A REVIEW OF CARBON SEQUESTRATION SCIENCE AND TECHNOLOGY OPPORTUNITIES BY THE U.S. DEPARTMENT OF ENERGY

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INTRODUCTION. The U.S. Department of Energy completed a two-year study of science and technology opportunities in carbon sequestration. The goal of this report is to identify areas for research and development that could lead to an understanding of the potential for future use of carbon sequestration as a major tool for managing carbon emissions. Under the leadership of the U.S.DOE, researchers from universities, industry, other government agencies, and DOE national laboratories were brought together to develop the technical basis for conceiving a science and technology road map. That effort resulted in the report entitled Carbon Sequestration Research and Development (DOE, 1999). This report develops much of the information needed for the road map and identifies the R&D topics necessary to understand and develop critical options for the capture, , conversion, and sequestration of carbon. The report addresses known sources of carbon (industrial sources, power plant flue gases, preprocessed fossil fuels before combustion), and options for sequestration sinks -- oceans, geologic formations, soils and vegetation. The report relies heavily on seminal studies on carbon management and sequestration, e.g., DOE, 1997; Herzog et al., 1993IEA, 1998; National Laboratory Directors, 1997; Parson and Keith, 1998; Socolow, ed., 1997; and Victor, 1998. The report has helped guide new research programs in carbon sequestration at both DOE's Office of Science (http://cdiac2.esd.ornl.gov/index.html) and Office of Fossil Energy (http://www.fe.doe.gov/coal_power/sequestration/index.html.

CARBON SEQUESTRATION AND FOSSIL FUELS. Most anthropogenic emissions of carbon to the atmosphere result from combustion of fossil fuels for the production of energy. If the demand for energy continues to increase, it is possible that the only way that fossil fuels can be used for large-scale energy production is through the development and implementation of carbon capture and sequestration options. Sequestration could be a major tool for reducing CO_2 emissions, it will allow greater flexibility in the future primary energy supply, and could offer other collateral benefits such as manufactured products, improved agricultural practices and enhanced recovery of oil and methane. The purpose of carbon sequestration is to keep anthropogenic carbon emissions from reaching the atmosphere by capturing them, isolating them, and diverting them to secure storage and/or to remove CO_2 from the atmosphere by various means and store it. Any viable system for sequestering carbon must be safe, environmentally benign, effective, economical, and acceptable to the public.

The vision for the Carbon Sequestration Research and Development Report is to: *Possess the scientific understanding of carbon sequestration and develop to the point of deployment those options that ensure environmentally acceptable sequestration to reduce anthropogenic CO_2 emissions and/or atmospheric concentrations. The goal is to have the potential to sequester a significant fraction of 1 GtC/year in 2025 and 4 GtC/year in 2050.*

STRATEGIC ISSUES IN CARBON SEQUESTRATION. Following are issues identified in the DOE Carbon Sequestration R&D report regarding the establishment of a comprehensive carbon sequestration program:

•Sequestration R&D could expand the world's future options for dealing with greenhouse gasses.

•Many carbon sequestration options are particularly amenable to improving existing activities -- such as CO_2 injection during secondary oil recovery -- and often provide important secondary benefits, such as improving ecosystems during reforestation.

•Some carbon sequestration options, such as improved agricultural practices, are available practically immediately. Examining ongoing, field-scale sequestration trials in terrestrial, geological, and ocean systems can provide critical experience for designing the necessary environmental research programs.

•Some carbon sequestration options that have limited capacity or relatively short carbon residence times could nonetheless make important near-term contributions during a transition to other longer-term carbon management options. Other carbon sequestration options can provide significant long-term contributions.

•For carbon sequestration to be a viable option, it needs to be safe, predictable, reliable, measurable, and verifiable; and it needs to be competitive with other carbon management options, such as improvements in energy efficiency and carbon-free energy sources.

•Carbon sequestration is an immature field, so multiple, fundamental R&D approaches are warranted and significant breakthroughs can be expected. The federal government is an appropriate sponsor of carbon sequestration R&D.

•Integrated analyses of the carbon sequestration system should be periodically updated to evaluate the potential contributions, costs, and benefits of various carbon sequestration options.

•The information from the R&D program should be provided to policy makers to aid them in developing policy and selecting the most efficient and effective solutions to the issues of climate change.

SCIENTIFIC AND TECHNICAL NEEDS FOR CARBON SEQUESTRATION. It is the opinion of the authors of the Report that the following research and development topics should be investigated to develop a robust path to the vision (http://www.ornl.gov/carbon_sequestration). Given the magnitude of carbon emission reductions needed to stabilize the atmospheric CO_2 concentration, multiple approaches to carbon management (i.e., improved energy efficiency and clean energy systems) will be needed. There are no simple solutions; a portfolio of technologies will be necessary (National Laboratory Directors, 1997), and all potentially important technical options in carbon management should be explored. The Carbon Sequestration report was organized into "focus areas" to identify the scientific and engineering issues (Fig. 1). Separation and capture, ocean sequestration, terrestrial systems, geological systems, and advanced biological and chemical approaches.

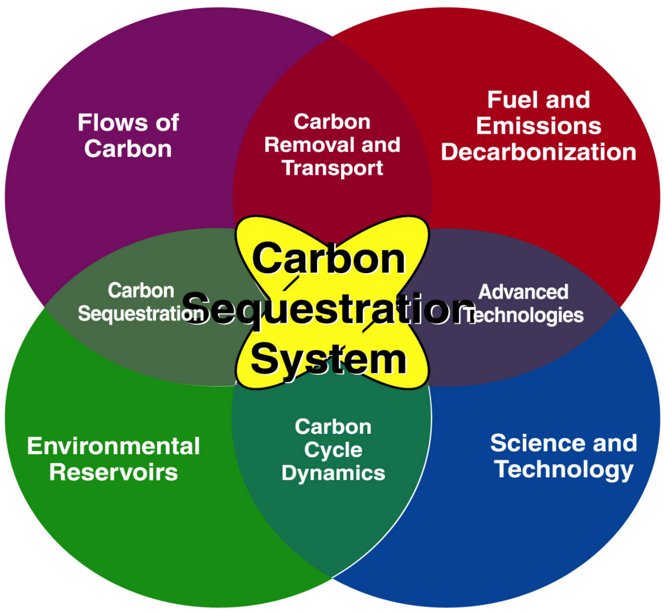

Figure 1: Carbon Sequestration System

Separation and Capture of CO_2 from the Energy System. Geologic or ocean storage sequestration options that use a concentrated source of CO2 require low-cost carbon separation and capture techniques to be viable options. The scale of the industrial system required to process gigatonnes of carbon warrants investigation into new solvents, adsorbents, and membrane separation devices for either pre- or post-combustion separation.

•A science-based and applications-oriented R&D program is needed to establish the efficacy of current and novel CO_2 separation processes as important contributions to carbon emissions mitigation. Important elements of such a program include the evaluation, improvement, and development of chemical and physical absorption solvents, chemical and physical adsorbents, membrane separation devices with selectivity and specificity for CO_2-containing streams, molecular and kinetic modeling of the materials and processes, and laboratory-scale testing of the selected processes.

•Field tests are needed of promising new CO_2 separation and capture options in small bypass streams at large point sources of CO_2, such as natural gas wells and hydrogen production plants.

•Transportation and compression plant costs should be considered as part of the capture and separation process.

Sequestration in the Oceans. The ocean provides a large potential reservoir. Active experiments are already under way in iron fertilization and other tests of enhanced marine biological sequestration, as well as deep CO_2 injection. Improvements in understanding marine systems will be needed before implementation of major marine sequestration campaigns.

•Field experiments of CO_2 injection into the ocean are needed to study the physical/chemical behavior of the released CO_2 and its potential for ecological impact.

•Ocean general circulation models need to be improved and used to determine the best locations and depths for CO_2 injection and to determine the long-term fate of CO_2 injected into the ocean.

- The effect of fertilization of surface waters on the increase of carbon sequestered in the deep ocean needs to be determined, as well as the potential ecological consequences on the structure and function of marine ecosystems and on natural biogeochemical cycling in the ocean.

- New, innovative concepts for sequestering CO_2 in the ocean need to be identified and developed.

Sequestration in Terrestrial Ecosystems. The terrestrial biosphere is a large and accessible reservoir for sequestering CO_2 that is already present in the atmosphere. Natural carbon fluxes are huge, so even small forced changes resulting from R&D advances would be very significant. It will be important to address the consequences of altering the natural flux.

- Carbon sequestration could be conceivably increased by several gigatonnes per year beyond the natural rate of 2 GtC/y, but this implies intensive management and/or utilization of a significant fraction of the globe's biomass. Emphasis should be on increasing the rate of long-term storage of C in soils in managed systems.

- Research on four key interrelated R&D topics is needed. (1) Increased understanding of ecosystem structure and function directed toward carbon allocation and partitioning. (2) Improved measurements of gross carbon fluxes and dynamic carbon inventories through improved methods, instrumentation and non-destructive belowground observation, (3) Use of new irrigation methods, efficient nutrient delivery systems, agricultural energy efficiency, and increased byproduct use. (4) Modeling (including life cycle analysis and ecosystem dynamics) of ecosystem response to carbon sequestration in an environment of changing climate.

- Field-scale experiments on large-scale ecosystems will be necessary to understand both physiological and geochemical processes regulating sequestration and to provide proof-of-principle testing of new sequestration concepts.

Sequestration in Geologic Formations. Limited geological sequestration is being practiced today, but it is not yet possible to predict with confidence storage volumes and integrity over long time periods. Many important issues must be addressed to reduce costs, ensure safety, and gain public acceptance.

- Fundamental and applied research is needed to improve the ability to understand, predict, and monitor the performance of sequestration in oil, gas, aqueous, and coal formations. Elements of such a program include multiphase flow in heterogeneous and deformable media; phase behavior; CO_2 dissolution and reaction kinetics, micromechanics and deformation modeling; coupled hydrologic-chemical-mechanical-thermal modeling; and high-resolution geophysical imaging. Advanced concepts should be included, such as enhancement of mineral trapping with catalysts or other chemical additives, sequestration in composite geologic formations, microbial conversion of CO_2 to methane, rejuvenation of depleted oil reserves, and CO2-enhanced methane hydrate production.

- A nationwide assessment is needed to determine the location and capacity of geologic formations available for sequestration of CO_2 from each of the major power-generating regions of the United States. Screening criteria for choosing suitable options and assessing capacity must be developed in partnership with industry, the scientific community, and public and regulatory oversight agencies.

- Pilot-scale field tests of CO_2 sequestration should be initiated to develop cost and performance data to help prioritize future R&D needs. The tests must be designed and conducted with sufficient monitoring, modeling, and performance assessment to enable quantitative evaluation of the processes responsible for geologic sequestration. Pilot testing will lay the groundwork for collaboration with industrial partners on full-scale demonstration projects.

Advanced Biological Processes. Advanced biological techniques may produce options too radical to predict. Some biological processes can sequester carbon products at low cost. New carbon sequestration options could become feasible and others could be improved using advanced biological techniques.

- Research should be initiated on the genetic and protein engineering of plants, animals, and microorganisms to address improved metabolic functions that can enhance, improve, or optimize carbon management via carbon capture technology, methods for sequestering in reduced carbon compounds, and use in alternative durable or recalcitrant materials.

- The objectives of advanced biological research should be linked to those specific problems and issues outlined for carbon sequestration in geologic formations, oceans, and soils and vegetation so that an integrated research approach can elucidate carbon sequestration at the molecular, organism and ecosystems levels.

- Short- and long-term goals in advanced biological research should be instituted so that scale-op issues, genetic stability in natural settings, and efficacy in the field can be addressed.

Advanced Chemical Concepts. Most carbon sequestration options rely on chemical reactions to achieve benign, stable, and inert products. Studies to enhance the relevant chemistry almost certainly will reduce the costs or increase the effectiveness of these options. Results from R&D on advanced chemical topics also may make it possible to generate useful and marketable byproducts.

- The proper focus of R&D into advanced chemical sciences and technologies is on transforming gaseous CO_2, or its constituent carbon, into materials that either are benign, inert, long-lived and contained in the earth or water of our planet, or have commercial value. Benign products should be developed since there is the potential to sequester large (gigatonne) amounts of anthropogenic carbon. Commercial products could potentially sequester millions of tonnes and have other collateral benefits tied to pollution prevention.

- The chemical sciences can fill crucial gaps identified in the other focus areas. In particular, environmental chemistry is an essential link in determining the impact and consequences of these various approaches.

SUMMARY. Given the federal government's role in supporting high-risk R&D in the long-term national interest, a carbon sequestration research and technology development program should be significantly expanded on the strength of the eventuality that such technology will be needed in the energy marketplace some time in the first quarter of the next century. This message is consistent with a recent report of the President's Council of Advisors on Science and Technology (PCAST, 1997) and other investigations. We should begin this R&D now, because the options available in 2025 and beyond will be determined by research being conducted today.

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FIGURE.

Figure 1. Deploying an effective carbon sequestration system will require an integrated program of science, enabling technology, and advanced power systems -- all dependent on better understanding of environmental carbon dynamics.