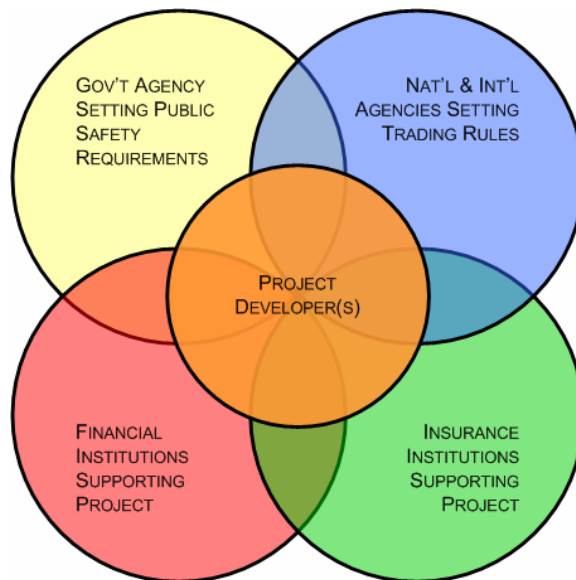


Regulatory and Policy Needs for Geological Sequestration of Carbon Dioxide

Edward S. Rubin,¹ M. Granger Morgan, Sean T. McCoy and Jay Apt
Carnegie Mellon University
Department of Engineering and Public Policy
Pittsburgh, Pennsylvania 15213 USA

Framing the Problem

What does it take to establish geological sequestration (GS) of captured CO₂ as an acceptable method of greenhouse gas emissions reduction? We frame the issue in terms of the overlapping concerns, responsibilities and authority of four key actors who currently define terms and conditions for a project developer, as illustrated in Figure 1. Although our analysis is motivated largely in the context of GS projects in the United States, the framework outlined here is intended to apply in other countries as well.



**Figure 1. Key actors participating in geological sequestration projects.
(All of these actors, especially government, also receive input from the public)**

The first actor is the national and/or local governmental institution with regulatory authority over the underground injection of fluids. In the United States this is the U.S. Environmental Protection Agency (USEPA). Today, the primary concern of this regulator is public health and safety. In particular, current U.S. restrictions on underground injection are aimed at preventing the contamination of drinking water supplies. In the context of a GS project, prevention of harm or injury to human health from seepage of injected CO₂ to

¹ Corresponding author: rubin@cmu.edu, Tel: +1 412 268 5897.

the surface, in addition to contamination of drinking water supplies, would be the primary concern of this agency.

The second actor is the national or international body that establishes rules and regulations regarding the accounting and trading of CO₂ allowances for purposes of greenhouse gas (GHG) emission reductions. The primary concern of this agency is establishing a fair and reliable system for ensuring that GHG emission reduction measures indeed avoid CO₂ emissions to the atmosphere. Issues related to GHG accounting, ownership of emission allowances, liabilities for sellers and buyers (related to the permanence of storage), and other related issues would thus be the concern of this agency. In practice, multiple agencies, both national and international, are likely to be involved in this activity. For example, the IPCC currently establishes GHG accounting guidelines under the Kyoto Protocol, but responsibility for such accounting lies with each national government. In the U.S., both the USEPA and USDOE have activities related to GHG emission inventories, although no regulatory program for GHG emission reductions exists at the present time. Under a future regime of required emission reductions in the U.S. it is likely that the USEPA would be the agency responsible for rules related to emissions accounting and trading of allowances.

The next two actors are private institutions who are critical to the viability of large-scale private-sector GS projects. These are the financial institutions that are typically involved in any large, capital-intensive project, and the insurance industry, involved in issues related to project liabilities. As a practical matter, the developer of a GS project will require the support and participation of both institutions. Financial organizations typically raise or provide a large share of the capital requirements for a project. Thus, they are primarily concerned with the economic viability of a project and the future solvency of its developer. Insurance companies share many of the same concerns, but their primary focus is on project risks and potential liabilities. In the context of a GS project, this would involve risks associated both with local health-related impacts of CO₂ seepage or migration, as well as with longer-term impacts related to CO₂ seepage into the atmosphere.

Given the overlapping nature of concerns and responsibilities of each of these players, what are the key issues that still need to be addressed? What are some possible approaches, and what is the best way forward? In the following sections, we briefly discuss the various needs of each of these parties and review where things currently stand. Then we outline a proposed structure for a regulatory framework to meet the basic needs of all parties.

Local and National Regulators' Needs

The most basic requirement of any regulatory system for geological sequestration is the protection of human health and the environment. This requires knowledge of the events through which GS can impact human health and the environment, the magnitude of these events and the likelihood of their occurrence—all of which are (to different extents) uncertain at this point in the field of GS. Moreover, this uncertainty is compounded by site-to-site variability; that is, the likelihood of occurrence of different events varies from site-to-site depending on the specific geological setting of the project. Nonetheless, the risks

resulting from GS can broadly be categorized as local or global. Local risks pose a direct and immediate risk to human health and the environment. Such risks generally result from CO₂ seepage to the surface or shallow subsurface; from effects of CO₂ on groundwater chemistry; and from displacement of fluids by CO₂ [1, 2].

Globally, the main risk resulting from CO₂ seepage to the atmosphere is that it will reduce the effectiveness of any national or international system of emissions reductions. Thus, at the national level, any regulatory system for GS must effectively account for the amount of CO₂ stored in the subsurface (i.e., the amount injected minus the amount of seepage). Knowledge of the amounts of CO₂ stored can also enable more effective protection of human health and the environment.

A regulatory system for GS also should seek to minimize the cost of protecting the public and the environment and the cost of compliance with the regulation for private actors. The costs associated with the regulatory system should be minimized because, as part of a solution to the larger problem of climate change, GS will ultimately reduce the cost of meeting any future emissions targets. Thus a regulatory framework should not unduly increase the cost of developing a GS project for both the developer and the public.

Similarly, a regulatory system for GS should share the long term-risk of GS projects between the public and private sectors, as both stand to benefit. If all risks are to be borne by the private actors, it is unlikely that GS will come to play a major role in mitigating climate change. Conversely, if the public sector assumed all risks, private operators would have little incentive to take appropriate precautions to ensure long-term containment of injected CO₂. A balanced approach to risk-sharing is therefore needed.

In summary, the four needs to create an effective system of regulation for GS from the standpoint of a local or national regulator are: protection of human health and the environment at a local level; accounting of the amount of CO₂ stored; minimization of the cost of regulation to both the public and private actors; and, sharing of the long-term risks of GS between the public and private actors.

Emissions Accounting and Trading Organization Needs

One objective of international agencies that allocate emissions allowances, certify emissions reductions, and facilitate trading of allowances is to ensure that the value of emissions allowances issued to nations under a trading scheme is not eroded by seepage of CO₂ to the atmosphere. For example, under the European Union Emissions Trading System (ETS), each country is allotted emissions allowances—each equal to 1 metric ton of CO₂ equivalent—based on its national allocation plan. These allowances can be traded within other ETS countries. However, the value of the emissions reductions resulting from a leaky GS project should be less than the value a project with zero seepage. Thus, there is a need for a more flexible trading system that can accommodate the potential for seepage from a GS facility.

To address this need, an international agency dealing with accounting and trading could certify that sequestration operations meet specified international standards and could certify emissions reductions resulting from GS projects in proportion to the time the CO₂ is withheld from the atmosphere (e.g., ton-year accounting, discussed in [3]). Alternatively, trading rules could assume any reductions are permanent and require parties responsible for GS facilities to purchase allowances to cover any CO₂ seepage [4].

In either case, the international trading and accounting organization, or the party responsible for the GS facility, must know with some certainty both the amount of CO₂ stored at a given time, as well as the rate at which stored CO₂ may be escaping to the atmosphere. This implies that any regulatory system should require that the owner or operator be able to certify the amount of CO₂ stored at any time, $m(t)$, which requires knowledge of the average injection rate of CO₂ over time (m) and the rate at which CO₂ is escaping the storage site (l). This can be expressed in equation form as:

$$m(t) = \int_0^t m dt - \int_0^t l dt \quad (1)$$

Consequently, a regulatory framework should incorporate verification protocols that will assure the CO₂ that is stored is properly accounted for. Details of such protocols remain to be developed.

A second, closely related concern would be to assure that no poorly operated facilities experience major incidents that could cast a shadow over the entire industry. Such an incident could lead to a dramatic loss of public support and confidence—in much the way, for example, that the Chernobyl accident had major negative impacts on nuclear power, even in countries that had outstanding designs and safety records. Thus, there is a likely need for requirements that all nations that engage in sequestration and wish to participate in international CO₂ trading markets, operate their sequestration facilities in accordance with a minimum set of site characterization, monitoring and safety standards.

Financial Underwriting Company Needs

In order to finance investments in GS projects, underwriting companies require a stable and predictable set of attributes. First, the revenue stream to the GS operator must be dependable and exceed the annual obligation of repayment of principal and a return on capital to investors in the GS project. This is likely to require long-term contracts for the life of the plant supplying the CO₂.

Second, the lenders will require assurance that the regulatory environment will remain in place for the life of the financing. To underscore this concern, U.S. lenders cite a 1996 Illinois law which voided the requirements of a 1987 act after three plants had been constructed with financing predicated on the 1987 law (which required local electric utilities to enter into 20-year contracts with waste recovery electricity producers). At least one \$100 million investment was lost as a result [5].

Third, the temporal mismatch between the GS owner's revenues (realized as injection occurs) and maintenance, monitoring, and contingent liabilities (that continue for the life of

the financing and beyond) must be resolved in a way that assures the underwriters that they will be paid. This temporal mismatch also occurs in the case of nuclear power plant decommissioning expenses. In the United States, each nuclear plant operator has the option of choosing one of three types of decommissioning funds approved by the Nuclear Regulatory Commission. These are:

- An external sinking fund to which regular contributions are made over the operating life of the plant; the fund is managed as a trust fund by external trustees.
- A pre-paid account into which funds are deposited prior to the initial operation of the plant, outside the control of the company and not co-mingled with its assets.
- A bond, letter of credit, or insurance policy that pays decommissioning costs if the operator defaults on its obligation to do so [6].

The U.S. mining industry has an analogous program for surface and underground mining reclamation and re-vegetation bonds [7].

Insurance Company Needs

The needs of insurers and re-insurers will depend upon the specific activities they are asked to cover, the period over which coverage extends, and the limits on liability (if any) that are provided under national law. There are three obvious areas in which insurance companies might be asked to play a role:

- Insurance to cover liability and remediation costs that a firm might face during the active period of operating a sequestration site, or the first few years of site closure.
- Insurance for the purchaser of a carbon credit or allowance who wishes to insure that the credit does not lose value over time if the sequestration site leaks, or if at some future time the sequestration facility is decertified for inadequate operations or post-closure stewardship.
- Insurance to cover possible remediation efforts required during the post-closure site stewardship period.

The first of these is probably the least problematic. As a condition of offering coverage an insurer could insist that an injecting firm operate in accordance with verifiable criteria that the insurance company specifies, limit liability to the term of the insurance, and write coverage on a year-to-year basis, or for a few years at a time.

The second option is more problematic. But in as much as the degree of liability will be limited by the price of allowances in international markets, and because policies could be written for fixed terms, the total liability assumed could be made manageable—especially if the insurer pools risks across a large number of sequestration sites, and operational and geological settings.

It is unlikely that most commercial insurance companies would be prepared to write long-term policies under the third category, that is, long-term coverage of possible remediation efforts required during the post-closure site stewardship period. Such coverage would effectively be open-ended. If an insurance company attempted to impose tight liability or

time limits, the coverage would presumably not be viewed as adequate by the party responsible for long-term stewardship.

Given that several regulatory analogs to geological sequestration exist today [8] and are being considered as a basis for future regulation of GS in the United States [9], it is pertinent to ask if current frameworks would meet the needs of a regulatory system for GS. Thus, in the following sections, the current regulatory system for GS in the United States is briefly summarized and its benefits and shortcomings identified in the context of GS.

The Current Regulatory System for Underground Injection in the United States

In the United States, injection of fluids into the subsurface is regulated through the Underground Injection Control (UIC) program with the goal of protecting Underground Sources of Drinking Water (USDWs) from contamination [10]. The UIC program applies to any well that is injecting fluids into the subsurface, but specifically excludes wells outside states territorial waters, small waste disposal systems (i.e., those designed to serve less than 20 persons), and natural gas storage operations. While the overall UIC program is administered by the EPA, individual states may apply for primacy enforcement authority to run their own UIC program.

The UIC program prohibits any injection that results in “the movement of fluid containing any contaminant into USDWs if the presence of that contaminant may cause a violation of any primary drinking water regulation.” Five classes of injection wells have been identified in the UIC regulations, as summarized in Figure 2. Details of this program have been discussed extensively elsewhere [1, 11, 12]. Of note is the general prohibition of any well meeting the criteria of Class IV (i.e., any well injecting hazardous wastes into or above formations that contain USDWs).

The different classes of wells each have differing requirements for construction, operation, monitoring, and closure. Class I wells injecting hazardous wastes have the most stringent requirements. The owner or operator of a Class I hazardous well must apply for a “no-migration petition” that demonstrates that the hazardous waste will not migrate vertically out of the injection zone or horizontally into contact with a USDW for 10,000 years. Moreover, the UIC program has financial assurance terms for Class I hazardous wells, requiring the owner or operator to pass a financial test or set-up a trust fund, post a bond, sign a letter of credit, or obtain insurance to ensure that the well will be properly plugged and abandoned.

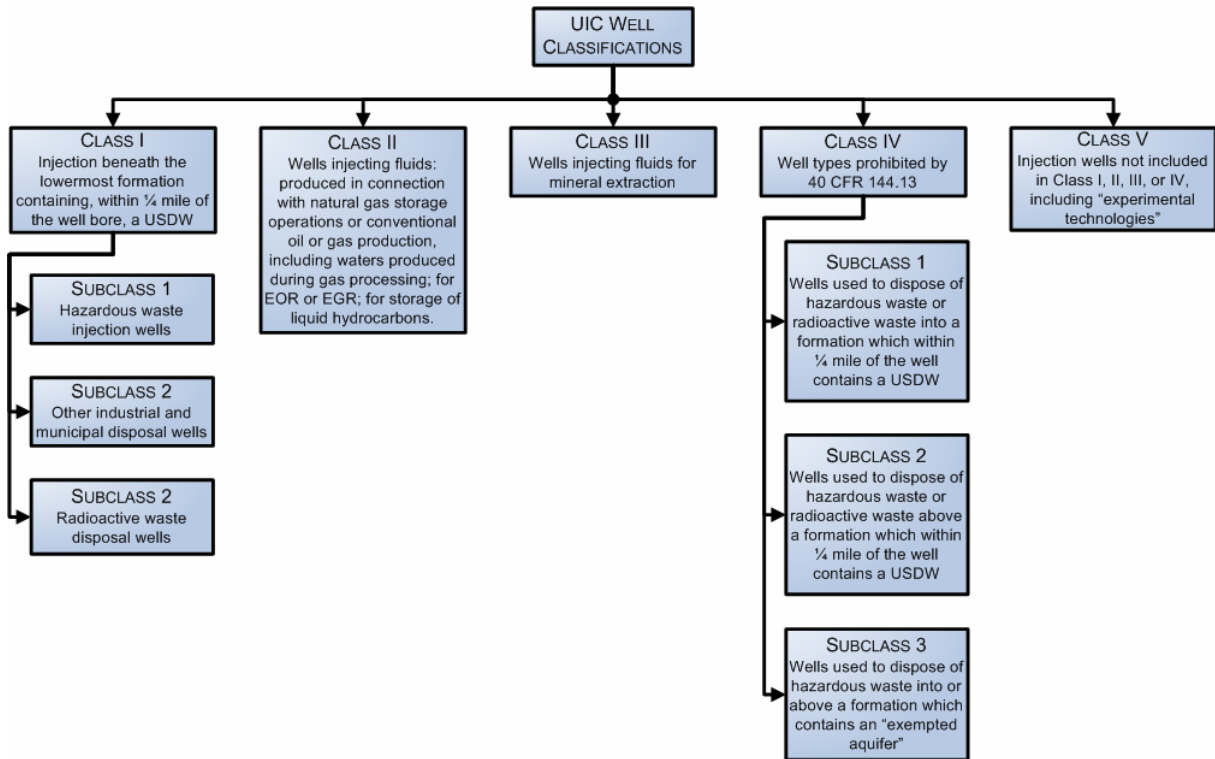


Figure 2. Well classifications under the U.S. Underground Injection Classification (UIC) program

At the current time, the EPA has issued guidance that directs the regional EPA administrators or state UIC directors to classify pilot CO₂ sequestration projects in saline aquifers as Class V wells [9]. Enhanced oil recovery (EOR) and enhanced gas recovery (EGR) projects will still be categorized as Class II projects according to the EPA guidance. In this context, pilot projects are “the limited number of experimental projects anticipated to be brought online in advance of commercial-scale operations over the next several years.” However, these pilot projects will likely be subject to different permitting rules should they become commercial projects in the future.

Limitations of Current System as a Basis for Geological Sequestration Regulation

While there are several problems with the current UIC program, as highlighted by the case of wastewater injection in Florida [11], the basic requirement of protection of human health and the environment is arguably met for the current well classes under the UIC. However, as others have pointed out [12], there are several factors that make GS different from the current practices regulated by the UIC. For one, the quantity of CO₂ injected could be as large as or larger than the largest injectant currently regulated under the UIC. CO₂ is much more buoyant than any other UIC regulated injectant intended for long-term disposal, and GS also may carry risks that are not related to contamination of USDWs (i.e., direct seepage of CO₂ to the surface).

There are several characteristics common to all well classes in the current UIC that would pose problems for GS projects. For example, the current UIC regulations specify an area of review for injection either ¼ mile radius about the well bore (2 miles for Class I hazardous wells) or based on the potential for migration of the injectant into USDWs, either of which would likely be inadequate for long-term large-scale CO₂ injection. Even in the case of hazardous Class I wells, little monitoring is required other than for protection of USDWs. Consequently, the current UIC program is not well-suited to deal with the large volumes of CO₂ that would likely be injected, nor is it suitable for assessing the amount of CO₂ stored, or whether there are paths to the surface (e.g., improperly plugged or orphaned wells) that could result in seepage. Moreover, the UIC program's monitoring requirements would not be sufficient to assess whether the CO₂ is behaving as predicted, or whether it is migrating outside of the injection zone and, in a worse case scenario, escaping to the atmosphere. Thus, it is likely that application of the current USDW-centric regulations to GS would allow for significant local and global risks to the human health and the environment.

The current UIC requirements also allow the owner or operator of an injection well to plug and abandon the well without demonstrating that the injectant has behaved as expected and will likely be contained. In the case of injection of large quantities of buoyant CO₂, this could result in significant risks long after the project has ceased injecting CO₂, and potentially after the owner or operator has vanished. Consequently, in the event of a release following closure of the project, there would be considerable uncertainty as to whether the public or the private actor (if that actor is still in existence) would be responsible for taking remedial actions. The uncertainty surrounding this question creates significant financial risk for both the public and private actors.

An additional shortcoming of the UIC program is that it specifically excludes “injection wells located on a drilling platform or other site that is beyond the State's territorial waters”[13]. In these circumstances, regulatory oversight is the domain of the Minerals Management Service of the Department of the Interior. As a consequence, CO₂ injection offshore would not be regulated by the same framework as onshore injection, which could result in a less stringent offshore regulatory environment for CO₂ storage. This could be of concern because, while there are fewer local impacts of concern, the global consequences of seepage from sub-sea GS are just as serious as for onshore injection.

A Suggested Regulatory Framework for Geological Sequestration

In light of the various needs identified above, we outline here a proposed approach to the regulation of GS projects that we believe addresses the major concerns and responsibilities of the key parties at interest. Our primary focus is on requirements for sequestration of CO₂ in deep saline formations, which offer the greatest storage potential for greenhouse gas mitigation [2], but which have not yet received as much regulatory attention as projects involving enhanced oil recovery (EOR). However, because CO₂-EOR operations have not heretofore had the dual objective of carbon sequestration, most of the discussions below

apply equally to EOR or other resource recovery processes involving injected CO₂ (such as enhanced gas recovery, EGR)².

We use Figure 3 to illustrate the life-cycle stages and activities of a sequestration project, and provide a framework for discussing the major institutional, regulatory and other issues that must be addressed.

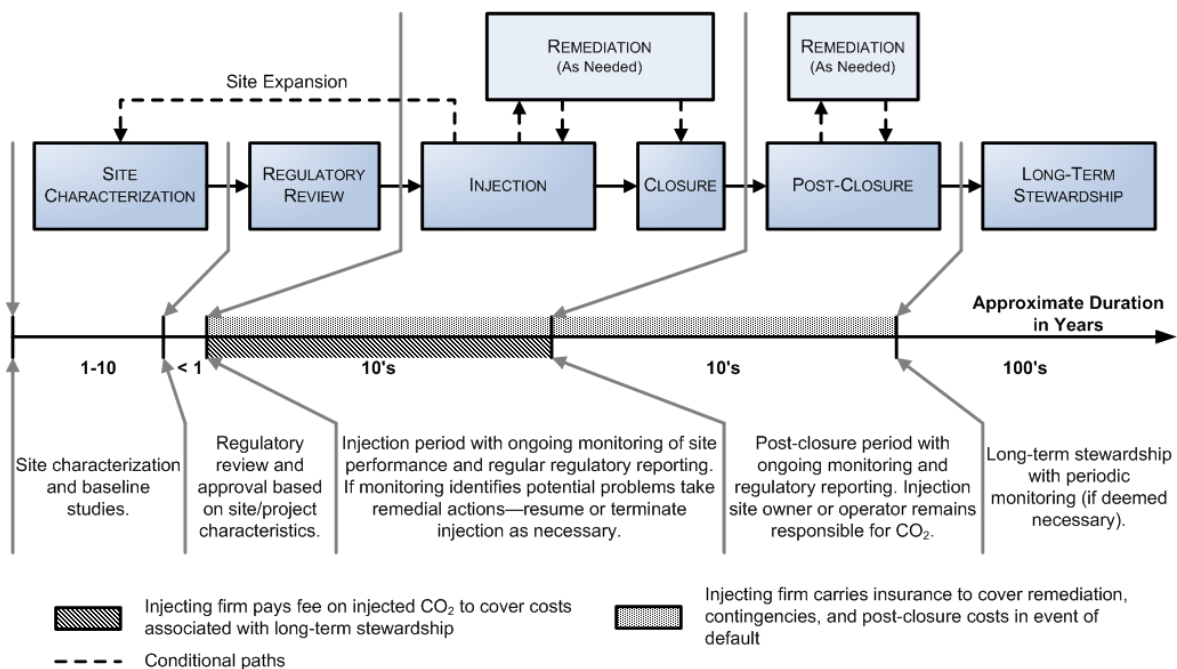


Figure 3. Life-cycle phases of a GS project with an approximate timeline and description of the regulatory processes and activities involved at each stage

This framework assumes that sequestration sites will be operated by commercial firms, that those firms will continue to have some responsibility for a limited period after the site is closed, but that after some finite time measured in decades, responsibility for long-term stewardship of the site will pass to the national government (which may, of course, choose to use private contractors to perform operational functions). We have taken this approach because we do not believe that there is any feasible way to assign long-term stewardship responsibility in perpetuity to any private entity, nor would private actors accept such responsibility. Our estimate of the time requirement for that stewardship is based on current estimates of the time needed to immobilize injected CO₂ via sub-surface trapping mechanisms that change over time [2]. Verification of those estimates ultimately will be required from long-term field monitoring programs.

² While we also recognize the potential for underground injection and storage of CO₂ in unminable coal seams, we do not include that option in this paper because it is not yet a demonstrated technology, nor do we believe that coal seams designated as “unminable” today will necessarily be viewed as such many years in the future. Since any future extraction of CO₂-laden coal resources could result in large releases of CO₂ to the atmosphere, sequestration in coal seams strikes us as problematic and outside the scope of the present paper

In order to move from this schematic representation to an effective national and international system for regulating, operating and managing a geological sequestration system, a number of questions must be addressed. In what follows we raise these questions in a general form, then in each case provide our own prescriptive answer.

Question 1: *Should regulatory authority for GS sites be the direct responsibility of the national government, or should delegation to States, Provinces, or other regional authorities be allowed, as now occurs with some U.S. states under the EPA's UIC program?*

Our Answer to Question 1: We believe that a strong case can be made for regulation being the direct responsibility of national governments. We take this position for four reasons:

- Unlike other substances that are injected under the UIC program, the issue of CO₂ is global in extent. While questions of local safety might be addressed at a local level, other issues, especially those involving potential seepage and trading of CO₂ allowances, are inherently national and even international in scope. States, provinces, and other regional authorities do not have the expertise, interest or standing to address such issues. Nor is it practical or efficient to share responsibilities between state agencies (concerned about local safety) and national agencies (concerned also about global impacts).
- Volumes of CO₂ injected in many cases will be much larger than waste quantities in all but a few of the injection facilities now being operated under existing UIC rules. Thus, a greater level of expertise and resources for assessing the adequacy of site characterization and subsequent oversight will be required. This is most efficiently achieved at a national level.
- There is less risk of private deals by local and regional authorities wishing to promote economic development in their region, and thus less risk of a "race to the bottom" if standards are developed and applied nationwide.
- As noted above, we believe the only viable way of ensuring long-term stewardship after the post-closure period is for the national government to assume responsibility for the site (see Figure 3). Hence, the national government again is the most appropriate agent to establish regulations from the outset, although different entities would be involved at the initial and final stages (see answers to Question 4 below).

As noted earlier, a limitation of the current UIC program in the United States is that the USEPA does not have authority for offshore projects in territorial waters beyond state jurisdictions (i.e., the outer continental shelf). Thus, national legislation would be required to extend that authority, or ensure in some other way that national requirements for GS projects apply in all situations.

Question 2: *What is the nature and extent of the pre-injection site characterization and of the ongoing site monitoring that should be required?*

Our Answer to Question 2: We think that most parties are now agreed that both pre-injection site characterization and ongoing site monitoring should be significantly greater in extent, and should involve a greater degree of empirical field study, than has been typical of most injection sites regulated under the current US UIC rules. This is especially true for injection into deep saline formations, but applies also to many aspects of EOR or EGR projects.

The specifics of what sorts of measurements should be made, and what sorts of analytical and modeling tools should be employed for a particular site probably cannot be finalized until results are available from the current round of experimental injection studies. Different criteria also might apply to sites involving enhanced oil or gas recovery, as opposed to deep saline aquifer storage. In any event, such decisions must be informed by people with much greater geological expertise and operational knowledge than the authors of this paper. However, whatever form those technical requirements take, we can outline some broad characteristics that we think the system should possess:

- It should be *comprehensive*. Regulatory and permitting requirements should consider the entire reservoir and the processes that may occur over time, and not focus only on the injection well and the possibility of contaminating drinking water aquifers, as is the primary focus of the current USEPA UIC regulations.
- It should be *adaptive*. It is unlikely that any characterization of subsurface conditions can be sufficiently exhaustive, in a reasonable amount of time, to anticipate all possible future developments—especially if later it is decided to expand the size of the site beyond initial plans. Thus, there should be the expectation of periodic reviews and revisions as experience builds and more knowledge of the site characteristics and performance is gained.
- It should be *risk-based*. While it is probably not realistic to impose strict probabilistic criteria, especially at the outset (e.g., probability p that fraction f of CO_2 injected will be retained after t years), once greater experience has been gained with the current experimental injection studies, it should be possible to develop a set of general quantitative design criteria that limit the potential local and global risks of CO_2 seepage.

Question 3: *How should the costs of any needed remedial actions or liability be covered during the periods in which a private firm is performing injection operations and also responsible for post-closure operations (see Figure 3)? Related to this, how long should the injecting firm be responsible for post-closure monitoring, and what conditions should be met before responsibility gets passed to the national government for long-term stewardship?*

Our Answer to Question 3: Any firm that engages in deep geological injection of CO_2 should, as a condition of initial and continued licensing, be required to obtain insurance that covers all potential remedial action. Presumably, insurance companies would want to make each policy limited to a certain volume of CO_2 injected, and require a re-negotiation if the size or scope of the project is expanded.

In addition to covering the potential costs of any technical remediation, regulators should require that coverage also include contingencies such as liability or damage costs that may arise from unanticipated developments (such as seepage into the atmosphere, damage to surface ecology, migration into areas not previously authorized resulting in damages for trespass or degradation of sub-surface assets, possibility of bankruptcy of the operating firm, etc.)

Detailed technical answers to the question of how long the operating firm should maintain and monitor the site, and the conditions it should meet before hand-off to the government entity responsible for long-term stewardship, should await insights and understanding from the current round of experimental injection studies. However, we think that there should be some minimum time (probably no less than 10 years) before such a hand-off should occur, and some maximum time (some several decades) after which hand-off would be required.

Question 4: *How should the operations of the government entity responsible for long-term stewardship be financed, and what should be the nature of that entity?*

Our Answer to Question 4: We believe that the national government entity responsible for long-term stewardship should be separate from the national government entity responsible for regulating and licensing injection and post-closure operations. If that were not the case, the risks of conflict in operational mission and institutional mission would simply be too great. In the U.S., similar considerations led to separation of operational and regulatory responsibilities between the Nuclear Regulatory Commission and Department of Energy when the old Atomic Energy Commission was broken up in the 1970s, and there are a number of other similar examples.

During the period in which injection is being performed, a fee (\$/kg CO₂ injected) should be paid by the injecting firm into a national stewardship fund which will be used to cover the operating costs and any remedial activities that must be undertaken by the government entity responsible for long-term stewardship. The magnitude of this fee can presumably be set only after data from current injection studies are completed. The fee may need to vary from site to site, depending on an assessment of geological conditions, and might change over time as new knowledge is obtained. However, for any given approved injection volume at any given site, it should be fixed for the duration of operations so that private firms can engage in necessary planning. Most sites, if they are properly designed and closed out, will need only occasional monitoring and will not require remedial activities. Thus, to keep the fees low, the fund should be pooled across all GS sites in the Nation, so as to provide risk-sharing. Details of who would collect the fee and how it would be administered remain to be developed. However, a key requirement is that this national stewardship fund should be established in such a form that politicians are unable to raid it to finance other unrelated objectives.

Question 5: *All of the structure laid out above is focused at the national level. How should international risk governance evolve, and how can all nations be required to adopt similar minimum standards for the operation, closure and long-term stewardship of their geological sequestration sites?*

Our Answer to Question 5: We believe that both public and private mechanisms should be used to ensure that all nations that engage in geological sequestration of CO₂ develop national standards comparable to those that we have outlined above. Presumably, as international carbon trading markets emerge, there will have to be some international entity responsible for overseeing and certifying the legitimacy of international trades. That entity can require proof that all CO₂ allowances traded in the market have been generated in ways that conform to procedures similar to those we have outlined.

However, because for a while we are likely to see "carbon management from the bottom up" [14, 15]— that is several different regional regimes that will only gradually coalesce over time—private parties, especially international financial institutions and insurance or re-insurance firms, can play a key role by developing model regulatory regimes of the sort we have outlined here, and insisting that projects operate under such regimes as a pre-condition for making loans or writing coverage for geological sequestration projects.

Acknowledgements

This paper was originally prepared for the International Risk Governance Council (IRGC) workshop on carbon capture and storage held in Washington, D.C., 15-16 March, 2007, with support provided by the IRGC and the Climate Decision Making Center (CDMC) at Carnegie Mellon University. The authors are grateful for insights gained from interactions with many individuals in the carbon sequestration community. However, the authors alone are responsible for the content of this paper.

References

1. Wilson, E.J., T.J. Johnson, and D.W. Keith, *Regulating the Ultimate Sink: Managing the Risks of Geologic CO₂ Storage*. Environmental Science and Technology, 2003. **37**: p. 3476-3483.
2. Benson, S., et al., *Underground geological storage*, in *IPCC Special Report on Carbon Dioxide Capture and Storage*, B. Metz, et al., Editors. 2005, Cambridge University Press: Cambridge, U.K.
3. Osman-Elasha, B., et al., *Implications of carbon dioxide capture and storage for greenhouse gas inventories and accounting*, in *IPCC Special Report on Carbon Dioxide Capture and Storage*, B. Metz, et al., Editors. 2005, Cambridge University Press: Cambridge, U.K.
4. Herzog, H., K. Calderia, and J. Reilly, *An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage*. Climatic Change, 2003. **59**: p. 293-310.
5. "Annual Report Pursuant to Section 13 or 15(d) of the Securities Exchange Act of 1934." Securities and Exchange Commission (SEC) Form 10-K405. 5/10/1999
6. Nuclear Energy Institute. Decommissioning of Nuclear Power Plants. 2002 May 2002 [cited 2007 January 15, 2007]; Available from: <http://www.nei.org/doc.asp?catnum=3&catid=278>.
7. "Abandoned Mine Reclamation." Title 30 U.S. Code, Sec. 1231. 2000 ed.

8. Reiner, D.M. and H.J. Herzog, *Developing a set of regulatory analogs for carbon sequestration*. *Energy*, 2004. **29**(9-10): p. 1561-1570.
9. Dougherty, C.C. and B. McLean, *Using the Class V Experimental Technology Well Classification for Pilot Carbon Geologic Sequestration Projects-UIC Program Guidance*, U.S.E.P. Agency, Editor. 2006.
10. "Underground Injection Control Program." Title 40. Code of Federal Regulations, Pts. 144-148. 2006 ed.
11. Keith, D.W., et al., *Regulating the Underground Injection of CO₂*. *Environmental Science and Technology*, 2005. **39**: p. 499A-505A.
12. Wilson, E.J., D.W. Keith, and M. Wilson. *Considerations for a Regulatory Framework for Large-Scale Geological Sequestration of Carbon Dioxide: A North American Perspective*. in *7th International Conference on Greenhouse Gas Control Technologies*. 2004. Vancouver, Canada: Elsevier Science.
13. "Underground Injection Control Program." Title 40 Code of Federal Regulations, Pt. 144. 2006 ed., 639-642.
14. Morgan, M.G., *Policy forum: Climate change - Managing carbon from the bottom up*. *Science*, 2000. **289**(5488): p. 2285-2285.
15. Victor, D.G., *Climate Change: Debating America's Policy Options*. 2004, Washington, DC: Council on Foreign Relations. 180.