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Project Title: **AN ASSESSMENT OF GEOLOGICAL CARBON SEQUESTRATION OPTIONS IN THE ILLINOIS BASIN (PHASE I)**

ICCI Project Number: DEV03-2
Principal Investigator: Robert J. Finley, Illinois State Geological Survey
Other Investigators: Scott M. Frailey, Illinois State Geological Survey
Project Manager: Ronald H. Carty, ICCI

ABSTRACT

Midwest Geological Sequestration Consortium (MGSC) has investigated the options for geological carbon dioxide (CO_2) sequestration in the 60,000-mi^2 Illinois Basin. Within the Basin, underlying most of Illinois, western Indiana, and western Kentucky, are deep uneconomic coal resources, numerous mature oil fields, and deep saline reservoirs potentially capable of storing CO_2. The objectives of the *Assessment* have been to determine the technical and economic feasibility of using these geological sinks for long-term storage to avoid atmospheric release of CO_2 from fossil fuel combustion and thereby avoid the potential for adverse climate change.

The MGSC is a consortium of the geological surveys of Illinois, Indiana, and Kentucky joined by six private corporations, five professional business associations, one interstate compact, two university researchers, two Illinois state agencies, and two consultants to assess carbon capture, transportation, and storage processes, and their costs and viability, in the three-state Illinois Basin region. The Illinois State Geological Survey served as Lead Technical Contractor for the Consortium. The Illinois Basin region has annual emissions exceeding 276 million metric tons of CO_2 (>70 million metric tons carbon equivalent), primarily from coal-fired electric generation facilities, some of which burn almost 5 million tons of coal per year. Assessing the options for capture, transportation, and storage of the CO_2 emissions within the region has been a 12-task, two-year process that has assessed 3,600 million (M) tonnes storage capacity in coal seams, 140 to 440 Mtonnes capacity in mature oil reservoirs, 7,800 Mtonnes capacity in two saline reservoirs beneath oil field structures, and 30,000 to 35,000 Mtonnes capacity in saline reservoirs on regional dip deeper than 4,000 ft.

The major part of this effort assessed each of the three geological sinks: coals, oil reservoirs, and saline reservoirs. We linked integrated options for capture, transportation, and geological storage with the environmental and regulatory framework to define sequestration scenarios and potential outcomes for the region. Extensive use of GIS and visualization technology was made to convey results to project sponsors, other researchers, the business community, and the general public. An action plan for possible technology validation field tests involving CO_2 injection was embodied in a Phase II proposal (successfully funded) to the Department of Energy with cost share from ICCI.

EXECUTIVE SUMMARY

The Midwest Geological Sequestration Consortium (MGSC) has investigated the options for geological carbon dioxide (CO_2) sequestration in the 60,000-mi^2 Illinois Basin. Within the Basin, underlying most of Illinois, western Indiana, and western Kentucky, are deep uneconomic coal resources, numerous mature oil fields, and deep saline reservoirs potentially capable of storing CO_2. The objectives of the *Assessment* have been to determine the technical and economic feasibility of using these geological sinks for long-term storage to avoid atmospheric release of CO_2 from fossil fuel combustion and thereby avoid the potential for adverse climate change. Assessing the options for capture, transportation, and storage of the CO_2 emissions within the region has been a 12-task, two-year process under Phase I of a Department of Energy (DOE)-funded Regional Carbon Sequestration Partnership with cofunding from the Illinois Office of Coal Development through the Illinois Clean Coal Institute (ICCI).

Within the Illinois Basin, underlying most of Illinois, southwestern Indiana, and western Kentucky, are deep uneconomic coal resources, numerous mature oil fields, and deep saline reservoirs potentially capable of storing CO_2. The Illinois Basin region has annual emissions exceeding 276 million metric tons of CO_2 (>70 million metric tons carbon equivalent) from fixed sources, primarily from 122, mostly coal-fired, electric generation facilities, some of which burn almost 5 million tons of coal per year. Most of these plants are equipped with pulverized coal boilers and use a simple steam cycle, and the flue gas from these plants contains about 14% CO_2. The distribution of emissions from these plants is highly skewed such that the 4 largest plants emit about 22% of total CO_2 emissions, the 13 largest plants emit more than 50% of total CO_2 emissions, and the 30 largest plants emit over 80% of total CO_2 emissions. CO_2 separation and capture from flue gases of various stationary sources can be described by either post-combustion or pre-combustion configurations. For PC plants, the post-combustion MEA process is the most technically and economically viable process for CO_2 capture however this process carries substantial costs due to the parasitic load imposed on the plant. A techno-economic study conducted for a 533 Mw (gross) Illinois-coal fired plant indicates a cost of electricity of 52 mills/kwh without capture and 91 mills/kwh with MEA absorption. The cost of CO_2 avoidance was \$54/tonne for the PC+MEA plant and \$36/tonne for the oxy-combustion plant, both 533 Mw (gross). The cost of electricity for a 533 Mw Illinois-coal fired IGCC+physical absorption (Selexol) plant is lower than for a PC+MEA plant at 64 mills/kwh, and the cost of CO_2 avoidance is \$17/tonne.

Transportation of CO_2 from capture sites to storage locations for other than limited pilot-scale and feasibility testing will be by pipeline. For pilot-scale testing, including field demonstration activities during Phase II, transportation will be by truck in combination with on-site storage in portable tanks in order to meet the injection schedule of the field test. To assess the approximate costs of pipeline transportation in the Illinois Basin, a 200-mile hypothetical pipeline length was selected from near Pekin, Illinois to Edwards County, southeastern Illinois, in the vicinity of multiple storage options. Considered were details of route selection and design, various capacity options, geohazards such as subsidence from coal mining, wall thickness increase needed in populous areas, and pressure drop with distance vs. pump station requirements. Permits required, right of way type and dimensions, construction practices, land use and compensation required (as for crops lost during construction), and operating costs were all assessed. For reference, the flow capacity of an 18 inch-diameter pipeline would be about 340 million scfd.

The opportunity to sequester CO_2 in coals judged unminable is based on both technical and economic considerations and could be supported by production of coalbed methane displaced from these coals. With respect to defining unminable coal, no consideration is given to coals shallower than 500 ft in depth. From 500 to 1,000 ft in depth, coals from 1.5 to 3.5 ft are considered sequestration targets. Maps and numerical assessments have been prepared of sequestration capacity by seam in tonnes per acre, and these maps generally reflect the configuration of the basin with the deepest coals in southeastern Illinois in the area along the Indiana border. Highest values exceed 1,000 tonnes CO_2 per acre. Highest methane production potential exceeds 2 million scf per acre in the same area.

Enhanced Oil Recovery (EOR) offers the most important economic offset to the costs associated with carbon sequestration in the Illinois Basin. To assess this potential, a basin-wide EOR assessment was made based on a new understanding of the original-oil-in-place (OOIP) in the basin, the CO_2 stored volume, the assessed EOR resource, the geographic distribution of EOR potential, the type of recovery mechanism (miscible vs. immiscible), and the daily EOR injection rate as a measure of CO_2 demand. The resource target for all three categories of EOR is 860 to 1,300 million barrels recoverable with consequent sequestered volume of 140 to 440 million tonnes of CO_2. The distribution of the unrecovered EOR resource has also been mapped by field with larger fields holding multiple reservoirs comprising a larger target. With CO_2 EOR projects linked to sequestration, an understanding of CO_2 demand has also been modeled. Modeling of demand for "new" CO_2 for five of the Illinois Basin oil reservoir studies shows that demand falls off rapidly after two to five years. Initial injection rate for immiscible floods may require 100-200 Mscf/day/stb-OOIP and miscible floods may require 250-500 Mscf/day/stb-OOIP.

Three major salt water-filled, or saline, reservoirs in the Illinois Basin were reviewed as potential CO_2 storage reservoirs: the Ordovician St. Peter Sandstone and the Cambrian Ironton-Galesville and Mt. Simon Sandstones. In addition, data were collected on the potential seals for these reservoirs. The St. Peter Sandstone is a widespread, porous and permeable sandstone that is generally fine-grained and has good lateral continuity. It can vary in thickness across the Illinois Basin from 100 to as much as 400 ft in thickness. Seals above the St. Peter include several hundred feet of dense limestone and dolostone overlain by 150 to 250 ft of Maquoketa Shale. The Ironton and Galesville Sandstones form a usable aquifer in northern Illinois and can have a combined thickness of over 200 ft. However, it was found that these units are thin and are not present in the central and southern parts of the basin so further consideration of them in the context of sequestration is not appropriate. Mt. Simon reservoir quality is expected to decline with depth based on porosity vs. depth plots; although data are limited below 6,000 ft, Mt. Simon at the Manlove Gas Storage Field does show porosity of about 9% in the 6,000-6,500 ft depth range. There are perhaps no more than 20 penetrations of the Mt. Simon in the southern part of the Illinois Basin, thus reservoir quality data are limited. Extrapolating studies of natural gas storage reservoirs in the Mt. Simon over the Illinois basin suggest a capacity of 5.9 Btonnes in the Mt. Simon and 1.9 Btonnes in the St. Peter in structural traps. An additional 28 to 33 Btonnes may be trapped by dissolution below 4,000 ft outside of structural traps and below deep natural gas storage, even in areas where no such storage is present.

An integrated study of capture and transportation costs was also carried out. The average cost of the sequestration process without byproduct recovery is about $53/tonne CO_2 sequestered. The cost of capturing CO_2 from power plants contributes to about 90% of the total sequestration costs. The average transportation and injection costs are less than 3% and 12%, respectively, of the total sequestration cost, depending on level of control. One of the reasons for the low cost of transportation is the rich geological storage structure in the Illinois Basin. The scattered geological fields in the Basin make the average transportation distance relatively short. For example, when no byproduct benefit is considered, the average transportation distance is only 13.6 miles for a 10% emission control level.

Finally, a module of six activities was developed for education and outreach on the topic of CO_2 sequestration and will be piloted in a series of educator workshops to be held during Phase II. In collaboration with educators and consortium members, the module will be refined and vetted for final publication and widespread use. The Phase II workshop plan is a comprehensive effort to educate teachers throughout the Illinois Basin area. The materials are designed for use in any of the three states and are tied to their specific learning standards and to national learning standards in an easy-to-read matrix. The materials are posted on the MGSC website and will continue to be updated and refined as new information becomes available and feedback from workshop participants is incorporated.

OBJECTIVES

The objectives of Phase I of the *Assessment* have been to determine the technical and economic feasibility of using these geological sinks for long-term storage to avoid atmospheric release of CO_2 from fossil fuel combustion and thereby avoid the potential for adverse climate change. Assessing the options for capture, transportation, and storage of the CO_2 emissions within the region has been a 12-task, two-year process under Phase I of a Department of Energy (DOE)-funded Regional Carbon Sequestration Partnership with cofunding from the Illinois Office of Coal Development through the Illinois Clean Coal Institute (ICCI).

Early Phase I work focused on database development and assessment of carbon capture and transportation options in the region. All available work on carbon capture technology and costs was compiled. Transportation focused on both truck and rail options for field tests and pipeline requirements for long-term sequestration. The primary effort under Phase I focused on the three geological sinks: coals, oil reservoirs, and saline reservoirs. The incremental coalbed methane and Enhanced Oil Recovery (EOR) recoverable resource was assessed in addition to the CO_2 volumes that may be sequestered. Finally links were created between capture, transportation, and geological storage to define sequestration scenarios and potential outcomes for the region. Extensive use of GIS technology was made to develop results for project sponsors, other researchers, the business community, and the general public. Two project-sponsored conferences were held to specifically inform public stakeholders of project results as part of a program of education and outreach carried out by MGSC members. Phase I results will, of course, flow directly into Phase II activities that have been designed to implement small-scale field testing of coal seam injectability, EOR processes, and the ability to inject into, and secure, small test volumes of CO_2 delivered to one of several saline reservoir targets.

INTRODUCTION AND BACKGROUND

The Midwest Geological Sequestration Consortium (MGSC) is a consortium of the geological surveys of Illinois, Indiana, and Kentucky joined by six private corporations, five professional business associations, one interstate compact, two university researchers, two Illinois state agencies, and two consultants to assess carbon capture, transportation, and storage processes, and their costs and viability, in the three-state Illinois Basin region. The Illinois State Geological Survey has served as Lead Technical Contractor for the Consortium.

The MGSC has investigated the options for geological carbon dioxide (CO_2) sequestration in the 60,000-mi^2 Illinois Basin. Within the Basin, underlying most of Illinois, southwestern Indiana, and western Kentucky, are deep uneconomic coal resources, numerous mature oil fields, and deep saline reservoirs potentially capable of storing CO_2. The Illinois Basin region has annual emissions exceeding 276 million metric tons of CO_2 (>70 million metric tons carbon equivalent) from fixed sources, primarily from 122, mostly coal-fired, electric generation facilities, some of which burn almost 5 million tons of coal per year. The Midwest Geological Sequestration Consortium-Illinois Basin (MGSC) has focused on the potential of deep, unminable coal seams to adsorb gaseous CO_2, the ability to coax more oil from old fields by CO_2 flooding, and the injection of CO_2 into saline reservoirs some 7,000 to 9,000 ft below the surface. Injection into deep coals may help produce methane to augment natural gas supplies. Injection into old oil fields will help recover some of the approximately 10 billion barrels of oil remaining in Illinois Basin reservoirs. These activities will accomplish sequestration while also helping to meet the nation's need for fossil fuels. The integrity of the entire process of CO_2 injection will be scrutinized in detail to understand what contribution Illinois Basin geological sinks can make to national and international goals in accomplishing carbon sequestration and what technology developed here can be extrapolated to other regions.

Carbon Capture

About 90 percent of the CO_2 emissions from fixed sources in the Illinois Basin are derived from coal-fired power plants (Table ES-1). Most of these plants are equipped with pulverized coal boilers and use a simple steam cycle, and the flue gas from these plants contains about 14% CO_2. The distribution of emissions from these plants is highly skewed such that the 4 largest plants emit about 22% of total CO_2 emissions, the 13 largest plants emit more than 50% of total CO2 emissions, and the 30 largest plants emit over 80% of total CO_2 emissions. The largest coal-fired power plant in the Illinois basin is the Rockport plant in Spencer Co., Indiana, which emits about 16 Mtonnes annually. The 10 percent of CO_2 emissions in the Illinois Basin from non-power generation sources include 5 refineries, 23 iron and steel plants, 8 cement plants, 1 lime plant, 2 aluminum plants, 1 ammonia plant, and 8 ethanol plants. Much of the ethanol plant production of CO_2 is captured for use in food products and for dry ice, and ethanol plants will be a likely source for CO_2 for Phase II small-scale field demonstration testing. Because the gas steam from an ethanol plant is >90% CO_2, the cost of capture is relatively low, estimated to be about $13.92/ton for a plant with 100 million gallon/year production capacity.

CO_2 separation and capture from flue gases of various stationary sources can be described by either post-combustion or pre-combustion configurations. Oxygen-enriched coal combustion can also be considered as a special case of the pre-combustion concept. For the power generation sector, the selection of a capture concept mainly depends on the power generation process used; for most industrial emission sources, post-combustion capture is potentially the most suitable option. Techno-economic assessments were made for three power generation scenarios: post-combustion capture from a pulverized coal (PC) boiler with an MEA absorption process, pre-combustion removal from an integrated gasification combined cycle process with a membrane reactor, and an oxygen-rich combustion process.

For PC plants, the post-combustion MEA process is the most technically and economically viable process for CO_2 capture however this process carries substantial costs due to the parasitic load imposed on the plant. A techno-economic study conducted for a 533 Mw (gross) Illinois-coal fired plant indicates a cost of electricity of 52 mills/kwh without capture and 91 mills/kwh with MEA absorption. Burning coal in an oxygen-enriched atmosphere is a potentially attractive technology for producing a CO_2-enriched flue gas for sequestration. The cost of electricity was estimated to be 81 mills/kwh for a similarly sized oxy-combustion power plant. The cost of CO_2 avoidance was $54/tonne for the PC+MEA plant and $36/tonne for the oxy-combustion plant, both 533 Mw (gross). The cost of electricity for a 533 Mw Illinois-coal fired IGCC+physical absorption (Selexol) plant is lower than for a PC+MEA plant at 64 mills/kwh, and the cost of CO_2 avoidance is $17/tonne.

Cost of electricity for the PC+MEA plant and the oxycombustion plant was determined to be independent of the type of coal used, either Illinois No. 6 or Powder River Basin (PRB). The CO_2 avoidance cost for the Illinois coal was slightly lower than for the PRB coal. An IGCC plant+Selexol process burning high-sulfur Illinois coal was more attractive than burning PRB coal as the elemental sulfur by-product is considered a salable commodity. Finally, the results of a sensitivity analysis demonstrated the impact on CO_2 avoidance cost of the heat of absorption of the MEA solvent and the energy consumption of the air separation unit at an oxy-combustion plant. A 50% reduction in heat of adsorption for MEA and 50% lower energy consumption in the air separation unit of an oxy-combustion plant would result in 27% and 37% reductions, respectively, in CO_2 avoidance cost for these two processes.

Transportation of CO_2

Transportation of CO_2 from capture sites to storage locations for other than limited pilot-scale and feasibility testing will be by pipeline. For pilot-scale testing, including field demonstration activities during Phase II, transportation will be by truck in combination with on-site storage in portable tanks in order to meet the injection schedule of the field test. An 18-wheel highway tank truck carries approximately 20 tons of liquid CO_2 whereas pipelines can be sized to deliver millions of tons per year of CO_2, as are the pipelines serving EOR projects in the Permian Basin of West Texas. To assess the approximate costs of pipeline transportation in the Illinois Basin, a 200-mile hypothetical pipeline length was selected from near Pekin, Illinois to Edwards County, southeastern Illinois, in the vicinity of multiple storage options. Considered were details of route selection and design, various capacity options, geohazards such as subsidence from coal mining, wall thickness increase needed in populous areas, and pressure drop with distance vs. pump station requirements. Permits required, right of way type and dimensions, construction practices, land use and compensation required (as for crops lost during construction), and operating costs were all assessed. For reference, the flow capacity of an 18 inch-diameter pipeline would be about 340 million scfd.

Finally, pipeline operating costs will be nominal compared to installation, but it is important to quantify those operating costs. If the inlet pressure were to be 2,500 psig and the minimum delivery pressure were to be 1,500 psig, which would maintain a liquid state, then intermediate compression would not be required for a 20-inch line in the sample case. Based on a recent 140 mile, 6-inch liquefied petroleum gas pipeline, operating costs are estimated to be $667/inch diameter/mile per year. The resulting costs for different line capacities are noted in Table ES-4.

Costs for CO_2 delivered by truck are approximately $80 to $82/ton based on the experience at the Frio Brine Pilot, Houston, Texas. Lower-cost options may be available in the Illinois Basin based on collaboration with new ethanol plants seeking markets for their CO_2 output, but this would require trucking arrangements outside of existing transportation arrangements for food grade CO_2.

Coalbed Sinks and Methane Production Options

The Illinois Basin includes substantial coal resources, with the State of Illinois holding the largest bituminous coal resource of any state, 211 billion short tons. Extraction techniques range from surface mines to room-and-pillar and longwall subsurface mining with most mining having occurred around the margins of the basin. Most of the basin's remaining resources are moderate to high in sulfur content therefore market share has been lost to low-sulfur western coal from the Powder River Basin and Illinois coal production has declined by half since 1990. The opportunity to sequester CO_2 in coals judged unminable is based on both technical and economic considerations and could be supported by production of coalbed methane displaced from these coals. With respect to defining unminable coal, no consideration is given to coals shallower than 500 ft in depth. From 500 to 1,000 ft in depth, coals from 1.5 to 3.5 ft are considered sequestration targets. A seam less than 3.5 ft in thickness would require specialized equipment to mine and would be costly to develop relative to seams of greater thickness which remain an abundant part of the resource base. Below 1,000 ft in depth, seams greater than 3.5 ft in thickness are a sequestration target, given the abundance of shallower resources that will be cheaper and more easily accessible for future mining.

Key characteristics of seven coals were mapped throughout the Illinois basin, including thickness, depth, elevation, moisture content, ash content, heating value, temperature, and expected reservoir pressure. Most data were available for the Herrin (No. 6) and Springfield (No. 5) coals, the major coal seams in the basin. High-vol bituminous coal samples were tested and existing data compiled, and results suggest that the adsorption isotherms for CO_2 are up to about 4.5 times greater for CO_2 than for methane. Gas contents for Illinois Basin coals are in the range of 100-150 scf/ton for the better samples while CO_2 adsorption capacity can range from 450-700 scf/ton at 300 psi. Permeability is an issue for Illinois Basin coals and COMET simulator modeling shows distinctly different breakthrough patterns for CO_2 injection based on permeability alone. Typical initial conditions for simulator modeling were thickness of 3.6 ft, depth of 652 ft, total porosity of 3%, permeability of 3 md, and area of ¼ of a 10-acre injection pattern. Output curves illustrated cumulative water production, cumulative CO_2 injection, cumulative CO_2 production after breakthrough, and cumulative methane production for various sets of conditions. Maps and numerical assessments have been prepared of sequestration capacity by seam in tonnes per acre (Table ES-5), and these maps generally reflect the configuration of the basin with the deepest coals in southeastern Illinois in the area along the Indiana border. Highest values exceed 1,000 tonnes CO_2 per acre. Highest methane production potential exceeds 2 million scf per acre in the same area.

Oil Reservoir Sinks and Oil Recovery Options

Enhanced Oil Recovery (EOR) offers the most important economic offset to the costs associated with carbon sequestration in the Illinois Basin. To assess this potential, a basin-wide EOR assessment was made based on a new understanding of the original-oil-in-place (OOIP) in the basin, the CO_2 stored volume, the assessed EOR resource, the geographic distribution of EOR potential, the type of recovery mechanism (miscible vs. immiscible), and the daily EOR injection rate as a measure of CO_2 demand. Oil recovery as a factor (E_R) and CO_2 storage as a factor (E_S) can be applied to the OOIP volume to estimate storage potential and oil recovery potential. Important to estimating these key factors has been detailed geological and reservoir modeling using reservoir descriptions for major reservoir types, reservoir pressure and temperature, and fluid properties of a generalized Illinois Basin crude oil. Also, general industry "rules of thumb" based on actual CO_2 injection and production response in West Texas have been applied to check results against field experience in the Permian Basin. A published estimate of 12 billion bbls OOIP has long been held for the Illinois Basin but reassessment of that volume now suggests that OOIP is closer to 14.1 billion bbls (Table ES-6).

With cumulative production for the basin of about 4.2 billion bbls, a nearly 10 billion bbl resource remains, primarily as unrecovered resources in known fields. To assess recovery potential of a part of this resource, and the concurrent stored CO_2 volumes, reservoir modeling and computational simulation were carried out. Parts of nine fields were used to create generic geologic models for the most prolific reservoirs in the Basin, the Aux Vases and Cypress Sandstones and the St. Genevieve Limestone. These models incorporated data from about 750 total wells, 145 wells with core, 3,200 core points, 12,000 field acres, and 22 flow zones. Structure and isopach maps were developed deterministically whereas porosity and permeability distributions were developed geostatistically for the reservoir simulator. Processes simulated were miscible and immiscible flooding, based on reservoir pressure and temperature, and both continuous and water-after-gas CO_2 injection. The nine study areas were parts of Dale, Griggs, Iola, Johnsonville, Mill Shoals, Olney, Sailor Springs, Wakefield, and Zeigler fields. Deterministic reservoir description created necessary maps and cross sections and geostatistical description created 3D descriptions of porosity and permeability required for geocellular modeling of primary, secondary, and tertiary (CO_2 EOR) recovery. E_R generally fit with the West Texas rules of thumb of 10% of OOIP or 25% of primary plus secondary (waterflood) recovery. Separate calculations were made for immiscible and miscible EOR conditions (Table ES-7).

It should be noted that immiscible conditions are believed to prevail at depths less than 2,000 ft, near miscible in the 2,000-3,000 ft depth range, and miscible conditions at greater than 3,000 ft. Further detailed studies may define the immiscible-miscible boundary more clearly, but for the moment the near-miscible category will be used because pressure and temperature gradients have been found to vary sufficiently with the basin such that general rules cannot always be applied. The distribution of OOIP by miscibility suggests 6.4 to 7.5 Bstb of immiscible oil, 3.5 to 4.1 Bstb of near miscible oil, and 2.1-2.5 Bstb of miscible oil. The resource target for all three categories of EOR is 860 to 1,300 million barrels recoverable with consequent sequestered volume of 140 to 440 million tonnes of CO_2 (Table ES-8).The distribution of the unrecovered EOR has also been mapped by field with larger fields holding multiple reservoirs comprising a larger target.

With CO_2 EOR projects linked to sequestration, an understanding of CO_2 demand has also been modeled. During EOR projects, as in West Texas, CO_2 is produced and recycled. If CO_2 is recycled then the largest demand for CO_2 is early in the project, and reinjection capability will have a significant impact on project economics and volumes actually sequestered. Modeling of demand for "new" CO_2 for five of the basin oil reservoir studies shows that demand falls off rapidly after two to five years. Initial injection rate for immiscible floods may require 100-200 Mscf/day/stb-OOIP and miscible floods may require 250-500 Mscf/day/stb-OOIP.

Deep Saline Reservoir Sinks

Three major salt water-filled, or saline, reservoirs in the Illinois Basin were reviewed as potential CO_2 storage reservoirs: the Ordovician St. Peter Sandstone and the Cambrian Ironton-Galesville and Mt. Simon Sandstones. In addition, data were collected on the potential seals for these reservoirs. The St. Peter Sandstone is a widespread, porous and permeable sandstone that is generally fine-grained and has good lateral continuity. It can vary in thickness across the Illinois Basin from 100 to as much as 400 ft in thickness. Seals above the St. Peter include several hundred feet of dense limestone and dolostone overlain by 150 to 250 ft of Maquoketa Shale. The Ironton and Galesville Sandstones form a usable aquifer in northern Illinois and can have a combined thickness of over 200 ft. However, it was found that these units are thin and are not present in the central and southern parts of the basin so further consideration of them in the context of sequestration is not appropriate.

The Mt. Simon Sandstone is commonly used for natural gas storage in the Illinois Basin. The Mt. Simon has fair to good permeability and porosity, and the overlying strata contain impermeable limestone, dolomite, and shale intervals. The Mt. Simon should be an appropriate reservoir in which to test injection of carbon dioxide. The depth of the Mt. Simon ranges from less than 2,000 to deeper than 14,000 feet below the surface, and it is a fresh water aquifer in the northern part of the Illinois Basin. Areas of fresh water resource are, of course to be avoided, as are areas where natural gas storage occurs; excluding these parts of the basin still leaves approximately the southern half of the basin where the reservoir is brine-filled and no oil or natural gas resources have ever been discovered in this unit. At its thickest point in the Illinois Basin the Mt. Simon is over 2,600 feet thick. The Mt. Simon does not crop out in Illinois, but correlative units are exposed in southern Wisconsin, southeastern Minnesota, and Missouri. The Mt. Simon is known in the subsurface throughout Indiana, Iowa, Michigan, and Ohio. Depending on the locality, the sandstone strata in the Mt. Simon can vary from fine to coarse grained.

There also appears to be zones of predominantly finer grained sandstone and coarser sandstone. Between some sandstone strata are thin beds of dark grey shale laminae and other lower reservoir quality deposits that would act as baffles to buoyant CO_2 and may disperse CO_2 injected low in the reservoir. The Mt. Simon Sandstone was deposited on an unconformity, an irregular erosional surface on the Precambrian basement, that was filed in as Mt. Simon deposition proceeded, creating some risk that the Mt. Simon is thin or absent in otherwise structurally favorable CO_2 storage sites. Seismic data will be essential to evaluate Mt. Simon storage sites during Phase II assessments and beyond.

Mt. Simon reservoir quality is expected to decline with depth based on porosity vs. depth plots; although data are limited below 6,000 ft, Mt. Simon at the Manlove Gas Storage Field does show porosity of about 9% in the 6,000-6,500 ft depth range. There are perhaps no more than 20 penetrations of the Mt. Simon in the southern part of the Illinois Basin, thus reservoir quality data are limited. One well, the Texaco Johnson No. 1 well at Salem field, has been studied intensively. The top of the Mt. Simon in this well is at 8,400 ft and the well penetrates about 850 ft of Mt. Simon. While the upper part of the sandstone shows negligible porosity, a lower 150 ft interval has log porosities up to 14% and averages around 10%. Location of test sites and long-term sequestration sites must take into account both thickness variation and reservoir quality variation within the Mt. Simon Sandstone. Importantly, internal heterogeneity in this unit may help in the retention and dispersal of any injected CO2, and this will be taken into account during further reservoir modeling as part of Phase II.

The ~ 20 mi^2 Manlove Gas Storage Field is an excellent analog for structural trapping of CO_2 as may occur during the sequestration process and has been studied extensively to take advantage of the well logs, core, reservoir mineralogy, water chemistry, and other data available from the field operator. The Manlove data were used to develop estimates of CO_2 trapping capability assuming an analogous structure such as might be found at depth below many of the major oil fields in the basin where EOR may take place. Stacking of these sinks is important with respect to cost offsets for pipeline delivery infrastructure and the possibility that stored CO_2 may be available for EOR as a commodity as the EOR process is demonstrated and implemented. A Mt. Simon structure like Manlove would trap about 15 Mtonnes of CO_2 as free phase until water was displaced to spill point leaving irreducible water saturation in the pore space. Capillary trapping of CO_2 in the transition zone below the free-phase contact is assessed at 7 Mtonnes. Below the transition zone, CO_2 is projected to dissolve in the formation water trapping another 12 Mtonnes for a total of about 34 Mtonnes CO_2 trapping potential in an analogous structure. Extrapolating these mechanisms over the Illinois basin suggest a capacity of 5.9 Btonnes in the Mt. Simon and 1.9 Btonnes in the St. Peter in structural traps. An additional 28 to 33 Btonnes may be trapped by dissolution below 4,000 ft outside of structural traps and below deep natural gas storage, even in areas where no such storage is present.

The abundant information from Manlove has allowed detailed compositional simulation (using Landmark Graphics' VIP software) to assess disposition of CO_2 within the Mt. Simon. The Mt. Simon has often been described in terms of reservoir vs. seal, the latter represented by the overlying Eau Claire Shale, which is a correct concept only at a large scale of description. Detailed, 2D modeling of a 225 ft thick Mt. Simon interval using 3 ft x 600 ft cells shows that CO_2 disperses laterally based on internal heterogeneities that represent impediments to vertical flow. The Mt. Simon is not uniform internally and has a distinct zonation of reservoir quality that needs to be better understood. Clearly, this finding will have great importance during Phase II field testing and subsequent planning for any large-scale sequestration activities.

Finally, an assessment of deep fault structure and seismicity in the Illinois Basin was conducted to help evaluate the integrity of deep saline reservoirs like the Mt. Simon that may be underlain by a basement fault. An assessment was made of observable spatial associations between earthquake parameters and subsurface structure as deduced from geological and geophysical data bases. Risks to sequestration storage sites would correlate to the degree to which faults with observable displacement propagate from Precambrian basement up into Paleozoic strata and the proximity of the faults to known areas of seismicity. Based on Phase I work, the fold structures along the La Salle anticlinal trend may present some risk for release of CO_2 stored in the deep Mt. Simon Sandstone which rests just above the basement-sedimentary cover contact, and this determination will need to be factored into storage site decisions.

Linked Capture-Transportation-Storage Options

An integrated sequestration process includes capture, transportation, and injection of CO_2 into geological reservoirs. The links between different emission sources and sinks, as well as different transportation routes, impact the economic performance of the sequestration process. A linkage assessment was designed to optimize the integrated CO_2 sequestration process in the Illinois Basin by determining the most economical distribution of captured CO_2, at capture levels ranging from 10 to 50%, among representative identified storage fields.

A commercial software package, LINGO, was used to optimize the integrated CO_2 sequestration system. All of the power plants and the 24 largest storage fields in the Basin were considered. The cost of CO_2 capture (90% reduction) from coal-fired power plants and pipeline transportation were obtained from an earlier techno-economic study completed by the MGSC in October 2004. The CO_2 capture costs ($40-60/tonne) were based on an amine-based process (MEA). The loss of electricity capacity in the Basin due to the installation of MEA plants was not included in the optimization study. Sequestration costs were evaluated with and without byproduct credits from enhanced oil recovery (EOR) and enhanced coal bed methane recovery (ECBM). A 30-year life span was considered for pipelines and the MEA process.

Results from the optimization study are summarized in Tables ES-9 and ES-10. The average cost of the sequestration process without byproduct recovery is about $53/tonne CO_2 sequestered. The cost of capturing CO_2 from power plants contributes to about 90% of the total sequestration costs. The average transportation and injection costs are less than 3% and 12%, respectively, of the total sequestration cost, depending on level of control. One of the reasons for the low cost of transportation is the rich geological storage structure in the Illinois Basin. The scattered geological fields in the Basin make the average transportation distance relatively short. For example, when no byproduct benefit is considered, the average transportation distance is only 13.6 miles for a 10% emission control level.

Due to the low cost of the pipeline transportation, the locations of power plants became less important compared with the scale of the plants. It was found that the storage of CO_2 emissions from the 20 largest power plants in the Basin provides the optimum sequestration cost. The economics of the sequestration process significantly improves ($38 to $50/tonne CO_2 sequestered) when the byproduct credits from the EOR ($20/tonne CO_2) and CBMR ($15/tonne CO_2) are included, especially at 10% emission control level (Table ES-10).

Results from a sensitivity analysis revealed that the CO_2 capture cost has the most impact on the overall cost of the of the sequestration process. The impact of the CO_2 capture cost is more pronounced with increasing level of CO_2 emissions control. At the 50% control level, there is a direct relationship between projected sequestration cost and percent reduction in capture cost. This observation indicates that future efforts to reduce the sequestration cost should be focused on developing more cost-effective capture technologies.

Education and Outreach

Our educational materials are centered on teaching about the sequestration process as well as dispelling commonly held misconceptions about climate change and ozone layer depletion. The materials developed reflect the specifics of the Illinois Basin region and are designed to mirror the research conducted in Phase I. The materials are further designed to be used by all three states participating in the MGSC: Illinois, Indiana, and Kentucky. The MGSC materials make connections between the concepts of climate change, physical geology and sequestration. Middle school and high school students will learn and understand concepts such as greenhouse gases, climate change, geologic structures, water quality permeability, porosity, and the geology of the Illinois Basin and how to relate them to our choice to test geologic sequestration in the MGSC region. The educator workshops conducted in Phase II will utilize the materials produced in Phase I and will also incorporate sequestration education materials from other partners in the MGSC, Keystone, and additional outsides sources.

A module of six activities was developed and will be piloted in a series of educator workshops to be held during Phase II. In collaboration with educators and consortium members, the module will be refined and vetted for final publication and widespread use. The Phase II workshop plan is a comprehensive effort to educate teachers throughout the Illinois Basin area. The materials are designed for use in any of the three states and are tied to their specific learning standards and to national learning standards in an easy-to-read matrix. The materials are posted on the MGSC website and will continue to be updated and refined as new information becomes available and feedback from workshop participants is incorporated. The three major educational outreach goals of being ready to plan and conduct workshops and carry out educational information delivery at the beginning of Phase II have been met. In addition, demonstrations of EOR, the nature of CO_2, and others modified from other DOE-supported work were presented at a Project Advisory Group and two public meetings. These demonstrations were well received and served as an ice-breaker for the meetings.

RESULTS AND DISCUSSION

Carbon Capture-Tasks 1 and 2

Table ES-1. CO_2 emissions in the U.S. and the Illinois Basin.

Sources	U.S. total tonnes	Illinois Basin tonnes	Basin to U.S. (%)	Industry (%) of Basin
Power generation	2,239,700,000[1]	254,260,000[2]	11.4	92.1
Coal	1,868,400,000[1]	249,216,000[2]	13.3	90.3
Natural Gas	299,100,000[1]	4,996,000[2]	1.7	1.8
Oil	72,200,000[1]	48,000[2]	0.1	0.02
Industries				
Refinery	184,918,000[3]	9,703,000[4]	5.2	3.5
Iron and steel	54,411,000[5]	3,857,000[6]	7.1	1.4
Cement	42,898,000[5]	3,245,000[6]	7.6	1.2
Ammonia	17,652,000[5]	214,000[6]	1.2	0.1
Aluminum	4,223,000[5]	820,000[6]	19.4	0.3
Lime	12,304,000[5]	273,000[6]	2.2	0.1
Ethanol	8,383,000[5]	3,734,000[7]	44.5	1.4
Total	**2,564,489,000**	**276,106,000**		**100**

About 90 percent of the CO_2 emissions from fixed sources in the Illinois Basin are derived from coal-fired power plants. The 10 percent of CO_2 emissions in the Illinois Basin from non-power generation sources include 5 refineries, 23 iron and steel plants, 8 cement plants, 1 lime plant, 2 aluminum plants, 1 ammonia plant, and 8 ethanol plants. Much of the ethanol plant production of CO_2 is captured for use in food products and for dry ice, and ethanol plants will be a likely source for CO2 for Phase II small-scale field demonstration testing. Because the gas steam from an ethanol plant is >90% CO2, the cost of capture is relatively low, estimated to be about $13.92/ton for a plant with 100 million gallon/year production capacity.

Transportation of CO_2-Task 3

Table ES-2. Summary of costs per mile for an Illinois Basin CO2 pipeline

Diameter (inches)	Right-of-way ($)	Materials ($)	Construction ($/mile)	Services ($)	Total cost ($)
4	36,713	24,303	85,071	29,217	175,304
6	36,713	47,630	115,915	38,049	238,307
8	44,500	79,370	141,753	47,812	313,435
10	44,500	115,424	173,476	56,678	390,078
12	51,731	159,084	210,730	67,447	488,992
16	66,750	247,199	275,533	88,422	677,905
18	66,750	310,766	306,206	95,721	779,444
20	66,750	381,893	336,354	102,050	887,047
22	66,750	460,465	365,978	107,183	1,000,375
24	66,750	546,136	395,601	121,018	1,129,505

A breakdown of the component costs per mile for a pipeline carrying liquid CO_2 at a nominal 1,900 psig shows that materials can exceed construction costs for larger diameters.

Table ES-3. Cost per inch-diameter mile and total cost for the sample Illinois Basin pipeline.

Diameter	($/mile)	($/diameter inch/mile)	($million /200 miles)
4	175,304	43,826	35
6	238,307	39,718	48
8	313,435	39,179	63
10	390,078	39,008	78
12	488,992	40,749	98
16	677,905	42,369	136
18	779,444	43,302	156
20	887,047	44,352	177
22	1,000,375	45,472	200
24	1,129,505	47,063	226

The total cost for the sample 200-mile pipeline is indicated in Table ES-3. Table ES-2 and ES-3 will be used to compare installation costs for various pipeline capacities, and eventually calculate the most economic transportation approach for CO_2.

Table ES-4. Pipeline annual operating costs for the sample Illinois Basin pipeline.

Diameter (inches)	($/mile)	($/200 miles)
4	2,667	533,333
6	4,000	800,000
8	5,333	1,066,667
10	6,667	1,333,333
12	8,000	1,600,000
16	10,667	2,133,333
18	12,000	2,400,000
20	13,333	2,666,667
22	14,667	2,933,333
24	16,000	3,200,000

The resulting costs for different line diameters relate to throughput, hence varying operating costs occur.

Coalbed Sinks and Methane Production Options-Task 4

Table ES-5. Methane recovery and sequestration potential for major coal seams in the Illinois Basin

Illinois Basin Seam	**ECBM recoverable (Bscf)**	**CO_2 storage (Tscf)**	**CO_s storage (Mtonnes)**
Danville/Baker	807	8	440
Hymera/Jamestown/Paradise	200	2	110
Herrin	902	10	518
Springfield	1,251	13	717
Survant	1,081	11	582
Colchester	1,274	13	667
Seelyville/Davis	1,163	11	602
Illinois Basin Totals			
Illinois	6,032	62	3,300
Indiana	361	3	186
Kentucky	286	3	152
TOTAL	**6,680**	**68**	**3,638**

Maps and numerical assessments have been prepared of sequestration capacity by seam in tonnes per acre in order to assess coalbed sinks and methane production options. Detailed maps will be available on CD showing the spatial distribution of capacity, which is concentrated in southeastern Illinois.

Enhanced Oil recovery-Task 5

Table ES-6. Distribution of original oil in place assessed by field size in the Illinois Basin. A total of 81 fields with OOIP of 25 million bbls or more would be major targets for CO_2 EOR.

Original Oil in Place	
OOIP **MMstb**	**Number of** **Fields**
>750	4
100-750	15
50-100	24
25-50	38
<25	>1000
14.1 Bstb	~1500 oil fields

A published estimate of 12 billion bbls OOIP has long been held for the Illinois Basin but reassessment of that volume now suggests that OOIP is closer to 14.1 billion bbls. The stored CO_2 volumes combined with reservoir modeling and computational simulation were used to assess recovery potential of a part of this resource.

Table ES-7. Oil recovery, E_R, and CO_2 storage, E_S, factors for the Illinois Basin.

Oil Recovery and CO_2 Storage Factors via Modeling Compared to West Texas Rules of Thumb					
Oil Recovery Factors			**CO_2 Net Utilization**		
Zone	**Imm**	**Misc**	**Zone**	**Imm**	**Misc**
Cyp	4.5-5.9	8.6-11	Cyp	1.7-3.1	4.6-9.0
A-V	5.6-7.1	11-15	A-V	1.5-3.3	4.6-8.8
St. G	5.0-6.5	8.6-16	St. G	1.4-5.4	4.6-9.2
W Tx	4-10	8-16	W Tx	5-10	
Bbl of oil produced per bbl of OOIP			Mscf of CO_2 stored per bbl oil produced		

Calculations made for immiscible and miscible EOR conditions. Miscibility depends on pressure and temperature conditions in each reservoir, which can be assessed in a general way from regional gradients but must be determined for each reservoir to precisely determine miscibility conditions.

Table ES-8. Recoverable oil target and sequestered CO_2 volume based on geologic and reservoir modeling, Illinois Basin.

CO_2 EOR and CO_2 SV (Distribution)		
Condition	**CO_2 Mtonne**	**EOR Bstb**
Miscible	58-180	0.24-0.387
Near	53-153	0.28-0.40
Immiscible	29-110	0.34-0.49
Total	140-440	0.86-1.3

The resource target for all three categories of EOR is 860 to 1,300 million barrels recoverable with consequent sequestered volume of 140 to 440 million tonnes of CO_2. This represents up to 25 percent of cumulative production of approximately 4.2 billion barrels.

Linked Capture-Transportation-Storage Options-Tasks 6-7-8

Table ES-9. Summary of CO_2 sequestration cost without byproduct credits.

Emission control level	50% (128.44MMT/Y)	25% (64.02MMT/Y)	10% (28.75MMT/Y)
Capture Cost $MM/Y	6055.8	3018.4	1506.6
Transportation Cost $MM/Y	137.81	33.06	7.3
Injection Cost $MM/Y	642.1	320.1	143.7
Total Cost $MM/Y	6835.8	3371.5	1426.3
Average cost $/ton CO_2 sequestered	53.2	52.7	52.4

A summary of the optimization study results.

Table ES-10. Summary of CO_2 sequestration cost with byproduct credits.

Emission control level	50% (128.4MMT/Y)	25% (64.0MMT/Y)	10% (27.0MMT/Y)
Capture Cost $MM/Y	6055.8	3018.4	1275.2
Transportation Cost $MM/Y	138.7	47.3	26.6
Injection Cost $MM/Y	230.7	-91.3	-276.20
Total Cost $MM/Y	6425.3	2974.3	1025.7
Average cost $/ton CO_2 sequestered	50.0	46.5	37.9

A summary of the optimization study results. The credits are based on enhanced recovery of coalbed methane and enhanced oil recovery from known fields. Saline reservoir storage does not yield salable products hence the byproduct credit is zero for the Mt.Simon or St. Peter Sandstones as storage reservoirs.

Additional reports will be produced to meet U.S. Department of Energy reporting requirements. These reports will include: 1) a detailed final report of results with more in-depth report of research outcomes and data documentation; 2) a topical report on the linkage of sources and the 24 largest structural geologic sinks in the Illinois Basin; 3) a paper on seismicity and deep basin structure, and 4) a CD of digital map products that will be developed as part of the conclusion of Phase I of the project. These products are due to DOE by December 31, 2005, and should be available following DOE review and approval.

CONCLUSION AND RECOMMENDATION

The Midwest Geological Sequestration Consortium-Illinois Basin (MGSC) has developed a framework within which to assess geological storage of CO_2 in deep coal seams, mature oil fields, deep saline reservoir formations of the Illinois Basin. With major funding from the U.S. Department of Energy and the Illinois Office of Coal Development, and led by the geological surveys of Illinois, Indiana, and Kentucky, MGSC has focused the ability of these types of reservoirs to serve as sinks for some of the 276 million tons of annual CO_2 emissions from fixed sources in the Illinois Basin. This includes the potential of deep, unminable coal seams to adsorb gaseous CO_2, the ability to coax more oil from old fields by CO_2 flooding, and the injection of CO_2 into saline reservoirs some 7,000 to 9,000 ft below the surface. Injection into deep coals may help produce methane to augment natural gas supplies. Injection into old oil fields will help recover some of the approximately 10 billion barrels of oil remaining in Illinois Basin reservoirs. These activities will accomplish sequestration while also helping to meet the nation's need for fossil fuels.

Led by the Illinois State Geological Survey, the MGSC-Illinois Basin is a consortium of the three geological surveys joined by industry, government, and business associations who have assessed multiple aspects of geological CO_2 storage in the Illinois Basin. During Phase I, existing data have indicated that the geology of the Basin is favorable for CO_2 storage, or sequestration. In some localities, two or more potential CO_2 sinks are vertically stacked. We have asssessed and will continue our investigations into the methods and economics of CO_2 capture at facilities such as coal-fired power plants and examine the costs of transportation of large quantities of CO_2 via pipeline. We have focused, however, on the properties of the rock units that control injectability of CO_2, the total capacity for storage near major CO_2 sources, the safety of injection and storage processes, and the security of the overlying rock units that act as seals for the reservoirs. We will address these issues in Phase II in much more detail through a series of six actual field tests. The overall integrity of the storage and sealing rock units is critical from the viewpoint of safety and of effectiveness in isolating CO_2 from the atmosphere and thereby avoiding the potential for adverse climate change. Each of our field tests will have an extensive monitoring program for air, shallow ground water, oil and water produced from oil reservoirs, and saline water produced from deep reservoirs to understand the fate of injected CO2 at our test sites. The integrity of the entire process will be scrutinized in detail to understand what contribution Illinois Basin geological sinks can make to national and international goals in accomplishing carbon sequestration and what technology developed here can be extrapolated to other regions.

Given that the original oil in place in the Illinois Basin is now understood to be about 14.1 billion barrels, about 2 billion barrels greater than before Phase I MGSC Partnership studies, CO_2 flooding of mature oil reservoirs will lead to both CO_2 storage and to incremental oil production. The value of the incremental production will help offset costs associated with collection and delivery of CO_2 to oil field operators. For unminable coal beds, any methane produced as CO_2 replaces the methane adsorbed on the coal adds to natural gas supplies and similarly offsets costs. Coalbed methane production in the Illinois Basin is in its infancy, however, and the most likely near-term economic benefits will come from enhanced oil recovery (EOR). Understanding of EOR processes is much further along than for enhanced coalbed methane production, and extrapolation of EOR performance parameters from West Texas to the Illinois Basin suggests that the Basin's EOR potential is substantial. Saline reservoirs offer the largest volume of storage capacity and CO_2 verifiably sequestered in such reservoirs may represent tradable carbon credits in the future.

The MGSC Phase II Partnership will carry out extensive public outreach with regard to its activities and to carbon sequestration generally. We will arrange presentations to industry, government, and the general public to provide information of the progress of our research and the importance of the Phase II field tests. We have 11 companies that have nominated 34 potential field test sites in the Basin for Phase II, and we have 16 companies, trade associations, and government agencies from Illinois, Indiana, Kentucky, and across the nation that serve on the MGSC's Project Advisory Group. We have had additional sites nominated since the submittal of our Phase II proposal. We have a growing body of information on our web site, www.sequestration.org, that we will continue to add to in order to keep our sponsors, team members, and the general public informed of the progress of our continued studies. Further, numerous Phase I products are forthcoming: a full Phase I final report, an additional topical report on the linked capture-transportation-sink network (including cost analysis), a Geoactivities educational module and related teaching materials on carbon sequestration, and a set of map products and digital GIS files (with metadata) characterizing the Illinois Basin region. All these products will create the basis for implmentation of field validation testing during Phase II, the plan for which will be incorporated into the full final report.

DISCLAIMER STATEMENT