An Assessment of Geological Carbon Sequestration Options in the Illinois Basin

Year 1 Annual Report

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Compiled by

Robert J. Finley

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Midwest Geological Sequestration Consortium
Preparer Contact: Robert J. Finley
Illinois State Geological Survey
615 E. Peabody Drive
Champaign, IL 61820
(217) 244-8389
finley@isgs.uiuc.edu

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Preparation of the Task 2 component of this report was prepared by S.S. Chen and Y. Lu under the direction of Massoud Rostam-Abadi, a member of the Technical Committee of the Midwest Geological Sequestration Consortium.

The Task 3 component of this report on pipeline transportation was prepared by J. Steve Dracos of Universal Ensco, Inc. under the general direction of Douglas J. Nyman of D. J. Nyman & Associates. The engineering and technical staff of Universal Ensco, Inc. assisted in data gathering and the development of unit cost estimates for the general pipeline transportation scenario. Douglas Nyman prepared the summary of geohazards potentially affecting the proposed pipeline route and reviewed the final report. W.J. Hall, professor emeritus of civil engineering, University of Illinois, served as project advisor and reviewed the final report.

The rail and truck transportation component of this report was prepared by Rajani Varagani of American Air Liquide, Chicago Research Center, as part of Air Liquide's contribution as a collaborating partner in the Midwest Geological Sequestration Consortium.

Abstract

The Midwest Geological Sequestration Consortium partnership, led by a collaboration of the Illinois, Indiana, and Kentucky geological surveys, has completed the first year of a Regional Carbon Sequestration Partnership sponsored by the U.S. Department of Energy, Office of Fossil Energy. Our focus is on the Illinois Basin, an area covering parts of three states that is the center of 276 million tonnes of annual carbon dioxide (CO_2) emissions from fixed sources, 90% of which result from the generation of electricity. Year 1 work encompasses six tasks with most of the effort focused on Tasks 4, 5, and 6. These tasks explored, respectively, the sequestration potential of deep unminable coal seams, mature oil reservoirs amenable to CO_2 enhanced oil recovery (EOR), and deep saline reservoirs that may store vast quantities of CO_2.

The project began by compiling all available data and creating a framework for the ongoing addition of data. Carbon capture options in the basin were then carefully assessed. Comparisons were made between carbon capture with monoethanolamine (MEA), oxy-combustion, and integrated gasification combined cycle (IGCC) and a base-case pulverized coal (PC) boiler with no carbon capture. Related costs and technical feasibility were assessed. Transportation of captured CO_2 will be by truck and/or rail for short-term research and pilot testing purposes and by pipeline for long-term operational sequestration. Costs and capabilities have been defined for each transportation option, including all costs and development considerations for a conceptual 200-mile pipeline from north-central Illinois in the vicinity of several major power plants to a sequestration "fairway" in southeastern Illinois containing deep coal seams, large mature oil fields, and the Mt. Simon Sandstone, a deep saline reservoir. In many areas of the "fairway" all three potential CO_2 sinks are vertically stacked.

The suitability and capacity of these geological sinks are being investigated in considerable detail. Data are being compiled and assessed from coalbed methane resource assessments, from past and ongoing studies of oil reservoirs and their stratigraphy and structure, and from natural gas storage fields in the Mt. Simon. Numerous investigations are ongoing to gain as complete a picture as possible of the utility of these formations for long-term CO_2 storage. In addition, numerous presentations are being made at various technical meetings to begin the outreach part of the project. Finally, a project Web site has been established at www.sequestration.org to make project results widely available. This site is being continually improved and also contains an intranet link for information sharing among project participants.

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Introduction to Year 1 Accomplishments

The members of the Midwest Geological Sequestration Consortium are developing an integrated understanding of carbon dioxide (CO_2) capture, transportation, and storage in the Illinois Basin, covering most of Illinois, western Indiana, and western Kentucky, with a focus on the region's three major geological carbon sinks: deep, uneconomical coal seams; mature oil reservoirs; and deep saline reservoirs. During Year 1, the period covered by this report, all existing and potential novel capture approaches and CO_2 transportation options were evaluated, total project data needs were defined, and existing data were assembled. The project moved on to focus on the three sinks in detail to define their characteristics, relative advantages and disadvantages, and the economic and regulatory framework within which their utilization must fit. This effort will continue into Year 2 of the project according to the timeframe laid out in the project task plan. Results for Year 1 are summarized herein.

Scope of Work for Year 1

The total effort proposed by the Midwest Geological Sequestration Consortium is a two-year, Phase I sequestration assessment focused on a set of carbon sinks within the geological framework of the Illinois Basin. The stationary emissions sources, primarily coal-fired electric generation, and their associated capture technologies and CO_2 transportation methods have been fully defined, compared, and evaluated during Year 1. The results are incorporated into a separate Topical Report as a Year 1 deliverable. Using Geographic Information Systems (GIS), the CO_2 sources, transportation options, and potentially suitable CO_2 sinks will be linked during Year 2 to develop integrated sequestration scenarios. The sinks are being fully assessed as to suitability, capacity, injectivity, and cost factors, among many other parameters, through a full-scale geological investigation integrating state-of-the-art subsurface characterization and visualization tools. Compatible capture-transportation-storage options will be reported at the close of Year 2 using multiple digital and hard copy tools including three-dimensional (3-D) visualizations; presentation through a Web site, print and digital media, digital training resources for teachers, project conferences, and technical presentations. These activities will lay the groundwork for actual sequestration field testing beyond Year 2 and will help maximize the likelihood of public acceptance during Phase II testing and beyond.

Summary of Year 1, Tasks 1 through 6

Work in Year 1 of the project included 6 of the 12 tasks making up the complete project. Tasks 1 through 3 are completed as outlined, although incremental data are being continually located or developed and are incorporated into project efforts on a regular basis. Tasks 4, 5, and 6 overlap into Year 2 and are planned to be completed by March 2005. A summary of the tasks primarily assigned to Year 1 follows.

Task 1: Compile Available Base Data and Assess Data Needs (4 months)

This task aims to bring together all needed data and to identify data gaps that may be filled by private-sector contacts. Our Project Advisory Group members have assisted with these contacts. We utilized

MIDCARB databases as a data foundation and identified other databases, including NATCARB, completed project reports, current projects, and unpublished information among the Consortium participants that were available to support the assessment.

Task 2: Assess Carbon Capture Options for Illinois Basin CO_2 Sources (9 months)

Under this task, we reviewed all current carbon capture options available for retrofit of major CO_2 sources in the Illinois Basin, assessed their suitability, and reviewed novel capture options and new combustion processes that may enhance capture or improve process efficiency.

Task 3: Assess CO_2 Transportation Options in the Illinois Basin (9 months)

This task focused on defining CO_2 transportation options in the Illinois Basin with respect to major stationary sources and with respect to needs for both research quantities and handling of large-scale quantities over the long term. D.J. Nyman & Associates in collaboration with Universal Ensco, Inc., both of Houston, Texas, handled this task for pipeline transportation in coordination with the Illinois State Geological Survey. American Air Liquide supported analysis of truck and rail transportation.

Task 4: Assess Coalbed Sinks and Methane Production Options (13 months)

The objective of this task is to assess all aspects of deep, uneconomical coal seams and of coalbed methane resource distribution within the Illinois Basin that define the coal's overall suitability and total capacity as a CO_2 sink. We are developing new volumetric data to help address the unknown CO_2 adsorption and methane release capability for Illinois Basin coals.

Task 5: Assess Oil Reservoir Sinks and Oil Recovery Options (15 months)

Under this task, reservoirs in plays with suitable reservoir characteristics and oil properties were defined to determine those best suited for enhanced oil recovery (EOR) utilizing injected CO_2. The CO_2 volumes potentially needed for EOR are being assessed, and the target oil volumes are being estimated for CO_2 EOR.

Task 6: Assess Deep Saline Reservoir Sinks (13 months)

The research effort under this task includes characterizing saline reservoirs— such as the Mt. Simon Sandstone, Ironton-Galesville Sandstone, and the St. Peter Sandstone—and their overlying caps and to determining their long-term suitability for CO_2 storage in the Illinois Basin. We are relying, in part, on computing resources at the National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign, for the geostatistical simulations as part of this characterization. In particular, closed geologic structures are being defined and assessed where monitoring of injected volumes can be readily accomplished by geophysical means during technology validation field activities.

Progress on Task 1: Compile Available Base Data and Assess Data Needs

The data assessment subtasks in this opening phase of the project were initiated simultaneously with subsequent tasks and ongoing through the subsequent tasks of (1) assessing carbon capture and transportation options from major point-sources (Tasks 2 and 3), and (2) mapping/assessment of geologic reservoirs (coal, petroleum, and saline reservoirs; Tasks 4, 5, and 6). The first major step after project initiation was to conduct a data inventory and needs assessment. A questionnaire was sent to all project participants asking for feedback on their data sets to contribute ranging from the general (e.g., contact information, intended use of data set, relative importance) to the specific (e.g., type, format, spatial extent of data, degree of documentation, proprietary issues), in addition to asking for requests regarding other data sets that were desired or deemed critical to the project. Combined answers to this questionnaire (1) provided the basis for a descriptive summary of our data inventory and needs, (2) helped identify key data sets and/or improvements to be made, and (3) identified working relationships and/or contacts to be facilitated by project and task managers.

Following the data inventory and needs assessment, standards for transferring spatial data layers and tabular data were developed, and guidelines were instituted to help organize and track the flow of data within the project among those who work hands-on with different data sets and share them. Data are transferred between project staff in .ZIP file format and are routed through key project database staff, so that data control information can be collected, and a zipped snapshot of the data can be archived. In addition, basic documentation is included with the data in order to better share data among project participants and to make any compilation or merging across state lines easier.

Data Compilation

Most of the data utilized for the project were compiled from multiple sources spanning multiple states, agencies, and time. Two of the greatest data management challenges of the project to date have been to achieve data consistency and to assess the quality of data from older geologic interpretations. Data collected by different agencies over time frequently have consistency issues because of different purpose, instrumentation, methodology, terminology, measurement resolution, or timing. Differences in documentation and how the raw data were compiled and archived are also issues. The raw data from which previous interpretations were made are not always available for quality assessments.

Quality Control

All data sets were examined for consistency, completeness, and accuracy, and data quality was improved if possible. When data consistency issues— such as differences in measurement resolution or terminology arose—strategies were devised to make these data more comparable. Some existing data sets were incomplete and required alternative sources and/or methods for improving or estimating values of the missing data. Often, multiple data sources were used to compile the most accurate data set. Whenever possible, data sets were checked to determine numeric, positional, or temporal accuracy, and new data were collected as necessary for comparison to existing data in order to ensure accuracy.

Once quality control procedures were completed, tabular data records were transferred to an Access database to maintain data integrity and ensure accurate data analysis. After importing a data set, the data were checked for duplicates and relational tables were checked to ensure no orphan records existed. Data quality analysis was performed using both Access queries and Excel.

Data Analysis, Archiving, and Dissemination

The geological surveys of Illinois, Indiana, and Kentucky utilize the same or similar software for GIS and tabular data analysis and storage. These include ArcGIS and ArcInfo for GIS data manipulation and analysis; ArcSDE and ArcIMS for GIS data storage, archiving, and dissemination; Excel and Access for datafile transfer and manipulation; and SQL Server or Oracle databases for institutional storage and archiving of tabular data. Additional software is used for specific contouring or modeling purposes.

Included in the standards for transferring data among project participants are specific protocols for spatial data. Geographic coordinates (longitude/latitude, in decimal degrees; 1983 North American Datum) are preferred for the transfer of GIS spatial data layers or for tabular data containing coordinates. These coordinates help standardize the input of spatial data into ArcGIS and allow for the most accurate reprojection of data to measurable coordinate space. The standard file types for GIS spatial data layers are zipped shape files or personal geodatabase files. ArcGIS projection information files (.prj file) are included with shape file data to enable and facilitate the ease of data reprojection. Also, a complete description of the reference coordinate system used (e.g. projection and datum) are included for tabular data not yet incorporated into GIS data layers.

Data are organized into project work areas and are regularly backed up. Project data and completed data sets have been loaded into institutional databases for archiving. Network access to these ArcSDE, Oracle, and SQL Server databases provides a robust connection that enables the simultaneous use of these data by many users. Significant data layers for major CO_2 sources and geological reservoirs in the Illinois Basin have been loaded into active Internet map services, utilizing ArcIMS software at the geological surveys of Illinois, Indiana, and Kentucky. These data sets are currently being shared through the NATCARB internet portal, as will the resultant data sets at the conclusion of this project.

Completion of Task 2: Assess Carbon Capture Options for Illinois Basin CO_2 Sources

This report describes CO_2 capture options from large stationary emission sources in the Illinois Basin, primarily focusing on coal-fired utility power plants. The CO_2 emissions data were collected for utility power plants and industrial facilities over most of Illinois, southwestern Indiana, and western Kentucky. Coal-fired power plants are by far the largest CO_2 emission sources in the Illinois Basin. The data revealed that fixed sources within the Illinois Basin emit about 276 million tonnes of CO_2 annually from 122 utility power plants and industrial facilities. Industrial facilities include 48 emission sources and contribute about 10% of total emissions.

A process analysis study was conducted to review the suitability of various CO_2 capture technologies for large stationary sources. The advantages and disadvantages of each class of technology were investigated. Based on these analyses, a suitable CO_2 capture technology was assigned to each type of emission source in the Illinois Basin. Techno-economic studies were then conducted to evaluate the energy and economic performances of three coal-based power generation plants with CO_2 capture facilities. The three plants considered were (1) pulverized coal (PC) + post combustion chemical absorption (monoethanolamine, or MEA), (2) integrated gasification combined cycle (IGCC) + pre-combustion physical absorption (Selexol), and (3) oxygen-enriched coal combustion plants. A conventional PC power plant without CO_2 capture was also investigated as a baseline plant for comparison. Gross capacities of 266, 533, and 1,054 MW were investigated at each power plant. The economic study considered burning of bituminous Illinois No. 6 coal and subbituminous Powder River Basin coal. The capture cost estimation included the cost for compressing the CO_2 stream to pipeline pressure.

CHEMCAD, a process simulation application, was employed to perform steady-state simulations of power generation systems and CO_2 capture processes. Financial models were developed to estimate capital costs, operations and maintenance, cost of electricity, and resulting CO_2 avoidance cost. Results showed that, depending on the plant size and the type of coal burned, CO_2 avoidance cost is between $47/ton to $67/ton for a PC +MEA plant, between $22.03/ton to $32.05/ton for an oxygen combustion plant, and between $13.58/ton to $26.78/ton for an IGCC + Selexol plant. A sensitivity analysis was conducted to evaluate the impact on the CO_2 avoidance cost of the heat of absorption of solvent in an MEA plant and energy consumption of the ASU in an oxy-coal combustion plant. An economic analysis of CO_2 capture from an ethanol plant was also conducted. The cost of CO_2 capture from an ethanol plant with a production capacity of 100 million gallons/year was estimated to be about $13.92/ton.

Completion of Task 3: Assess CO_2 Transportation Options in the Illinois Basin

Transportation capabilities were divided into (1) truck and rail and (2) pipeline transportation options. Truck and/or rail will certainly be utilized for near-term sequestration research and pilot studies, but pipelines will be needed when large quantities of CO_2 are sequestered on an ongoing operational basis. The nation's current CO_2 truck and rail transportation infrastructure capacity is about 30,000 tons/day. As with the Frio Brine Pilot on the Gulf Coast, near-term testing of storage options would involve transportation of CO_2 as a liquid with a pressure range of 275 to 300 psi and at a temperature range of 0 to 10°F in a thermally insulated truck trailer. On-site tank storage will typically be required. A typical truck trailer will carry up to 22 tons of CO_2, and on-site portable storage tanks have a capacity of 60 to 90 tons. Truck transport costs $1.75 to $2.00/mile. Transport by railcar costs about $25/ton to $30/ton, but distance traveled has minimal impact on transportation costs. Both trucks and rail cars can be leased, as can pumping skids and related equipment necessary for injection. Lease costs, purchase costs, and lease durations have all been determined and documented as part of this task. This task was completed by American Air Liquide as part of their in-kind contribution to the Midwest Geological Sequestration Consortium, and their results are part of a Topical Report.

Pipeline transportation was assessed by a subcontractor team made up of D.J. Nyman & Associates and Universal Ensco, Inc., both of Houston, Texas. This task required the identification of all materials, costs, operating considerations, and regulatory practices associated with pipeline development for CO_2 transportation in the Illinois Basin. A conceptual route was established consisting of a 200-mile pipeline from near Peoria, Illinois (where there is a concentration of large, coal-fired power plants), to southeastern Illinois within a "sequestration fairway" that contains the three major types of potential storage reservoirs: deep coal seams, mature oil reservoirs amenable to enhanced oil recovery, and deep saline reservoirs. This task involved developing the details of all processes and operations necessary for development of this pipeline such that the unit costs could then be applied to specific source-transportation-storage scenarios developed later in the project.

Specifically, in completion of this task and inclusion of results in a Topical Report, the team has addressed the following aspects of CO_2 pipeline design, construction, and operation:

1. Identify and describe the elements of a CO_2 pipeline transportation system, the general properties of CO_2, and the impact of these properties on pipeline design, operations and related safety issues.

2. Describe design, material, and construction practices that are common to CO_2 pipelines, including grades of steel, corrosion allowances, pipe and valve standards, type and spacing of mainline valves, and common pumping and metering equipment, with comments based on practices specifically suitable to the Illinois Basin.

3. Identify right-of-way considerations and permitting requirements for pipelines in the Illinois Basin, including co-location with existing pipelines and power lines, as well as agricultural mitigation (e.g., topsoil handling, drain tile avoidance).

4. Describe operating practices such as pipeline blow-down considerations, marking the pipeline for third-party damage prevention, and community awareness programs necessary as part of sequestration outreach activities.

5. Prepare a cost matrix of approximate cost per mile based on diameter and construction settings such as urban and rural, including adjustment factors as appropriate for farmland, timber, terrain, and soil and rock conditions. Include Illinois Basin land values and cost per acre of crops (corn and soybeans) lost during and after construction. Include power costs based on pipeline diameter and transport volume.

Completion of this task was based on a wide range of information and data sources, including pipeline projects recently completed in the Illinois Basin and a CO_2 pipeline recently completed in another state, both by Universal Ensco, Inc. Unit costs for materials and construction were developed by contact with various vendors and construction firms. Permitting requirements and land values were developed through contact with state and county agencies. Narrative on all cost parameters is included in a Topical Report covering pipeline diameters of 4 to 24 inches. Included here, to illustrate the level of detail included in that report, are a few of the cost data tables. All data were developed with respect to the terrain, land use, number of road and river crossings, and expected construction practices for the 200-mile conceptual pipeline from north-central Illinois sources to a southeastern Illinois geological storage fairway.

Table 1. Pipeline right-of-way cost

Diameter (inches)	($/mile)	($/diameter inch/mile)	($1,000/ 200 miles)
4	36,713	9,178	7.3
6	36,713	6,119	7.3
8	44,500	5,563	8.9
10	44,500	4,450	8.9
12	51,731	4,311	10.3
16	66,750	4,172	13.4
18	66,750	3,708	13.4
20	66,750	3,338	13.4
22	66,750	3,034	13.4
24	66,750	2,781	13.4

Table 2. Pipeline material cost

Diameter (inches)	($/mile)	($/diameter inch/mile)	(million $/ 200 miles)
4	24,303	6,076	5
6	47,630	7,938	10
8	79,370	9,921	16
10	115,424	11,542	23
12	159,084	13,257	32
16	247,199	15,450	49
18	310,766	17,265	62
20	381,893	19,095	76
22	460,465	20, 930	92
24	546,136	22,756	109

Table 3. Pipeline construction cost

Diameter (inches)	($/mile)	($/diameter inch/mile)	(million $/ 200 miles)
4	85,071	21,268	17
6	115,915	19,319	23
8	141,753	17,719	28
10	173,476	17,348	35
12	210,730	17,561	42
16	275,533	17,221	55
18	306,206	17,011	61
20	336,354	16,818	67
22	365,978	16,635	73
24	395,601	16,483	79

Table 4. Support services cost

Diameter (inches)	($/mile)	($/diameter inch/mile)	(million $/ 200 miles)	Factor (%)
4	29, 217	7,304	6	20
6	38,049	6,341	8	19
8	47,812	5,977	10	18
10	56,678	5,668	11	17
12	67,447	5,621	13	16
16	88,422	5,526	18	15
18	95,721	5,318	19	14
20	102,050	5,102	20	13
22	107,183	4,872	21	12
24	121,018	5,042	24	12

Table 5. Total cost, Illinois Basin conceptual route

Diameter (inches)	($/mile)	($/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

Table 6. Annual pipeline operating costs, Illinois Basin conceptual route

Diameter (inches)	Right-of-way ($/mile)	Materials ($/mile)	Construction ($/mile)	Services ($/mile)	Total cost ($/mile)
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

Progress on Task 4: Assess Coalbed Sinks and Methane Production Options

The objective of this task is to assess the potential for deep, uneconomic coal seams in the Illinois Basin for both CO_2 sequestration and enhanced coalbed methane production that may be enabled by CO_2 injection. The latter potential hinges primarily on the suitability of Illinois Basin coals for receiving and adsorbing CO_2 and thereby displacing producible methane from the coals. We are developing and analyzing both abundant extant and specific new data to better understand reservoir characteristics of the Illinois Basin coals and to volumetrically assess their potential for CO_2 adsorption and coalbed methane recovery. Progress has been made toward accomplishing all of the Task 4 subtasks. The following summarizes some of the principal Year 1 accomplishments.

Coal Data Compilation

Coal availability data, previously generated for all of the Illinois Basin seams with significant volume, have been compiled, formatted, and loaded as layers into a GIS database, essentially completing a basic coal data compilation except for new data additions. Maps have been completed of area, thickness, structural elevation, and depth for all of the Illinois Basin coal horizons of volumetric significance.

These include the Danville, Hymera/ Jamestown/ Paradise, Herrin, Springfield, Survant, Colchester, and Seelyville/ Dekoven/ Davis horizons. Additional information on coal quality is being compiled and formatted for integration into the GIS database layers, including moisture, ash, sulfur, calorific content (BTU), vitrinite reflectance (R_o), temperature, and pressure. Coal cleat and fracture data have been collected and are being mapped.

Screening criteria to designate areas of coal seams as "unminable" were determined after extended discussion. The implication is that, by infusing them with CO_2, seams that might otherwise be minable at some future time will be rendered unminable. Because of the relatively shallow depths of the seams in the Illinois Basin, all seams thicker than 42 inches may have to be avoided because their thickness may make them candidates for future underground mining. Seams less than 18 inches will not be considered because of difficulties in evaluating and targeting these seams, and seams less than 500 feet in depth were deemed to be too shallow for sequestration due to potential minability and safety considerations.

Team members have evaluated and continue to evaluate newly collected coal core quality, sorption, and reservoir data from other projects by the participating geological surveys. Core samples from these projects were made available for laboratory testing specific to CO_2 and methane sorption and flow properties impacting sequestration potential. Those sorption tests and matrix strain with sorption experiments have been designed, and laboratory testing has been conducted on available coal samples. That work is continuing as new samples are acquired for testing. Investigations of the impact of bulk petrographic and maceral composition on CO_2 adsorption capacity are also being conducted.

Modeling of Enhanced Coalbed Methane Recovery

The coal reservoir properties and the parameters necessary for understanding the coal CO_2 sink were identified, and those having the most affect on coal seam reservoir simulations (COMET3) are currently being tested for their relative sensitivity in controlling CO_2 sequestration and methane recovery performance. Coal characteristics for use in the reservoir models were identified, and probabilistic ranges of the input parameters were made. The set of possible values was first made for the COMET3 simulator input parameters on a Basin-wide basis. Then, more restricted distributions were made for depth-partitioned subsets (500 to 900 ft, 900 to 1,200 ft, >1,200 ft, and the relatively deep grabens of western Kentucky). Values from each of these subsets will be used in a parametric study to test the sensitivity of the critical input parameters on the modeled CO_2 storage and methane recovery volumes.

Gas samples from coal core canister desorption tests have been characterized in terms of their isotopic composition. That and any such new data will be compared to gases from likely CO_2 sources for a geological sequestration demonstration to distinguish the native from injected CO_2. This work is ongoing at the end of Year 1.

Progress on Task 5: Assess Oil Reservoir Sinks and Oil Recovery Options

Defining plays of oil reservoirs as miscible or immiscible is important in determining the potential for EOR during CO_2 sequestration. The term *miscible* describes CO_2 and crude oil that become a single mixture under certain temperature and pressure conditions via the mass transfer of intermediate hydrocarbons (C_5 to C_{12}) from the crude oil to the CO_2 phase. *Immiscible* describes CO_2 and crude oil under conditions where separation of the two fluids is distinct and identifiable. Mass transfer exists in immiscible CO_2 flooding of the oil reservoir; however, there is a CO_2-rich phase and a crude oil-rich phase.

The critical pressure (1,073 psia) and temperature (87.8°F) of CO_2 are important to determining miscible and immiscible potential of oil reservoirs. For miscibility to occur, CO_2 must exist as a critical fluid (i.e., dense phase, liquid-like, supercritical CO_2); this condition is only possible for reservoir temperature exceeding the critical temperature of CO_2 and reservoir minimum miscibility pressure (MMP, which increases with temperature and is at least equal to the critical pressure of CO_2).

Immiscible conditions exist at reservoir temperature and pressure generally less than the critical temperature of CO_2 and temperatures above the critical temperature when reservoir pressure is less than the MMP pressure. Under immiscible conditions, liquid or gas-like phases of CO_2 are possible.

Determining Conditions of Immiscibility and Miscibility

For the Illinois Basin, the critical pressure and temperature criteria for assessing immiscible/miscibility conditions of a reservoir were assessed relative to a +/– 2°F and approximately 100 psia "window" where either condition of CO_2 EOR may be possible. These temperature and pressure criteria were reduced to equations, and, in turn, the equations were solved for depth to define the depth ranges of our classification categories.

GIS and tabular data on oil fields and reservoirs were compiled for the Illinois Basin from Illinois, Indiana, and Kentucky. As oil fields contain multiple reservoirs, the average depths of each reservoir *per field* were weighted by the area-thickness product, and the bulk volume-weighted average depth for each oil field was calculated and used in obtaining the classification of CO_2 EOR conditions for each oil field. Thus, conditions were estimated to be *predominately* miscible, immiscible, or near-miscible in each oil field, and the resultant classifications were mapped for the Illinois Basin area of study. *Near-miscible* describes oil fields that are in the transition between immiscible and miscible criteria. Near-miscible will need to be identified on a field-by-field basis using field-specific pressure and temperature, not the average gradients of these parameters.

Quantifying Key Reservoir Parameters for Major Plays

A study to calculate the original oil in place (OOIP) using field-specific reservoir volumetrics in the Illinois Basin and validated with decline curve data was undertaken because estimations completed in the early 1970s were based on cumulative production data that are now out-of-date. Reservoir thickness and porosity data for each major producing horizon in the top 66 oil fields, which account for 80% of the oil production in the Illinois Basin, were estimated using waterflood unit data submitted by field operators from 1946 to the present. Waterflood unit data for Illinois fields has been compiled into an Access database and include reservoir thickness, porosity, permeability, and oil gravity information for most producing horizons. Another Access database consisting of 168,000 core plugs with porosity and permeability measurements was used to supplement the waterflood unit database. This database was used to calculate the average porosity for reservoirs in the Cypress, Aux Vases, Ste. Genevieve (the three major oil-producing stratigraphic units in the Illinois Basin) and for selected other formations.

The volumetric method requires area (A), average net thickness (h), average porosity (ϕ), and average water saturation (S_w). Oil formation volume factor (B_o) is also required. The decline curve method requires annual production data (q), a recovery factor (E), and abandonment rate. Abandonment criteria (oil price, royalty, operating expense per barrel basis) may be used to estimate the abandonment rate. Additionally, at very low annual rates, the extension of field life by a few years has an insignificant effect on cumulative production. The previous estimate of 12 billion stock tank barrels (Bstb) was determined using cumulative production and assumed recovery factors for primary and secondary. Monte Carlo simulation will be investigated as a possible statistically based technique for solving the volumetric equation.

Volumetric Parameters

A GIS calculated area using a buffer radius (or area) to define interwell acreage. The GIS approach is considered the "best" area given the available data and the necessity of basin-wide analysis. The calculated area by reservoir will be considered as a single number. There is greater confidence in this value than the other parameters in the volumetric equation.

h Statistical approach using the mean thickness by formation and using a standard deviation for the high and low estimate. A few values for known fields will be compared to Oil Reports.

ϕ Statistical approach was adopted using the mean porosity by formation and a standard deviation for the high and low estimate. A few values for known fields will be compared to values published in the industry trade press.

S_w Water saturation used three values (minimum, most likely, and maximum) based on reservoir geologists' experience/observations.

B_o Oil formation volume factor is pressure, temperature and crude oil composition dependent. A very narrow range of 1.1 to 1.2 recovery barrels (rb)/stb is likely. Little impact on OOIP estimate is anticipated.

Decline Curve Parameters

q Annual oil production by well, lease, unit, and field is acceptable.

E Decline curve analysis estimates ultimate cumulative production from field development at the time of the estimate. Ultimate cumulative production and a recovery factor combined yield OOIP. Primary recovery factor (solution gas, gas cap drive, and water drive) and waterflood recovery factor are required to estimate OOIP from decline curve analysis depending on which operation is active at the time of the estimate.

q_{abd} Abandonment rate is calculated from economic criteria defining the equality of annual income and annual operating expenses. This calculation requires a forecast of oil price and operating expenses. This is an equality made on a produced barrel basis so operating expenses must be in dollars per barrel.

Select Fields for EOR Studies

Fields were selected for reservoir characterization for EOR studies based on screening completed early in Task 5. Fields with both miscible and immiscible EOR potential by CO_2 injection were selected for additional study. Other criteria used for field selection require at least one field study from each state in the consortium, assurance of equitable spatial distribution, and assurance of geological representation. To ensure geologic representation reservoirs from the most prolific producing horizons in the Illinois

Basin, the Cypress Sandstone, Ste. Genevieve Limestone, and the Aux Vases Sandstone were selected. Reservoirs from each of the major producing horizons that have been subjected to secondary waterflooding were also selected. Reservoirs that have been waterflooded are the best candidates for CO_2 EOR recovery techniques.

The deterministic segment of the geologic model for each selected field requires creation of digital structure contour maps and reservoir thickness maps based on interpretation of reservoir features using geophysical logs. The probabilistic segment of the geologic model uses available porosity and permeability data to represent distribution of porosity and permeability in areas of the reservoir that do not have core data. The maps and data generated from the deterministic model are combined with porosity and permeability information from the probabilistic model to complete the geologic model, which is then used for input into a reservoir flow model.

The porosity and permeability distributions were developed using geostatistical characterization and modeling methods. The geostatistical characterization of the data for the upper zone of the Aux Vases at the Iola Field, our initial modeling effort, included calculation of average values of porosity and permeability within the upper zone for each well; histogram analysis of these average values; normalization of both porosity and permeability; auto- and cross-semivariogram analysis of the transformed data; and conditional simulation of the field using a turning bands algorithm. Conditional simulation is a stochastic modeling (interpolation) technique that differs from the traditional kriging by adding a random noise value on to the kriged value at each node location. The random values are obtained from the transformed histogram of values and the modeled semivariograms so that the values contain the observed amount of variability and spatial continuity. Because kriging results in average, or smoothed, values, reservoir models generated via kriging will underpredict the high and low ends of both porosity and permeability and the resultant connectivity of these values. Reservoir models generated using conditional simulation methods have petrophysical architecture that is more similar to outcrop characteristics, and the models tend to perform better in fluid flow simulators.

Progress on Task 6: Assess Deep Saline Reservoir Sinks

The screening for suitably sized, closed geological structures containing saline reservoirs has been completed by evaluating the size of shallower Mississippian oil reservoirs and, where possible, confirming with 2-D seismic data that shallower structures appear at greater depths. It is often seen that the top of the structural high has shifted in lateral position from the depth of oil production (e.g., 2,000 to 4,000 ft) to the depth of, for example, the Mt. Simon Sandstone (e.g., 6,000 to 10,000 ft).

All of the available porosity and permeability data from core from the Mt. Simon Sandstone have been collected and are included in the sequestration database. Both porosity and permeability core values have been evaluated with respect to depth. Down to depths of about 4,750 ft, core-derived porosity and permeability data are abundant from the development of natural gas storage fields and from deep, Underground Injection Control (UIC) Class I injection wells in the Illinois Basin. Samples of the various lithofacies of the Mt. Simon Sandstone from the Manlove (natural gas storage) Field have been examined in thin section. The coarser and most abundant facies, consisting of primarily cross-bedded sandstone, were composed of clean quartz grains, a few% potassium feldspar, silica cement, and traces of illite clay. Finer-grained sandstone facies commonly occur with interbedded, thin, detrital shale laminae and are much less abundant than are the coarser sandstones

X-ray diffraction and elemental analyses were made of various lithofacies of the Mt. Simon Sandstone from Manlove Field and of the Eau Claire Formation samples from the Jones and Laughlin #1 Waste Disposal Well in Putnam County, Illinois. The analyses were completed by the Albany Laboratories of the U.S. Department of Energy (U.S. DOE). These data and the following information have been integrated into a geochemical model for chemical interaction during sequestration using the Manlove Field (Champaign County, Illinois) as the type area: (1) formation depth, pressure, and temperature, (2) formation water chemical composition both regionally and at Manlove Field, (3) mineralogical and chemical analyses of the Mt. Simon Sandstone, (4) mineralogical and chemical analyses of shaley interbeds within the Mt. Simon Sandstone, and (5) mineralogical and chemical analyses of the Eau Claire Formation. The Eau Claire lies immediately above the Mt. Simon and is an impermeable shale-carbonate succession that, as evidenced by successful gas storage development, is expected to be the primary seal to any CO_2 volumes stored in the Mt. Simon.

We have acquired, installed, and tested the geochemical modeling software package, The Geochemists Workbench®, which is a suitable analytical tool for simulating geochemical reactions in saline aquifers under pressure, temperature, and salinity conditions similar to the Mt. Simon reservoir. We have developed a conceptual model of the Mt. Simon Sandstone and formation water at Manlove Field and have simulated the geochemical reactions that will occur when CO_2 is injected and reacts with formation water. We also have examined the resulting fluid reactions with the sandstone. Initial results suggest that the Mt. Simon will not be very reactive to CO_2 injection.

A preliminary geostatistical model of the Mt. Simon at Manlove Field is currently being completed. This model should better represent the reservoir heterogeneity than previous geologic models. A 3-D animation of the facies distribution in the Mt. Simon reservoir sandstone at Manlove gas storage project has been completed and is currently waiting uploading to the Midwest Geological Sequestration Consortium project Web site.

The scanning and archiving of seismic paper records donated to the Illinois State Geological Survey by industry has been completed and has been integrated into the central sequestration seismic database. The relevant geographic and earthquake data required for seismotectonic interpretation of the reflection data have been acquired. Preliminary interpretation of the regional seismic grid has started, and areas of potential pre-Cambrian paleohighs have been mapped. These areas are important because the Mt. Simon is commonly thinner over paleohighs. Interpretations to date indicate it will be extremely important to carry out a 3-D seismic survey prior to drilling at any Mt. Simon storage test site to verify structural closure and to make the best possible assessment of Mt. Simon thickness.

Preliminary maps of the Trenton and Mt. Simon structures have been completed for Illinois and Indiana. Geologic information from Kentucky is still being integrated into the basinal map. The Trenton Formation is an Ordovician-age carbonate that is an oil producer in the Illinois Basin. There is significantly more well control on the Trenton compared to the Mt. Simon; therefore, an initial structure map was completed on the Trenton horizon, and the Trenton structure was used to create the deeper Mt. Simon structure map. The final Mt. Simon structure honors all of the deeper Mt. Simon wells, but also extrapolates the details of the shallower Trenton structure to greater depths.

Approximately fifty wells from Illinois, Indiana, and Kentucky have been digitized and integrated into a regional cross section grid. These wells constitute the key Mt. Simon wells in the Illinois Basin. We have an additional 200 digitized Mt. Simon wireline logs from a previous U.S. DOE-sponsored research program on natural gas storage fields in Illinois. These gas storage project logs are being used to evaluate Mt. Simon reservoir heterogeneity. The Mt. Simon is being categorized into unique electrofacies using V-shale estimations from the gamma-ray log and from porosity logs. Pressure transient analysis was used to approximate the pressure disturbance surrounding a CO_2 injection field in a deep saline formation in the Basin. The results of the analysis showed that a pressure change of only 1 psi occurs 30 to 40 miles from the well area after 30 years of injecting 1 million tons CO_2/year.

Reservoir Simulation: An Effort Cutting across Multiple Tasks

Tasks 4, 5, and 6 are designed to estimate the CO_2 storage capacity and potential injection rates of CO_2 into coalbeds, oil reservoirs, and saline formations within the Illinois Basin. Oil reservoirs will likely benefit from additional oil recovery, and coalbeds may see enhanced methane production as a consequence of geologic CO_2 sequestration. The approach to making these estimates is intended to improve and refine the MIDCARB approach to reflect the specific geology and well configurations in the Basin by including microscopic and macroscopic displacement efficiency. Traditional volumetric analyses using currently available petrophysical and fluid property data provides an estimate of total fluids in place. Constant values for these properties that represent the entire field or structure are required. However, these total in-place volumes do not reflect the volume of fluid that may be displaced (or produced) as a consequence of CO_2 injection.

The reservoir simulations will provide an approximation of displacement efficiency, injection rate, and fluid movement. The modeling has two major objectives: (1) to provide recovery and storage factors that are a fraction of the original fluid in place that represent and can be scaled to the entire Illinois Basin and (2) to yield site-specific geologic and reservoir modeling of a CBM field, oil field, and saline formation that may be considered for Phase II of the U.S. DOE Regional Carbon Sequestration Partnerships. Injection rates are required to complete the design and economics of transportation, which include size and route of pipelines and/or number of trucks and railcars from sources to the geologic sinks.

Coalbed Methane Reservoir Simulation

COMET, a commercially available software marketed by Advanced Resources International (ARI), is being used to estimate CO_2 injection rate, coal sequestered CO_2 (CSC) volume, and enhanced coalbed methane (ECBM) recovery. Large volumes of in-place CBM have been estimated for years; however, historical attempts at commercial production have been inconsequential, and active CBM fields are very limited. Because CBM production in the Basin has only recently been investigated, petrophysical and fluid property data are very sparse, especially for the deepest, unmined coals. Consequently, in addition to the simulations for recovery and storage factors and of specific sites, a parametric study of the physical and fluid properties of coals is under way.

Coal maps of the Illinois Basin that provide thickness and depth are available. Because there are very few active CBM fields in the Basin, representative portions of these maps will be used to develop geologic models for input to reservoir simulation. Wells will be placed on 40-acre spacing, which is currently the anticipated spacing of CBM wells in the Basin. A five-spot pattern for CO_2 injection will likely involve the conversion of one of the existing wells instead of drilling a new well. Well spacing of 40 acres yield a five-spot injection pattern of 80 acres. To increase the number of grid cells that can be used to simulate CO_2 movement through a coalbed, the symmetry of flow paths of a five-spot is used so that only a corner (1/4) of a five-spot is simulated. These injection patterns of Illinois Basin coals will be simulated to estimate CSC and ECBM as a fraction of the original CBM in place. These fractions will be used to estimate CSC and ECBM for the entire Illinois Basin using the coal maps. To provide data to the transportation design and economics, CSC, ECBM, and injection delivery rate will be spatially located via GIS. Consequently, CSC, ECBM, and injection rate will be made on a unit-area basis such as per section, township, or county.

A portion of one specific CBM field will be studied in order to attempt a history match of any available production and pressure data to validate the geologic and reservoir model. This may provide a more representative estimate of CO_2 injection rate and additional insight on a potential CO_2 sequestration CBM pilot for the U.S. DOE Phase II partnership program.

The outcome of the parametric study will identify the relative degree of influence of the petrophysical and reservoir parameters on CSC/ECBM so that more emphasis can be placed on obtaining additional data for those parameters from currently available sources and so that new tests and experiments can be planned for the initial months of any Phase II. Currently, coal properties are divided into four categories based on depth and geographic location. The first three categories are applicable to the Illinois and Indiana portions of the Illinois Basin and are based on depth: 500 to 900 ft, 900 to 1,200 ft, and >1,200 ft. The fourth category is to reflect the coals that are found in the grabens of western Kentucky. A range of petrophysical and fluid properties were developed for each of these categories and will be used as simulation input. Incremental changes in injection rate, CSC, and ECBM will be used to define the more critical properties of Illinois coals.

Oil Field Compositional Reservoir Simulation

VIP, a commercially available software marketed by Landmark Graphics, is being used to estimate CO_2 injection rate, oil sequestered CO_2 (OSC) volume, and the EOR potential. Compared to coalbeds and saline formations, extensive petrophysical data are available for the oil fields. However, fluid properties, especially with regards to CO_2-crude oil equation-of-state work, are sparse.

Because developing geologic and reservoir models of every oil field in the Illinois Basin is impractical, a few select reservoirs must be used to represent the entire Basin. Three geologic formations, Aux Vases, St. Genevieve and Cypress, make up approximately 75 to 80% of the Basin's production. Consequently, geologic models of these formations are being developed so that oil recovery and CO_2 storage factors can be found via reservoir simulation that can be applied to these formations across the entire Basin. A total of nine fields, three fields that are producing from each of these three formations, were selected based on available core data, presence of a waterflood, and proximity to the deeper part of the Basin. Three geologic models, based on an actual oil field waterflood, will be built for input to the reservoir simulations so that the OSC and EOR factors are developed that represent a single geologic unit. A deterministic approach to the structure and isopach maps (three finished in Year 1, two in-progress, five planned) and a probabilistic approach to the porosity and permeability maps (one finished in Year 1, one in-progress, seven planned) are under way.

Oil recovery and CO_2 storage factors are a fraction of the OOIP; therefore, the OOIP for each field is required. A total Illinois Basin OOIP has been estimated at 12 Bstb, but the spatial distribution of the OOIP has not been established. A revised OOIP study based on volumetric data available is under way; preliminary results suggest OOIP may be as high as 14 Bstb. Statistics of volumetric parameters were used to complete data requirements of fields that had incomplete data sets. The net thicknesses of the larger oil fields were verified through re-evaluation of well logs from these fields.

To improve the understanding of the OOIP estimate, Monte Carlo simulation is planned for the Illinois Basin OOIP study; it will provide a probability of occurrence of the estimated Basin OOIP. Additionally, for a select few of the larger oil fields, decline curve analysis with assumed recovery factor for the given reservoir drive mechanism is under way to validate the volumetric approximation to OOIP. Wells will be placed on 10-acre spacing, which is currently the most common well spacing of oil fields in the Illinois Basin. A five-spot pattern for CO_2 injection will likely involve the conversion of one of the existing wells instead of drilling a new well. Well spacing of 10 acres yield a five-spot injection pattern of 20 acres. Five spots were blanketed across the oil field models such that actual well locations in these fields were not used. This was intentional in case that the well location and spacing in the oil fields studied were dissimilar to all other oil fields within the state. The recovery and storage factors sought for basin-scale application should be based only on the geologic and reservoir descriptions and the injection pattern.

Oil production in the Illinois Basin is considered mature, therefore, initial conditions for the simulated CO_2 floods follow an extensive period of primary production and waterflood. Because no pressure-volume-temperature (PVT) or CO_2/oil properties are available for specific geologic formations, an equation of state was sought that yields PVT properties generally seen in the Basin. Currently, a four-component equation of state is being used to represent a medium API gravity crude oil, which is typical of the Illinois Basin. Historically, Illinois Basin primary production is estimated as 24%, and primary plus waterflooding is 48%; as such, the reservoir simulation of oil recovery is expected to reflect these generalizations. Two West Texas-based rules of thumb for CO_2 EOR recovery are 10% of OOIP or 25% of primary plus waterflood cumulative production. Illinois Basin model results will be compared to these generalizations on EOR recovery. To complete the estimate of the CO_2 EOR of the Basin, these geologic models will be studied under miscible and immiscible conditions so that shallower formations that may be in the immediate vicinity of sequestration injection facilities can be evaluated for EOR potential.

One specific oil field in the Basin will be selected for history matching of production, pressure, and water injection. At this time, a portion of the Mill Shoals field has been chosen. The history match of a specific Illinois Basin oil field may provide a more representative estimate of CO_2 injection rate and additional insight on a potential CO_2 sequestration EOR pilot for DOE Phase II. To provide data to the transportation design and economics, OSC, EOR, and injection delivery rate will be spatially described via GIS. Consequently, OSC, EOR, and injection rate will be made on a unit-area basis such as per field, section, township, or county.

Outreach and Technology Transfer

Outside of U.S. DOE-sponsored meetings, nine posters and oral presentations have been made at technical meetings such as those sponsored by the American Association of Petroleum Geologists, the Illinois Oil Producers Association, the Society of Petroleum Engineers, Environmental Systems Research Institute, the Illinois Mining Institute, and Greenhouse Gas Control Technologies-7. Each presentation has focused on a technical aspect of the assessment of Illinois Basin reservoirs for carbon sequestration. The expectation is that additional presentations will be made to regional and local groups as more final results become available with regard to the character and suitability of these reservoirs and with the release of the Topical Report on capture and transportation options. Typical of this regional focus will be three presentations in October and November 2004 to the faculty and staff of Illinois State University, the Illinois Oil and Gas Association, and the Consulting Engineers Council of Illinois.

In Year 1, we held two meeting of our Project Advisors Group. The first meeting (January 2004) largely acquainted the advisors and the collaborating members of the Midwest Geological Sequestration Consortium with the goals and objectives of the project and with the project task schedule. The second meeting (September 2004) provided specific results for capture and transportation and a detailed status report on the reservoir characterization tasks. Numerous questions were received and the answers appeared satisfactory to the advisors.

Finally, a Midwest Geological Sequestration Consortium project Web site was established at www.sequestration.org to include project details, copies of presentations, information on the Illinois Basin, links to U.S. DOE sequestration partnership materials and technology road maps, and news items related to geological sequestration. Content on this site is expected to expand rapidly as more research is conducted and more links are added to sequestration-related sites around the world. The site also includes a password-protected intranet for exchange of information among project researchers at different locations.