THE POTENTIAL ROLE

OF GEOLOGIC STORAGE AND CARBON DIOXIDE

IN A SUSTAINABLE FOSSIL FUELS FUTURE

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ABSTRACT

Various geologic settings are beginning to be examined as possible sinks for storage of CO_2. These include depleting and depleted oil and gas reservoirs, deep unmineable coal seams, and deep saline or brine formations. It is well known that there are many methanogens in nature which convert CO_2 to CH_4. Some of these are extremeophiles, existing at high temperatures and pressures. At least one has been the subject of genome mapping. It is also known that "directed development" is a methodology that is being utilized to develop "designer microbes" with selected or enhanced traits. The concept described here is that through a coordinated biological, chemical, and geophysical effort, either designer microbes or biomimetic systems can be developed to produce closed-loop fossil fuel systems. In such systems, geologic repositories of CO_2 could be converted to CH_4, thereby closing the fuel cycle in a sustainable manner.

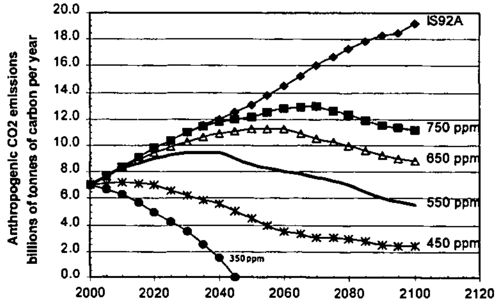
Keywords: carbon sequestration, global climate change, methanogenesis

INTRODUCTION

This paper is an early output from an ongoing investigation of the state-of-the-art related to the concept of geologic storage of CO_2 with subsequent conversion to methane. In most of the areas reviewed, the research has been performed for reasons other than that which is the focus of this paper–carbon management in response to global climate change. For example, hydrocarbon seeps have been studied to develop better oil exploration techniques, thermal vents have been studied to better understand their environmental impacts, and hydrocarbon emissions from natural sources have been studied for knowledge about global climate change.

We believe that there is a need and opportunity to bring together researchers and knowledge from diverse fields to identify and conduct focused scientific and technologic research to determine the potential of options discussed in this paper along with other novel concepts that may emerge.

Due to growing concern about the effects of increasing carbon dioxide in the atmosphere, the United States and 160 other countries ratified the Rio Mandate, which calls for " . . . stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." While the level of greenhouse gases that represents "stabilization" is open to debate, a range of 350-750 parts per million (ppm) is widely discussed. As shown in the various scenarios in Figure 1, all of these scenarios are significantly lower than a "business as usual" scenario (1S92A). When one considers the anticipated growth in the global population and the global economy over the next 50-100 years, even modest stabilization will require enormous amounts of fossil energy with very low greenhouse gas emissions. Many energy producers are now recognizing the major role that carbon sequestration must play if we are to continue to enjoy the economic and energy security benefits which fossil fuels bring to the world's energy mix.



Source: *Nature*, Volume 379, January 16, 1996, pp. 240-243

Figure 1. Scenarios for the Stabilization of Global Carbon

Under virtually any stabilization and market scenario, fossil fuels will remain the mainstay of energy production for the foreseeable future. To achieve any level of atmospheric stabilization that is ultimately deemed acceptable, there are three basic approaches: 1) reduce the carbon content of fuels, 2) improve the efficiency of energy use, and 3) capture and sequester the carbon. The approach of sequestration is comparatively new, and is now discussed as both a technology and policy option to mitigate global climate change (1). In the United States, sequestration has joined the first two approaches within the Department of Energy (DOE) as a valuable option, with funding of sequestration R&D activities (2). A report prepared jointly by the U.S. DOE Office of Science and the DOE Office of Fossil Energy (DOE/FE) identified five pathways to sequestration (3).

- Capture and sequestration
- Sequestration in geologic formations
- Ocean sequestration
- Sequestration in terrestrial ecosystems (soils and vegetation)
- Chemical, biological and other advanced concepts for CO_2 fixation or reuse.

Within the DOE/FE, the Carbon Sequestration Program has further delineated these research pathways and the current R&D activity within the pathways (4). Figure 2 shows the program's research areas. Together they cover the carbon sequestration life cycle of capture, separation, transport, and storage or reuse. A recent report by DOE/FE outlines the national needs, benefits, strategy, plans, and milestones for the program (5). Within this context is an emphasis on enhancing natural CO_2 sequestration processes, including enhancement of storage in various geologic formations, in soils and biomass, and through enhanced mineralization.

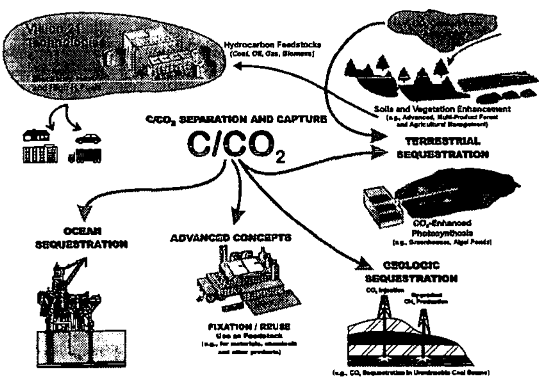


Figure 2. Carbon Sequestration Pathways

DISCUSSION

Natural CO_2 reservoirs are relatively common. They are in fact commercially exploited for CO_2 production for commodity use. In addition to these comparatively pure CO_2 reservoirs, CO_2 is found in many other formations. Reservoirs of various kinds exist throughout the world containing mixtures of CO_2, methane, and various other fluids. Many of these geologic settings are being examined as possible sinks for storage of CO_2. These include depleting and depleted oil and gas reservoirs, deep unmineable coal seams, and deep saline or brine formations. In one current commercial project CO_2 is being sequestered under the North Sea (1). The Norwegian oil company Statoil is recovering CO_2 from natural gas processing, and injecting approximately one million tons per year of CO_2 into a sandstone layer. This is a saline formation under the sea associated with the Sleipner West Heimdel gas reservoir. The amount being sequestered is equivalent to the output of a 250-MW gas-fired power plant.

Methanogenesis is a biological process which is widely found in nature. Methanogenic bacteria generate methane by several pathways, principally the fermentation of acetate and the reduction of CO_2 (6)(7). Generally a consortium, or food chain of microbial organisms, operates together to effect a series of biochemical reactions in the production of methane in energy-yielding cellular processes. Methanogens are anaerobic bacteria of the family Archaea, and are found in such diverse environments as landfills, digestive systems of animals, in deep ocean vents, and in coal seams. Chemosynthetic communities are found in close association with cold hydrocarbon seeps, for example, and demonstrate complex relationships that include the mineralization of CO_2 as well as methanogenesis (8). In one location, sampling of hydrocarbon gases from ocean-floor cold hydrocarbon seeps in Monterey Bay, California suggest that most of the methane produced is microbial in origin (9). In coal seams, methanogens may increase coalbed methane production. Laboratory study of microbially enhanced coalbed methane processes indicate that microbial consortia can increase gas production through conversion of coal and enhancement of formation permeability, leading to the potential for substantially increased methane production (10).

In general, methane in the earth's crust may be formed by both biogenic (that is, the conversion of organic matter) and abiogenic processes. The vast majority appears to be biogenic in origin, and results from a combination of microbial production and thermogenic processes (11). It is believed that 20% of the natural gas in the earth is from methanogens, of which 2/3 is by acetate fermentation and 1/3 by CO_2 reduction (7). While the portion generated by methanogen varies, there is strong evidence that it may be the predominant mechanism in some fields. For example, in the Terang-Sirusan Field in the East Java Sea, methane is generated exclusively by methanogens using the CO_2-reduction pathway (12). Furthermore, recent study of oil and gas fields in the Gulf of Mexico shed light on the rate of methane evolution. It appears that they may be significant recharge of reservoir methane in a timeframe (decades) that is significant to commercial uses (13).

Developments in genetic decoding, gene sequencing, identification of novel enzymes, and selection of desirable traits have the potential to result in enhanced CO_2 to CH_4 conversion processes. The potential exists for both improved biological processes using engineered biological systems, or processes that mimic biologically-based catalysts and processes (biomimetics). For example, advances in the "directed development" of microorganisms offers the potential for enhancing biochemical processes and pathways of interest for commercial applications (14).

In the area of biological or biomimetic advanced concepts, a number of potential CO_2 sequestration pathways have been discussed, including mineralization of CO_2 to carbonates. One such approach is the enzymatic catalysis of CO_2 to carbonic acid and thence to carbonate materials (15). A second major pathway is methanogenesis. Extremophile organisms have been isolated from deep-sea ocean vents where they live at high temperatures and pressures. One such organism, *Methanococcus jannaschii*, was first isolated at a hydrothermal vent in the Pacific Ocean, and is currently the subject of genome mapping under the U.S. DOE Microbial Genome Mapping Program (16). These extremophile characteristics may be compatible with conditions in oil- and gas-producing formations. Alternatively, compatible characteristics could be obtained through directed development.

The conceptual system proposed here would close the carbon-cycle loop for fossil energy by converting CO_2 produced by power plants into CH_4 for subsequent power production. It would consist of the following.

- The development of an enhanced microbial consortium to produce CH_4 at a commercially-useful rate.
- The use of depleting or depleted oil or gas reservoirs, or saline reservoirs, as storage sites for captured CO_2. CO_2 has historically been widely used in enhanced oil recovery operations.
- The use of the enhanced microbial consortium in a reservoir to convert the stored CO_2 to CH_4.
- The reservoir would largely be left alone for a period of 10 years to several decades while the microbial consortium operated, with reservoir monitoring to assess gas composition.
- As CH_4 evolved over time, it would be produced through the existing field well and collection structure.

Figure 3 depicts the general concept and the geologic setting. An alternative approach would be to perform the conversion above-ground in rapid-contact reactors. This would assume a biomimetic pathway with kinetics greatly enhanced over the reservoir approach.

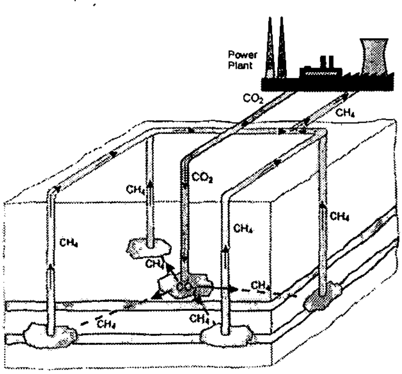


Figure 3. Closed-Loop-Carbon-Cycle Power Production

CONCLUSIONS

The attainment of "closed-loop" fossil fuel carbon cycles could provide the energy supply needed for economic security and environmental quality over the next century while renewable energy sources develop. Geologic storage of CO_2 with subsequent biological or biomimetic conversion to CH_4 would provide one such closed cycle. While there appears to be a sound fundamental basis for this and related approaches, several areas of research are indicated.

- A better understanding of emerging sequestration processes in various geological settings is required.

- The kinetics of known microbial conversions appear to be relatively slow; increases of many orders of magnitude will be required for processes of commercial scale.

- Related factors, such as growth cofactors needed to sustain a healthy microbial population, the source of hydrogen for CO_2 conversion, and the mechanisms to remove waste products in a geological setting must be determined.

- While the approach would build on natural geophysical and biochemical processes combined with novel or enhanced enzyme and energy pathways, our present understanding of these processes is fragmented in this context. A systematic assessment of the linkages and relationships of the geologic, chemical, and biological components will be necessary.

- Public acceptance of the process as a safe, benign mechanism for commercial-scale applications must be assured.

If these barriers can be resolved, the concept would provide significant benefits.

- The closed loop process would enable continued use of hydrocarbon fuels without requiring a totally decarbonized fuel product or total conversion of the energy infrastructure to a hydrogen-based economy.

- The approach would expand geologic sequestration options to include essentially unlimited value-added production of a fuel form (beyond what could be achieved through CO_2-enhanced oil recovery or CO_2-enhanced recovery of coal-bed methane, where CO_2 enhances production only of the existing gas- or oil-in-place).

- The process would support sustainable, closed-loop energy production without the large surface-area requirements and impacts of biomass, wind, or photovoltaic systems.

- When combined with other pathways to permanent sequestration (e.g., mineralization), it would provide a more robust basis for a zero-carbon fossil energy infrastructure.

The authors wish to interest researchers from various disciplines in beginning an open and extended dialogue on the potential of novel concepts, such as one discussed here, in developing science and technology options to mitigate global climate change. The role of novel science and technology approaches will be critical to the development of effective mechanisms to stabilize greenhouse gas concentrations.

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