TITLE: **Midcontinent Interactive Digital Carbon Atlas and Relational Database (MIDCARB)**

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FOREWORD

This report is a product of a cooperate project involving five different organizations. These organizations are the geologic surveys in Illinois, Indiana, Kansas, Kentucky and Ohio. The people participating in the project are listed on the web at: http://www.midcarb.org/contacts.shtml.

ABSTRACT

This annual report describes progress in the second year of the three-year project entitled ***"Midcontinent Interactive Digital Carbon Atlas and Relational Database (MIDCARB)".*** This project, funded by the Department of Energy, is a cooperative project that assembles a consortium of five states (Indiana, Illinois, Kansas, Kentucky and Ohio) to construct an online distributed Relational Database Management System (RDBMS) and Geographic Information System (GIS) covering aspects of carbon dioxide geologic sequestration (http://www.midcarb.org). The system links the five states in the consortium into a coordinated regional database system consisting of datasets useful to industry, regulators and the public. The project is providing advanced distributed computing solutions to link database servers across the five states into a single system where data is maintained at the local level but is accessed through a single Web portal and can be queried, assembled, analyzed and displayed.

Each individual state has strengths in data gathering, data manipulation and data display, including GIS mapping, custom application development, web development, and database design. Sharing of expertise provides the critical mass of technical expertise to improve CO_2 databases and data access in all states. This project improves the flow of data across servers in the five states and increases the amount and quality of available digital data.

Data is being assembled to analyze CO_2 sequestration potential from a single object (e.g., power plant or well) to a region and across geographic boundaries. The MIDCARB system is robust and capable of being updated from multiple sources on a daily basis.

The MIDCARB project has developed improved online tools to provide real-time display and analysis of CO_2 sequestration data. The MIDCARB project is a functional template for distributed data systems to address CO_2 sequestration and other natural resource issues that cross the boundaries between institutions and geographic areas. The system links together data from sources, sinks and transportation within a spatial database that can be queried online. Visualization of high quality and current data can assist decision makers by providing access to common sets of high quality data in a consistent manner.

EXECUTIVE SUMMARY

The Midcontinent Interactive Digital Carbon Atlas and Relational DataBase (MIDCARB) is a joint project between the Geological Survey's of Illinois, Indiana, Kansas, Kentucky, and Ohio, with funding from the Department of Energy's National Energy Technology Laboratory. The purpose of MIDCARB is to enable the evaluation of carbon sequestration potential in these states. The digital spatial database allows users to estimate the amount of carbon dioxide (CO_2) emitted by source supplies (such as power plants, refineries and other fossil fuel consuming industries) in relation to geologic reservoirs that can provide safe and secure sequestration over geologic periods of time. MIDCARB is organizing and enhancing the critical information about CO_2 sources, and develop the technology needed to access, query, model, analyze, display, and distribute natural-resource data related to carbon management into a system that is robust and capable of being updated from multiple sources on a daily basis.

The project has established reliable communication and data sharing among all the various servers of the MIDCARB Consortium. Data and information on CO_2 Sources and geologic sequestration sites is obtained from multiple and heterogeneous servers and databases in five different states. The MIDCARB Internet Map Server processes data on servers remote from the data and the results are displayed on the user's desktop (http://www.midcarb.org). The process is relatively seamless and response time is good. Web-database connectivity uses state-of-the-art tools to provide access to heterogeneous relational databases and software maintained independently on numerous servers in the five sites.

The project has developed tools to query, display and analyze CO_2 source, transportation and sink data. Data is obtained from the databases plotted and analyzed in real-time. The MIDCARB project is a functional template for distributed data systems to address CO_2 sequestration and other natural resource issues that cross the boundaries between institutions and geographic areas. The MIDCARB system is capable of being easily expanded to access, query and display CO_2 sequestration data on any accessible server. Visualization of high quality and current data can assist decision makers by providing access to common sets of high quality data in a consistent manner.

PROJECT OBJECTIVES

Current federal energy policy assumes that hydrocarbons will continue to be the primary source of energy for the United States and the world well into the 21st century. However, there is concern about increasing atmospheric concentrations of carbon dioxide and its possible role in global climate change. For this reason, it may become necessary to manage anthropogenic CO_2. Sequestering CO_2 in geological reservoirs may be one way to safely sequester carbon over long periods of time, if the proper data and tools to analyze the geological feasibility as well as the associated costs can be developed.

The Midcontinent Interactive Digital Carbon Atlas and Relational DataBase (MIDCARB) is a joint project between the Geological Survey's of Illinois, Indiana, Kansas, Kentucky, and Ohio, with funding from the Department of Energy National Energy Technology Laboratory. The purpose of MIDCARB is to enable the evaluation of carbon sequestration potential in these states. When completed, the digital spatial database will allow users to estimate the amount of carbon dioxide (CO_2) emitted by source supplies (such as power plants, refineries and other fossil fuel consuming industries) in relation to geologic reservoirs that can provide safe and secure sequestration over geologic periods of time. MIDCARB is organizing and enhancing the critical information about CO_2 sources, and develop the technology needed to access, query, model, analyze, display, and distribute natural-resource data related to carbon management.

Large stationary sources of CO_2 emissions are identified, located, and characterized. Potential CO_2 sequestration targets, including producing and depleted oil and gas fields, unconventional oil and gas reservoirs, uneconomic coal seams, and saline aquifers, will be characterized to determine quality, size, and geologic integrity. All information will be available online through user query. Information will be provided through a single interface that will access multiple servers in each state. The approach is one of the first demonstrations of large scale distributed natural resource databases and geoinformatics. Access to the up-to-date technical information can be used at the regional and national level as a tool to minimize the negative economic impact, and maximize the possible value of the CO_2 sequestration to hydrocarbon recovery from oil and gas fields, coal beds, and organic-rich shales.

PROJECT STATUS

Web-database connectivity has been established among the five consortium members using ARC-Internet Map Server (IMS), ARC-Spatial Data Engine (SDE) and custom tools developed in JAVA and Coldfusion. MIDCARB applications access large relational databases for the analysis of both CO_2 sources and potential geologic sequestration sites. Software on numerous servers across the five sites provides distributed tools for data analysis and display. Tools have also been developed to provide distributed manage of the system (i.e., data and SDE coverages can be edited and loaded from anywhere in the MIDCARB system). The software systems developed as part of the MIDCARB project represent cutting edge approaches to online data access and management. The data assembled represents one of the most comprehensive data sets assembled to address questions of CO_2 sequestration.

ACCOMPLISHMENTS

This reports concentrates on selected major project accomplishments that occurred over the last year. Where appropriate, future work is highlighted. Major MIDCARB project accomplishments are:

1) Established a distributed project team and management that cross both institutional and technical boundaries. The pooling of subject domain and computing technical expertise has resulted in a product that could not be completed by any of the individual participating research institutions. The distributed team provides both interaction and innovation within a focused area. The project structure can serve as a model for addressing other natural resource issues that cross boundaries among institutional and geographic entities.
2) The project has developed an online distributed system architecture that provides reliable communication and data sharing among all the various servers of the MIDCARB Consortium. The interactive Web-based applications allow the five

states in the MIDCARB consortium to share, integrate, and display spatial data pertinent to CO_2 sources and geologic sequestration sites across the consortium states. Data remains local to be updated and expanded. However, data is available for use in regional analysis and to increase the accessibility of this information to all interested parties.

3) The project has developed an online distributed system for the management of the MIDCARB system. Local site administrators for each of the consortium states can add new or modify existing SDE coverages and metadata. All modifications and additions are online through the Internet from any facility. The distribution of site administration provides better management of components to create a system that supports the distribution of high quality maps and GIS functionality on the Internet. In addition, an automated procedures alerts system administrators to problems.

4) The project has generated and assembled a very large quantity of data elements pertaining to CO_2 sources and potential geologic sequestration sites. Data includes over 100 SDE layers, numerous relational database tables and access to millions of records across the consortium states for sources and sites. Each state in the MIDCARB Consortium is responsible for construction, enhancement, and maintaining the data. Data quantity is extremely large and constantly increasing. Specialized data and parameters have been generated and used to enhance the SDE coverages and analysis tools (e.g., corrected reservoir/aquifer temperature, minimum miscibility pressure for oil, and coalbed adsorption/desorption).

5) Sets of calculators have been developed to provide analysis and display tools that can be accessed directly or through the MIDCARB Internet Map Server (IMS) and the SDE layers. Tools include clients to query and plot emissions or production through time for a single object or to sum total emissions across an individual state, to determine the solubility or physical properties of CO_2 under various environmental conditions.
6) We have provided technology transfer to the geologic and sequestration community and to the general public through talks papers and posters (see http://www.midcarb.org/events.shtml for a listing and examples). Numerous upcoming presentations are scheduled.

Short-Term Goals

Immediate short-term goals that will be realized prior to the end of the next project year are to:

1) Add significant new coverages and databases that increase the richness of the MIDCARB site. Expand and provide the same coverage types in every state of the consortium. We have concentrated on getting one data type going in one state. However, we will clone the approach in the others (example CO2 estimating sequestration potential in Ohio oil reservoirs). This approach provides a synergy by allowing individual states to pioneer coverage and database types and spread the expertise to the other states.
2) Develop and add better query and analysis tools. The present tools represent a significant increase in capability, but are still relatively crude. The biggest need is to develop complex query capabilities that provide flexible and focused access to specific data types (e.g., all the coal beds at a specified depth and within a given distance of a CO_2 source that have a predetermined reservoir characteristics).
3) Expand the data sets to include more information on the properties of the reservoir and the fluids. Property data is very sparse compared to the number of wells, reservoirs and area of coal. We need to work on catalogs that can be used as analog properties in order to compute at least rough viable values. For example: There are only a few values of methane content of subsurface coals and these are usually concentrated in a small spatial area. We need to let the user select from a viable range of values to be able to compute the methane content of

an individual coal bed covering a very large area. You can extend this uncertainty and paucity of data to the potential CO_2:CH_4 substitution ratios.

4) Provide improved display and analysis tools to summarize data over a specified area (e.g., total annual CO_2 emissions within a polygon and plot the emission data on a quarterly basis over the year). Provide flexibility to designate scales of plots. Provide improved download capabilities to move data and coverages to the client's machine for additional analysis.
5) Provide a method to maintain the communication and growth in the databases after the project has ended. We need to get over the hump and make this a system that will be maintained by the individual organizations. We also need to provide an incentive for other states to join and link to the MIDCARB system.

OVERVIEW OF TECHNICAL PROGRESS

A major challenge of the MIDCARB project is to create an efficient, easy to access, and readily maintained knowledge management system with many millions of records pertaining to CO_2 sequestration that resides in the five states of the MIDCARB Consortium (Illinois, Indiana, Kansas, Kentucky and Ohio). The MIDCARB system provides global access across the organizations to manipulate pertinent geologic and engineering data related to the issues involved in identifying and evaluating opportunities for geologic CO_2 sequestration. Relational databases are developed in each state to characterize stationary sources of CO_2 and potential oil, gas, coal, and brine reservoirs for sequestration.

The MIDCARB Consortium uses a distributed approach with applications, such as Internet Map Server (IMS) and analysis clients, that access and aggregate data from Relational Database Management Systems (RDBMS) at each organization (Figure 1). The system provides pre-selected map themes, custom map themes, and flexible query capabilities. The IMS is a scalable and failure-resistant system that can issue spatial queries to a spatial database engine (SDE) sitting on top of the various RDBMS on each of the cooperating computers maintained by each MIDCARB organization. The system is built to be highly reliable and efficient with programming focused on interface technologies that will be of particular benefit to end-users in particular discipline areas, policy makers, and the interested public. Online users see a single window to enter queries and receive results. However, the technical and spatial information on, both CO_2 sources and potential CO_2 sequestration sites, reside and are maintained at the local level (i.e., the individual states), and data is stored in relational tables of varying structure on systems that are unique to each participant.

The MIDCARB Internet Map Server (IMS) issues spatial data queries to spatial data engines (SDE) and relational database management systems (RDBMS) operating on servers in each of the five states of the consortium. The IMS approach is scalable and flexible. It does not require individual organizations to follow rigid standards for hardware, software, metadata or data formatting. Additional states and organizations could be added to the MIDCARB System with little additional effort. The data assembled using the MIDCARB browser comes from up to five different servers in five different organizations. The MIDCARB Internet Map Server, related analysis tools and available data sets are rapidly evolving and growing. The system that is described in this report will be very different from week-to-week, but functionality, data richness and response time will constantly improve. The MIDCARB system is one of the first distributed systems of natural resource data focused on CO_2 sources and potential geologic sequestration sites.

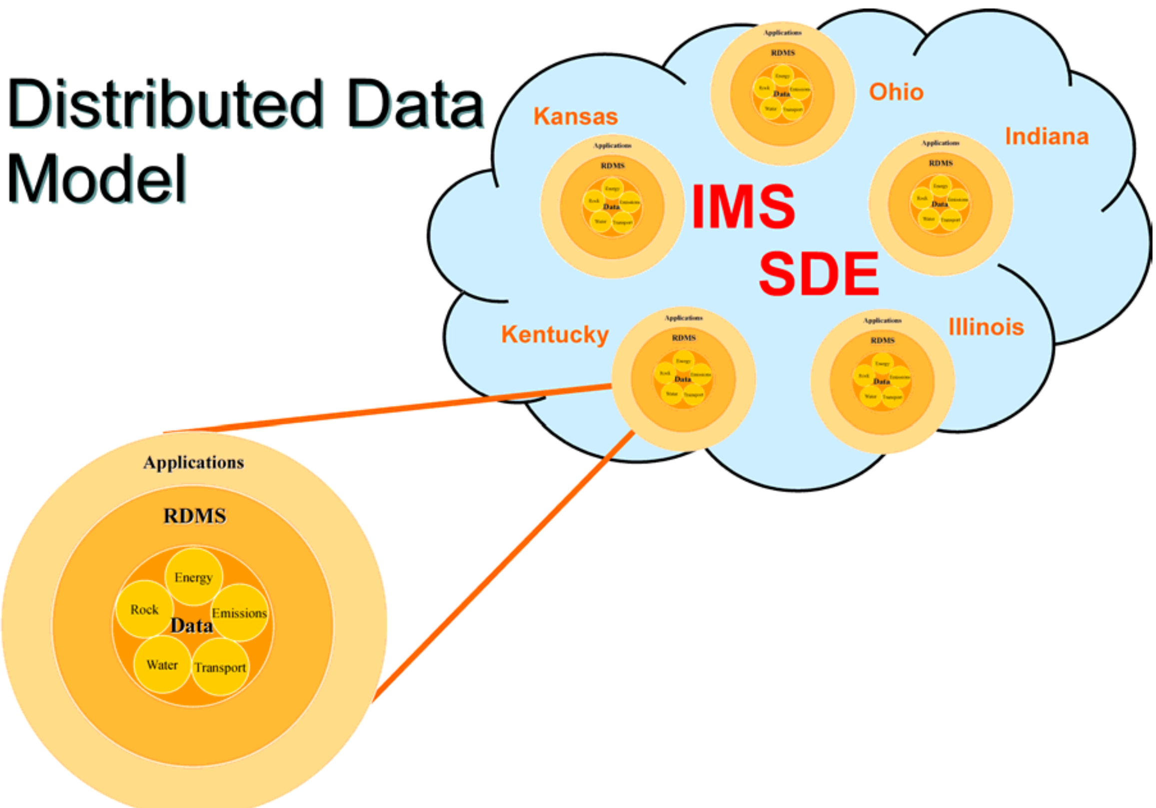


Figure 1 – Conceptual diagram of the MIDCARB data model. Data covering aspects of the sources and geologic sinks related to CO_2 sequestration are on located servers in each state of the MIDCARB Consortium (Illinois, Indiana, Kansas, Kentucky and Ohio). Data are stored in data tables with various structures within a relational database management system (RDBMS). Mapped data structures at each site are linked to the MIDCARB Internet Map Server (IMS) using spatial data engines (SDE's) operating at MIDCARB site.

MIDCARB PROJECT STRUCTURE AND MANAGEMENT

MIDCARB assembles a consortium of five states (Indiana, Illinois, Kansas, Kentucky and Ohio) to construct an online distributed Relational Database Management System (RDBMS) and Geographic Information System (GIS) covering aspects of carbon dioxide geologic sequestration (http://www.midcarb.org). The system links the five states in the consortium through a coordinated regional database system consisting of datasets useful to industry, regulators and the public. The MIDCARB project organization is unique in that it is distributive, geographic and overlapping. The organization is structured along both geographic boundaries and broad functions. The geographic focus provides strong local expertise to characterize both CO_2 sources and potential geologic sequestration targets. The distributive focus provides a critical mass of technical people. A strong technical computing team was assembled across institutional boundaries and is working on the hardware and software issues. This computing group pools technical expertise from each institution to work collaboratively on issues that are on the edge of distributed computing (Figure 2, highlighted in purple). No one institution has the technical computing expertise to create a system such as MIDCARB. The technical computing leads keep the institutional management informed (Figure 2, highlighted in yellow), and also interact closely with the individuals working on technical information concerning CO_2 sources and potential geologic sequestration sites (i.e., domain knowledge; Figure 2, highlighted in green). The interaction of between computing and domain teams at the local level provided unique solutions to address challenges and advanced both areas. The flexibility provided by the distributive structure of the MIDCARB system allows for local experiments in data type, structure and display. These "experiments", if successful, spread among the states.

Overall project organization is provided through the University of Kansas. Budgetary items are run through the Kansas University Center for Research (KUCR; Figure 2 highlighted in blue) and overall project coordination is provided through the Kansas Geological Survey.

Interaction between domain and computing technical experts within individual institutions and across institutions is on a daily basis. This is monitored through the local institutional leads and shared through list-servers and through monthly phone conferences. Project integration is to a significant degree organic in that all information has the same geographic structure, and has a similar look and feel. However, the monthly phone conferences and periodic meetings (usually associated with technical meetings) are used to improve working relationships across institutions and to provide a focus for periodic milestones (e.g., "Let's have the aquifer calculator up and running before the XYZ meeting next month"). Another positive is that each institution has a similar mission that is focused on natural resources and the environment in each state.

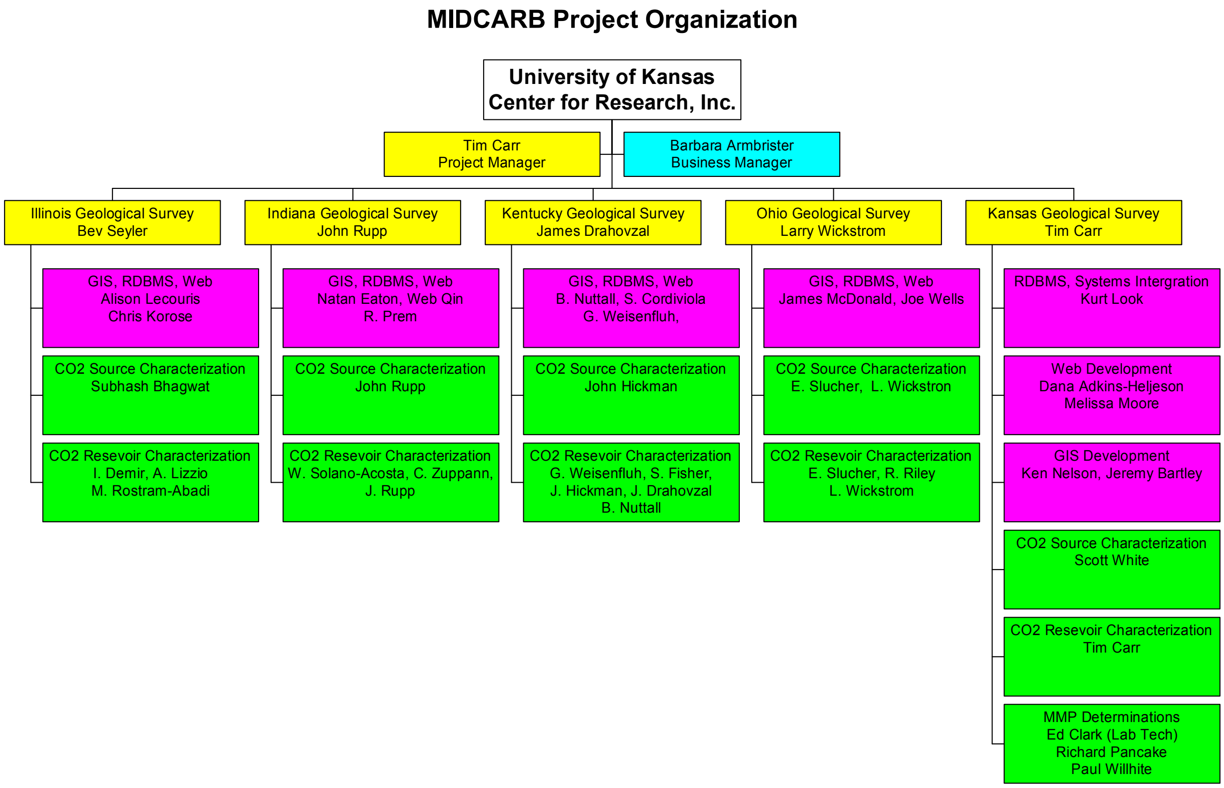


Figure 2 – MIDCARB project organization and participants. Computing, database, GIS and web expertise is highlighted in purple. Expertise on CO_2 sources and potential geologic sequestration sites is highlighted in green. Management functions are highlighted in yellow. Business expertise is provided through the Kansas University Center for Research (KUCR).

MIDCARB SYSTEM ARCHITECTURE

The MIDCARB system provides reliable communication and data sharing among all the various servers of the MIDCARB Consortium. It is not obvious to the user that data and information is obtained from multiple and heterogeneous servers and databases in five different states. The MIDCARB Internet Map Server processes data on servers remote from the data and the results displayed on the user's desktop. The process is relatively seamless and response time is good. Web-database connectivity uses ColdFusion and JAVA tools running on an application server, and ARC-Internet Map Server (IMS) using ARC Spatial Data Engine (SDE). These applications access heterogeneous relational database management systems (RDBMS) and software maintained independently on numerous servers in the five sites.

The web-based tools for the MIDCARB project use an Internet Map Server client (IMS), to access Spatial Data Engines (SDE) that run in each state on top of five individual relational database management systems (RDBMS; Figure 3). Each RDBMS has different data structures (i.e. tables and variables) and the consortium states use various versions and different RDBMS systems (i.e., Oracle and SQL Server). Internet Map Server (IMS) provides a common platform to distribute geographic information systems (GIS) and mapping services via the Internet. The MIDCARB Project uses ArcIMS software (an ESRI product, http://www.esri.com/software/arcims/overview.html). ArcIMS is scalable, standards-based software for managing mapping services over the Internet. ArcIMS integrates data from local sources across the Internet for display, query, and analysis in an easy-to-use Web browser. ArcIMS distributes geographic data to numerous concurrent users and allows users to undertake independent analyses. IMS operates in a distributed environment that consists of both client side and server side components. The client requests information from an Internet server. Then the server processes the request and sends the information back to the client viewer. In addition to the GIS front-end, data can both be input and disseminated through web-based tools developed with ColdFusion and Java (Figure 3).

Spatial Data Engines (SDE's) are client/server software that enables managing spatial data in a database management system. ArcSDE (an ESRI product, http://www.esri.com/software/arcgis/arcinfo/arcsde/index.html) allows the MIDCARB project to manage geographic information in commercial database management systems (e.g., Oracle, Microsoft SQL Server, Sybase, IBM DB2, and Informix), as well as being able to integrate the spatial (geometric) search capability provided by the DBMS vendors within the GIS client software applications such as Internet Map Server. ArcSDE, for the MIDCARB project, serves as the connector that enables remote connectivity to each of the other state's spatial databases, and is a key component in managing a distributed multi-user spatial database (Figure 1).

The distributive web-based design provides complete access to near real-time data and maps. Data is maintained at the local level in various formats, so it remains current. However, data is accessible online and can be displayed in a common format (e.g., table, map or plot) for either regional analysis or local query. Each state has an intimate understanding of their organization's data table definitions and can use SDE to provide access and integrate data across servers. The public, industry, legislators, federal agencies, etc. have access to up-to-date maps, data, imagery, etc. to enhance their decision-making and scientific processes. Products can be tailored to the individual and collective requirements of the states and regions.

The interactive Web-based GIS applications allow the five states in the MIDCARB consortium to share, integrate, and display spatial data pertinent to CO_2 sources and geologic sequestration sites across the consortium states. Data remains local to be updated and expanded. However, data is available for use in regional analysis and to increase the accessibility of this information to all interested parties.

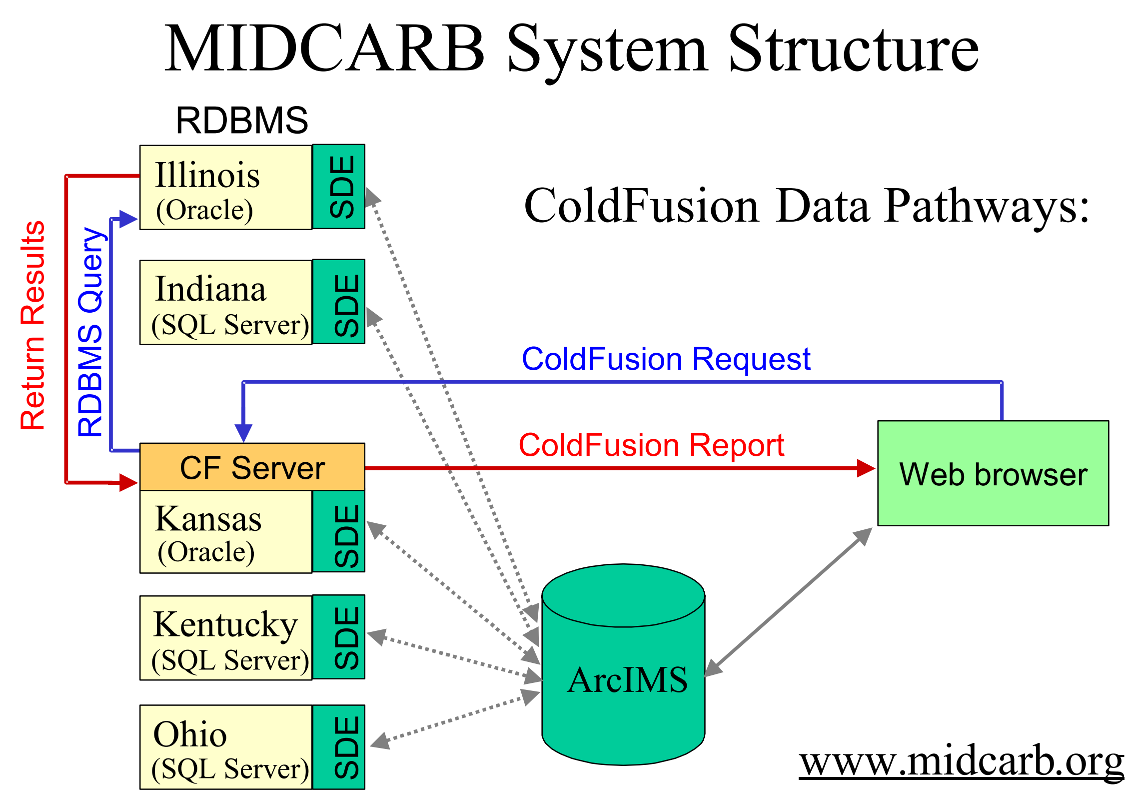


Figure 3 – MIDCARB system structure links tabular databases from the five cooperating states using an Internet Map Server (IMS) and custom tools developed in ColdFusion and Java. The diagram shows how requests from the Web browser travel back to the ColdFusion or IMS server in Kansas. The ColdFusion server then queries appropriate RDBMS databases or the IMS queries through a Spatial Data Engine (SDE), in this example the Illinois Oracle database. Results of the query are returned to the ColdFusion or IMS server in Kansas and then delivered as a pure html report or GIS object image to the client's web browser.

Future Work

The MIDCARB project is evaluating open-platform methodologies that allow improved data sharing across servers. This area is changing rapidly but the current approach involves Extensible Markup Language standards (XML). We are working to develop XML standards to map individual state databases, develop data table definitions (DTD's) and implement front ends to respond to XML queries with data that can be processed by the requestor using either online or stand-alone software. This process involves cooperating to develop simple XML definitions for CO_2 entities and front-end software to map local databases onto XML responses to satisfy a query. This approach requires expertise familiar with database structures at each location. Transfer, display and analysis of features from remote databases will illustrate the capability of the XML dictionary. This step will provide a clear mechanism for additional repositories of CO_2 sources and potential geologic sequestration sites to join the effort to distribute large volumes of locally maintained data.

We are evaluating tools to automate the mapping of an arbitrary sequestration database from any of the five institutions to the standard XML/DTD definitions. This will involve developing software to read an XML string and search for a match in the data dictionary. Over time, the data dictionary will provide the base for automated interpretation of an XML string to an unknown structure. Manual verification of the mapping by geoscientists would be required. However, verification would no longer be a labor-intensive development process, but more efficient verification of the automatically generated code. These mapped variables would provide georeferenced datasets that could be used directly with existing geospatial analysis tools even as the tools themselves are being developed and expanded.

We are also working to evaluate tools that completely automate the process of returning an XML response to a generic earth science data query specified in an arbitrary XML request. This will be an attempt to minimize or eliminate the need for DTD's and create generic earth science response software.

MIDCARB SYSTEM MANAGEMENT

The strength of the MIDCARB Project approach is that both data, management of data and management of the software have been distributed to individual consortium members. The project has established reliable communication, data sharing and distributive software among all the various servers of the MIDCARB Consortium. Data and information on CO_2 sources and geologic sequestration sites is constantly being generated, stored, modified and obtained from multiple and heterogeneous servers and databases in each of the five different states. Web-database connectivity developed as part of the MIDCARB Project uses state-of-the-art software tools to provide independent access to numerous servers in the five sites. This increases the flexibility of the system so that it is constantly improving through both data enhancement and improvements in GIS coverages. The MIDCARB approach treats GIS coverages as another form of distributed data. Access is limited to a single administrator at each site through an entitlement site (password protected). Members of the consortium are empowered to improve their individual coverages and to add new coverages. Since each consortium institution has a personal stake in presenting high quality coverages security can be maintained. Problems are limited to failure to inform other consortium members of new or radically improved coverages.

Distributed Data Management

A ColdFusion application has been developed that stores the ArcXML (AXL) file in the RDBMS at the Kansas Geological Survey (Oracle). ArcXML is the eXtensible Markup Language (XML) based protocol for communicating with the ArcIMS Spatial Server. The Cold Fusion connector works with the custom clients developed in the MIDCARB Project to modify ArcXML. We also use and modify the ArcIMS command line tools to administer our map services remotely through ColdFusion. An ***Entitlement*** (password protected) site allows each consortium member to add/or remove layers, and modify layer display characteristics (Figure 4). This application is distributed and can be accessed remotely through the Internet.

In the attached example, a list of all MIDCARB layers is requested and then limited to only layers located on the server at the Kentucky Geological Survey (Figures 4 and 5). For example, an administrator can view and edit the metadata for the coverage ***KY- CO2 Sources*** (Figure 6). All users through the MIDCARB IMS browser can view this metadata information, but modification can only be accomplished through the Entitlement site. Spatial data appearance can be modified through the same entitlement page. In this example, the ArcXML for the ***KY- CO2 Sources*** can be viewed (Figure 7). Clicking on the SDE button provides the administrator a view of the coverage (Figure 8).

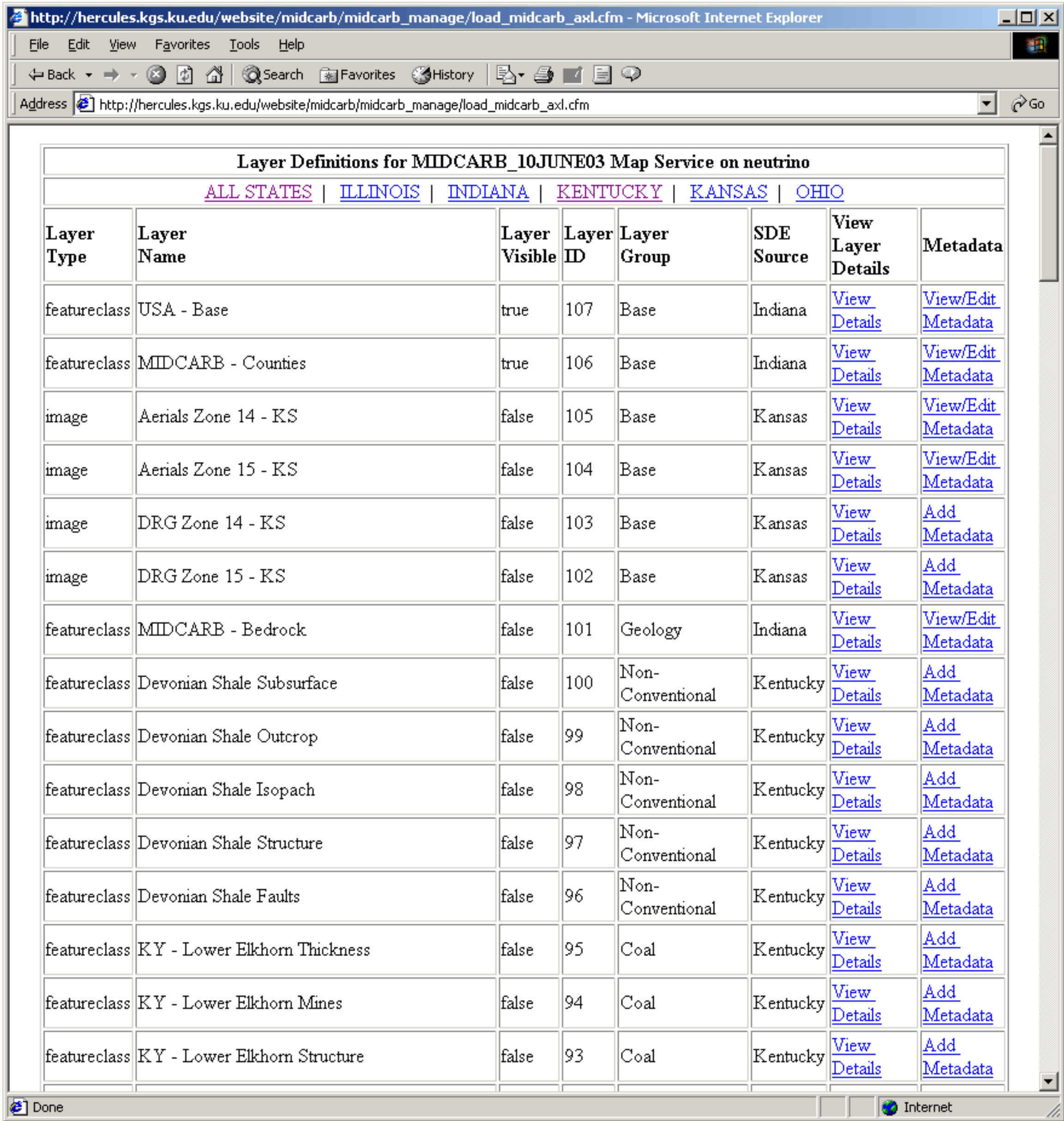
The administrator can modify the coverage. In this example, the administrator changes for the ***KY- CO2 Sources*** coverage the size the Kentucky Electric Generation sites and the color of the other Kentucky CO2 sources (Figure 9). The result can be viewed by the administrator and if satisfied can be accepted (Figure 10). The result is now available to all users on the MIDCARB system.

In addition to modifying existing SDE layers, site administrators for each of the consortium states can add new layers (Figure 11). These SDE layers can be added remotely through the Internet from any facility. The goal of partial distribution of site administration is to better manage these components to create a system that supports the distribution of high quality maps and GIS functionality on the Internet.

The MIDCARB administrator in Kansas also controls the overall operation of the Web mapping site. The administrator can manage map services, servers, and folders. The MIDCARB Administrator can reconfigure MIDCARB sites or add a new site. The MIDCARB administrator can monitor application performance, site stability, and compile statistical information. In addition, we are currently developing an automated procedure that periodically pings each States SDE servers to see if they are alive and accepting connections, alerts system administrators if there is problem, and dynamically removes bad SDE connections from the main map service.

Future Work

The MIDCARB project is working to expand the MIDCARB model of distributed relational databases to develop a carbon sequestration information-system that provides reliable and efficient access through geospatial and intelligent tabular queries to accurate and current baseline information, and co-location of CO_2 sources and potential sequestration sites. We plan to modify the current MIDCARB ColdFusion Internet Map Server (CF/IMS) to support multiple map services beyond the states of the current consortium. Work to improve the functionality of the map service client to support Open GIS Consortium Web Map Service (WMS) and to incorporate advanced spatial analysis using Open GIS Consortium Web Feature Services (WFS). Develop improved query and data extraction routines for both spatial and tabular data. Provide improved tools and increased information that permits both regional analysis and focused queries (e.g., a single well bore or CO_2 source). It is hope that the MIDCARB system will be a tool for researchers to address carbon management issues, provide the information basis to develop a portfolio of strong carbon sequestration demonstration projects, and be a primary path of technology transfer and public outreach.

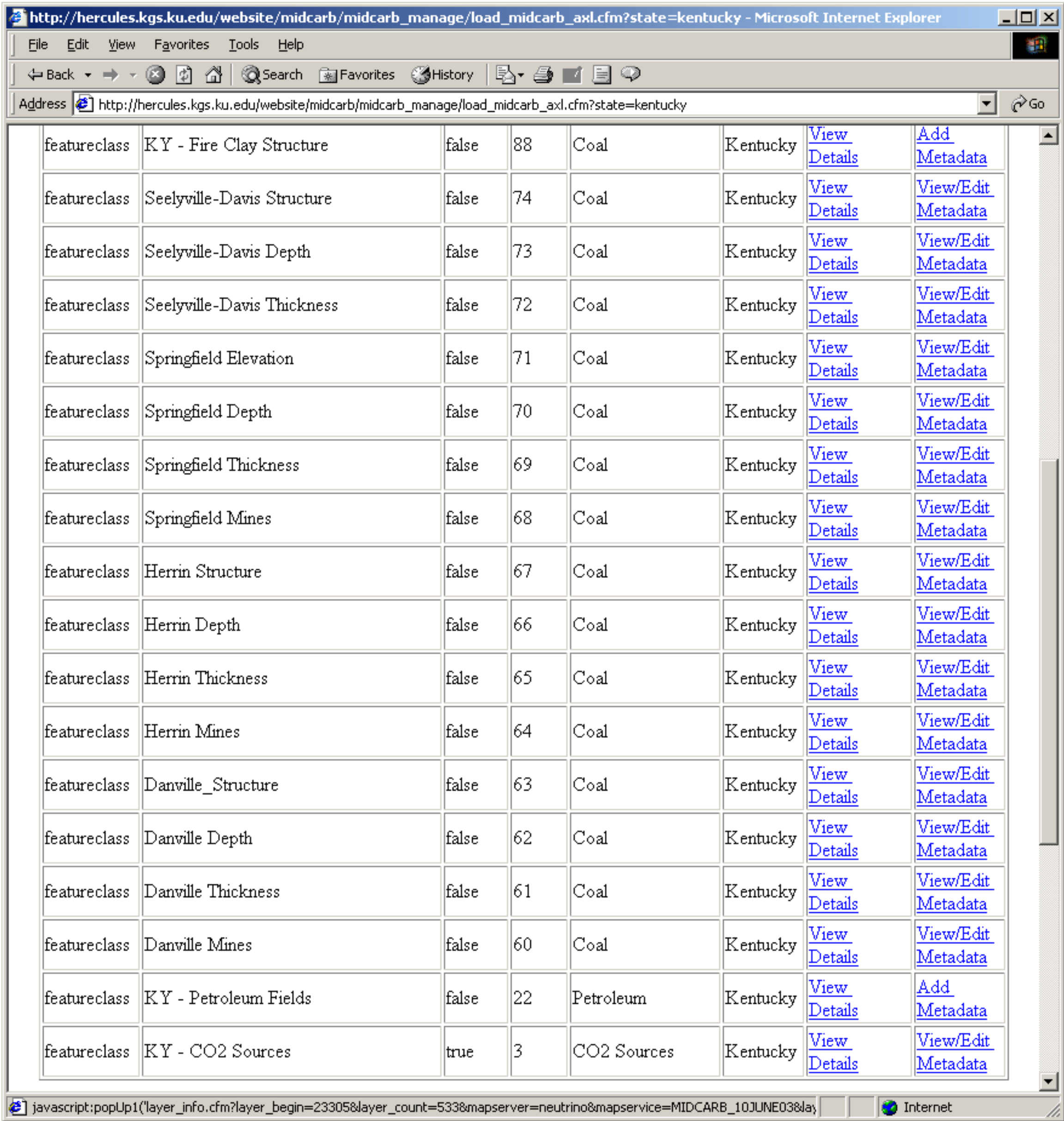


Layer Definitions for MIDCARB_10JUNE03 Map Service on neutrino

ALL STATES | ILLINOIS | INDIANA | KENTUCKY | KANSAS | OHIO

Layer Type	Layer Name	Layer Visible	Layer ID	Layer Group	SDE Source	View Layer Details	Metadata
featureclass	USA - Base	true	107	Base	Indiana	View Details	View/Edit Metadata
featureclass	MIDCARB - Counties	true	106	Base	Indiana	View Details	View/Edit Metadata
image	Aerials Zone 14 - KS	false	105	Base	Kansas	View Details	View/Edit Metadata
image	Aerials Zone 15 - KS	false	104	Base	Kansas	View Details	View/Edit Metadata
image	DRG Zone 14 - KS	false	103	Base	Kansas	View Details	Add Metadata
image	DRG Zone 15 - KS	false	102	Base	Kansas	View Details	Add Metadata
featureclass	MIDCARB - Bedrock	false	101	Geology	Indiana	View Details	View/Edit Metadata
featureclass	Devonian Shale Subsurface	false	100	Non-Conventional	Kentucky	View Details	Add Metadata
featureclass	Devonian Shale Outcrop	false	99	Non-Conventional	Kentucky	View Details	Add Metadata
featureclass	Devonian Shale Isopach	false	98	Non-Conventional	Kentucky	View Details	Add Metadata
featureclass	Devonian Shale Structure	false	97	Non-Conventional	Kentucky	View Details	Add Metadata
featureclass	Devonian Shale Faults	false	96	Non-Conventional	Kentucky	View Details	Add Metadata
featureclass	KY - Lower Elkhorn Thickness	false	95	Coal	Kentucky	View Details	Add Metadata
featureclass	KY - Lower Elkhorn Mines	false	94	Coal	Kentucky	View Details	Add Metadata
featureclass	KY - Lower Elkhorn Structure	false	93	Coal	Kentucky	View Details	Add Metadata

Figure 4 – MIDCARB Entitlement (password protected) site showing some of the over 100 coverage layers stored on servers across all the MIDCARB sites (SDE Source Column). Clicking on the Kentucky link limits view only to coverages stored on the server located at the Kentucky Geological Survey (Figure 5). Members of the Consortium have the ability to manage their SDE layers through the MIDCARB site.



featureclass	KY - Fire Clay Structure	false	88	Coal	Kentucky	View Details	Add Metadata
featureclass	Seelyville-Davis Structure	false	74	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Seelyville-Davis Depth	false	73	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Seelyville-Davis Thickness	false	72	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Springfield Elevation	false	71	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Springfield Depth	false	70	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Springfield Thickness	false	69	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Springfield Mines	false	68	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Herrin Structure	false	67	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Herrin Depth	false	66	Coal	Kentucky	View Details	View/Edit Metadata
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featureclass	Herrin Mines	false	64	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Danville_Structure	false	63	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Danville Depth	false	62	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Danville Thickness	false	61	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Danville Mines	false	60	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	KY - Petroleum Fields	false	22	Petroleum	Kentucky	View Details	Add Metadata
featureclass	KY - CO2 Sources	true	3	CO2 Sources	Kentucky	View Details	View/Edit Metadata

Figure 5 – MIDCARB Entitlement (password protected) site showing only the coverage layers being served from the SDE server located at the Kentucky Geological Survey. The bottom layer in this list is entitled ***KY- CO2 Sources*** and is examined in the following figures.

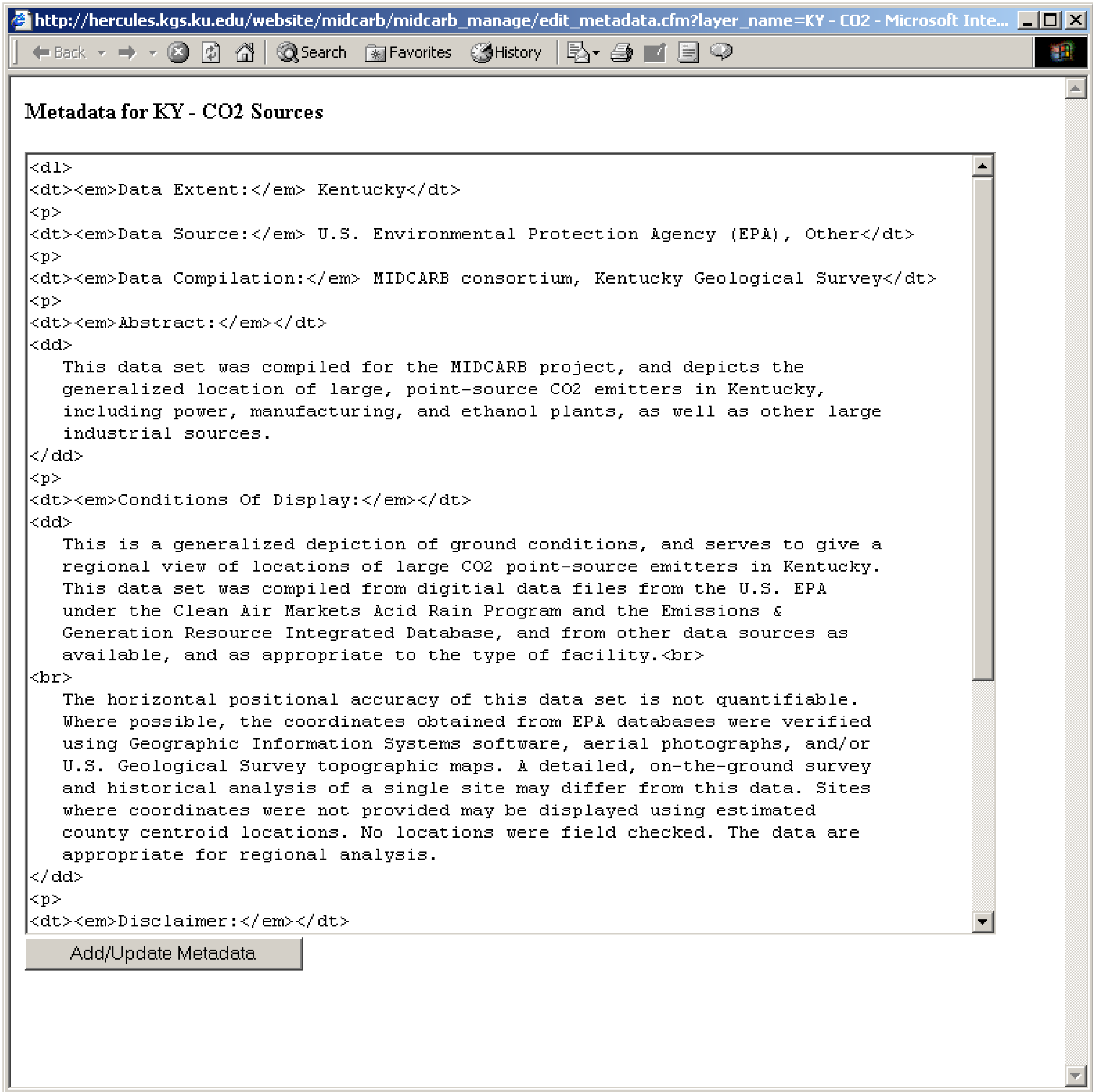


Figure 6 – Metadata detail from the MIDCARB coverage layer in this list is entitled ***KY-CO2 Sources***. The administrator can easily add and update metadata. After submission, any additions or modifications are instantly available to the user through the MIDCARB server.

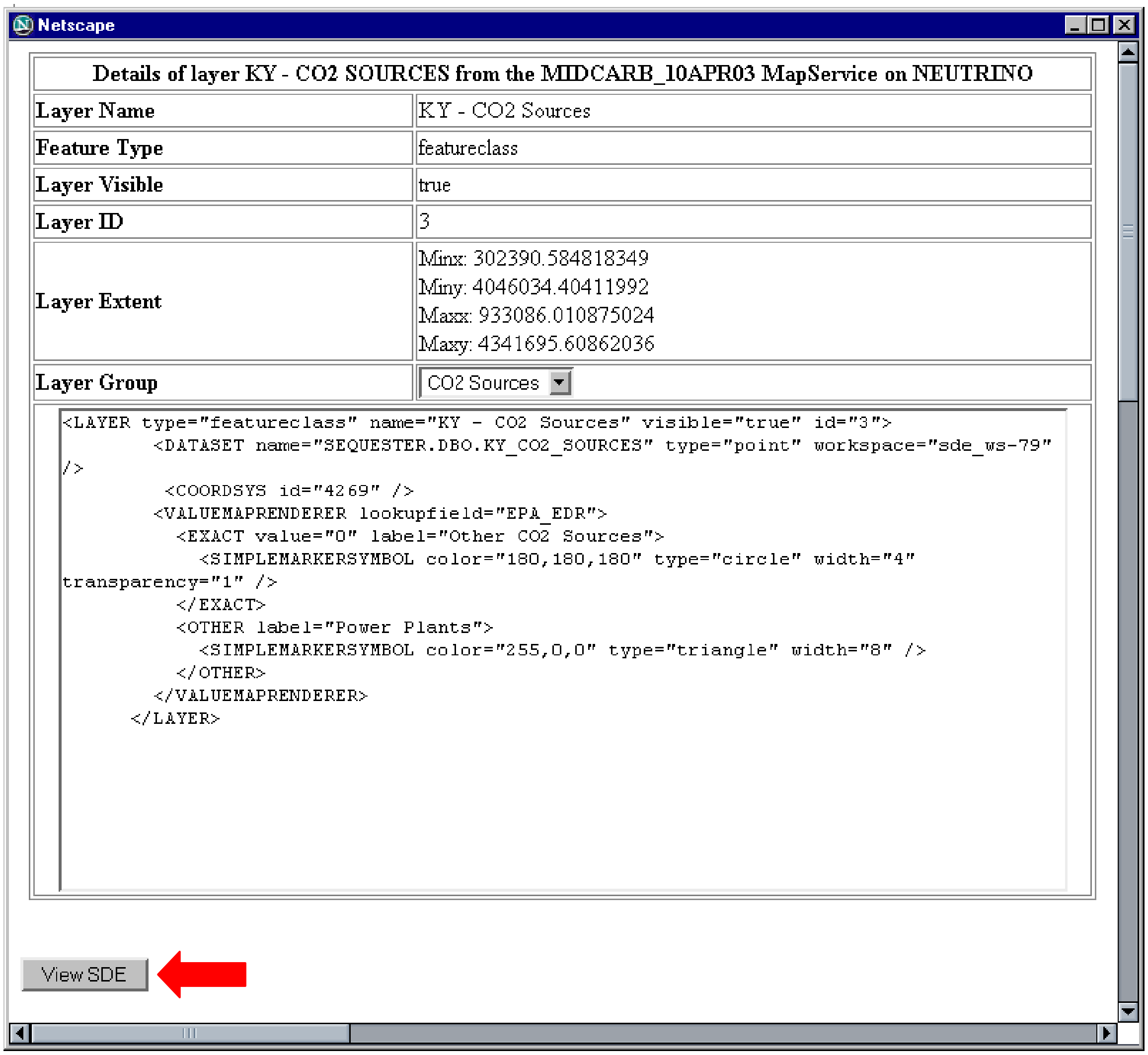


Figure 7 – A view of the ArcXML for the ***KY- CO2 Sources***. ArcXML can be edited. Clicking on the SDE button (red arrow) provides the administrator a view of the coverage (Figure 8).

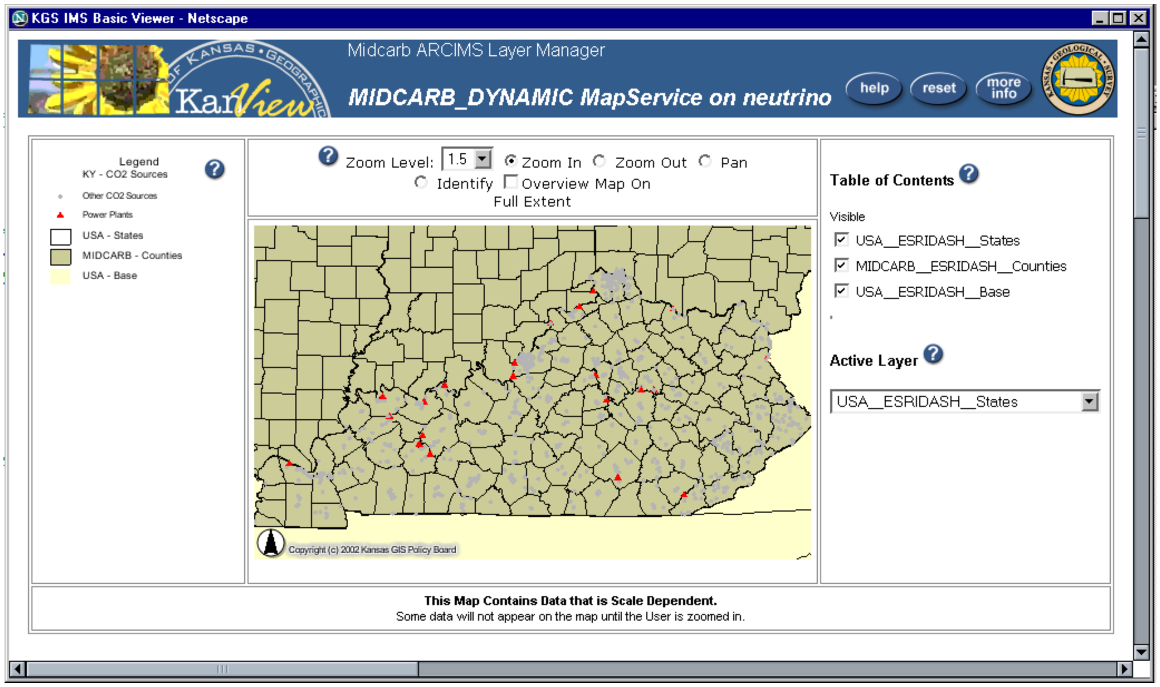


Figure 8 – A view of the modified SDE coverage for ***KY- CO2 Sources***. In this example, the administrator will modify the coverage (Figure 9). The size the Kentucky Electric Generation sites and the color of the other Kentucky CO_2 sources will be changed.

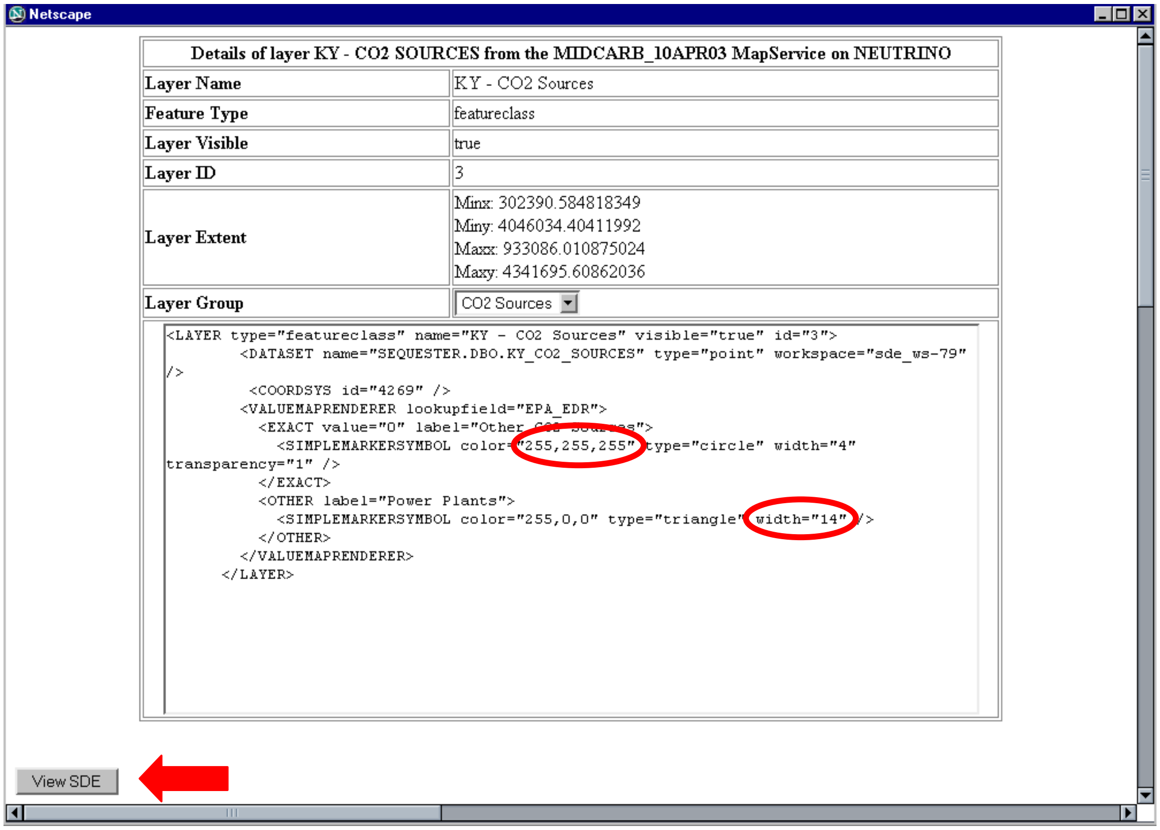


Figure 9 – For the coverage ***KY- CO2 Sources***, the administrator changes the size of Kentucky electric generation sites and the color of the other Kentucky CO_2 sources (red ellipses - see Figure 7 for previous object characteristics). The result can be viewed by the administrator (red arrow) and if satisfied can be accepted (Figure 10). After acceptance, the result is available to all users on the MIDCARB system.

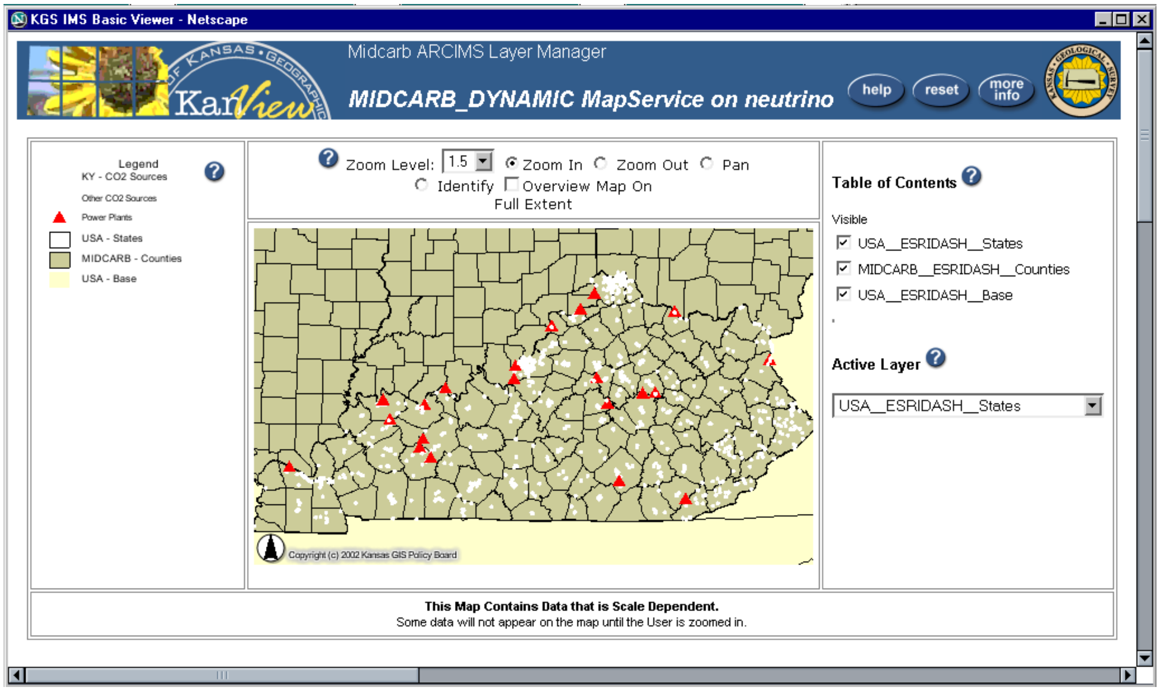


Figure 10 – A view of the modified coverage ***KY- CO2 Sources*** showing the change in the size of Kentucky electric generation sites and the color of the other Kentucky CO_2 sources. This modified coverage is now available to all users of the MIDCARB site.

ADD MIDCARB MAPLAYER	
Layer Name	
Layer Type Image not supported	featureclass
Layer Visible	true
Layer Max Scale (Leave blank if none, otherwise like "1:1000000")	
Layer Min Scale (Leave blank if none, otherwise like "1:1000000")	
Layer Group	CO2 Sources
Dataset Name	
Dataset Workspace	Indiana
Dataset Type	point
Add New Layer	

Figure 11 – The entitlement site provide the site administrator for each member of the consortium the ability to add new SDE layers to the MIDCARB site.

MIDCARB SYSTEM DATA ELEMENTS

MIDCARB Project data includes several types

- SDE Layers
- Relational Data Tables
- Special Data

    e.g., Minimum Miscibility Pressures

Each state in the MIDCARB Consortium is responsible for construction, enhancement, and maintaining the data. Data quantity is extremely large and constantly increasing. Numbers of records are in the many millions, involve over a century of anthropogenic activity, and cover a range of natural resource types (e.g., aquifers, to petroleum to coal). The data is extremely important to general natural resources and environmental questions in each state. As a result, each institution tries to insure the highest degree of quality control. However, with any extremely large, long-term and heterogeneous data set, individual data items can be incorrect. As a general activity of the institutions, the data is being constantly corrected and enhanced. The MIDCARB Project leverages this state activity, by adding a CO_2 focus and providing data specific to geologic sequestration.

SDE Layers

Spatial Database Engines (SDE's) provide a spatial extension to the underlying commercial Relational Database Management System (RDBMS), thereby enabling all data (spatial and non-spatial) to be stored within a single RDBMS. SDE is a method to store, manage and access from a RDBMS both GIS data (shapefiles, images and coverages) and tabular data that are spatially referenced. A client can query the RDBMS, and data extracted for processing and display by the client software (Figure 12). As an example, a query for an individual CO_2 source using the hyperlink tool can return CO_2 emissions data that is arranged into a table or a plot (Figure 13, 14).

There are currently over 108 SDE layers that are stored on the five consortium servers (Table 1). Data fall into the following categories:

- CO2 Sources (5 Layers)
- Infrastructure (2 Layers)

Additional layers available but removed

- Base (15 Layers)
- Petroleum (9 Layers)
- Coal (38 Layers)
- Geology (3 Layers)
- Aquifer (29 Layers)
- Non-Conventional (5 Layers)

Through the SDE layers the user can use clients to access relational tables that include very large quantities of data that is pertinent to understand CO_2 emissions and potential geologic sequestration sites.

Relational Data Tables

The MIDCARB Project has used existing data tables of natural resource information and constructed new tables. In many cases existing data tables have been modified to include parameters that are critical to evaluation of potential geologic sequestration. Existing Tables cover:

- Aquifers
- Coal
- Nonconventional Reservoirs
- Oil and Gas

As an example of the size of databases available through MIDCARB, Kansas has data from over 395,000 oil and gas wells, 73,000 leases and 6,300 fields. The Kansas brine database contains water geochemistry data from over 4,000 wells (Figure 15). This data is used to construct data tables and new parameters. As an example in Ohio, data has been gathered on basic reservoir parameters (e.g., thickness, area, porosity and water saturation). The Ohio data can be accessed, queried and displayed through the MIDCARB site and used to estimate the quantity of CO_2 that could be sequestered in Ohio reservoirs that meet certain criteria (Figure 16). In addition, data can be downloaded to the client side for additional analysis (Figure 17). New parameters required for evaluation of geologic CO_2 sequestration have been computed from existing as well as new data. An example would be corrected temperature for the Arbuckle-Knox saline aquifer in Kansas (Figure 18). Over 19,000 bottom hole temperatures were extracted from a data table of electric log headers and linked to formation (Arbuckle Knox) at total depth. The extracted data (Figure 18a) can be used to derive a correction factor for Arbuckle-Knox aquifer (Figure 18b). The results can be used to generate coverages for aquifer temperature across the entire state (Figure 19). The temperature can be combined with pressure and brine geochemistry to generate an Arbuckle-Knox CO_2 sequestration potential assuming solubility (Figure 20).

Other data tables are unique to CO_2 sequestration and were modified or constructed for the MIDCARB project. In Kansas 15 data tables were developed to cover CO_2 emissions. Data tables are populated with data from numerous sources including US Department of Energy (EGRID), Environmental Protection Agency and local sources (Table 2, Figure 21).

Special Data

In a number of cases new data was generated as part of the MIDCARB effort. Data includes minimum miscibility measurements for oil and methane desorption/adsorption coal beds with the five-state MIDCARB project area. The minimum miscibility pressure (MMP) tests were performed on selected oils from all consortium states (Appendix A). The thermodynamic MMP is critical for determining recovery efficiency of CO_2 enhanced oil recovery, which has a significant impact on the economics of value-added CO_2 sequestration in oil reservoirs. The selected MMP measurements in each state provide tie points. These tie points can be extrapolated using correlations and mathematical models that incorporate equations of state to other reservoirs in each state (Jarrell and others 2002).

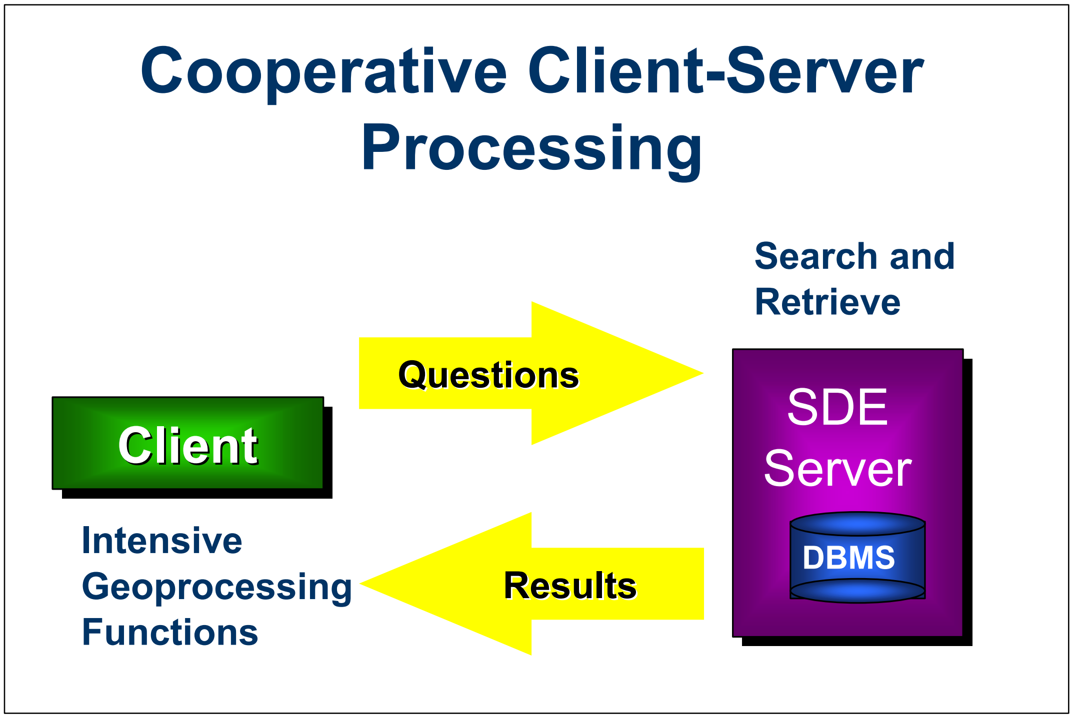


Figure 12 – A client function such as an Internet Map Server provides a method to design a query (e.g., emissions from a source by using the hyperlink tool in IMS – Figure 13 and 13). The results are returned to the client software for display or analysis.

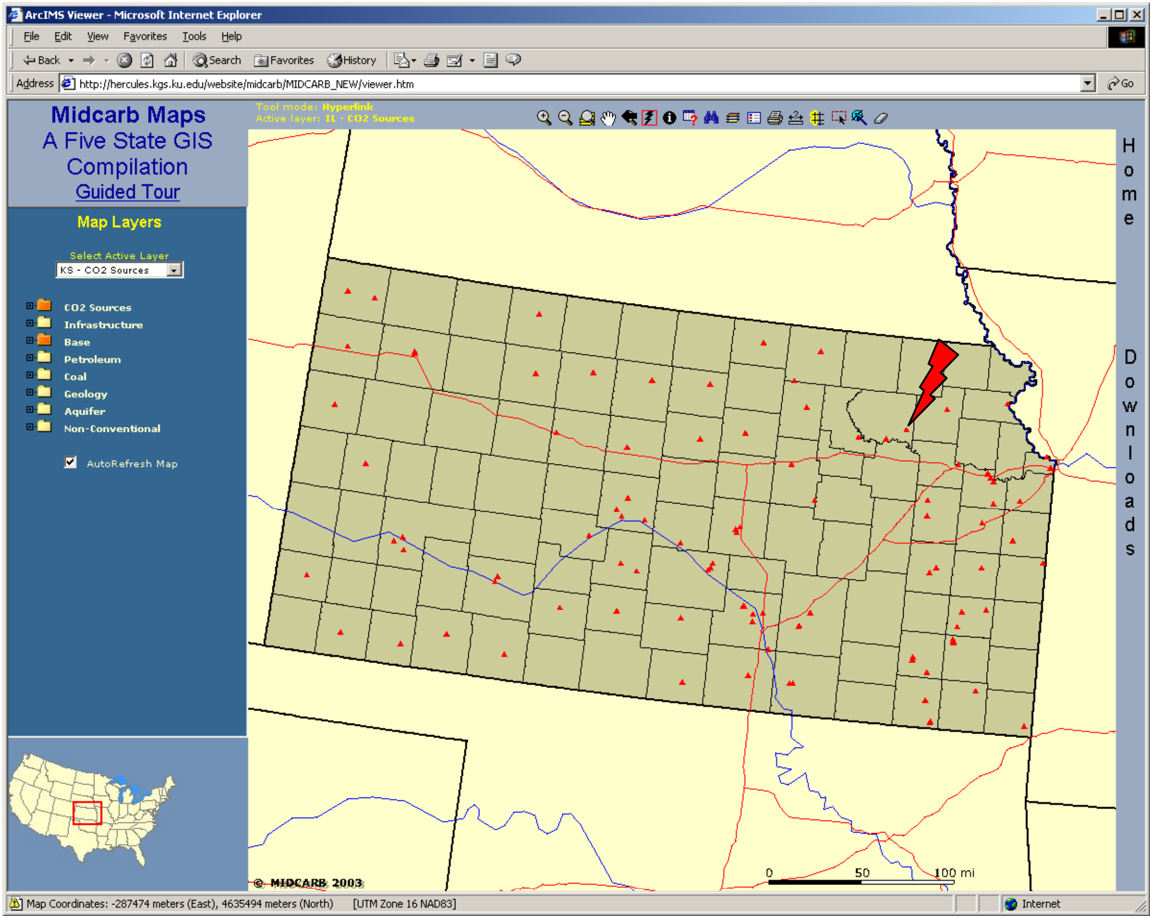


Figure 13 – MIDCARB IMS browser showing a query of emissions from a source in Kansas by using the hyperlink tool in IMS. This client can query the relational database and return results to other clients for display or analysis (Figure 14).

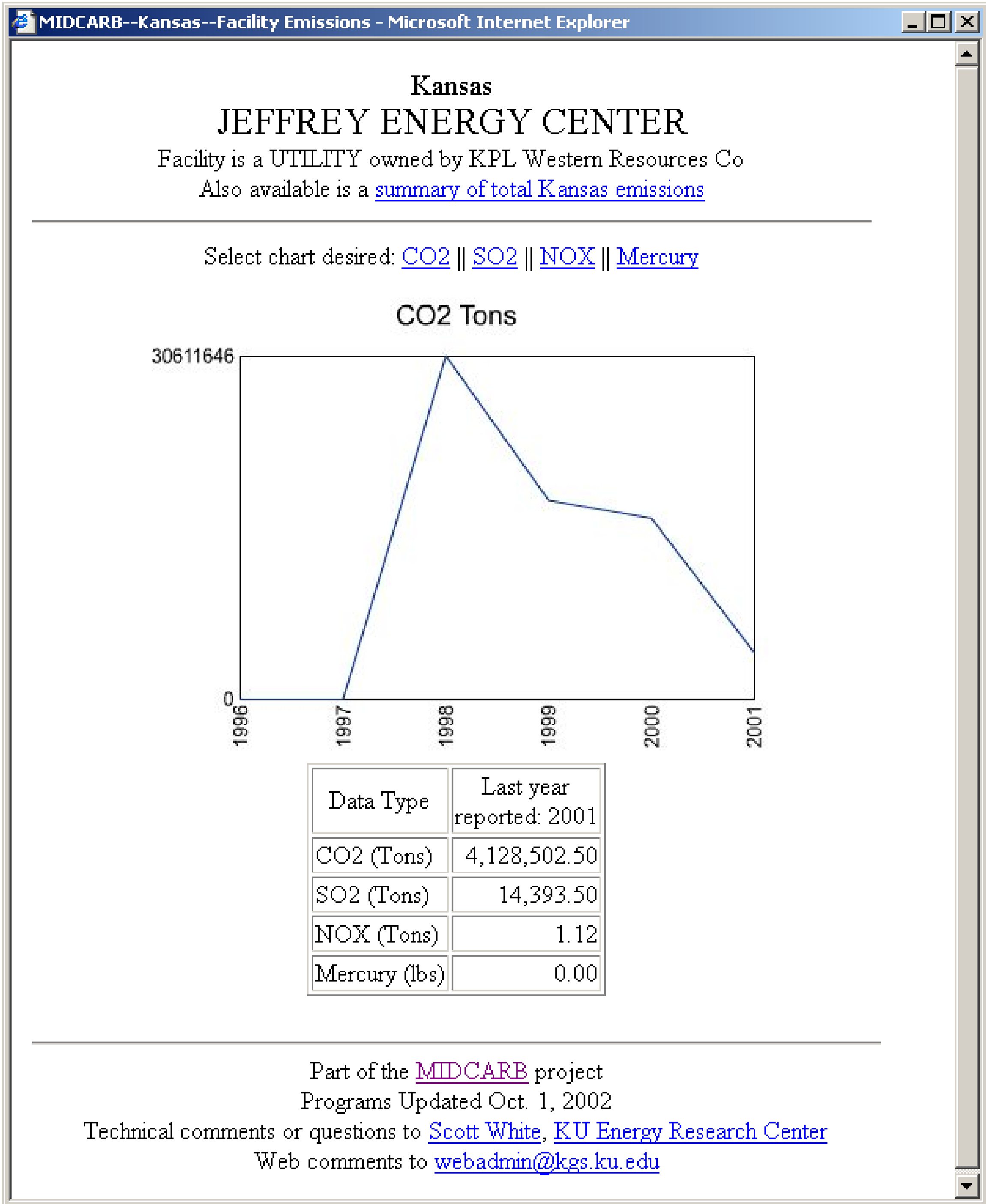
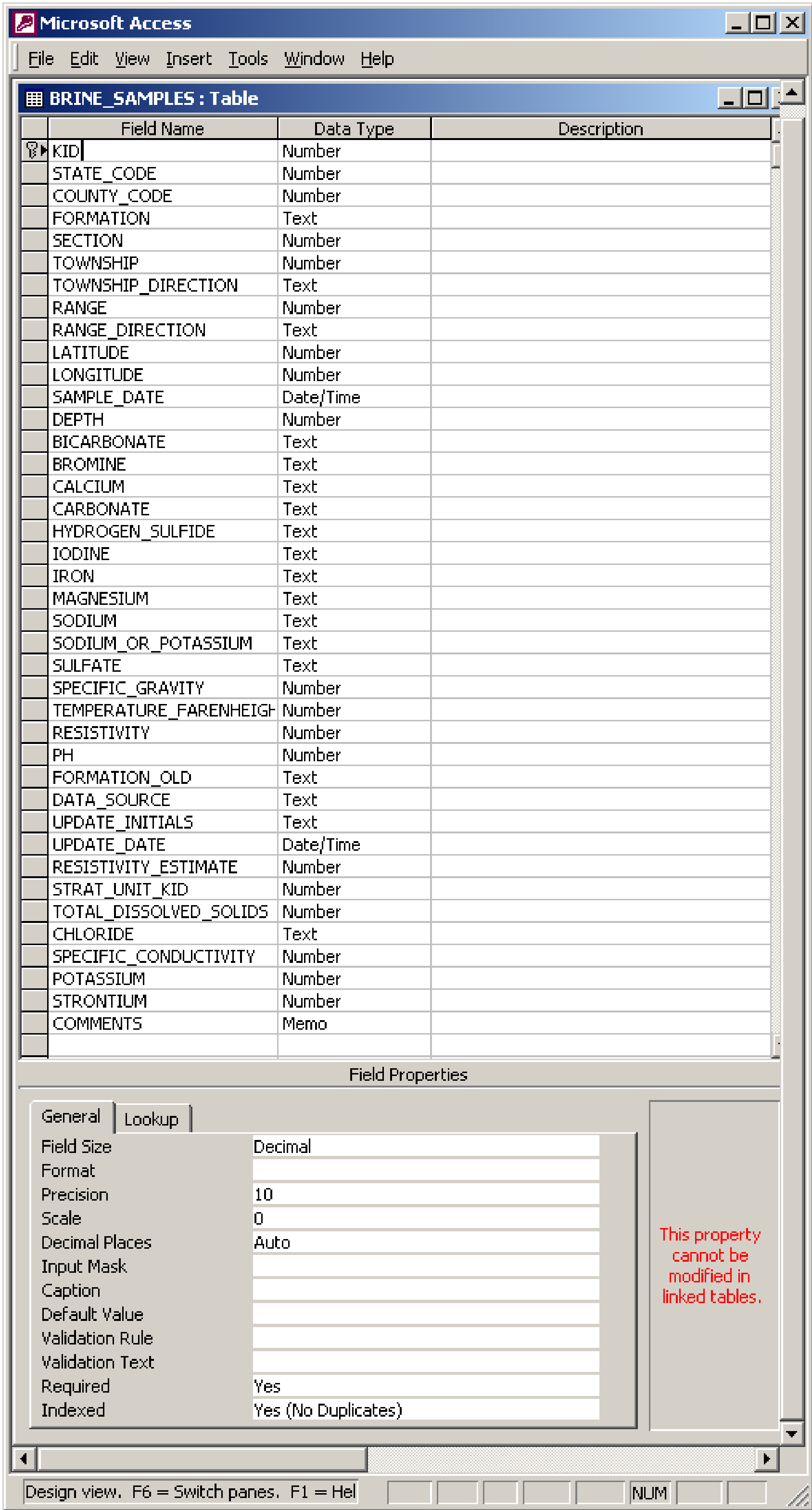


Figure 14 – Results of query through a SDE Layer (***KS-CO2 Sources)*** that is returned to a client for plotting. The final result is returned to the online user as an html formatted web page. In this example the result is a plot of annual CO_2 emissions from a single power plant in Kansas.



Field Name	Data Type	Description
KID	Number	
STATE_CODE	Number	
COUNTY_CODE	Number	
FORMATION	Text	
SECTION	Number	
TOWNSHIP	Number	
TOWNSHIP_DIRECTION	Text	
RANGE	Number	
RANGE_DIRECTION	Text	
LATITUDE	Number	
LONGITUDE	Number	
SAMPLE_DATE	Date/Time	
DEPTH	Number	
BICARBONATE	Text	
BROMINE	Text	
CALCIUM	Text	
CARBONATE	Text	
HYDROGEN_SULFIDE	Text	
IODINE	Text	
IRON	Text	
MAGNESIUM	Text	
SODIUM	Text	
SODIUM_OR_POTASSIUM	Text	
SULFATE	Text	
SPECIFIC_GRAVITY	Number	
TEMPERATURE_FARENHEIGH	Number	
RESISTIVITY	Number	
PH	Number	
FORMATION_OLD	Text	
DATA_SOURCE	Text	
UPDATE_INITIALS	Text	
UPDATE_DATE	Date/Time	
RESISTIVITY_ESTIMATE	Number	
STRAT_UNIT_KID	Number	
TOTAL_DISSOLVED_SOLIDS	Number	
CHLORIDE	Text	
SPECIFIC_CONDUCTIVITY	Number	
POTASSIUM	Number	
STRONTIUM	Number	
COMMENTS	Memo	

Field Size	Decimal
Format	
Precision	10
Scale	0
Decimal Places	Auto
Input Mask	
Caption	
Default Value	
Validation Rule	
Validation Text	
Required	Yes
Indexed	Yes (No Duplicates)

Figure 15 – View of brine geochemistry data table containing over 4,000 samples that is accessible from the MIDCARB IMS using the hyperlink tool on sample points from ***KS-Arbuckle-Knox Sample Sites*** SDE layer.

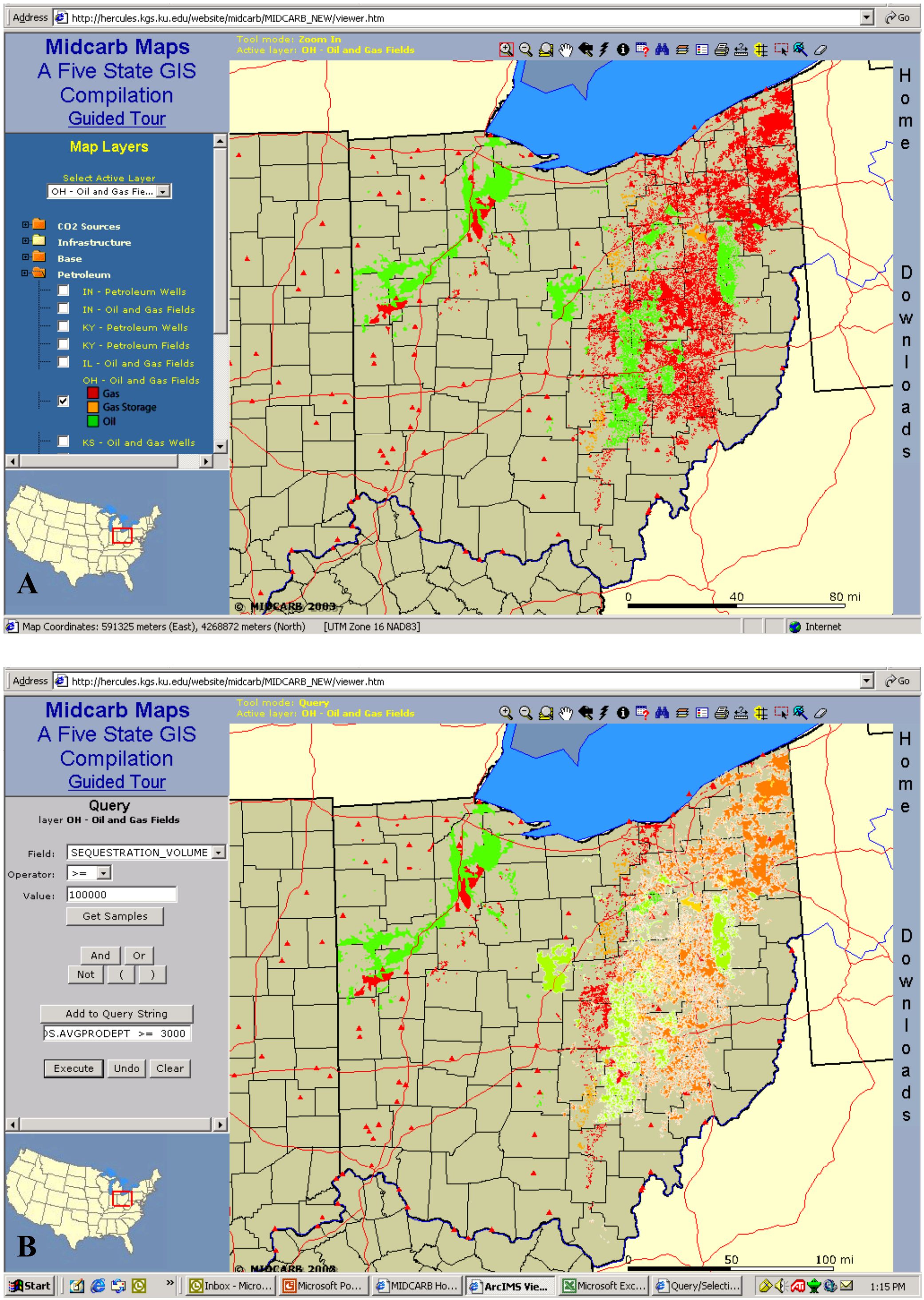
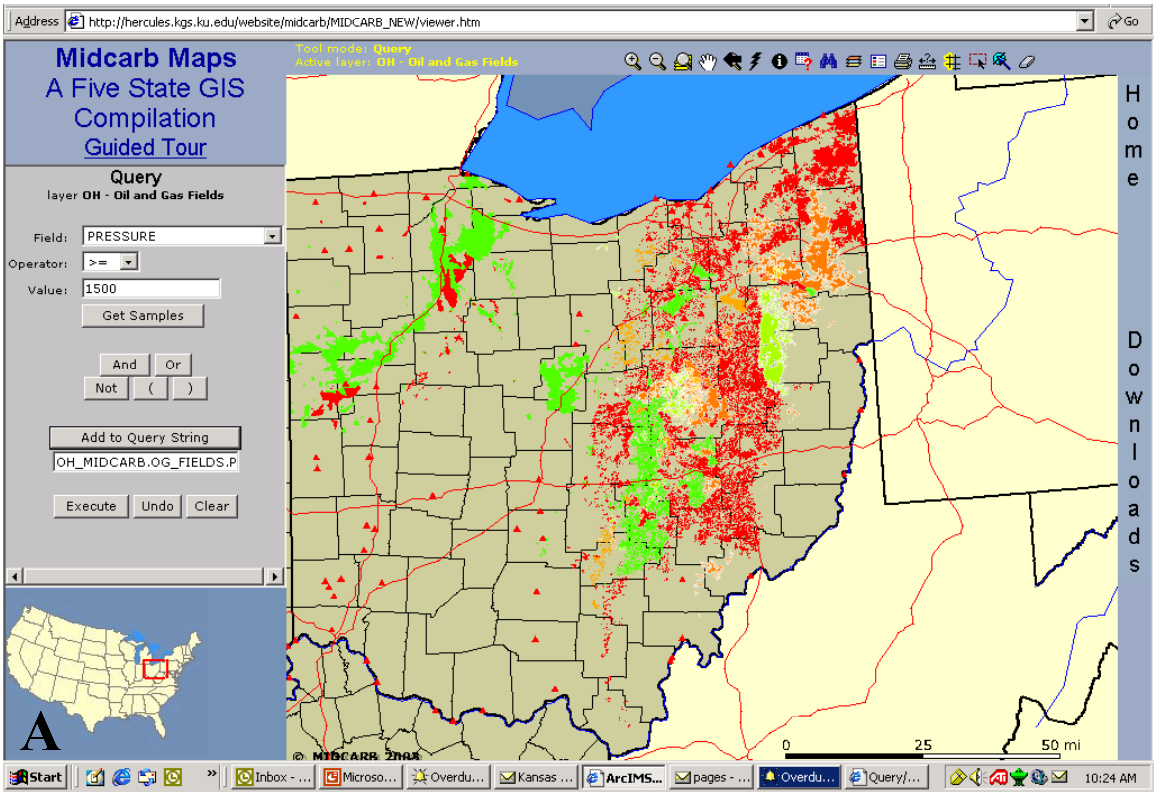


Figure 16 – A) MIDCARB IMS Browser showing SDE layer entitled ***Ohio Oil and Gas Fields***. **B)** Using the query tool, the relational data base containing data on Ohio oil and gas fields can be query to highlight fields with sequestration potential greater than 100,000 metric tonnes. Sequestration potential is determined from reservoir volumetrics, temperature and depth.



B

	FIELDID	PLAY	FMTN_CODE	FIELD_NAME	DEPTH	Thick	TEMP	PRES	POROSITY	DISCOVERY_YEAR	SW	NUMBER_OF_WELLS	ACRES	No. Pools	CO2_DENSITY	SEQUESTRATION_VOLUME	PRODUCTION_TYPE
2	1369	KNOX	BKMN	BRANNONS FORK	7469	10	110	2600	0.15	1983	50	3	501	1	2172337.2	371025.3195	GAS
3	1392	KNOX	BKMN	PLEASANT GROVE	6040	10	100	2100	0.15	1994	50	6	967	1	2144458.8	706940.3385	GAS
4	1397	KNOX	RSRN	ROCKBRIDGE	4334	35	90	1500	0.08	1993	50	37	4747	6	2056467.6	6212214.716	GAS & OIL
5	1401	KNOX	RSRN	COLFAX	4219	35	90	1500	0.08	1995	50	15	1615	1	2056467.6	2113487.838	OIL
6	1359	KNOX	RSRN	LAKE OTTO	4962.5	35	100	1700	0.08	1997	50	18	2890	3	1995048	3669074.64	GAS
7	1393	KNOX	RSRN	RUSH CREEK	5327	35	100	1800	0.08	1988	50	115	13307	12	2040786	17281561.37	GAS & OIL
8	1390	KNOX	RSRN	FRAZEYBURG	5825	30	100	2000	0.08	1989	30	133	16901	6	2113966.8	27283316.75	GAS
9	1378	KNOX	RSRN	DORSET	6011	35	100	2100	0.08	1990	50	10	1687	2	2144458.8	2302173.997	GAS
10	1374	KNOX	RSRN	GRIGGS CORNERS	5808	35	100	2000	0.08	1995	50	3	403	1	2113966.8	542136.3948	GAS
11	1377	KNOX	RSRN	MUNSON HILL	5494	35	100	1900	0.08	1999	50	12	1613	1	2079554.4	2134568.066	GAS
12												TOTAL POOLS		34		62,616,499	
13																CO2 SEQ Potential	

Figure 17 – A) Using query tool the SDE layer entitled ***Ohio Oil and Gas Fields*** is queried and only fields with reservoir pressure greater than 1500 psi are highlighted. This pressure criterion is the minimum miscibility pressure for Ohio oils in the Copper Ridge Dolomite (Appendix A). The MMP indicates which Ohio pools have the highest potential for enhanced CO_2 oil recovery value-added sequestration. (Appendix A). **B)** Using the query tool, information on the 34 pools that meet the MMP cutoff can be extracted from the relational database containing data on Ohio oil and gas pools and loaded into user programs (e.g., Microsoft Excel). Sequestration volumes are in metric tonnes and determined from reservoir volumetrics, temperature and depth.

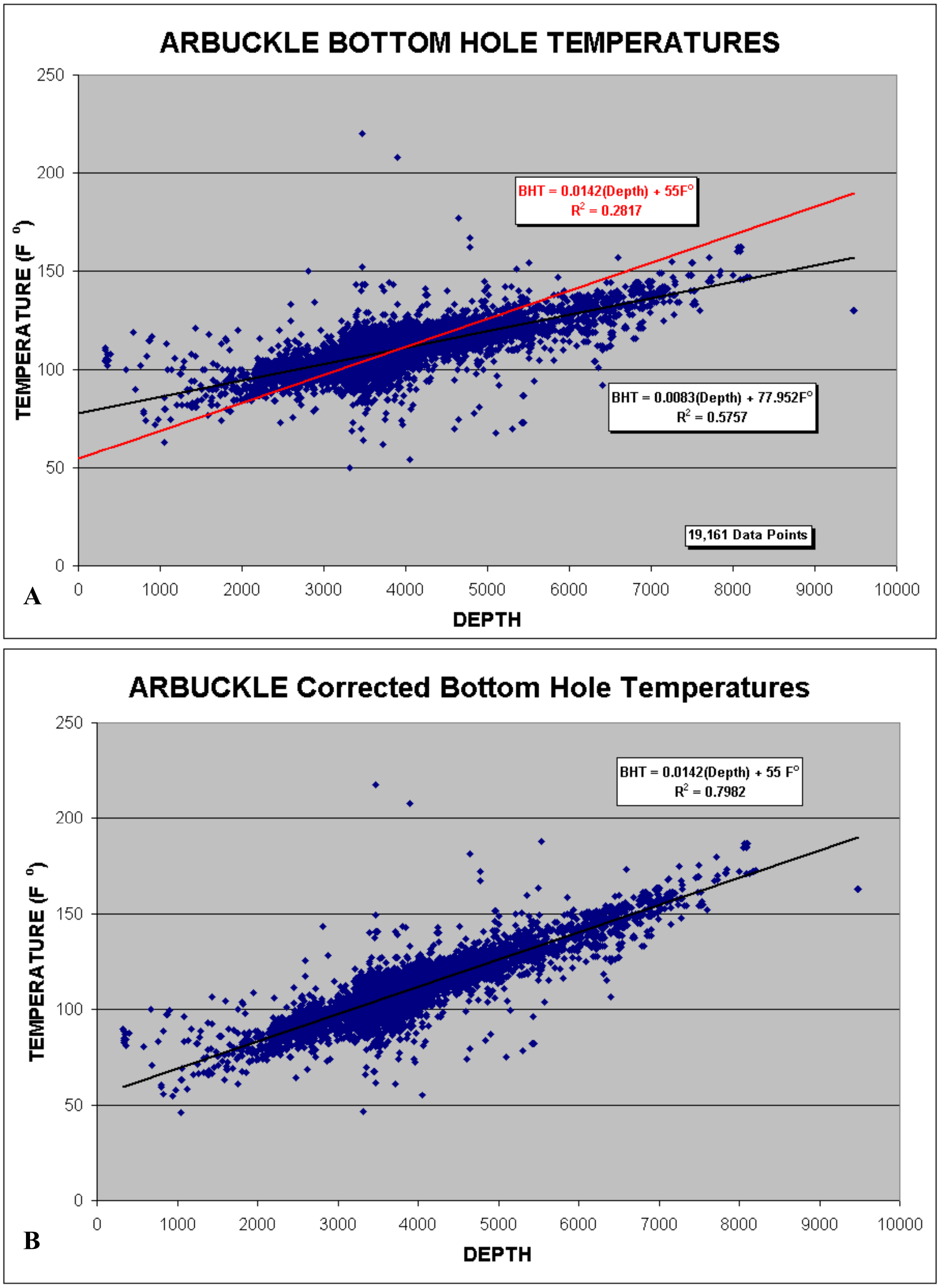


Figure 18 – A) Bottom-hole temperatures (BHTs), recorded from 19,161 wells, are not at equilibrium with formation temperature and require correction. The BHT correction factor adjusts the temperature recorded during logging to the "true" formation temperature. **B)** The corrected BHTs for the Arbuckle show the same relationship of temperature with depth and an improved fit ($R^2 = 0.8$). The scattered outliers are obvious on the crossplots and are probably the result of tool malfunction, reading or recording errors at the time of logging, or data entry errors.

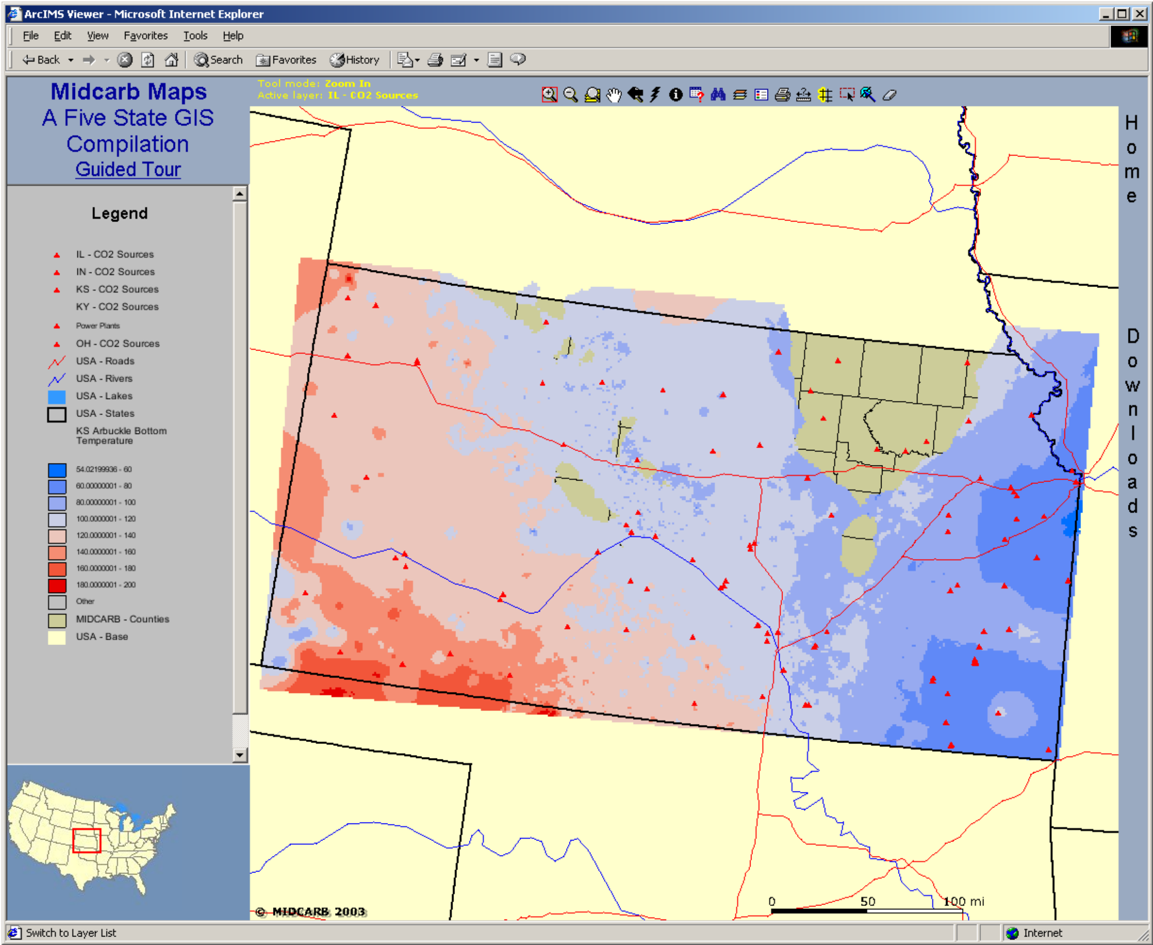


Figure 19 – View of ***KS-Arbuckle-Knox Aquifer Temperature*** SDE layer using corrected bottom hole temperatures from 19,161 wells across Kansas (Figure 17).

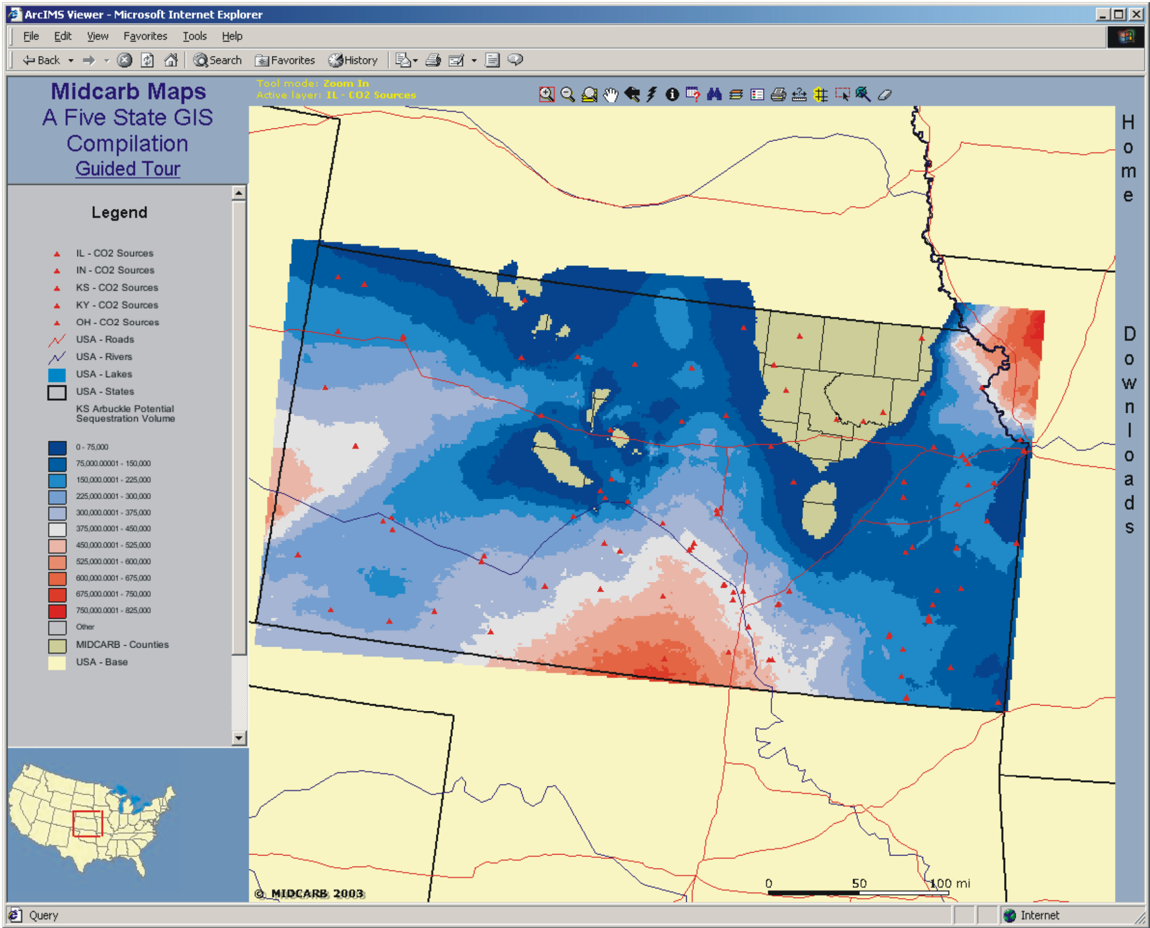


Figure 20 – Estimated CO_2 sequestration potential in the Arbuckle-Knox saline aquifer. SDE layer generated for each square mile of Kansas from aquifer temperature, pressure, salinity, porosity and thickness coverages. The entire Arbuckle Aquifer underlying Kansas has the potential to sequester a very large quantity of CO_2 - A number approaching 16,994 trillion cubic feet of CO_2. (894 billion metric tonnes). Assumes solubility in brine. If displacement is more significant the volumes will be significantly greater.

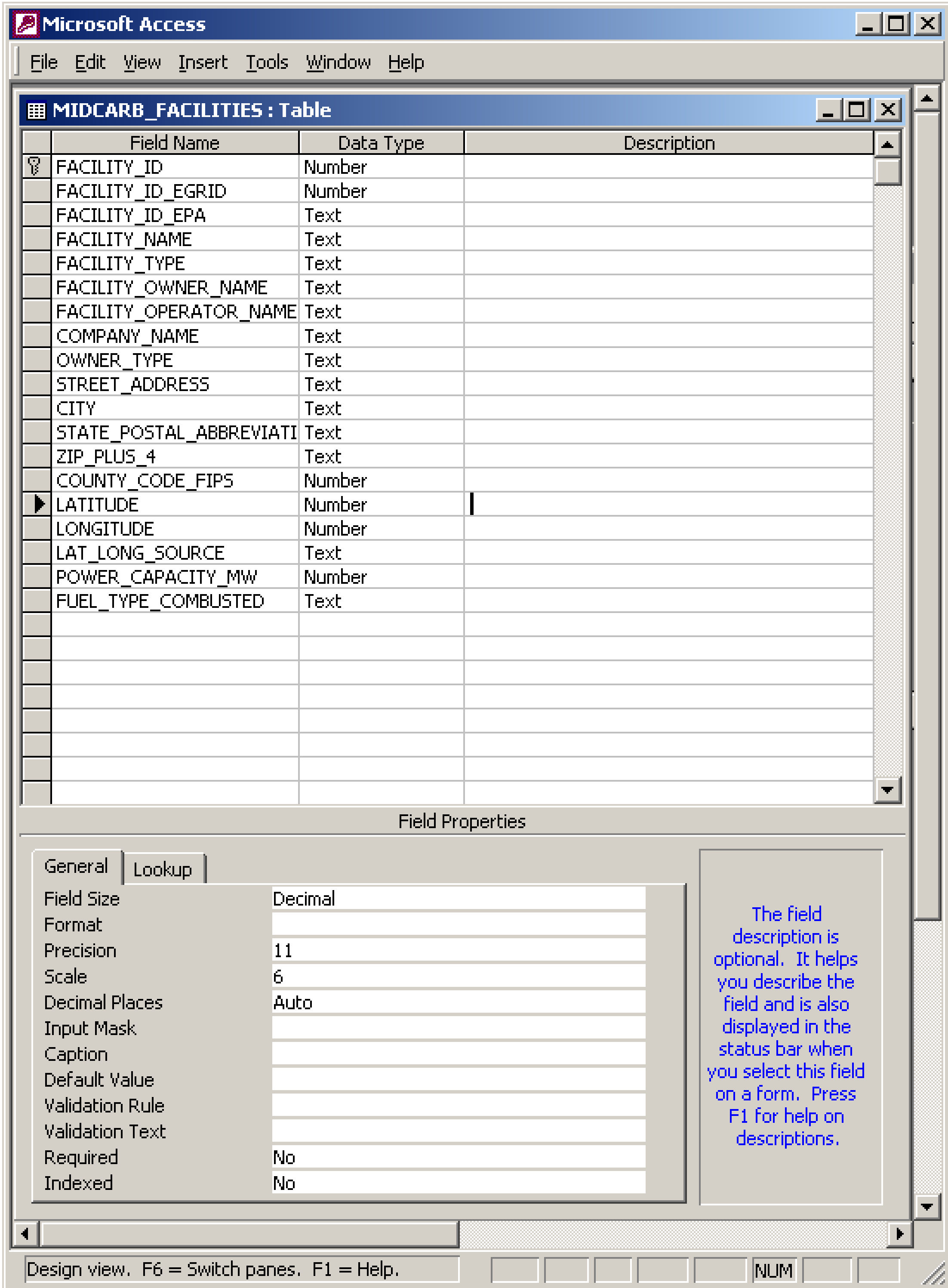


Figure 21 – View of selected data table containing facilities that are major sources of CO_2 emissions in Kansas. A listing of all data tables associated with the RDBMS covering CO_2 emissions in Kansas is provided in Table 2. Similar data tables exist in each of the five states of the MIDCARB Consortium and provide the data that is accessible across all states through the MIDCARB IMS browser and SDE layers.

Table 1 – List from MIDCARB administration web page of all current SDE layers maintained on the servers of the MIDCARB Consortium (June 10, 2003). SDE source shows storage location for individual SDE layers and the institution responsible for maintaining layer. Total number of layers is 108. **Note:** Only default layers are listed as visible. However all layers are visible if selected by user.

Layer Definitions for MIDCARB_10JUNE03 Map Service on neutrino							
ALL STATES | ILLINOIS | INDIANA | KENTUCKY | KANSAS | OHIO							
Layer Type	**Layer Name**	**Layer Visible**	**Layer ID**	**Layer Group**	**SDE Source**	**View Layer Details**	**Metadata**
featureclass	USA - Base	true	107	Base	Indiana	View Details	View/Edit Metadata
featureclass	MIDCARB - Counties	true	106	Base	Indiana	View Details	View/Edit Metadata
image	Aerials Zone 14 - KS	false	105	Base	Kansas	View Details	View/Edit Metadata
image	Aerials Zone 15 - KS	false	104	Base	Kansas	View Details	View/Edit Metadata
image	DRG Zone 14 - KS	false	103	Base	Kansas	View Details	Add Metadata
image	DRG Zone 15 - KS	false	102	Base	Kansas	View Details	Add Metadata
featureclass	MIDCARB - Bedrock	false	101	Geology	Indiana	View Details	View/Edit Metadata
featureclass	Devonian Shale Subsurface	false	100	Non-Conventional	Kentucky	View Details	Add Metadata
featureclass	Devonian Shale Outcrop	false	99	Non-Conventional	Kentucky	View Details	Add Metadata
featureclass	Devonian Shale Isopach	false	98	Non-Conventional	Kentucky	View Details	Add Metadata
featureclass	Devonian Shale Structure	false	97	Non-Conventional	Kentucky	View Details	Add Metadata
featureclass	Devonian Shale Faults	false	96	Non-Conventional	Kentucky	View Details	Add Metadata
featureclass	KY - Lower Elkhorn Thickness	false	95	Coal	Kentucky	View Details	Add Metadata
featureclass	KY - Lower Elkhorn Mines	false	94	Coal	Kentucky	View Details	Add Metadata

featureclass	KY - Lower Elkhorn Structure	false	93	Coal	Kentucky	View Details	Add Metadata
featureclass	KY - Upper Elkhorn No.3 Thickness	false	92	Coal	Kentucky	View Details	Add Metadata
featureclass	KY - Upper Elkhorn No.3 Mines	false	91	Coal	Kentucky	View Details	Add Metadata
featureclass	KY - Fire Clay Thickness	false	90	Coal	Kentucky	View Details	Add Metadata
featureclass	KY - Fire Clay Mines	false	89	Coal	Kentucky	View Details	Add Metadata
featureclass	KY - Fire Clay Structure	false	88	Coal	Kentucky	View Details	Add Metadata
featureclass	Calculated Gas Content in Seelyville-Davis-Dekovan Coals	false	87	Coal	Indiana	View Details	Add Metadata
featureclass	Data Points for Calculated Gas Content	false	86	Coal	Indiana	View Details	Add Metadata
featureclass	Vitrinite Reflectance in Seelyville-Davis-Dekovan Coals	false	85	Coal	Indiana	View Details	Add Metadata
featureclass	Data Points for Vitrinite Reflectance	false	84	Coal	Indiana	View Details	Add Metadata
featureclass	Mississippian-Pennsylvanian Extent	false	83	Coal	Kansas	View Details	Add Metadata
featureclass	OH - Net Coal Thickness	false	82	Coal	Kansas	View Details	Add Metadata
featureclass	IL - Net Coal Thickness	false	81	Coal	Illinois	View Details	View Metadata
featureclass	Middle Kittanning Overburden	false	80	Coal	Kansas	View Details	Add Metadata
featureclass	Middle Kittanning Isopach	false	79	Coal	Kansas	View Details	Add Metadata
featureclass	Middle Kittanning Structure	false	78	Coal	Kansas	View Details	Add Metadata
featureclass	OH Upperfreeport Overburden	false	77	Coal	Kansas	View Details	Add Metadata
featureclass	OH Upperfreeport Isopach	false	76	Coal	Kansas	View Details	Add Metadata

featureclass	OH Upperfreeport Structure	false	75	Coal	Kansas	View Details	Add Metadata
featureclass	Seelyville-Davis Structure	false	74	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Seelyville-Davis Depth	false	73	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Seelyville-Davis Thickness	false	72	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Springfield Elevation	false	71	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Springfield Depth	false	70	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Springfield Thickness	false	69	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Springfield Mines	false	68	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Herrin Structure	false	67	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Herrin Depth	false	66	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Herrin Thickness	false	65	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Herrin Mines	false	64	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Danville_Structure	false	63	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Danville Depth	false	62	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Danville Thickness	false	61	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	Danville Mines	false	60	Coal	Kentucky	View Details	View/Edit Metadata
featureclass	KS - Weir-Pitt Structure	false	59	Coal	Kansas	View Details	Add Metadata
featureclass	KS - Weir-Pitt Thickness	false	58	Coal	Kansas	View Details	Add Metadata
featureclass	KS Arbuckle-Knox brine TDS mg per l	false	57	Aquifer	Kansas	View Details	Add Metadata

featureclass	KS Arbuckle-Knox brine specific gravity g per ml	false	56	Aquifer	Kansas	View Details	Add Metadata
featureclass	KS Arbuckle-Knox brine Cl g per ml	false	55	Aquifer	Kansas	View Details	Add Metadata
featureclass	KS Arbuckle-Knox brine Ca mg per l	false	54	Aquifer	Kansas	View Details	Add Metadata
featureclass	KS Precambrian Structure sub-sea ft	false	53	Aquifer	Kansas	View Details	Add Metadata
image	KS Arbuckle-Knox Structure sub-sea ft	false	52	Aquifer	Kansas	View Details	Add Metadata
image	KS Arbuckle Thickness	false	51	Aquifer	Kansas	View Details	Add Metadata
image	KS Arbuckle Potential Sequestration Volume	false	50	Aquifer	Kansas	View Details	Add Metadata
image	KS Arbuckle Bottom Temperature	false	49	Aquifer	Kansas	View Details	Add Metadata
image	KS Arbuckle Pressure	false	48	Aquifer	Kansas	View Details	Add Metadata
image	KS Arbuckle Total Dissolved Solids	false	47	Aquifer	Kansas	View Details	Add Metadata
featureclass	KS Arbuckle-Knox Sample Sites	false	46	Aquifer	Kansas	View Details	Add Metadata
featureclass	OH Precambrian Structure Polygons	false	45	Aquifer	Kansas	View Details	Add Metadata
featureclass	OH Precambrian Structure Contours	false	44	Aquifer	Kansas	View Details	Add Metadata
featureclass	OH Precambrian Structure Faults	false	43	Aquifer	Kansas	View Details	Add Metadata
featureclass	Regional-Mount Simon Structure Contours	false	42	Aquifer	Kansas	View Details	Add Metadata
featureclass	Regional-Mount Simon Structure Faults	false	41	Aquifer	Kansas	View Details	Add Metadata
featureclass	Regional-Mount Simon Isopach Polygons	false	40	Aquifer	Kansas	View Details	Add Metadata
featureclass	Regional-Mount Simon Sandstone Points	false	39	Aquifer	Kansas	View Details	Add Metadata
featureclass	Regional-Mount Simon Isopach Contours	false	38	Aquifer	Kansas	View Details	Add Metadata

featureclass	Regional-Mount Simon Isopach Faults	false	37	Aquifer	Kansas	View Details	Add Metadata
featureclass	Regional-Mount Siimon Isopach Polygons	false	36	Aquifer	Kansas	View Details	Add Metadata
featureclass	Regional-Knox Structure Contours	false	35	Aquifer	Kansas	View Details	Add Metadata
featureclass	Regional-Knox Structure Faults	false	34	Aquifer	Kansas	View Details	Add Metadata
featureclass	Hunton Aquifer Top Contour	false	33	Aquifer	Indiana	View Details	View/Edit Metadata
featureclass	Hunton Aquifer Top Extent	false	32	Aquifer	Indiana	View Details	View/Edit Metadata
featureclass	Hunton Aquifer Bottom Contour	false	31	Aquifer	Indiana	View Details	View/Edit Metadata
featureclass	Hunton Aquifer Thickness	false	30	Aquifer	Indiana	View Details	Add Metadata
featureclass	Hunton Aquifer Bottom Extent	false	29	Aquifer	Indiana	View Details	View/Edit Metadata
featureclass	KS Cumulative Gas Production	false	28	Petroleum	Kansas	View Details	Add Metadata
featureclass	KS Cumulative Oil Production	false	27	Petroleum	Kansas	View Details	Add Metadata
featureclass	KS OIL-GAS FIELD BOUNDARIES	false	26	Petroleum	Kansas	View Details	Add Metadata
featureclass	KS - Oil and Gas Wells	false	25	Petroleum	Kansas	View Details	Add Metadata
featureclass	OH - Oil and Gas Fields	false	24	Petroleum	Kansas	View Details	Add Metadata
featureclass	IL - Oil and Gas Fields	false	23	Petroleum	Illinois	View Details	View Metadata
featureclass	KY - Petroleum Fields	false	22	Petroleum	Kentucky	View Details	Add Metadata
featureclass	IN - Oil and Gas Fields	false	21	Petroleum	Indiana	View Details	View Metadata
featureclass	IN - Petroleum Wells	false	20	Petroleum	Indiana	View Details	View Metadata
featureclass	KS - Section Lines	false	19	Base	Kansas	View Details	Add Metadata

featureclass	IN - Section Lines	false	18	Base	Indiana	View Details	Add Metadata
featureclass	IL - Section Lines	false	17	Base	Illinois	View Details	Add Metadata
featureclass	IL - Township Lines	false	16	Base	Illinois	View Details	Add Metadata
featureclass	USA - States	true	15	Base	Indiana	View Details	Add Metadata
featureclass	USA - States	true	14	Base	Indiana	View Details	Add Metadata
featureclass	USA - Cities	false	13	Base	Indiana	View Details	Add Metadata
featureclass	USA - Cities, Detailed	false	12	Base	Indiana	View Details	Add Metadata
featureclass	USA - Lakes	true	11	Base	Indiana	View Details	Add Metadata
featureclass	USA - Rivers	true	10	Base	Indiana	View Details	Add Metadata
featureclass	USA - Roads	true	9	Base	Indiana	View Details	Add Metadata
featureclass	IN - Electric Lines	false	8	Infrastructure	Indiana	View Details	View Metadata
featureclass	IN - Pipelines	false	7	Infrastructure	Indiana	View Details	View Metadata
featureclass	KS-Stone-Soil	false	6	Base	Kansas	View Details	Add Metadata
featureclass	KS-Sand-Gravel	false	5	Base	Kansas	View Details	Add Metadata
featureclass	OH - CO2 Sources	true	4	CO2 Sources	Kansas	View Details	View/Edit Metadata
featureclass	KY - CO2 Sources	true	3	CO2 Sources	Kentucky	View Details	View/Edit Metadata
featureclass	KS - CO2 Sources	true	2	CO2 Sources	Kansas	View Details	View/Edit Metadata
featureclass	IN - CO2 Sources	true	1	CO2 Sources	Indiana	View Details	View/Edit Metadata
featureclass	IL - CO2 Sources	true	0	CO2 Sources	Illinois	View Details	View/Edit Metadata

Table 2 – List of data tables in RDBMS associated with CO_2 sources in Kansas. Local tables where generated as part of the MIDCARB Project. Other data tables from Department of Energy (DOE) and Environmental Protection Agency (EPA) are national in scope and have been modified to fit the needs of the MIDCARB Project. A view of the table design for the ***MIDCARB_FACILITIES*** data table is provided in Figure 30.

Data Table Name	*Source*	*Number of Records*	*Number of Fields*
MIDCARB_FACILITIES	LOCAL	106	19
MIDCARB_FACILITIES_EMISSIONS	LOCAL	614	11
MIDCARB_FUEL_TYPE_COMBUSTED	LOCAL	38	3
MIDCARB_INDUSTRIAL_FACILITIES	LOCAL	15	11
MIDCARB_INDUSTRIAL_FACILITIES_ANNUAL	LOCAL	5	11
MIDCARB_EPA_FACILITIES	EPA	22	11
MIDCARB_EPA_FACILITIES_UNITS	EPA	41	21
MIDCARB_EPA_FACILITIES_UNITS_FUELS	EPA	58	6
MIDCARB_EPA_FACILITIES_UNITS_QUARTERS	EPA	657	19
MIDCARB_EGRDEGCO96	DOE	2086	53
MIDCARB_EGRDEGCO97	DOE	2072	53
MIDCARB_EGRDEGCO98	DOE	1971	53
MIDCARB_EGRDPLNT96	DOE	4849	116
MIDCARB_EGRDPLNT97	DOE	4815	116
MIDCARB_EGRDPLNT98	DOE	4636	116

MIDCARB SYSTEM ANALYSIS TOOLS

As part of the MIDCARB Project a number of display and analysis tools were developed. All the tools work across the entire MIDCARB system and can be accessed through the MIDCARB IMS browser. Tools include clients to query and plot emissions or production through time for a single object (Figure 14) or to sum total emissions across an individual state (Figure 22). The query and analysis tools can also be accessed through the MIDCARB web page as independent calculators (www.midcarb.org).

For the CO_2 solubility calculator, a RDBMS table was constructed to provide estimates of the solubility of CO_2 in aquifer water. Data for the table is empirical (Chang and others, 1996; Crawford and others, 1963; Holm, 1963; Johnson and others, 1952; Martin, 1951). The tool is designed to access an automated look-up table (Figure 23). First the solubility of CO_2 is estimated as a function of pressure and temperature interpolating between empirical curves. Second, the CO_2 solubility is corrected to the salinity of the water (independent of pressure and temperature). This approach provides a first-order estimate for solubility of CO_2 in saline aquifers. The calculator is used with the pressure, temperature and salinity data to generate SDE coverage for saline aquifers in the MIDCARB project (e.g., Arbuckle-Knox in Kansas; Figure 20). However, if the solubility curves are adjusted in the future or new salinity, pressure or temperature data is entered into the databases, the MIDCARB approach permits rapid generation of new estimates of CO_2 sequestration potential.

Another calculator was developed to estimate the physical state and density of CO_2 at different pressures and temperatures. Small deviation in pressure and temperature from the triple point will cause CO_2 to exist as a solid, liquid or vapor. At pressures and temperatures above the critical point (1,071 psi at 87.8^{o}F), CO_2 is neither a true vapor nor liquid, but exists as a dense vapor phase. As a result the amount of CO_2 that can be sequestered in a reservoir is highly dependent on temperature and pressure. Using empirical data (Jarrell and others, 2002), a RDBMS table was constructed to provide CO_2 properties under various temperatures and pressures (Figures 24, 25). These physical properties can be combined with other physical parameters to estimate the volume of CO_2 that can be sequestered in a selected reservoir of group of reservoirs (e.g., Figures 16, 17).

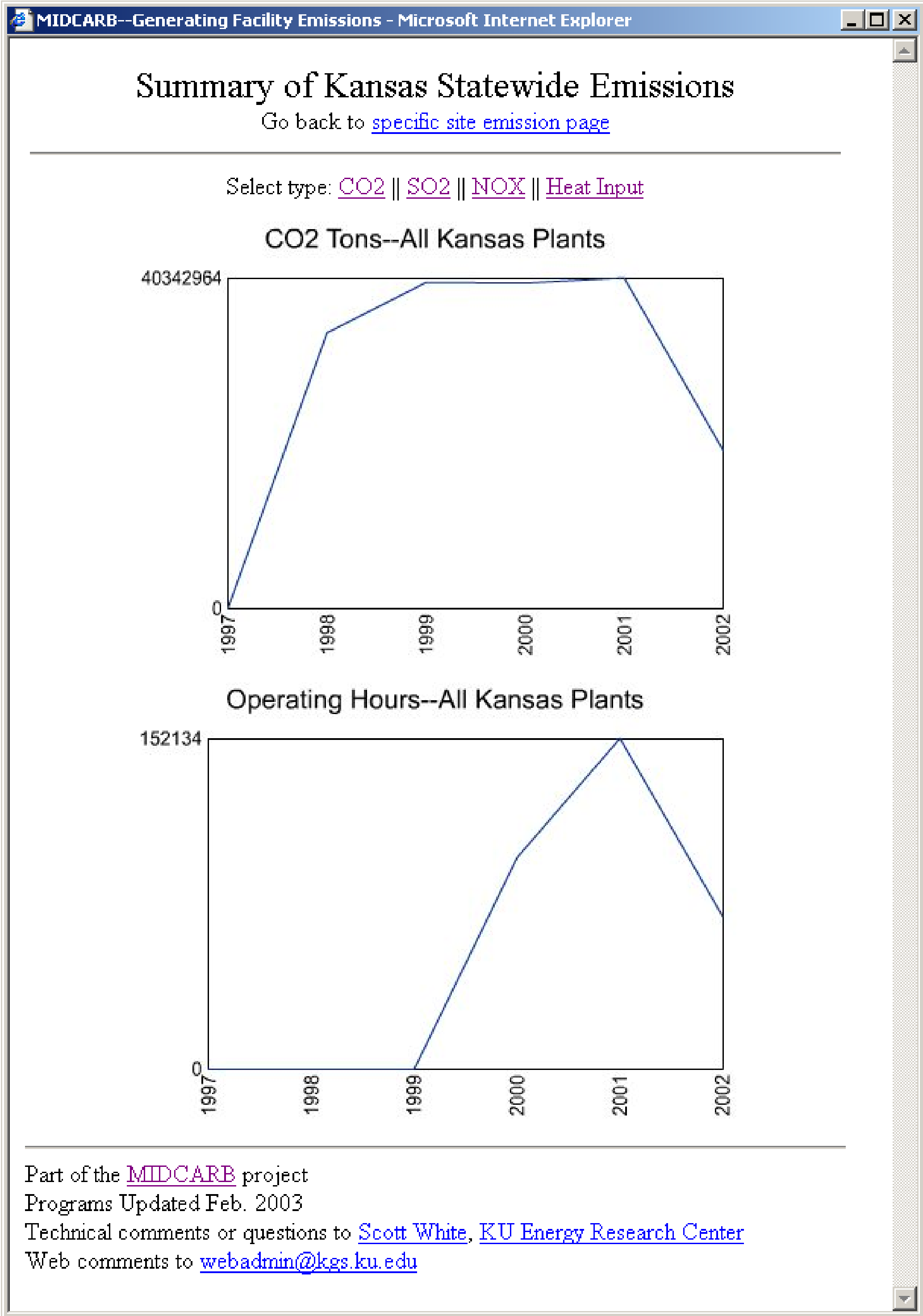
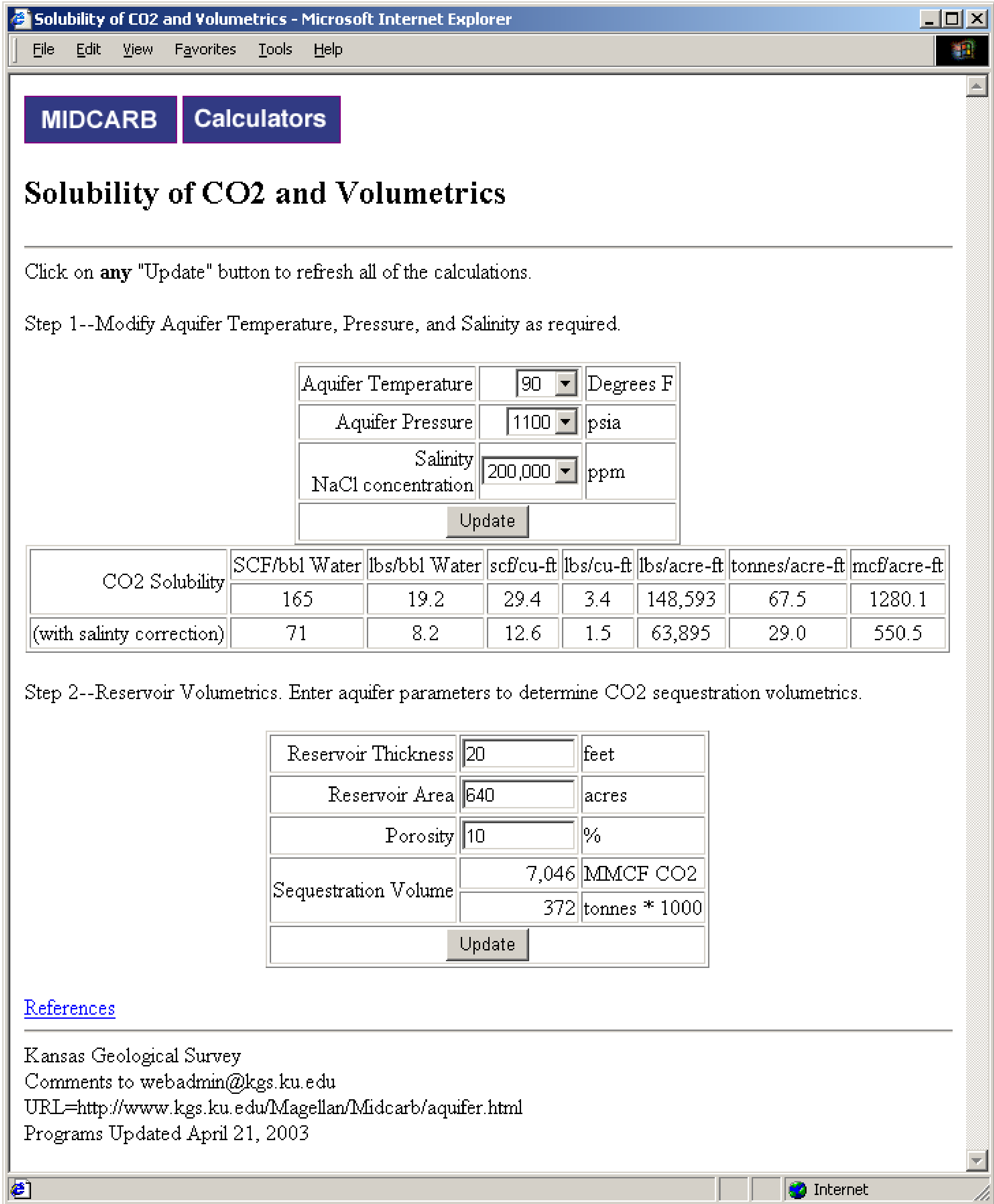


Figure 22 – Results of request for summation of CO_2 emissions for all sources through SDE Layer (***KS-CO2 Sources)*** that is returned to a client for plotting. The result is returned to the online user as an html formatted web page. In this example the result is a plot of annual CO_2 emissions from all sources in the MIDCARB databases for Kansas (See Figure 14 for a single source example).



Solubility of CO2 and Volumetrics - Microsoft Internet Explorer

File Edit View Favorites Tools Help

MIDCARB Calculators

Solubility of CO2 and Volumetrics

Click on **any** "Update" button to refresh all of the calculations.

Step 1--Modify Aquifer Temperature, Pressure, and Salinity as required.

Aquifer Temperature	90	Degrees F
Aquifer Pressure	1100	psia
Salinity NaCl concentration	200,000	ppm
	Update	

	SCF/bbl Water	lbs/bbl Water	scf/cu-ft	lbs/cu-ft	lbs/acre-ft	tonnes/acre-ft	mcf/acre-ft
CO2 Solubility	165	19.2	29.4	3.4	148,593	67.5	1280.1
(with salinty correction)	71	8.2	12.6	1.5	63,895	29.0	550.5

Step 2--Reservoir Volumetrics. Enter aquifer parameters to determine CO2 sequestration volumetrics.

Reservoir Thickness	20	feet
Reservoir Area	640	acres
Porosity	10	%
Sequestration Volume	7,046	MMCF CO2
	372	tonnes * 1000
	Update	

References

Kansas Geological Survey
Comments to webadmin@kgs.ku.edu
URL=http://www.kgs.ku.edu/Magellan/Midcarb/aquifer.html
Programs Updated April 21, 2003

Internet

Figure 23 –CO_2 solubility in water calculator, a RDBMS table constructed to provide estimates of the solubility of CO_2 in aquifer water. The tool is designed to access an automated look-up table of empirical data. First the solubility of CO_2 is estimated as a function of pressure and temperature interpolating between empirical curves. Second, the CO_2 solubility is corrected to the salinity of the water (independent of pressure and temperature). The user selects the temperature, pressure and salinity from pull-down menus.

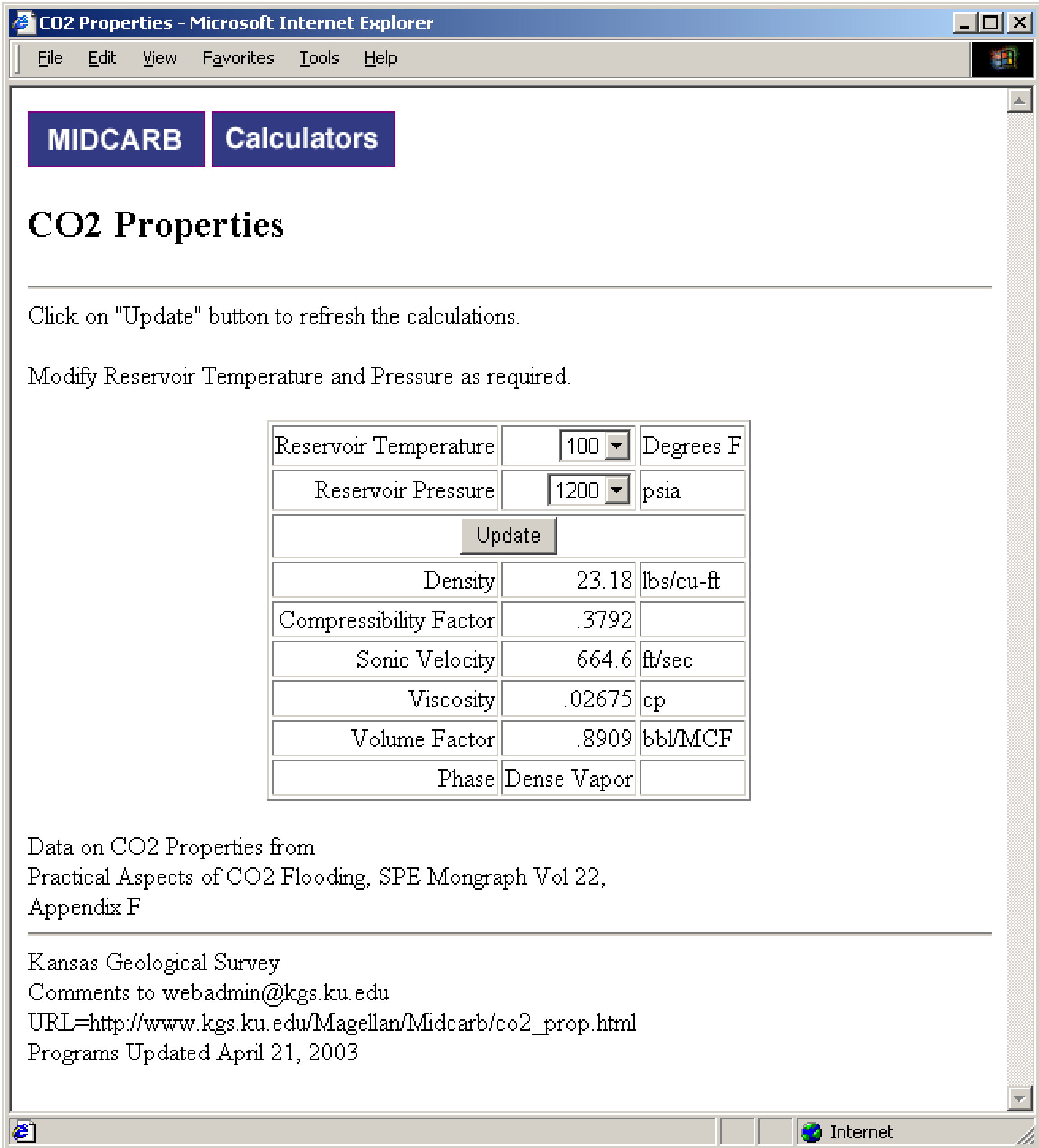


Figure 24 – Calculator for physical properties of CO_2. A RDBMS table constructed to provide estimates of the physical properties of CO_2. The tool is designed to access an automated look-up table of empirical data based on pressure and temperature. The user selects the temperature and pressure from pull-down menus.

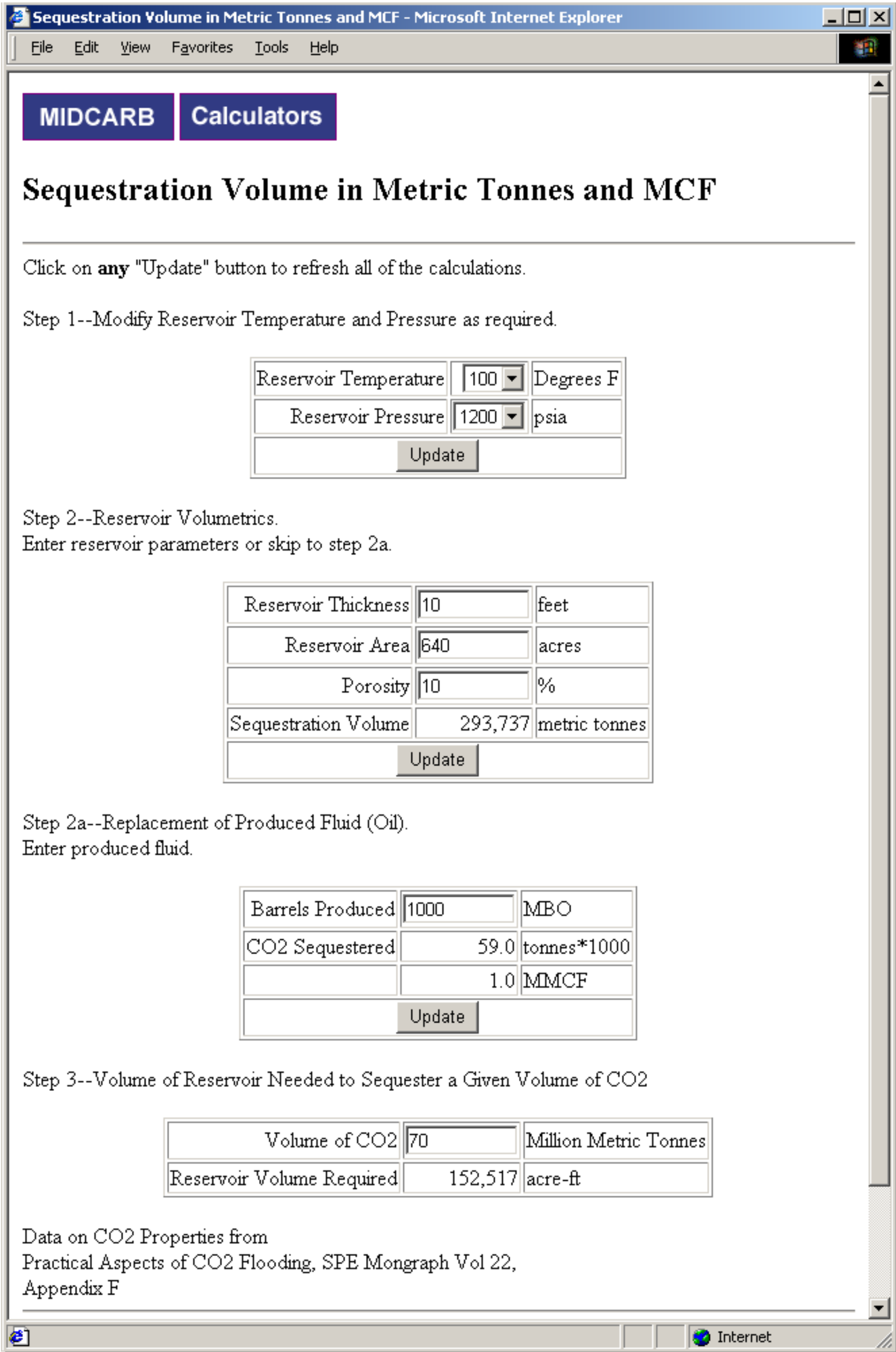


Figure 25 – Calculator for determining volume of CO_2 sequestered. A RDBMS table constructed to provide estimates of the sequestration volume of CO_2 (metric tonnes and MCF). The tool is designed to access an automated look-up table of empirical data based on pressure and temperature, and physical reservoir parameters (e.g., reservoir thickness, area, porosity and produced fluids). The user selects the temperature and pressure from pull-down menus and enters physical reservoir parameters.

TECHNOLOGY TRANSFER

The development of the MIDCARB atlas is in itself a technology transfer activity, and will be ongoing from project initiation. In addition the members of the consortium have been very active in presenting results. The following technology transfer activities have occurred since the last annual report:

1) Solano-Acosta, Wilfrido, Charles W. Zuppann, and J.A. Rupp, Assessment of Oil and Gas Fields in Indiana for CO_2 Sequestration, Online Tools to Evaluate Oil and Gas Fields for CO_2 Sequestration; AAPG Annual Meeting 2003, May 11-14, 2003, Salt Lake City, Utah, http://www.midcarb.org/Documents/AAPG-May-2003/Oil&Gas_Fields_Indiana.html
2) Wickstrom, Lawrence H., James McDonald, Ronald A. Riley, Timothy R. Carr, Brandon Nuttall, John A. Rupp, Wilfrido Solano-Acosta, Charles W. Zuppann, and Beverly Seyler, Online Tools to Evaluate Oil and Gas Fields for CO_2 Sequestration; AAPG Annual Meeting 2003, May 11-14, 2003, Salt Lake City, Utah, http://www.midcarb.org/Documents/AAPG-May-2003/Online_Tools-Oil&Gas.pdf
3) Carr, Timothy R., Lawrence H. Wickstrom, Christopher P. Korose, R. Stephen Fisher, Wilfrido Solano-Acosta, and Nathan Eaton, Online Tools to Evaluate Saline Aquifers for CO_2 Sequestration, AAPG Annual Meeting 2003, May 11-14, 2003, Salt Lake City, Utah, http://www.kgs.ku.edu/PRS/publication/2003/ofr2003-33/index.html
4) Slucher, Ernie R. and Vinciguerra, Mark, GIS Technology: A Pathway for Regional Geospatial Analysis of Coalbed Methane Assessment and Future Energy Resource Development, AAPG Annual Meeting 2003, May 11-14, 2003, Salt Lake City, Utah, http://www.midcarb.org/Documents/AAPG-May-2003/GIS-technology.pdf
5) White, Scott W., Timothy R. Carr, James A. Drahovzal, Brandon Nuttall, John A. Rupp, Beverly Seyler, Ernie Slucher, and Joe Wells, An Update on the Midcontinent Interactive Digital Carbon Atlas and Relational dataBase

(MIDCARB) and its Future, Second Annual Conference on Carbon Sequestration: Developing and Validating the Technology Base to Reduce Carbon Intensity, May 5-8, 2003, Alexandria, VA, http://www.midcarb.org/Documents/NETL-May-2003.pdf

6) Dubois, Martin K., Scott W. White, Timothy R. Carr, Co-generation, Ethanol Production and CO_2 Enhanced Oil Recovery: A Model for Environmentally and Economically Sound Linked Energy Systems: Developing and Validating the Technology Base to Reduce Carbon Intensity, May 5-8, 2003, Alexandria, VA, http://www.carbonsq.com/pdf/5B1.pdf
7) Jeremy Bartley, Jeremy and Timothy R. Carr, Dynamic Mapping of Kansas Oil and Gas Data with ArcSDE and ArcIMS, ESRI Petroleum Users Group Annual Meeting, March 10-12, 2003, Houston Texas, http://www.midcarb.org/Documents/ESRI%20March%202003/Dynamic-Mapping.html
8) Solano-Acosta, Wilfrido, RUPP, John, and ZUPPANN, Charles W., Estimating the CO_2 Sequestration Capacity of Deep Saline Aquifers in Southwestern Indiana, GSA Annual Meeting 2002, October 27-30, 2002, Denver, Colorado, http://www.midcarb.org/Documents/GSA_2002_Solano/Solano_GSA2002.pdf
9) Carr, Timothy R., Bartley, Jeremy D., Nelson, Kenneth A., Adkins-Heljeson, Dana, Weisenfluh, Gerald A., Eaton, Nathan, Korose, Christopher P., and Wells, Joseph G., The MIDCARB Carbon Sequestration Project: Midcontinent Interactive Digital Carbon Atlas and Relational database, GSA Annual Meeting 2002, October 27-30, 2002, Denver, Colorado, http://www.kgs.ku.edu/PRS/publication/2002/ofr2002-45/GSA2002.pdf
10) Riley, Ronald A., McDonald, James,Wells, Joseph G., Wickstrom, Lawrence, H., Potential for CO2 Sequestration through Enhanced Recovery in Ohio, presented at Eastern AAPG, Oct. 2-4, 2002, Champaign, IL, http://www.midcarb.org/Documents/AAPG%20Eastern%202002/Potential-Sequestration.html
11) Solano-Acosta, Wilfrido, Zupann, Charles, W., Eaton, Nathan K., and Escolar, Racelle, Estimating carbon dioxide sequestration potential in mature multi-pay

petroleum fields in Indiana, presented at the Eastern AAPG in Champaign, Ill, Oct 2-4, 2002, http://www.midcarb.org/Documents/AAPG%20Eastern%202002/Estimating-Sequestration.html

12) Eaton, Nathan, Jerry Weisenfluh, Jim McDonald and Ken Nelson, Distributed Spatial Databases, Presented at ESRI International User Conference 2002 July 8-12, 2002, San Diego, California, http://www.midcarb.org/Documents/ESRI-July%202002/index.shtml
13) Eaton, Nathan, Jerry Weisenfluh, and Jim McDonald, Distributed Spatial Databases, Presented at Digital Mapping Techniques '02 Hosted by Utah Geological Survey & University of Utah Department of Geology and Geophysics Convened by Association of American State Geologists and U.S. Geological Survey Salt Lake City, Utah, May 19-22, 2002, http://www.midcarb.org/Documents/DistribSpatialDbases.shtml
14) Drahovzal, J.A., 2003, "Energy and Environment", talk, May Meeting of the Lexington Torch Club, May 15, Lexington.
15) Drahovzal, J.A., 2003, "Energy and Environmental Programs", talk, Kentucky Geological Survey 43rd Annual Meeting, Research Highlights and Innovations in the Use of Digital Geologic Maps, May 16, 2003, Lexington.

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Jarrell, P.M., C.E. Fox, M.H. Stein, and S.L. Webb, 2002, Practical Aspects of CO2 Flooding; Society Petroleum Engineers Monograph v22, 220p.

Johnson, W.E., Macfarlane, R.M., and Breston, J.N., 1952, Changes in Physical Properties of Bradford Crude Oil When Contacted with CO2 and Carbonated Water: Producers Monthly (November) 16.

Martin, J.W., 1951, Additional Oil Production Through Flooding with Carbonated Water: Producers Monthly (July) 18.

APPENDIX A – MINIMUM MISCIBILITY PRESSURE RESULTS

MMP Test Reports prepared by Jyun-Syung Tsau, University of Kansas, Tertiary Oil Recovery Project. Reports summarize minimum miscibility pressure (MMP) test results on samples with slim-tube experiments.

Indiana - The oil sample was collected at 12-3S-14W, Gibson County, Indiana. The oil was produced from Cypress formation at completion interval between 2517-2531 feet. The reservoir temperature was 101 °F. The physical properties of the oil sample are summarized in Table A1. Brookfield Micro-Viscometer was used to determine oil viscosity and Anton Paar DMA 4500 density meter was used to determine oil density. Samples centrifuged and filtered were used in slim-tube experiment.

Table A1. Physical properties of Indiana oil sample

Oil Sample	Viscosity (cp)		Density (g/cc)		API
	77 °F	101 °F	77 °F	101 °F	60 °F
Filtered 12-3S-14W	**7.5**	**5.7**	**0.838**	**0.828**	**35.9**

A 40-foot long slim tube was used for CO_2 displacement test. The slim tube had a porosity of 0.39, permeability of 4600 md and pore volume (PV) of 142 cc. In each experiment, the slim tube was first cleaned with 4 PV of Methylene Chloride and displaced with 2 PV of oil to establish the initial oil saturation. Four tests were conducted at 101 °F with backpressure varied from 1000 to 1300 psia. A high-pressure syringe pump (ISCO Model 260 D) was used to inject mineral oil into a piston accumulator where CO_2 was displaced into the slim tube. The pump rate was set at 3.6 cc/hr.

The experiment results are presented in Figure A1, where cumulative oil production is plotted as a function of CO_2 injection volume. Since CO_2 was injected by displacing mineral oil into a piston accumulator via a constant rate pump, the real CO_2 injection volume was determined by material balance calculation on the remaining CO_2 in the accumulator during the experiment. The recoveries estimated at 1.2 hydrocarbon pore volume (HCPV) injections of CO_2 were 93.0, 92.3, 83.7 and 62.0 % at 1300, 1200, 1100 and 1000 psia, respectively. Figure A2 presents the oil recovery at 1.2 HCPV of CO_2 injection as a function of pressure. The MMP is about 1200 psia, based on the trend line and the definition of reaching 90% recovery at 1.2 HCPV of CO_2 injection.

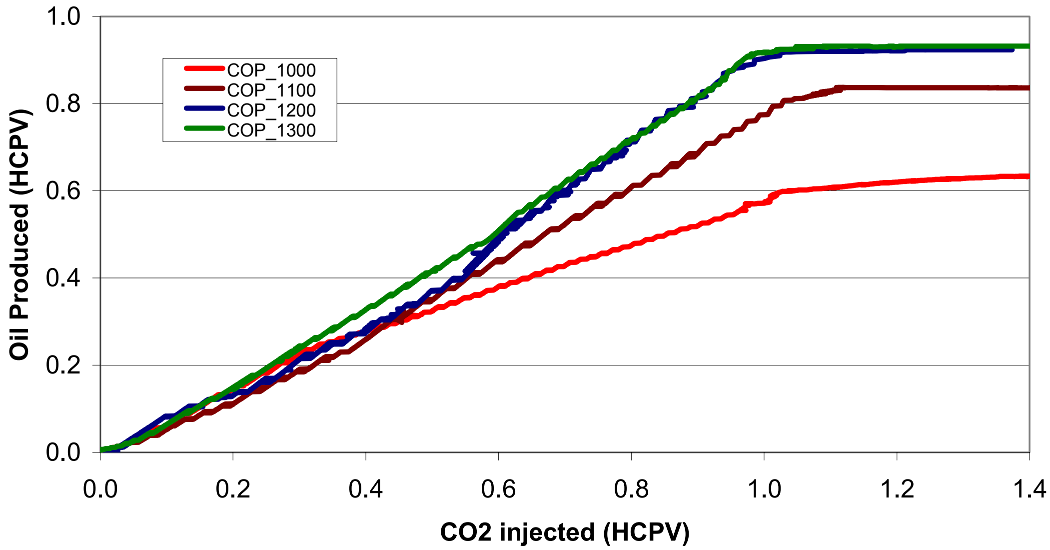

Figure A1 - Oil recovery results in slim-tube experiment with CO_2 displacing Indiana oil sample at 101 °F.

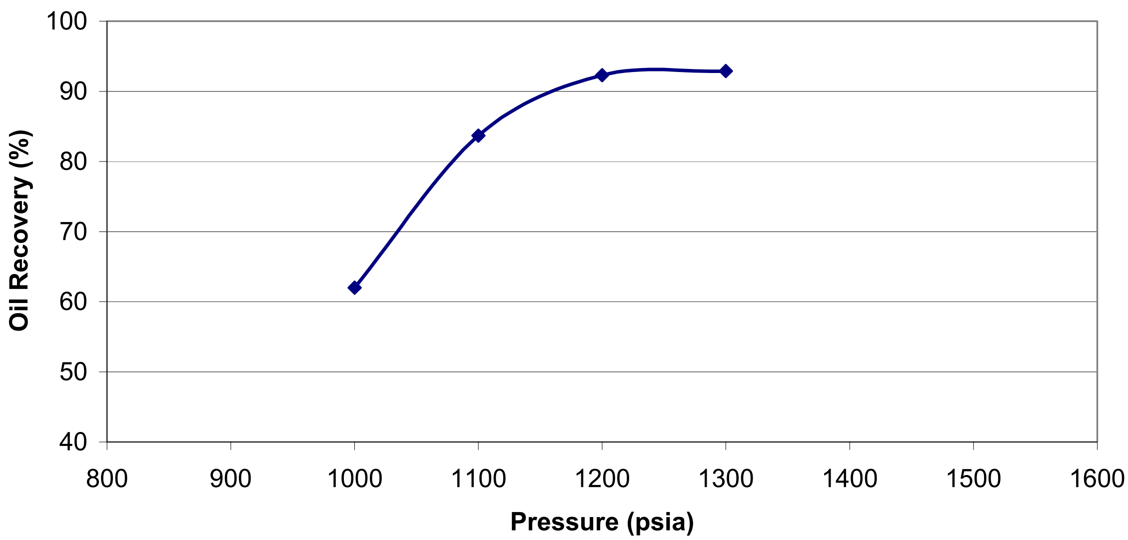

Figure A2 - Ultimate oil recovery as a function of pressure for Indiana oil sample at 101 °F.

Kentucky - The oil sample Kentucky #22 was collected at Well Number 2 (operated by Daugherty Petroleum), Bell County, Kentucky. The oil was produced from formation 333BIGL at 2610 feet. The reservoir temperature was 79 °F.

The physical properties of the oil sample are summarized in Table A2. Brookfield Micro-Viscometer was used to determine oil viscosity. Anton Paar DMA 4500 density meter was used to determine oil density. Samples centrifuged and filtered were used in slim-tube experiment.

Table A2. Physical properties of Kentucky oil sample

Oil Sample	Viscosity (cp)	Density (g/cc)	API
	79 °F	79 °F	60 °F
Unfiltered	**6.20**	**0.8215**	**39.0**
Filtered	**5.27**	**0.8207**	**39.1**

A 40-foot long slim tube was used for CO_2 displacement test. The slim tube had a porosity of 0.39, permeability of 4600 md and pore volume (PV) of 142 cc. In each experiment, the slim tube was first cleaned with 4 PV of Methylene Chloride and displaced with 2 PV of oil to establish the initial oil saturation. Five tests were conducted at 79 °F with backpressure varied from 750 to 1200 psia. A high-pressure syringe pump (ISCO Model 260 D) was used to inject mineral oil into a piston accumulator where CO_2 was displaced into the slim tube. The pump rate was set at 3.6 cc/hr.

The experiment results are presented in Figure A3, where cumulative oil production is plotted as a function of CO_2 injection volume. Since CO_2 was injected by displacing mineral oil into a piston accumulator via a constant rate pump, the real CO_2 injection volume was determined by material balance calculation on the remaining CO_2 in the accumulator during the experiment. The recoveries estimated at 1.2 hydrocarbon pore volume (HCPV) injections of CO_2 were 97.8, 95.7, 94.2, 67.0 and 64.5 % at 1200, 1000, 930, 810 and 750 psia, respectively. Figure A4 presents the oil recovery at 1.2 HCPV of CO_2 injection as a function of pressure. The MMP is about 930 psia, based on the trend line and the definition of reaching 90% recovery at 1.2 HCPV of CO_2 injection.

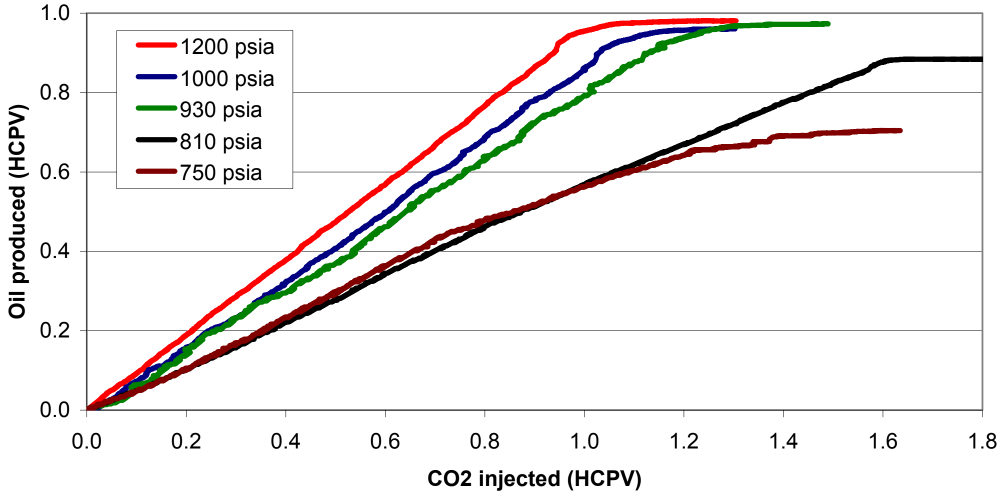

Figure A3 - Oil recovery results in slim-tube experiment with CO_2 displacing Kentucky oil sample #22 at 79 °F.

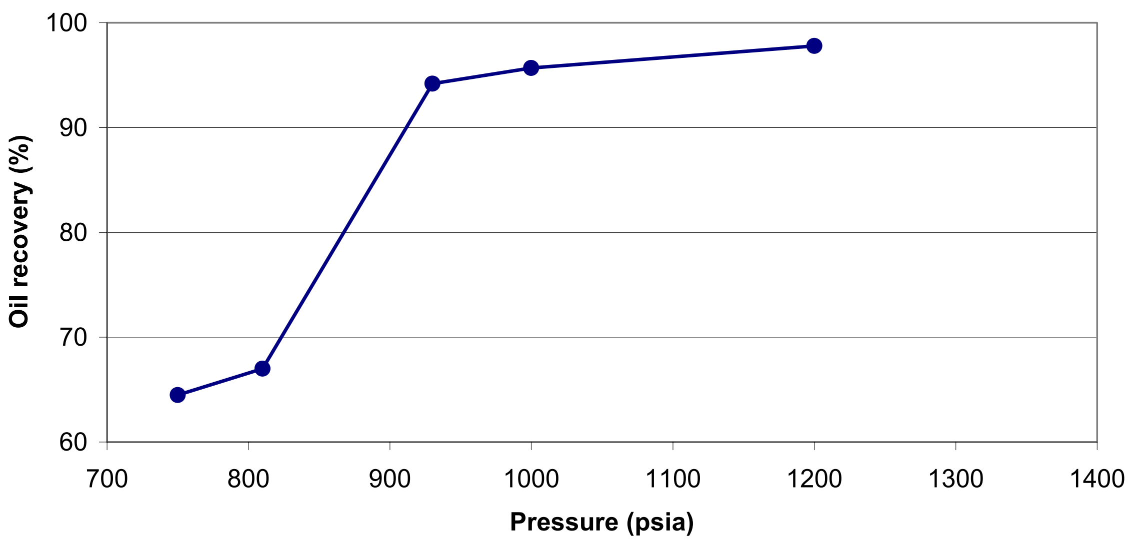

Figure A4 - Oil recovery (at 1.2 HCPV injection of CO_2) as a function of pressure for Kentucky oil sample #22 at 79 °F.

Illinois - The oil sample was collected at Well C. Crackel #1 (API 120470142400), Edwards County, Illinois. The oil was produced from Cypress sandstone formation at 2703-2722 feet. The reservoir temperature was 111 °F.

The physical properties of the oil sample are summarized in Table A3. Brookfield Micro-Viscometer was used to determine oil viscosity. Anton Paar DMA 4500 density meter was used to determine oil density. Samples centrifuged and filtered were used in slim-tube experiment.

Table A3. Physical properties of Illinois oil sample

Oil Sample	**Viscosity (cp)**		**Density (g/cc)**		**API**
	77 °F	**111 °F**	**77 °F**	**111 °F**	**60 °F**
Unfiltered	**6.02**	**4.29**	**0.8350**	**0.8214**	**36.4**
Filtered	**6.01**	**4.30**	**0.8357**	**0.8222**	**36.2**

A 40-foot long slim tube was used for CO_2 displacement test. The slim tube had a porosity of 0.39, permeability of 4600 md and pore volume (PV) of 142 cc. In each experiment, the slim tube was first cleaned with 4 PV of Methylene Chloride and displaced with 2 PV of oil to establish the initial oil saturation. Three tests were conducted at 111 °F with backpressure varied from 1100 to 1300 psia. A high-pressure syringe pump (ISCO Model 260 D) was used to inject mineral oil into a piston accumulator where CO_2 was displaced into the slim tube. The pump rate was set at 3.6 cc/hr.

The experiment results are presented in Figure A5, where cumulative oil production is plotted as a function of CO_2 injection volume. Since CO_2 was injected by displacing mineral oil into a piston accumulator via a constant rate pump, the real CO_2 injection volume was determined by material balance calculation on the remaining CO_2 in the accumulator during the experiment. The recoveries estimated at 1.2 hydrocarbon pore volume (HCPV) injections of CO_2 were 94.9, 93.1 and 70.3 % at 1300, 1200 and 1100 psia, respectively. Figure A6 presents the oil recovery at 1.2 HCPV of CO_2 injection as a function of pressure. The MMP is about 1200 psia, based on the trend line and the definition of reaching 90% recovery at 1.2 HCPV of CO_2 injection.

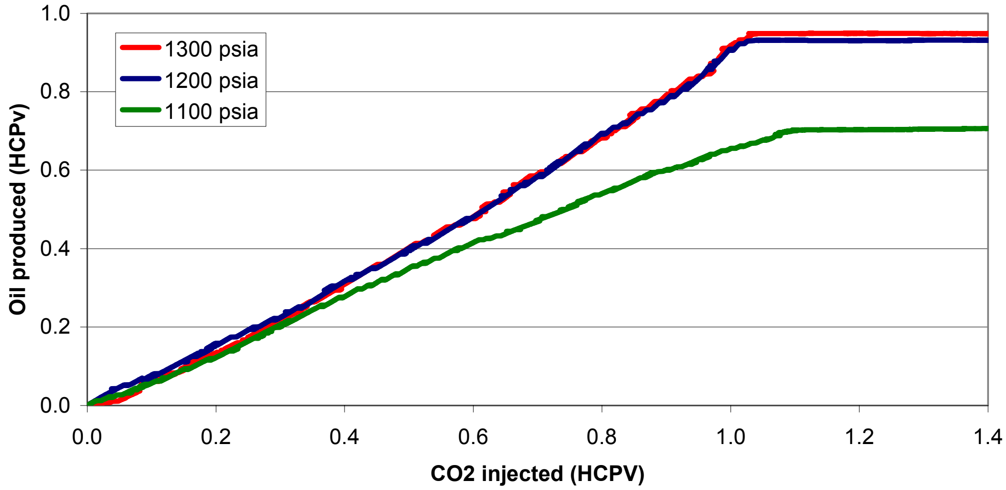

Figure A5 - Oil recovery results in slim-tube experiment with CO_2 displacing Illinois oil sample at 111 °F.

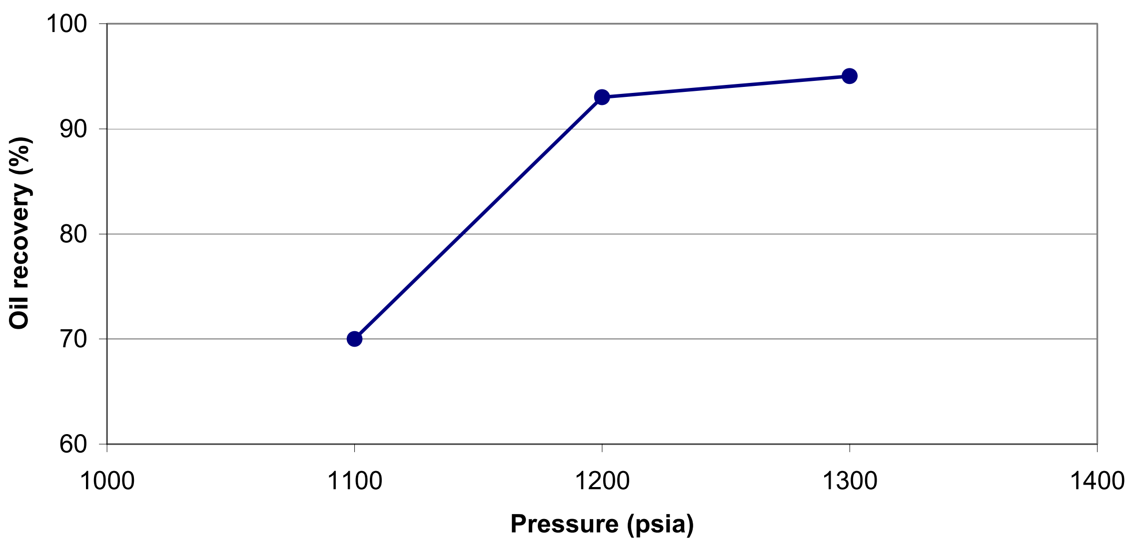

Figure A6 - Oil recovery (at 1.2 HCPV injection of CO_2) as a function of pressure for Illinois oil sample at 111 °F.

Ohio - The oil sample was collected at Well Number 34-169-2-5035, Wayne County, Ohio. The oil was produced from Copper Ridge sandstone formation. The reservoir temperature was 107 °F.

The oil sample received in the glass jug appeared to have strong water in oil emulsions with precipitates and possibly paraffin. The physical properties of oil sample are summarized in Table A4. Brookfield Micro-Viscometer was used to determine oil viscosity. Anton Paar DMA 4500 density meter was used to determine oil density. Samples centrifuged and filtered were used in slim-tube experiment.

Table A4. Physical properties of Ohio oil sample

Oil Sample	Viscosity (cp)		Density (g/cc)		API
	77 °F	107 °F	77 °F	107 °F	60 °F
Unfiltered	5.69	3.33	0.8113	0.7998	41.22
Filtered	4.83	3.20	0.8111	0.7997	41.21

A 40-foot long slim tube was used for CO_2 displacement test. The slim tube had a porosity of 0.39, permeability of 4600 md and pore volume (PV) of 142 cc. In each experiment, the slim tube was first cleaned with 4 PV of Methylene Chloride and displaced with 2 PV of oil to establish the initial oil saturation. Four tests were conducted at 107 °F with backpressure varied from 1200 to 1600 psia. A high-pressure syringe pump (ISCO Model 260 D) was used to inject mineral oil into a piston accumulator where CO_2 was displaced into the slim tube. The pump rate was set at 3.6 cc/hr.

The experiment results are presented in Figure A7, where cumulative oil production is plotted as a function of CO_2 injection volume. Since CO_2 was injected by displacing mineral oil into a piston accumulator via a constant rate pump, the real CO_2 injection volume was determined by material balance calculation on the remaining CO_2 in the accumulator during the experiment. The recoveries estimated at 1.2 hydrocarbon pore volume (HCPV) injections of CO_2 were 94.8, 91.7, 86.4 and 81.1 % at 1600, 1500, 1400 and 1200 psia, respectively. Figure A8 presents the oil recovery at 1.2 HCPV of CO_2

injection as a function of pressure. The MMP is about 1500 psia, based on the trend line and the definition of reaching 90% recovery at 1.2 HCPV of CO_2 injection.

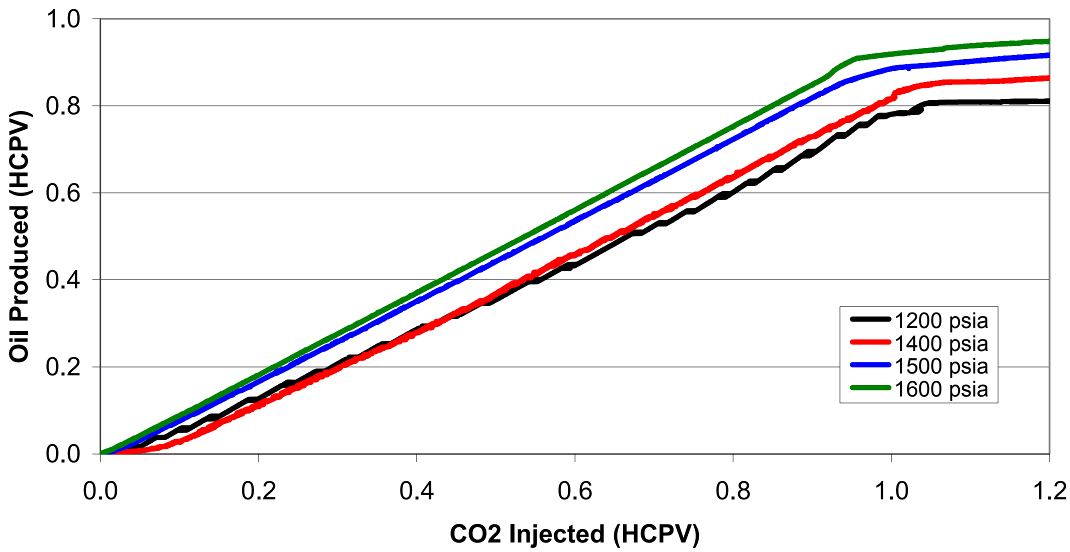

Figure A7 - Oil recovery results in slim-tube experiment with CO_2 displacing Ohio oil sample at 107 °F.

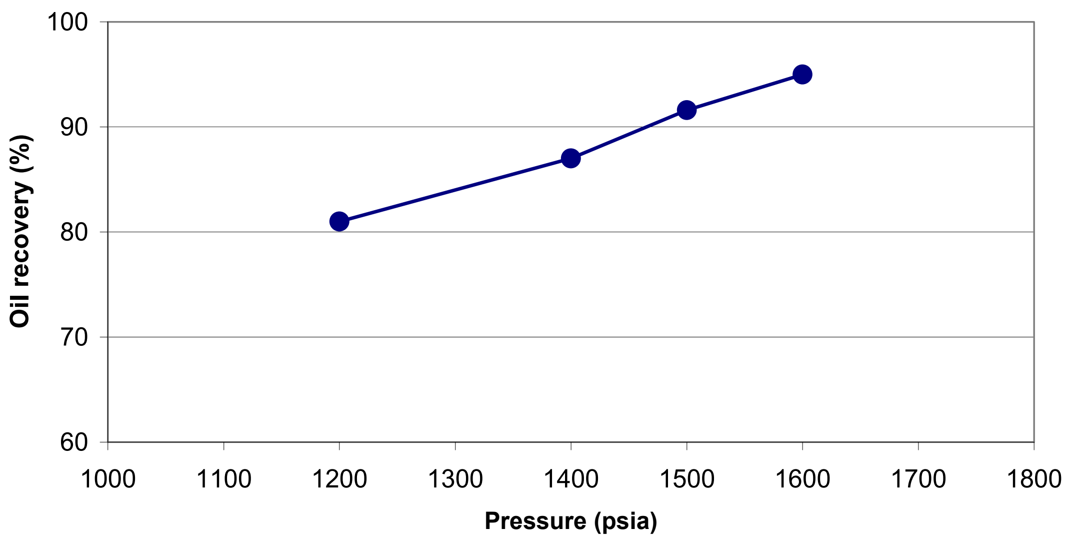

Figure A8 - Oil recovery (at 1.2 HCPV injection of CO_2) as a function of pressure for Ohio oil sample at 107 °F.