chapter 8; or IPCC 2005, Chapter 5). This situation is in contrast to other industrial projects. If a nuclear power plant is determined to be at risk of a particular type of failure, even after it is operating it can

be modified to reduce the risk by addition of redundant pumps, replacement of pipes, and so on. No analogous simple modifications are possible for a GCS site.

Because geologic characteristics of a given site cannot be modified, the most important factor determining the success of a GCS project is its initial siting. As stated in California Energy Commission (2007), “Site characterization and proper site selection and certification are paramount to the success of GCS projects, both for assuring sequestration goals and for environmental and human health and safety.”

The report (Chapter 4) recommends criteria for site selection, highlighting “injectivity” (the rate at which fluids can be injected into the geologic formation without causing fractures), “capacity” (the total amount of fluid that can be trapped by the geologic feature), and “effectiveness” (the ability of the formation to store the injected CO₂ for an adequate length of time). If a site is effective at trapping CO₂ it will not endanger people (or their drinking water); this is what is meant by the earlier statement that site selection is paramount for “environmental and human health and safety.” This attitude, which we agree with, supports the standard regulatory approach of focusing on the probability of failure, and on the steps that can be taken to reduce that probability. However, there is an important feature that is missing from this view, and that is the consequences of failure in the unlikely event that things go wrong. In this regard, too, site selection is of paramount importance.

We suggest that rather than focusing on the probability of failure, the consequences of failure should be given at least equal importance and perhaps even emphasized,

especially in early GCS projects. (These are the C_i values in Equation 1.)

Specifically, just as a site would be rejected if the failure *probability* is unacceptably high, we suggest that a site should be rejected if the failure *consequence* is unacceptably serious.

Figure 1 shows a highly idealized graphical view of the decision-making process.

The top left panel (Figure 1a) illustrates the ideal (unattainable) case in which there is only a single failure mode, for which the cost of failure and the probability of failure can be estimated very precisely, as represented by the dot on the figure. A line of acceptable risk (i.e., a constant value of probability times failure cost), determined by lawmakers or other decision-makers, is shown on the plot. If the project's risk is lower than the acceptable risk, as in this figure, the project should be approved.

The top right panel (Figure 1b) illustrates the current default approach to regulation. Although the probability of failure is very uncertain, required site selection and design techniques will be implemented in an effort to ensure that it is low. The gray area shows the resulting region in the space of probabilities and costs. The failure probability lies somewhere in the gray area, but much of this area lies above the line of acceptable risk; without analysis of the cost of failure there is no way to put an upper limit on the cost (or the risk).

The bottom left panel (Figure 1c) illustrates our recommendation. The failure probability is as uncertain as in Figure 1b. Now the cost of failure for the project and its uncertainty is also estimated, and this estimate is shown as a horizontal gray area. The cost of failure is easier to estimate than the probability of failure. In this simplified example, the estimated failure probability and failure cost combine to define a rectangular region of parameter space. Dashed lines in Figure 1 indicate the high end of the estimated ranges of failure probability and failure cost. In the example shown, even if the probability and cost are at the high end of their ranges, the risk barely exceeds the curve of acceptable risk. We would recommend accepting the project illustrated here.

The bottom right panel (Figure 1d) shows another project with exactly the same range of failure probability, but with a cost of failure several times higher than the one in Figure 1c. This cost profile might be applicable to a city whereas the one in Figure 1c would be for a sparsely populated area. The project's risk exceeds the curve of acceptable risk even if the failure risk is in the middle of its estimated range, or near the bottom. We would recommend rejecting this project even though the failure probability is the same as for the one in Figure 1c.

In practice, projects will likely not have just a single failure mode, nor will they have a universally accepted probability of failure (and even the range in which the probability lies) or a single curve of "acceptable risk." However, even if it is not possible to make idealized graphs like those in Figure 1, it will be possible to

determine the cost of a major failure -- a quantity that, though still uncertain, can be estimated with far more precision than can the failure probability. Limiting this cost will help ensure that, even if the failure probability is higher than expected, the project's risk is at least not far above the acceptable level.

Over time, experience with GCS will allow geoscientists and engineers to become better at evaluating sites and predicting failure probabilities. At present, with limited experience in large-scale GCS site performance, consideration of the consequences of failure should be a primary criterion for site selection and permitting. This contrasts with the current situation as we perceive it, in which the consequence of failure plays only an indirect role in site selection.

Legal and Regulatory Issues

It may seem obvious that the consequences of failure of a GCS project should be considered in the siting of GCS projects, at least until the failure probability can be demonstrated to be extremely low. However, the current legal and regulatory framework for underground waste disposal focuses almost entirely on limiting the probability of failure rather than the consequences.

To implement our suggestion that failure consequences should be taken into account, it will be necessary to determine what failure modes to consider when evaluating consequences. Critics of a proposed project may insist on evaluating the worst conceivable consequence of failure, even if the consequence could not in fact occur.

Conversely, proponents may insist that a given consequence is literally impossible, when in fact it is simply thought to be extremely unlikely. We think this is an area in which regulators of the first large-scale GCS projects should utilize the best available technical information and then err on the side of caution to ensure the success of early GCS projects..

Another significant issue is that the estimated potential consequence of failure will often be found to be lower for GCS projects in sparsely populated areas than for otherwise similar projects in densely populated areas. As an anonymous reviewer of this paper pointed out, “it is easy to imagine ... challenges on the grounds of equity, and other moral challenges.” These moral and social equity issues are tied to others, such as the amount of compensation to affected people in the event of failure, and who would provide the compensation.

Discussion

As we have discussed above, many current regulatory approaches to limiting environmental and health risks focus on reducing the probability of failure (the P_i terms in Equation 1). While certain aspects of failure probability such as the likelihood of abandoned wells or faults being encountered by the CO₂ plume can be estimated from geostatistics and modeling of the injection plume, the overall probability of leakage through these features is much harder to estimate because transport properties (e.g., permeability) of abandoned wells and faults are

notoriously difficult to assess. In the case of GCS, limiting the failure probability largely means selecting a site that is very unlikely to fail (e.g., has few abandoned wells), although there are other engineering requirements as well (e.g., limiting the injection rate, and ensuring that abandoned wells in the area are adequately sealed).

While the present paper was being prepared, the USEPA released draft rules for regulating GCS. The only siting requirements mentioned in the USEPA draft rules (EPA 2008) are aimed at reducing the failure probability by ensuring “the presence and adequacy of the various geologic features necessary to receive and confine large volumes of injected CO₂.” The implications of siting on the consequences of failure are not mentioned.

As we have illustrated with the example of drinking water in a large city, potential consequences of failure are likely to be quantifiable with much greater certainty than the failure probabilities are, so consequence-based criteria should be *relatively* straightforward to apply. We say “relatively” straightforward because there will still be substantial complications, such as (1) defining the worst plausible consequence that should be considered, and (2) assigning a cost to a major failure that might occur in the very distant future, when (for example) a city’s population might have changed substantially.

We think that carefully implemented GCS is a safe, effective way to reduce CO₂ emissions. One thing that would stop GCS from being implemented on a large scale

is the failure of an early sequestration project, especially if the public and elected officials have been assured that sequestration is “safe.” The experience of the U.S. nuclear industry, whose growth was effectively stopped by Three Mile Island, provides an important cautionary lesson: As Wood (1983) points out, “An accident causing the damages of Three Mile Island would have been predicted [before the accident] to occur once in 33,000 reactor-years, but actually occurred after 500 reactor-years.” People were already wary of nuclear power, and once they lost confidence in the assurances that it was safe, support for the technology fell away. Geologic carbon sequestration proponents point out, correctly, that the potential consequences in the event of failure of a GCS site is far smaller than from failure of a nuclear power plant, but we fear GCS, too, could suffer a loss of public support if the public is assured that it is safe and then finds that an especially damaging failure has occurred in an early project.

Acknowledgments

This work was supported by Lawrence Berkeley National Laboratory under Department of Energy Contract No. DE-AC02-05CH11231. We thank Chin-Fu Tsang (LBNL) for constructive review comments, and Daniel S. Hawkes (LBNL) for help with the presentation.

References

- [1] Benson, S.M., Hepple, R., Apps, J., Tsang, C.F., and Lippmann, M., 2002. Lessons Learned from Natural and Industrial Analogues for Storage of Carbon Dioxide in Deep Geologic Formations. Lawrence Berkeley National Laboratory Report LBNL-51170.
- [2] California Energy Commission, 2007. Geologic Carbon Sequestration Strategies for California: The Assembly Bill 1925 report to the California Legislature. Report number CEC-500-2007-100-SD.
- [3] Chadwick, A., Arts, R., Eiken, O., Williamson, P., and Williams, G., 2006. "Geophysical monitoring of the CO₂ plume at Sleipner, North Sea." *Advances in the Geological Storage of Carbon Dioxide*, in: Lombardi S., Altunina, L.K., and Beaubien, S.E. (Eds.), NATO Science Series: Springer, Netherlands.
- [4] Environmental Protection Agency, 2008. Federal Requirements Under the Underground Injection Control Program for Carbon Dioxide Geologic Sequestration Wells. EPA-HQ-OW-2008-0390.
- [5] Gunter, W.D., Bachu, S., and Benson, S., 2004. The role of hydrogeological and geochemical trapping in sedimentary basins for secure geological storage of carbon dioxide, *Geological Society, London, Special Publications* 233:129–145.
- [6] Hepple, R.P., and Benson, S.M., 2004. Geologic storage of carbon dioxide as a climate change mitigation strategy: performance requirements and the implications of surface seepage. *Env. Geol.* 47:576-585.
- [7] Hovorka, S.D., Benson, S.M., Doughty, D., Freifeld, B.M., Sakurai, S., Daley, T.M., Kharaka, Y.K., Holtz, M.H., Trautz, R.C., Nance, S.H., Myer, L.R., and Knauss, K.G., 2006. Measuring permanence of CO₂ storage in saline formations; the Frio experiment, *Environmental Geosciences* 13(2):105-121.
- [8] IPCC (2005) Intergovernmental Program on Climate Change (IPCC) Special Report on Carbon Dioxide Capture and Storage, Metz, B., Davidson, O., de Connick, H., Loos, M., and Meyer, L., eds., Cambridge University Press, New York.
- [9] Lewicki, J.L., Birkholzer, J.T., and Tsang, C.-F. 2007. Natural and industrial analogs for leakage of CO₂ from storage reservoirs: identification of features, events, and processes and lessons learned, *Env. Geol.* 52(3) 457-467.

- [10] Maliva, R.G., Weixing, G., and Missimer, T., 2007. Vertical migration of municipal wastewater in deep injection well systems, South Florida, USA. *Hydrogeology Journal* 15:1387–1396.
- [11] Paula, J.H., Rose, J.B., Jianga, S.C., Zhoua, X., Cochran, P., Kellog, C., Kang, J.B., Griffin, D., Farrah, S., Lukasik, J., 1997. Evidence for groundwater and surface marine water contamination by waste disposal wells in the Florida keys. *Water Research* 31:1448– 1454.
- [12] Tsang, C.-F., Birkholzer, J.T., and Rutqvist, J., 2008. A comparative review of hydrologic issues involved in geologic storage of CO₂ and injection disposal of liquid waste, *Env. Geol.* 54(8):1723-1737.
- [13] U.S. Nuclear Regulatory Commission, 1982. Technical Guidance for Siting Criteria Development. Prepared by Sandia National Laboratories. NUREG/CR-2239, Washington, DC.
- [14] Wilson, E.J., Friedmann, S.J., and Pollak, M.F., 2007. Research for deployment: incorporating risk, regulation, and liability for carbon capture and sequestration. *Environmental Science and Technology* 41:5945–5952.
- [15] Wood, W., 1983. Nuclear Safety Risks and Regulation. American Enterprise Institute for Public Policy Research, Washington, DC.
- [16] Zweigel, P., Arts, R., Lothe, A.E., and Lindeberg, E., 2004. Reservoir geology of the Utsira Formation at the first industrial-scale underground CO₂ storage site (Sleipner area, North Sea). *Geological Society of London, Special Publications.* 233:165– 180.

Figure Caption

Figure 1. (a) Top left: Curve of constant acceptable risk (failure probability times failure cost denominated in dollars), with a hypothetical project's failure probability and failure cost identified with a dot. Projects that fall above the line should not be permitted. (b) Top right: An idealized representation of a decision rule based on failure probability only. The failure probability (represented by the gray region) of a hypothetical project is highly uncertain. (c) Bottom left: An idealized representation of the decision rule recommended in the present paper. The failure probability remains highly uncertain (vertical gray bar); the cost of failure is also uncertain (horizontal gray region). In this example, the worst case (most costly) failure is indicated by the horizontal dashed line, and the most pessimistic estimate of the failure probability is indicated by the vertical dashed line. The resulting rectangular region lies almost entirely below the curve of acceptable risk; this hypothetical project should be approved. (d) Bottom right: Failure probability and cost estimates for a hypothetical project. The failure probability range is the same as in Figure 1c, but the cost of a major failure is higher. The region of overlap of failure cost and failure probability lies largely above the acceptable risk curve. This project should be rejected.

