CSLF-T-2004-7
8 December 2003

TECHNICAL GROUP

DRAFT
CARBON SEQUESTRATION LEADERSHIP FORUM
TECHNOLOGY ROADMAP

Note by the Secretariat

Barbara N. McKee
Tel: +1 301 903 3820
Fax: +1 301 903 1591
CSLFSecretariat@hq.doe.gov

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Background

At its inaugural meeting on 25 June 2003, the Technical Group decided that a near-term objective was the development of a robust, comprehensive, global carbon sequestration technology roadmap. Toward this end, a draft Carbon Sequestration Leadership Forum Technology Roadmap has been prepared.

Action Requested

The Technical Group is requested to recommend approval of the Draft Carbon Sequestration Leadership Forum (CSLF) Technology Roadmap to the Policy Group.

Conclusions

The Technical Group is invited to note in the Minutes of its meeting of 21 January 2004 that:

> "The Technical Group recommended approval of the Draft Carbon Sequestration Leadership Forum (CSLF) Technology Roadmap to the Policy Group."

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Technology Roadmap for the
Carbon Sequestration Leadership Forum

Vision Statement

The Carbon Sequestration Leadership Forum (CSLF) will facilitate the development and deployment of technologies for the separation, capture, transportation and storage of carbon dioxide. The CSLF will advance technological capacity by collaborative efforts to address key technical, economic, and environmental obstacles. The CSLF will also promote awareness and champion legal, regulatory, financial, and institutional environments conducive to such technologies. By the year 2013, collaborative projects will be completed in many regions of the world, demonstrating the safety and cost-effectiveness of geologic carbon sequestration.

I. Goals of the CSLF Technical Group

The CSLF will facilitate the development of new technologies for the separation, capture, transportation and storage of carbon dioxide. As suggested by the international representatives to the inaugural technical group meeting in June 2003, the principle objectives and issues related to this overarching CSLF goal include the following:

- Achieving cost reduction for sequestration technologies;
- Developing an understanding of global geologic storage potential;
- Matching CO_2 sources with potential sinks;
- Demonstrating the effectiveness of geologic CO_2 storage; and
- Building technical competence and confidence through multiple demonstrations.

This Technology Roadmap addresses these and related issues. Organizationally, the Technical Group within the CSLF has the following functions and responsibilities:

- Identify key technical, economic, and environmental obstacles to achieving improvements in carbon sequestration technologies;
- Establish an inventory of potential areas of needed research;
- Identify areas of multilateral collaboration on carbon capture and storage technologies;
- Foster collaborative research, development, and demonstration projects reflecting consensus priorities of CSLF Members; and

- Support the CSLF Policy Group as it champions legal, regulatory, financial, and institutional environments conducive to carbon sequestration technologies.

II. Key Technical Obstacles and Potential Projects in Carbon Sequestration

A. CO_2 Separation and Capture

CO_2 capture and separation projects can cover a wide range of technology areas, including amine absorbents, carbon adsorbents, membranes, sodium and other metal-based sorbents, electrochemical pumps, hydrates, and mineral carbonation. Some CO_2 capture technologies can be applied to a wide range of CO_2-containing process streams, while others are more specialized. Some advanced fuel conversion technologies such as gasification, oxygen combustion, electrochemical cells, advanced steam reforming, and chemical looping produce a CO_2-rich exhaust stream that is highly amenable to CO_2 sequestration – or ready for transport and storage. Other technologies produce CO_2 in a more dilute form, necessitating different approaches for separation and capture. However, in all cases there is a strong synergistic link between improved efficiency of fossil fuel conversion systems and carbon capture; the cost of carbon capture per unit of product is less for a more efficient process.

The discussion below tends to focus on coal-based systems for gasification and power generation. This reflects the large role of coal in world energy use as well as its higher carbon content. However, it is noted that many of the gasification projects now in operation are based on other high-carbon fuels such as heavy oils and petroleum coke. It is anticipated that much of the information and developments that come from coal and other high-carbon fuel projects will readily transfer to oil-based and gas-based power systems, and later to other CO_2 sources in the industrial, commercial, residential, and transportation sectors.

A1. Pre-Combustion De-carbonization

There are high costs and energy penalties in applying existing CO_2 capture technology to gasification technologies. System inefficiencies lead to costs exceeding US$100/tonne of CO_2. Because the amines undergo degradation and become corrosive, existing CO_2 capture technology uses relatively low-strength amine solvents to chemically absorb CO_2 at temperatures well below the boiling point of water. Degradation of the amines requires as much as eight pounds of amine replacement per tonne of CO_2 captured. Using dilute amine solvents requires larger equipment and higher regeneration energy requirements, and in turn requires more steam use and energy consumption. The need to operate below the boiling point of water creates energy losses through cooling, and the water condensation can create unwanted contamination.

Prospective Approaches and Illustrative Projects:

- Develop advanced chemical-based systems that address the cost and energy load problems of existing amine-based systems.
- Develop dry, physical/chemical, regenerable sorbent systems that can adsorb/absorb CO_2 at elevated temperatures and regenerate the sorbent and release the CO_2 at low energy loads.
- Develop separation membranes capable of operating at elevated temperatures and pressures to dramatically reduce energy requirements and operating costs.

A2. Oxygen-Fired Combustion

Oxygen-fired combustion (OFC) is a new technology approach made possible by emerging technological advances. Since combustion converts nearly all of the fuel's carbon to CO_2, OFC requires roughly three times more oxygen per kilowatt hour than gasification. This oxygen consumption is a significant cost because existing air separation units needed to provide the oxygen are capital and energy intensive. Because combustion using pure oxygen produces temperatures that are too high for existing boiler heat transfer and turbine hot gas path materials, CO_2 is recycled to dilute the oxygen and moderate temperatures. CO_2 compression for recycle is both costly and energy intensive, with current minimum CO_2 recycle of about five pounds of CO_2 per pound of coal. But even with CO_2 recycle, OFC has the potential to reduce boiler size given the absence of nitrogen (78 percent of air's volume). Because OFC produces large quantities of water and SO_2 commensurate with the coal's quality, many sequestration applications also require water and SO_2 removal.

Prospective Approaches and Illustrative Projects:

- Develop air separation membranes to reduce the cost and energy load for oxygen production.
- Develop compact boilers designed specifically for OFC and advanced cooling cycles to optimize thermal and water management and remove pollutants.
- Develop boiler heat transfer and turbine materials capable of enduring higher than conventional temperatures and pressure regimes to reduce CO_2 recycle requirements.

A3. Post-Combustion Capture

Worldwide, coal accounts for about 38 percent of the world's electricity generation, and this is dominated by pulverized coal-fired (PC) capacity. Because the use of air in PC boiler combustion produces flue gas with low CO_2 concentration (12-18 percent volumetrically, at a pressure of only 10-15 psi), these existing boiler designs complicate the challenge of CO_2 capture. Amine scrubbing represents the state-of-the-technology for CO_2 capture from PC power plants, but applying amine scrubbing and compressing CO_2 to 1,200 psi for sequestration currently can require US$2,000/kW in additional capital cost and reduces the net power output by 12.5 percent.

Prospective Approaches and Illustrative Projects:

- Develop advanced chemical-based systems, dry regenerable sorbent systems, and separation membranes, with additional emphasis on effective contact of the dilute phase CO_2 and the capture/separation media.
- Explore electrochemical means of separating CO_2, drawing upon fuel cell technology.

B. CO_2 Storage

Many power plants and other large point sources of CO_2 emissions are located near geologic formations that are amenable to CO_2 storage, including depleting oil reservoirs, depleting gas reservoirs, unmineable coal seams, saline formations, shale formations with high organic content, and others. These formations have provided natural storage for crude oil, natural gas, brine, and CO_2 over millions of years. And in more recent years, some formations have been used for long-term storage of injected municipal and even hazardous waste. In some formations, recovery of embedded hydrocarbons can also be enhanced concurrent with the storage of CO_2.

Each type of formation has its own mechanism for storing CO_2 and a resultant set of research priorities and opportunities. CSLF projects can help us understand the global potential for geologic storage, the effectiveness of various storage technologies, and an improved matching of CO_2 sources with potential sinks.

B1. Depleted Oil Reservoirs

Many enhanced oil recovery projects already inject CO_2 into depleting light oil reservoirs. This practice is often called "miscible gas recovery" because the injected CO_2 not only drives the residual oil in the reservoir, but mixes and dissolves in the oil. This process enhances residual oil mobility by swelling the oil and reducing its viscosity. Storage mechanisms include mechanical/geologic trapping, formation of carbonate minerals, adsorption on hydrocarbons (such as coal), and solution in the residual oil. Computer models have been developed to support design of optimum oil recovery procedures for reservoirs encountered, but not for optimum CO_2 storage.

Prospective Approaches and Illustrative Projects:

- Demonstrate a 5-fold increase globally in CO_2 storage in depleting oil reservoirs (focus on developing countries for projects).

B2. Unmineable Coal Seams

Unmineable coal seams represent both major sources of methane (CH_4) and vast CO_2 storage potential. Coalbed methane recovery is being practiced at a number of sites around the world. Typically, coalbed methane is recovered by removal of in-situ water to depressurize the coal seams. In an experimental process known as "enhanced coalbed methane recovery," injection of CO_2 or other gases preferentially displaces CH_4 and increases recovery potential. Research has shown that CO_2 has roughly twice the affinity of CH_4 for adsorption on coal, and that CO_2/N_2 "blends" displace more CH_4 than CO_2 alone. The beneficial use of N_2 offers possibilities of injecting flue gas and avoiding CO_2 separation. Much of the coalbed methane reserves are in deep coal seams (greater than 1,000 meters) that typically have low permeability, a drawback to methane recovery. Commercialization of enhanced coalbed methane recovery and its concurrent use as CO_2 storage sites requires predictability of CH_4 production and CO_2 storage, and methods for overcoming low permeability in deep coal seams. Current estimated storage capability for enhanced coalbed methane recovery is 1.5 standard cubic feet of CO_2 per standard cubic foot of CH_4 recovered.

Prospective Approaches and Illustrative Projects:

- Develop an understanding of CO_2-N_2-CH_4 adsorption and displacement mechanisms as a function of reservoir characteristics.
- Demonstrate net CO_2 storage in an unmineable coal seam of 3 standard cubic feet per standard cubic foot of CH_4 recovered.
- Develop drilling and completion technology to enhance permeability of deep coal seams.

B3. Saline Formations

Saline formations represent vast potential for CO_2 storage, potentially hundreds of years of storage at present global emission rates. Found around the world, these saline formations are typically deep and removed from potable water formations, often accompanied by good cap rock seals, and not suitable for irrigation or other applications. When injected, CO_2 would partially dissolve in the formation's saline water, and in some formations would slowly react with minerals to form carbonates, essentially locking up the CO_2 permanently. Ongoing successful injection of one million tonnes of CO_2 per year in the saline formation beneath the Sleipner West gas field contributes to growing confidence in reliable CO_2 storage in saline formations. Remaining uncertainties include the reactions and associated impact on permanent storage that may occur among the CO_2, the saline liquid, and the minerals in the surrounding strata. Also, geology and injection methods will affect CO_2 flow and the extent of delivery into the formation.

Prospective Approaches and Illustrative Projects:

- Explore the chemistry of CO_2-brine-mineral reactions, with emphasis on CO_2 reactions leading to carbonate formation.
- Demonstrate drilling and completion methods for optimum CO_2 delivery into saline formations such as horizontal or multi-lateral wells with hydraulic fracturing.
- Conduct detailed storage capacity assessments of promising formations through field testing.

B4. Novel Geologic Formations

Other hydrocarbon-rich formations – including Devonian shales, depleting gas reservoirs, and low-rank coal deposits – are large in size and could potentially store CO_2 and produce value-added products. Although promising, these formations are as yet untested for CO_2 storage capacity and saleable by-product production.

Prospective Approaches and Illustrative Projects:

- Investigate the technical and economic viability of CO_2 storage in promising formations.
- Demonstrate the viability of CO_2 storage in one of the promising formations.

C. Monitoring and Verification of Sequestration

Measurement, monitoring, & verification (MM&V) is defined as the capability to measure the amount of CO_2 stored at a specific sequestration site, to monitor the site for leaks or other deterioration of storage integrity over time, and to verify that the CO_2 is transported and stored without harm to the host ecosystem. MM&V also includes the development of protocols and methodologies for calculating the net avoided CO_2 emissions from systems with carbon capture, transport, and storage systems. Current MM&V practices are time-consuming and costly, and this situation is further complicated by a lack of standard, acceptable protocols for carbon measurement and accounting.

C1. Geologic Sequestration

Confidence in CO_2 storage technologies requires an ability to measure the amount of CO_2 stored at a site, monitor the site for leaks or other deterioration of storage integrity over time, and verify that the CO_2 is not harmful to the host ecosystem. Existing geophysical imaging techniques – including seismic, electromagnetic, and electrical resistance methods – can characterize reservoir properties before and after CO_2 injection, but these techniques need to be refined for the specific purpose of CO_2 storage. Improvements are also needed in above-ground technologies to detect leaks and ecological impacts. Accepted protocols are needed to calculate net avoided CO_2 emissions.

Prospective Approaches and Illustrative Projects:

- Adopt geophysical imaging hardware and procedures to quantify CO_2 storage and assess reservoir impacts.
- Develop leak detection and ecological impact technology and protocols.
- Develop an accepted protocol for calculating net avoided CO_2, including protocols for measurement/accounting.

C2. CO_2 Transport Systems

Widespread acceptance and use of carbon sequestration technologies would require a substantial transportation infrastructure, on the order of what presently exists for oil and natural gas transport. Systems are needed for ensuring the integrity of the CO_2 transport infrastructure, and to detect and locate leaks from above- or underground CO_2 pipelines.

Prospective Approaches and Illustrative Projects:

- Adapt and test natural gas pipeline leak detection systems for applicability to CO_2 transport.

III. CSLF Technical Roadmap

Figure 1. Draft CSLF Technical Roadmap