EXHIBIT 3

The Future of Coal

AN INTERDISCIPLINARY MIT STUDY

The Future of Coal

OPTIONS FOR A
CARBON-CONSTRAINED WORLD

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Chapter 4 — Geological Carbon Sequestration

Carbon sequestration is the long term isolation of carbon dioxide from the atmosphere through physical, chemical, biological, or engineered processes. The largest potential reservoirs for storing carbon are the deep oceans and geological reservoirs in the earth's upper crust. This chapter focuses on geological sequestration because it appears to be the most promising large-scale approach for the 2050 timeframe. It does not discuss ocean or terrestrial sequestration[1,2].

In order to achieve substantial GHG reductions, geological storage needs to be deployed at a large scale.[3,4] For example, 1 Gt C/yr (3.6 Gt CO_2/yr) abatement, requires carbon capture and storage (CCS) from 600 large pulverized coal plants (~1000 MW each) or 3600 injection projects at the scale of Statoil's Sleipner project.[5] At present, global carbon emissions from coal approximate 2.5 Gt C. However, given reasonable economic and demand growth projections in a business-as-usual context, global coal emissions could account for 9 Gt C (see table 2.7). These volumes highlight the need to develop rapidly an understanding of typical crustal response to such large projects, and the magnitude of the effort prompts certain concerns regarding implementation, efficiency, and risk of the enterprise.

The key questions of subsurface engineering and surface safety associated with carbon sequestration are:

Subsurface issues:

- Is there enough capacity to store CO_2 where needed?
- Do we understand storage mechanisms well enough?
- Could we establish a process to certify injection sites with our current level of understanding?
- Once injected, can we monitor and verify the movement of subsurface CO_2?

Near surface issues:

- How might the siting of new coal plants be influenced by the distribution of storage sites?
- What is the probability of CO_2 escaping from injection sites? What are the attendant risks? Can we detect leakage if it occurs?
- Will surface leakage negate or reduce the benefits of CCS?

Importantly, there do not appear to be unresolvable open technical issues underlying these questions. Of equal importance, the hurdles to answering these technical questions well appear manageable and surmountable. As such, it appears that geological carbon sequestration is likely to be safe, effective, and competitive with many other options on an economic basis. This chapter explains the technical basis for these statements, and makes recommendations about ways of achieving early resolution of these broad concerns.

SCIENTIFIC BASIS

A number of geological reservoirs appear to have the potential to store many 100's – 1000's of gigatons of CO_2.[6] The most promising reservoirs are *porous and permeable rock bodies*, generally at depths, roughly 1 km, at pressures and temperatures where CO_2 would be in a supercritical phase.[7]

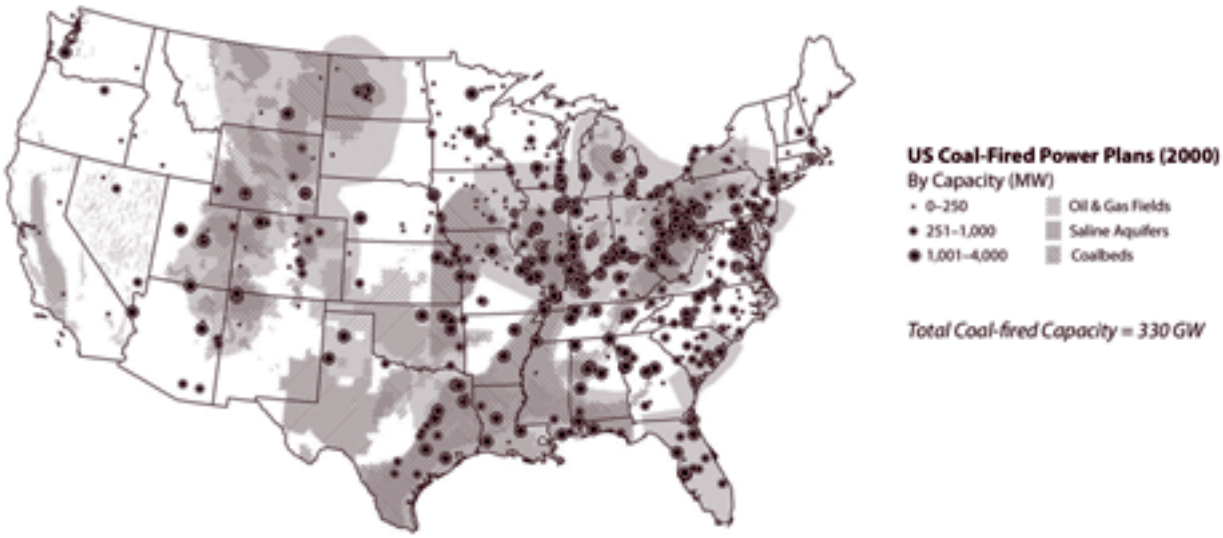
- *Saline formations* contain brine in their pore volumes, commonly of salinities greater than 10,000 ppm.
- *Depleted oil and gas fields* have some combination of water and hydrocarbons in their pore volumes. In some cases, economic gains can be achieved through enhanced oil recovery (EOR)[8] or enhanced gas recovery[9] and substantial CO_2-EOR already occurs in the US with both natural and anthropogenic CO_2.[10]
- *Deep coal seams*, often called unmineable coal seams, are composed of organic minerals with brines and gases in their pore and fracture volumes.
- Other potential geological target classes have been proposed and discussed (e.g., oil shales, flood basalts); however, these classes require substantial scientific inquiry and verification, and the storage mechanisms are less well tested and understood (see Appendix 4.A for a more detailed explanation).

Because of their large storage potential and broad distribution, it is likely that most geological sequestration will occur in saline formations. However, initial projects probably will occur in depleted oil and gas fields, accompanying EOR, due to the density and quality of subsurface data and the potential for economic return (e.g., Weyburn). Although there remains some economic potential for enhanced coal bed methane recovery, initial economic assessments do not appear promising, and substantial technical hurdles remain to obtaining those benefits.[6]

For the main reservoir classes, CO_2 storage mechanisms are reasonably well defined and understood (Figure 4.1). To begin, CO_2 sequestration targets will have *physical barriers* to CO_2 migration out of the crust to the surface. These barriers will commonly take the form of impermeable layers (e.g., shales, evaporites) overlying the reservoir target, although they may also be dynamic in the form of regional hydrodynamic flow. This storage mechanism allows for very high CO_2 pore volumes, in excess of 80%, and act immediately to limit CO_2 flow. At the pore scale, *capillary forces* will immobilize a substantial fraction of a CO_2 bubble, commonly measured to be between 5 and 25% of the pore volume. That CO_2 will be trapped as a residual phase in the pores, and acts over longer time scales as a CO_2 plume which is attenuated by flow. Once in the pore, over a period of tens to hundreds of years, the CO_2 will *dissolve* into other pore fluids, including hydrocarbon species (oil and gas) or brines, where the CO_2 is fixed indefinitely, unless other processes intervene. Over longer time scales (hundreds to thousands of years) the dissolved CO_2 may react with minerals in the rock volume to *precipitate* the CO_2 as new carbonate minerals. Finally, in the case of organic mineral frameworks such as coals, the CO_2 will physically *adsorb* onto the rock surface, sometimes displacing other gases (e.g., methane, nitrogen).

Although substantial work remains to characterize and quantify these mechanisms, they are understood well enough today to trust estimates of the percentage of CO_2 stored over some period of time—the result of decades of studies in analogous hydrocarbon systems, natural gas storage operations, and CO_2-EOR. Specifically, it is very likely that the fraction of stored CO_2 will be greater than 99% over 100 years, and likely that the fraction of stored CO_2 will exceed 99% for 1000 years[6]. Moreover, some mechanisms appear to be self-reinforcing.[11,12] Additional work will reduce the uncertainties associated with long-term efficacy and numerical estimates of storage volume capacity, but no knowledge gaps today appear to cast doubt on the fundamental likelihood of the feasibility of CCS.

Figure 4.7 Location of Coal Plants Relative to Potential Storage Sites



Map comparing location of existing coal-fired power plants in the US with potential sequestration sites. As stated earlier in the report, our knowledge of capacity for sequestration sites is very limited. Some shaded areas above may prove inappropriate, while detailed surveys may show sequestration potential in places that are currently not identified.

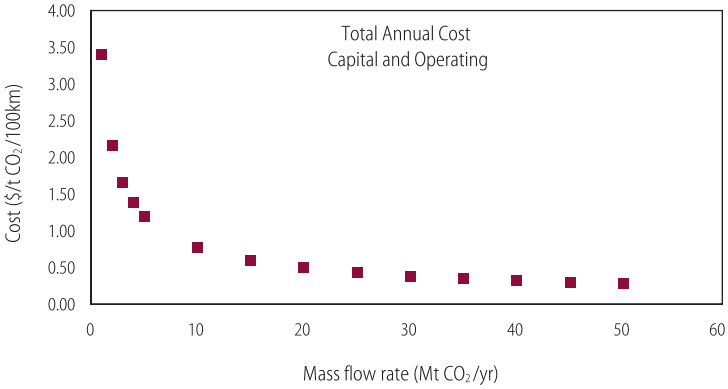
Costs for injecting the CO_2 into geologic formations will vary on the formation type and its properties. For example, costs increase as reservoir depth increases and reservoir injectivity decreases (lower injectivity results in the drilling of more wells for a given rate of CO_2 injection). A range of injection costs has been reported as \$0.5-8/tCO_2.[6] Costs will also vary with the distance transported, the capacity utilization of the pipe, the transport pressure and the costs of compression (which also produces CO_2).

It is anticipated that the first CCS projects will involve plants that are very close to a sequestration site or an existing CO_2 pipeline. As the number of projects grow, regional pipeline networks will evolve. This is similar to the growth of existing regional CO_2 pipeline networks in west Texas and in Wyoming to deliver CO_2 to the oil fields for EOR. For example, Figure 4.7 suggests that a regional pipeline network may develop around the Ohio River valley, transporting much larger volumes of CO_2.

RECOMMENDATIONS

Our overall judgment is that the prospect for geological CO_2 sequestration is excellent. We base this judgment on 30 years of injection experience and the ability of the earth's crust to trap CO_2. That said, there remain substantial open issues about large-scale deployment of carbon sequestration. Our recommendations aim to address the largest and most important of these issues. Our recommendations call for action by the U.S. government; however, many of these recommendations are appropriate for OECD and developing nations who anticipate the use CCS.

Figure 4.8 Cost for CO_2 Transport Via Pipeline as a Function of CO_2 Mass Flow Rate



1. The US Geological Survey and the DOE, and should embark of a 3 year "bottom-up" analysis of US geological storage capacity assessments. This effort might be modeled after the GEODISC effort in Australia.

2. The DOE should launch a program to develop and deploy large-scale sequestration demonstration projects. The program should consist of a minimum of three projects that would represent the range of US geology and industrial emissions with the following characteristics:

   - Injection of the order of 1 million tons CO_2/year for a minimum of 5 years.
   - Intensive site characterization with forward simulation, and baseline monitoring
   - Monitoring MMV arrays to measure the full complement of relevant parameters. The data from this monitoring should be fully integrated and analyzed.

3. The DOE should accelerate its research program for CCS S&T. The program should begin by developing simulation platforms capable of rendering coupled models for hydrodynamic, geological, geochemical, and geomechanical processes. The geomechanical response to CO_2 injection and determination or risk probability-density functions should also be addressed.

4. A regulatory capacity covering the injection of CO_2, accounting and crediting as part of a climate regime, and site closure and monitoring needs to be built. Two possible paths should be considered — evolution from the existing EPA UIC program or a separate program that covers all the regulatory aspects of CO_2 sequestration.

5. The government needs to assume liability for the sequestered CO_2 once injection operations cease and the site is closed. The transfer of liability would be contingent on the site meeting a set of regulatory criteria (see recommendation 4 above) and the operators paying into an insurance pool to cover potential damages from any future CO_2 leakage.

CITATIONS AND NOTES

1. From a technical perspective, ocean sequestration appears to be promising due to the ocean's capacity for storage (IPCC 2005). Presently, because of concerns about environmental impacts, ocean sequestration has become politically unacceptable in the US and Europe.
2. Terrestrial storage, including storage in soils and terrestrial biomass, remains attractive on the basis of ease of action and ancillary environmental benefits. However, substantial uncertainties remain regarding total capacity, accounting methodology, unforeseen feedbacks and forcing functions, and permanence.
3. Pacala, S., and Socolow, R., Stabilization Wedges: Solving the Climate Problem for the Next 50 Years Using Current Technologies, *Science*, 2004, v.305, pp. 986
4. US Dept. of Energy, Climate Change Technology Program Strategic Plan, 2005, Washington, 256 p. http://www.climatetechnology.gov/
5. A 1000 MW bituminous pulverized coal plant with 85% capacity factor and 90% efficient capture would produce a CO_2 stream mass of 6.24 million t/yr. If injected at 2 km depth with a standard geothermal gradient, the volume rate of supercritical CO_2 would be 100,000 barrels/day (for comparison, the greatest injection rate for any well in the world is 40,000 bbl/d, and typical rates in the US are <3000 bbl/d). This suggests that initially either multiple long-reach horizontal wells or tens of vertical wells would be required to handle the initial volume. Over 50 years, the lifetime typical of a large coal plant, this would be close to 2 billion barrels equivalent, or a giant field for each 1000 MW plant.
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