PERGAMON

Energy Conversion and Management 44 (2003) 2699–2712

ENERGY CONVERSION & MANAGEMENT

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Integrated collaborative technology development program for CO_2 sequestration in geologic formations—United States Department of Energy R&D

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Received 10 October 2002; accepted 28 January 2003

Abstract

A major contributor to increased atmospheric CO_2 levels is fossil fuel combustion. Roughly one third of the carbon emissions in the United States comes from power plants. Since electric generation is expected to grow and fossil fuels will continue to be the dominant fuel source, there is growing recognition that the energy industry can be part of the solution to reducing greenhouse gas emissions by capturing and permanently sequestering CO_2. Consequently, an important component of the United States Department of Energy's (DOE) research and development program is dedicated to reducing CO_2 emissions from power plants by developing technologies for capturing CO_2 and for subsequent utilization and/or sequestration.

Injection of CO_2 into geologic formations is being practiced today by the petroleum industry for enhanced oil recovery, but it is not yet possible to predict with confidence storage volumes, formation integrity and permanence over long time periods. Many important issues dealing with geologic storage, monitoring and verification of fluids (including CO_2) in underground oil and gas reservoirs, coal beds and saline formations must be addressed. Field demonstrations are needed to confirm practical considerations, such as economics, safety, stability, permanence and public acceptance.

This paper presents an overview of DOE's research program in the area of CO_2 sequestration and storage in geologic formations and specifically addresses the status of new knowledge, improved tools and enhanced technology for cost optimization, monitoring, modeling and capacity estimation. This paper also highlights those fundamental and applied studies, including field tests, sponsored by DOE that are measuring the degree to which CO_2 can be injected and remain safely and permanently sequestered in geologic formations while concurrently assuring no adverse long term ecological impacts.
Published by Elsevier Science Ltd.

Keywords: Carbon dioxide sequestration; Geological media; Sedimentary basins

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0196-8904/03/$ - see front matter Published by Elsevier Science Ltd.
doi:10.1016/S0196-8904(03)00042-6

1. Introduction

Predictions of global energy use in this century suggest a continued increase in carbon emissions and rising concentrations of CO_2 in the atmosphere. A major contributor to increased greenhouse gas (GHG) emission levels is fossil fuel combustion. Roughly one third of the carbon emissions in the United States comes from power plants. Since electric generation is expected to grow and fossil fuels will continue to be the dominant fuel source, there is growing recognition that the energy industry can be part of the solution to reducing GHG emissions by capturing and permanently sequestering CO_2. Carbon sequestration holds great potential to reduce GHG emissions at costs and impacts that are economically and environmentally acceptable. The year 1997 represents the start of DOE's Office of Fossil Energy's (FE) formal Carbon Sequestration Program. The objective of the Carbon Sequestration Program is to provide long range options for drastically reducing CO_2 emissions from fossil fuel fired heat and power facilities [1,2].

The Carbon Sequestration Program is pursuing five technology pathways to reduce GHG emissions:

- Separation and Capture targets novel, low cost approaches for capture of carbon or CO_2 from energy production and conversion systems.
- Geologic Sequestration assesses the applicability and effectiveness of long term CO_2 storage in geological structures, such as oil and gas reservoirs, unmineable coal seams and deep saline aquifers.
- Terrestrial Sequestration examines the potential to enhance terrestrial uptake and retention of atmospheric CO_2 by coupling improved agricultural and forestry practices with fossil energy production and use systems.
- Oceanic Sequestration examines potential mechanisms for enhancing ocean uptake of atmospheric CO_2 or for deep ocean storage of liquid CO_2.
- Novel Sequestration Systems examines novel approaches to chemical, biological or other processes to recycle or reuse CO_2 produced by energy systems.

These five pathways encompass a broad set of opportunities for both technology development and partnership formation for national and international cooperation. A paper discussing the first of these pathways, separation and capture, was recently published [3]. This paper deals mainly with the second of these pathways, geologic sequestration. Summaries of technology developments emerging from the Carbon Sequestration Program are presented.

2. Sequestration of carbon dioxide in geologic formations

Geologic CO_2 sequestration involves the injection of CO_2 into geologic formations, the most important of which are deep coal seams, saline aquifiers and depleted oil and gas reservoirs. The estimated capacity of geologic formations (see Fig. 1) is large enough to store decades to centuries worth of emissions. These capacity estimates are likely to be conservative, as the CO_2 seques-

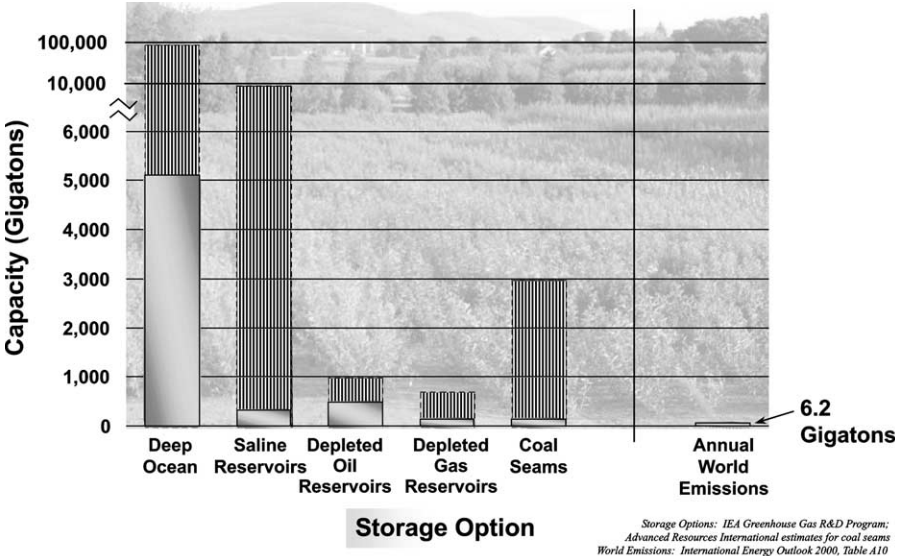

Fig. 1. Large potential worldwide storage capacity.

tration potential of geologic reservoirs depends on many factors that are, as yet, poorly understood. These include reservoir integrity, volume, porosity, permeability and pressure. Because these factors vary widely, even within the same reservoir, it can be difficult to establish a reservoir's storage potential with certainty.

Injection of CO_2 into geologic formations is being practiced today by the petroleum industry for enhanced oil recovery (EOR), but it is not yet possible to predict with confidence storage volumes, formation integrity and permanence over long time periods. Many important issues dealing with geologic storage, such as interactions between CO_2 and reservoir rock and other fluids and monitoring and verification of fluids (including CO_2) in underground oil and gas reservoirs, coal beds and saline formations, must be addressed.

Large scale field demonstrations are needed to confirm practical considerations, such as economics, safety, stability, permanence and public acceptance. Early tests will involve sequestration experiments in which collateral benefits are likely, such as storing CO_2 in depleted oil and gas reservoirs where additional hydrocarbons may be produced and sequestering CO_2 in coal seams in conjunction with coal bed methane (CBM) production. The main driver, however, is to ensure the safety of, and gain public acceptance for, large scale CO_2 sequestration projects. The purpose of DOE sponsored research in geologic sequestration is to provide answers to the many remaining questions.

The three major research thrusts of the geologic sequestration activity are:

- monitoring and verification;
- health, safety and environmental risk assessment;
- knowledge base and technology for CO_2 storage reservoirs.

3. Monitoring and verification

A critical R&D need is to develop a comprehensive monitoring and modeling capability that not only focuses on technical issues but also can help ensure that geologic sequestration of CO_2 is safe. Long term geologic storage issues, such as leakage of CO_2 through old well bores, faults, seals, or diffusion out of the formation, need to be addressed. Many tools exist or are being developed for monitoring geologic sequestration of CO_2, including well testing and pressure monitoring; tracers and chemical sampling; surface and bore hole seismic; and electromagnetic/geomechanical meters, such as tiltmeters. However, the spatial and temporal resolution of these methods may not be sufficient for performance confirmation and leak detection. Therefore, further monitoring needs include:

- high resolution mapping techniques for tracking migration of sequestered CO_2;
- deformation and microseismicity monitoring;
- remote sensing for CO_2 leaks and land surface deformation.

Fig. 2 provides an overview of the participants, approach and synergies for monitoring and verification projects within the DOE program. Following are descriptions of major projects aimed at developing effective monitoring tools and technologies, which hold high potential for improving our ability to characterize the location, quantity and condition of sequestered CO_2.

Sandia National Laboratory, Los Alamos National Laboratory, and the National Energy Technology Laboratory have partnered with an independent producer, Strata Production Company, to investigate down hole injection of CO_2 into a depleted oil reservoir, the West Pearl Queen Field, in New Mexico. A comprehensive suite of computer simulations, laboratory tests, field measurements and monitoring efforts will be used to understand, predict and monitor the geomechanical and hydrogeologic processes involved. Injection into this reservoir is planned through an inactive well, while a producing well and two shutoff wells will be used for monitoring. CO_2 migration and surface detection studies will be conducted by combining satellite visible light and infrared views with satellite radar and optical aerial photography. Remote geophysical surveys will attempt to detect and characterize changes in fluid saturation and pressure by observing the seismic response of the reservoir during injection. These observations will be used to calibrate, modify and validate modeling and simulation tools.

Use of new reservoir mapping and predictive tools (surface seismic and tracer injection) to develop a better understanding of the behavior of CO_2 in a geologic formation in conjunction with the Weyburn unit is being addressed by Natural Resources Canada and Dakota Gasification Company. Weyburn Field, in southwestern Saskatchewan, Canada, was discovered in 1954. Starting in 2001, several thousand tons per day of CO_2 are being pumped into this reservoir to produce incremental oil. The CO_2 is being transported by pipeline 330 km from the Great Plains Synfuels Plant in Beulah, North Dakota. It is expected that $\approx$50% of the CO_2 will remain sequestered with the oil that remains in the ground. The 50% that comes to the surface with the produced oil will come out of solution as the pressure drops and be recycled to the injection wells. This work will examine the way CO_2 moves through the reservoir rocks, the precise quantity that can be stored in a reservoir and how long the CO_2 could be expected to remain trapped in the underground formation.

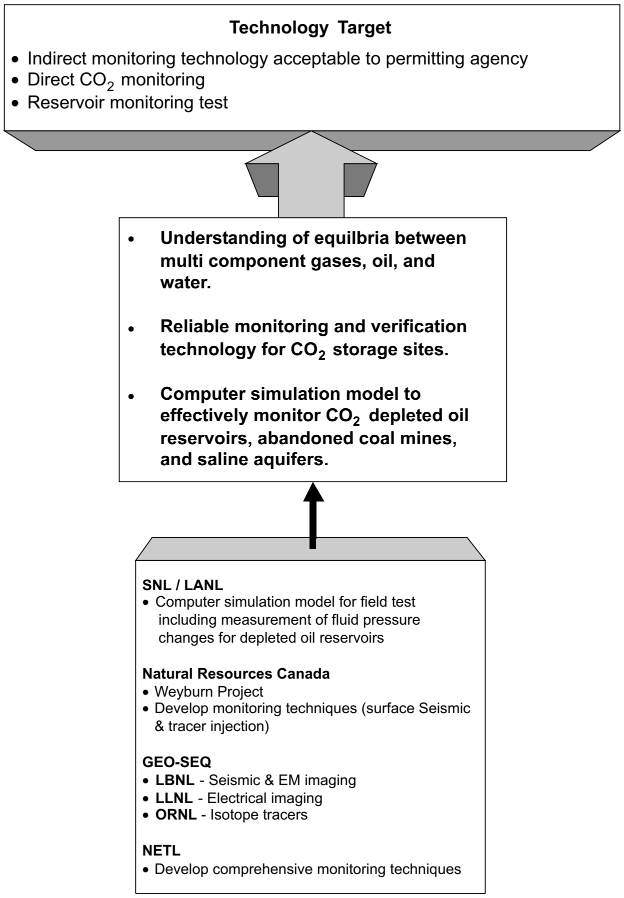

Fig. 2. Monitoring and verification.

Lawrence Berkley, Lawrence Livermore and Oak Ridge National Laboratories and their partners are developing innovative monitoring technologies to track migration of CO_2. Called GEO-SEQ, described later in conjunction with other major activities, the project will develop and use seismic techniques, electrical imaging and isotope tracers for optimizing value added sequestration technologies for brine, oil and gas and coal bed methane formations.

4. Health, safety and environmental risk assessment

Assessing the risks of CO_2 release from geologic storage sites is fundamentally different from assessing risks associated with hazardous materials, for which best practice manuals are often available. Because CO_2 is benign at low concentrations, a new framework for assessment, implementation and regulation will be needed.

Health, safety and environmental risk assessment is a process for identifying adverse health, safety and environmental consequences and their associated probabilities. The assessment of the risks associated with sequestration of CO_2 in geologic formations includes identifying potential subsurface leakage modes, likelihood of an actual leak, leak rate over time and long term implications for safe sequestration. Diagnostic options need to be developed for assessing leakage potential on a quantitative basis. Fig. 3 provides an overview of project participants, their approach, technology targets and the synergies involved in the DOE program.

Advanced Resources International is evaluating the effect of slow or rapid CO_2 leakage on the environment during initial operations or the subsequent storage period. The study will include a comprehensive and multi-disciplinary assessment of the geologic, engineering and safety aspects of natural analogs. Five large natural CO_2 fields, which provide a total 1.5 billion ft^3/day of CO_2 for EOR projects in the United States, have been selected for evaluation [4]. Based on the results of a geochemical analysis of CO_2 impacts and geomechanical modeling, an evaluation of environmental and safety related factors will be made.

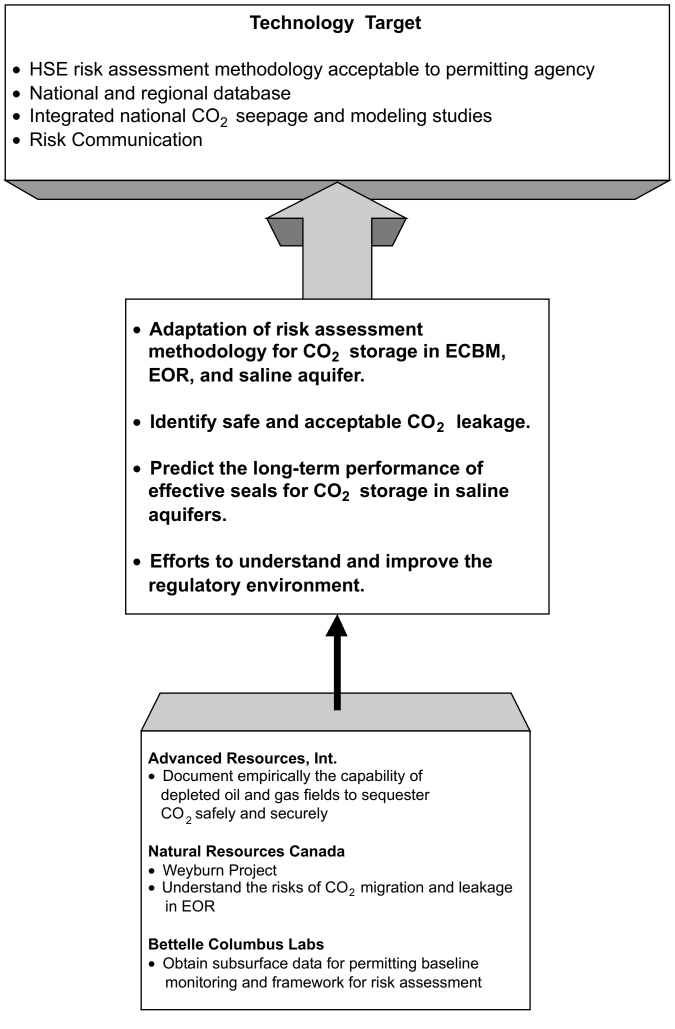

Fig. 3. Health, safety and envirnomental risk assessment.

The Weyburn project will focus on direct injection of CO_2 into a partially depleted carbonate reservoir in the Williston Basin as part of a large scale, commercial EOR operation in Saskatchewan. The miscible CO_2 EOR flood will be monitored from its inception to its conclusion. The study will confirm the ability of an oil reservoir to geologically contain, isolate and permanently store a significant amount of CO_2. It will produce a credible assessment of the permanent containment of injected CO_2, evaluated by long term predictive simulations and formal risk analysis techniques. Such an assessment will help answer questions by regulatory bodies as to the security of large volume CO_2 sequestration/storage, not only in the Williston Basin but also in other areas where geological similarities exist.

Battelle is leading a research team, which includes national laboratories, academia and the energy industry, to conduct site assessment to develop the baseline information necessary to make decisions about a potential CO_2 geologic sequestration demonstration and verification experiment in a saline aquifer. This project will be focused in the Ohio River Valley area, which is home to the largest concentration of coal based electricity generation in the nation. Tests will be conducted to comprehensively characterize the reservoirs, cap rocks and overlying layers. These and other fundamental issues will be used to develop and apply a comprehensive Risk Analysis and Stakeholder Involvement Process for the transport, injection and long term sequestration of CO_2 at a field demonstration site.

5. Knowledge base and technology for CO_2 storage reservoirs

The object for this group of projects is to increase the knowledge base and technology options for sequestering CO_2 in geologic formations. Fig. 4 presents a summary of projects being sponsored by the DOE program in the area.

6. Sequestration in deep coal seams

An attractive option for disposal of CO_2 is sequestration in deep, unmineable coal seams [5]. Not only do these formations have high potential for adsorbing CO_2 on coal surfaces, but the injected CO_2 can displace adsorbed methane, thus producing a valuable by-product and decreasing the overall cost of CO_2 sequestration. Because it has a large internal surface area, coal can store several times more CO_2 than the equivalent volume of a conventional gas reservoir.

To date, only a few experimental enhanced coal bed methane (ECBM) tests involving CO_2 injection have been conducted throughout the world. The sites for these tests show great potential for both CO_2 sequestration and ECBM production. Coal bed thickness is of great importance for ECBM production, both because thicker coal beds have greater volumes and, thus, yield more gas and because advanced production techniques are more applicable in thick coal beds. However, knowledge of this critical parameter is not available for the majority of deep unmineable coal seams.

CONSOL Energy Inc. has initiated a project on CO_2 ECBM production from unmineable coal seams. The world's CBM reserves are estimated at over 30,000 trillion ft^3, but much of this reserve is in coal seams deeper than 1000 m [6]. Efforts to produce CBM from these reservoirs have had

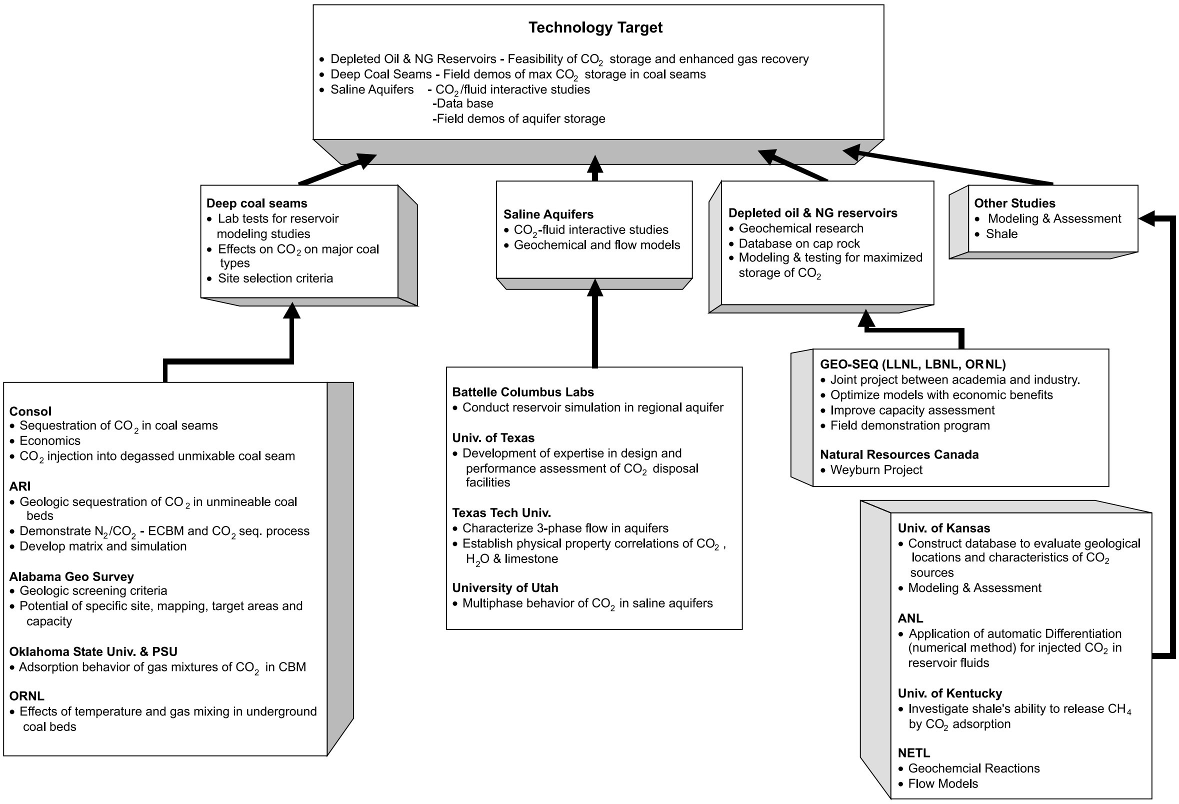

Fig. 4. Knowledge base and technology for CO_2 storage reservoirs.

only limited success because of very low reservoir permeability. A new approach, combining slant (horizontal) holes, hydrofracing with coiled tubing and carbon dioxide flooding is proposed to produce gas from deep, low permeability reservoirs. The project's objectives are to demonstrate the applicability of CBM production using this novel approach and to demonstrate that the injected CO_2 remains sequestered at the intended location.

Advanced Resources International (ARI) is conducting an important project related to storing CO_2 in coal beds. The ARI project involves field testing of injection of CO_2, N_2 and CO_2/N_2 blends into coal seams. The reason for considering N_2 in addition to CO_2 is that N_2 is also an effective methane displacer, and N_2 makes up 80–90% of most flue gas. If flue gas could be sequestered without the need for CO_2 separation and capture, costs could be reduced. The work plan involves analyzing data from field tests at three locations to understand reservoir mechanisms. Technical issues that need to be addressed in this study are flue gas conditioning, compression, delivery and N_2/CH_4 separation. Flue gas injection appears to enhance methane production to a greater degree than is possible with CO_2 alone, while still sequestering CO_2. The information obtained will be used to develop a universal screening model to assess the potential for coal bed CO_2 sequestration in the US. Once developed, the model will be disseminated for use by others.

The Geological Survey of Alabama is conducting a project whose primary goals are to develop a screening model that is widely applicable, to quantify the CO_2 sequestration potential of the Black Warrior CBM region and to use the screening model to identify favorable CO_2 sequestration demonstration sites. The CBM region of the Black Warrior basin is a logical location to develop screening criteria and procedures. According to the US Environmental Protection Agency, Alabama ranks ninth nationally in CO_2 emissions from power plants, and two coal fired power plants are within the CBM region. Production from the Black Warrior basin is now leveling off, and CO_2 injection has the potential to offset the impending decline and extend the life and geographic extent of the region far beyond current projections.

Oklahoma State University is leading an effort to investigate and test the ability of injected CO_2 to enhance CBM production. The specific focus of this project is to investigate the competitive adsorption behavior of methane, CO_2 and nitrogen on a variety of coals. Measurements are focused on adsorption of the pure gases and various mixtures. Data will be taken on coals of varying physical properties at appropriate temperatures, pressures and gas compositions to identify the coals and conditions for which CO_2 sequestration applications are the most attractive.

Mathematical models are being developed to accurately describe the observed adsorption behavior. The combined experimental and modeling results will be generalized to provide a sound basis for performing reservoir simulation studies. These studies will evaluate the potential for injecting CO_2 or flue gas into coal beds to simultaneously sequester CO_2 and enhance CBM production. Future computer simulations will assess the technical and economic feasibility of coal bed CO_2 sequestration at specific candidate injection sites.

Oak Ridge National Laboratory (ORNL) is conducting a program aimed at acquiring critically important technical information for assessing the feasibility of sequestering CO_2 in deep unmineable coal beds. Since this carbon management technology is still in the development phase, fundamental and applied research programs are needed to fill major knowledge gaps. To enable reliable numerical modeling of CO_2 enhanced natural gas production, the effect of CO_2/methane mixing on gas pressure and sorption reactions in deep coal beds must be known quantitatively. Existing computer models are not adequate for this purpose, and experiments must be performed to obtain the data needed to upgrade these models. A significant part of this project involves autoclave measurement of the behavior of CO_2/methane mixtures. The data will be used to predict the behavior of CO_2 when injected into coal beds containing methane.

7. Sequestration in saline aquifers

Another option for geologic sequestration of CO_2 is in saline aquifers. The idea that large aquifers with good top seals can provide effective sequestration sites is a relatively new concept. About two thirds of the US is underlain by deep saline aquifers that have significant sequestration potential [7]. Since the water from such aquifers is typically not suitable for irrigation and other uses, injection of CO_2 does not present a problem for potential future use. Because of the potential for CO_2 to dissolve in the aqueous phase, the storage capacity of saline aquifers is enhanced. However, there are a large number of uncertainties associated with the heterogeneous reactions that may occur between CO_2, brine and minerals in the surrounding strata, especially with respect to reaction kinetics.

There is a growing base of experience with CO_2 disposal in aquifers. One large project being carried out by Statoil involves recovering the CO_2 in natural gas from the Sleipner Vest offshore gas field in Norway at a rate of one million tonnes per year and reinjecting it into a nearby aquifer under the North Sea [8]. CO_2 migration is currently being monitored. Data from this project is contributing to the growing scientific confidence in the reliability of storing CO_2 in saline aquifers. However, more research, field testing, modeling and monitoring are needed to reduce the uncertainties relating to CO_2 storage in these formations.

Battelle Memorial Institute is managing an important project, the objective of which is to design an experimental CO_2 injection well and get it ready for permitting. Tasks involved include subsurface geologic assessment in the vicinity of the experimental site, seismic characterization of the site, borehole drilling to characterize the reservoir and cap rock formations, injection and monitoring system design and risk assessment. The proposed well site is to be located in the panhandle of West Virginia. This site has the advantage of providing access to both saline formations and deep coal beds. It is also in close proximity to a number of power plants that could serve as potential CO_2 sources. Another geologic factor in the vicinity of the site is the formation depth, at about 9000 ft, which provides significant cap rock containment potential and separation from freshwater. To obtain a more realistic assessment of CO_2 breakthrough, a 2-D seismic survey will be performed; a 3-D or 4-D survey will also be performed in preparation for future injection.

The Bureau of Economic Geology at the University of Texas is leading a research team to conduct a CO_2 sequestration field demonstration in a brine bearing formation near Houston, Texas. Two experiments will be conducted, the first involving a small volume of CO_2 using a single well for both injection and monitoring and the second using one well for injection and a second up-structure well for monitoring CO_2 migration. Response will be monitored both within the injection sandstone bed and in an overlying thin sandstone bed.

The study site provides for a rapid startup by using existing idle wells and has a low risk of adverse impacts because injection will take place in a hydrologically isolated reservoir compartment of a well known geologic structure. This project will extend the demonstration of modeling and monitoring capabilities for sequestration into a geologic formation for which very large scale sequestration is feasible in an area where significant CO_2 is produced. Texas is the state with the largest volume of CO_2 emissions [9].

Texas Technical University is conducting a project to develop a well logging technique using nuclear magnetic resonance (NMR) to characterize geologic formations, including the integrity and quality of the cap rock. Since well logging using NMR does not require coring, it can be performed more quickly and efficiently. Prior studies have identified several issues as impediments to the economic viability of sequestering CO_2 in deep saline aquifers and other geologic formations. These issues include the injection rate, the pressure required to achieve an economic throughput and how to assure the long term containment of CO_2. This research is aimed at determining suitable sites for injection of CO_2, sites at which artificial zones of high permeability can be created by controlled hydraulic fracturing. Hydraulic fracturing could reduce the number of injection wells required by an order of magnitude.

The University of Utah is heading a project that is studying naturally occurring CO_2 saline aquifers in the Colorado Plateau and Southern Rocky Mountains. These formations serve as natural analogs for CO_2 sequestration in saline aquifers. Studying them can provide much useful data to verify computer models. Also, small amount of natural leakage from these reservoirs is occurring, and studying these leaks can provide insight into the environmental problems caused by leaks, under what circumstances leaks can occur and how they can be mitigated. The project also includes numerical simulation of CO_2 sequestration in these formations, including reactive modeling, that is modeling that accounts for chemical reactions between the formation rocks and CO_2.

8. Sequestration in depleted oil and gas reservoirs

Yet another option for geologic sequestration of CO_2 is in depleted oil and gas reservoirs. Since such formations are generally gas tight, the risk of leakage is expected to be minimal. Furthermore, there is the potential for enhanced oil and gas production, the sale of which can help mitigate sequestration costs. Most EOR projects in the US are in the Permian Basin of Texas. Most of the CO_2 for these projects is being transported by pipeline from natural CO_2 reservoirs in Colorado, New Mexico and Wyoming. It is anticipated that, with high oil prices, recovery of CO_2 using the flue gas of coal burning power plants could be profitable for EOR use in the region.

The GEO-SEQ Project is being conducted by a consortium of national laboratories, educational institutions, and private industry firms. The project's goal is to reduce the cost of sequestration, develop a broad suite of sequestration options and ensure that long term sequestration practices are effective and do not introduce any new environmental problems. This objective is being approached by dividing the effort into four targeted interrelated tasks: cost optimization, monitoring technology, performance assessment models and capacity assessment. One important task is to develop methods for simultaneously optimizing sequestration of CO_2 in depleted oil and gas fields and increased oil and gas production. Such methods would have obvious multiple benefits. Results will lay the groundwork for rapidly evaluating performance at candidate sequestration sites, as well as monitoring the performance of CO_2 enhanced oil and gas recovery.

Natural Resources Canada is conducting a study of the injection of CO_2 into the Weyburn Unit. Understanding the mechanism, reservoir storage capability and the economics of CO_2 sequestration requires mapping the migration and distribution of the existing formation fluids, as well as the injected fluids. The project is focused on the acquisition of information from the enhanced oil recovery operation, on conducting geological, geophysical and geochemical assessments and on reservoir model simulations.

9. Other studies

DOE is also supporting other related studies. These mainly involve computer model development and project assessment.

The Midcontinent Interactive Digital Carbon Atlas and Relational Data Base (MIDCARB) is a joint project among the Geological Surveys of Illinois, Indiana, Kansas, Kentucky and Ohio being coordinated by the University of Kansas. The purpose of MIDCARB is to enable the evaluation of the potential for carbon sequestration in the participating states. When completed, the digital spatial data base will allow users to estimate the amount of CO_2 emitted by major sources in relation to geologic reservoirs that can provide safe and secure sequestration over geologic time periods. MIDCARB is organizing and enhancing critical information about CO_2

sources and developing the technology needed to access, query, model, analyze, display and distribute natural resource data related to carbon management.

Argonne National Laboratory is working on the development of improved computer models of the sequestration process. There is growing interest in linking reservoir flow models to geochemical models. If the formation has an aqueous phase, the injected CO_2 will dissolve in the reservoir liquid. In this case, the reactions of the CO_2-rich fluid with the host rock to form minerals should also be considered. More importantly, a geological CO_2 storage reservoir simulation must be effective in developing a design for optimal injection. The key element in finding the optimal CO_2 injection scheme is to work with an inverse modeling and sensitivity analysis tool for forward mode reservoir simulations.

Argonne National Laboratory is applying automatic differentiation (AD) as an alternative to the usual finite difference method of calculating derivatives. This technique will interface with existing geological CO_2 sequestration models to improve both the accuracy and speed of derivative computations. By using the new models generated by the AD method, it is possible to automatically determine the sensitivities of reservoir simulation output variables to any given independent input parameter, thus making the computer design of an optimal CO_2 storage scheme feasible.

The University of Kentucky Research Foundation is conducting an analysis of Devonian black shale in Kentucky for its potential for CO_2 sequestration and methane production. In testing the hypothesis that organic rich shales can adsorb significant amounts of CO_2 while releasing methane, the objective will be to characterize the shale, determine its CO_2 adsorption isotherm, the relationship of shale properties to CO_2 adsorption capacity, the effect of CO_2 adsorption on methane release and whether there are zones in the shale that have higher CO_2 adsorption capability and the extent of such zones.

The National Energy Technology Center (NETL) is pursuing a number of projects aimed at increasing the knowledge base relative to geologic sequestration of CO_2. One project, being conducted jointly with the US Geological Survey, has the objective of conducting an experimental study to assess the role of the chemistry of formation water on CO_2 solubility and the role of rock mineralogy in determining the potential for CO_2 sequestration through geochemical reactions. Another project being pursued in conjunction with a number of other organizations is aimed at providing guidelines for drilling new CBM production wells and determining what factors contribute to poor methane production/CO_2 sequestration performance. A third project, being conducted with West Virginia and Clarkson Universities, is aimed at building a system of flow equations relevant for core and field studies that incorporates unstable pore level flow patterns and to compare results with those of experiments and existing flow theory. A fourth project, involving Clarkson and Pennsylvania State Universities and CONSOL Energy Inc., has the objective to optimize the quantity of CO_2 that can be sequestered, the economic viability of coal bed sequestration, and the environmental acceptability of the technology.

10. BP carbon capture project, an example of integrated collaboration

An important cross-cutting driver for CO_2 sequestration R&D is integrated collaboration. An excellent example of this is the BP Carbon Capture Project (CCP). DOE is a partner in the CCP, an international technology development effort, involving the US, Norway and the European Union and directed toward the development of CO_2 capture and sequestration technology [10]. The objective is to share in program development in order to leverage funding and results and reduce duplication. BP, Chevron-Texaco, ENI (Italy), Shell, Norsk Hydro (Norway), Pan Canadian (Canada), Statoil (Norway) and Suncor (Canada) have formed the CCP, recognizing the advantages in pooling resources, experience and innovation to make the delivery of the needed technology more efficient and to provide the best opportunity for success.

The approach of the CCP is to define relevant scenarios and technology targets, solicit proposals and make awards. Technology teams, using various economic models, provide continuous project evaluation so that resources can be concentrated on the most promising technologies. Fig. 5 presents an overview of projects being conducted by the CCP. This figure shows that the CCP incorporates a wide spectrum of activities, involving all the areas already discussed. In general, these projects have smaller budgets and a shorter time frame than the projects discussed previously. The idea is to generate information that can feed into other development work as rapidly as possible.

Some projects are examining problems associated with long term monitoring and verification of formation integrity. A project is underway to develop a new method of monitoring gas injection

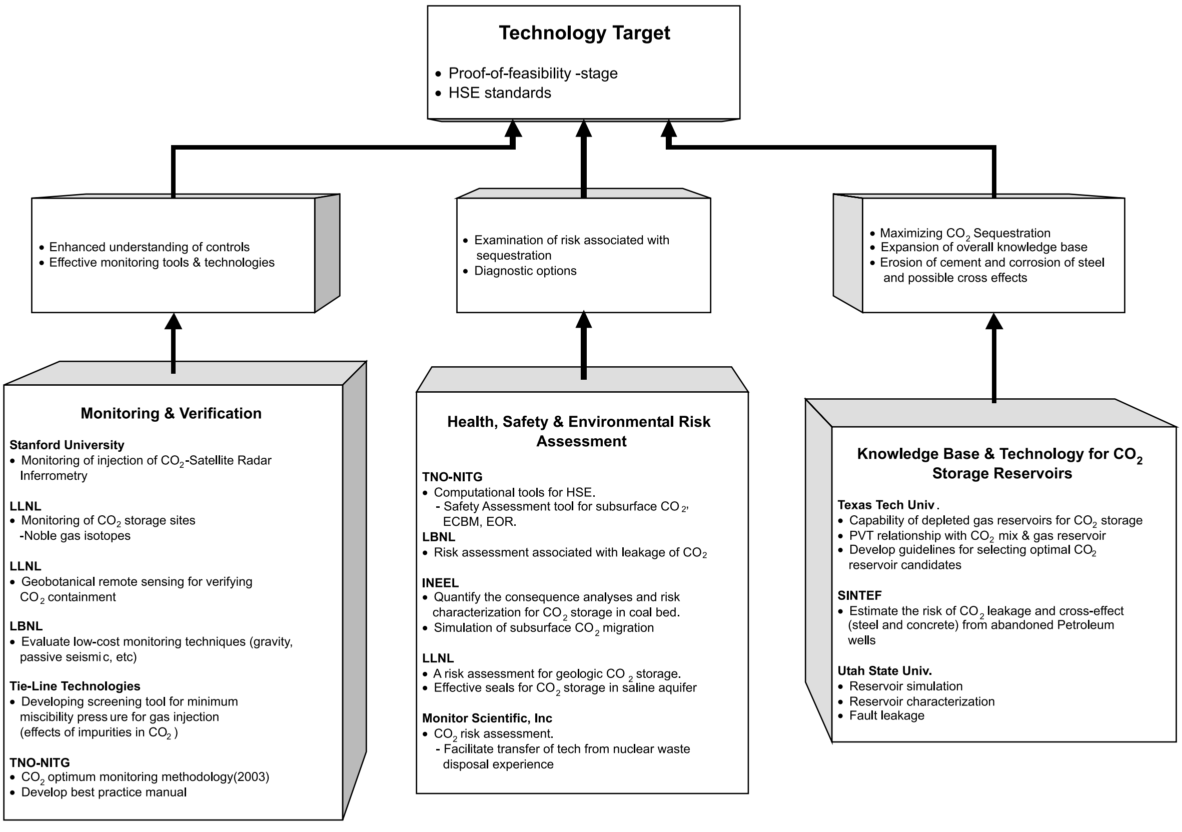

Fig. 5. BP carbon capture project (CCP).

using space borne satellite radar technology. This approach will permit observation of changes in surface elevation as small as 1 cm at 20 m spacing over an area 100 km square, so that the spatial distribution of elevation changes may be mapped in detail.

Another project is developing methodology and computational tools for health, safety and environmental risk assessment of geological CO_2 sequestration in various geologic strata of the North Sea region. This work will be integrated with the parallel system analysis activities of the Weyburn project.

11. Conclusions

The DOE Carbon Sequestration Program is developing a portfolio of technologies that hold great potential for the permanent sequestration of CO_2 in geologic formations. The programmatic timeline is to demonstrate a series of safe and cost effective greenhouse gas mitigation technologies at the commercial scale by 2012, with deployment leading to substantial market penetration beyond 2012. Developments are directed toward substantial improvement in performance and costs compared to the current state-of-the-art. Wide deployment of these technologies holds great promise to slow the growth of GHG emissions to the atmosphere in the near term while ultimately leading to stabilized emissions towards the middle of the 21st century. This paper has presented a brief overview of the portion of the DOE Carbon Sequestration Program dedicated to geologic storage of CO_2. More details on these and other R&D projects in the portfolio can be found at the referenced web site [2].

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