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December 30, 2009

Ms. Karlene Fine
Executive Director
North Dakota Industrial Commission
600 East Boulevard Avenue
State Capitol, 14th Floor
Bismarck, ND 58505-0840

Dear Ms. Fine:

Subject: EERC Plains CO_2 Reduction (PCOR) Partnership Phase II Final Report for the Period October 1, 2005 – December 31, 2009
Contract No. FY06-LV-143
Contract No. G005-014

Enclosed is a hard copy of the final report for Phase II of the PCOR Partnership Program. Also enclosed is a CD containing a pdf of the final report.

If you have any questions, please contact me by phone at (701) 777-5279 or by e-mail at esteadman@undeerc.org.

Sincerely,

Edward N. Steadman
PCOR Partnership Program Manager
EERC Senior Research Advisor

ENS/jre

Enclosures

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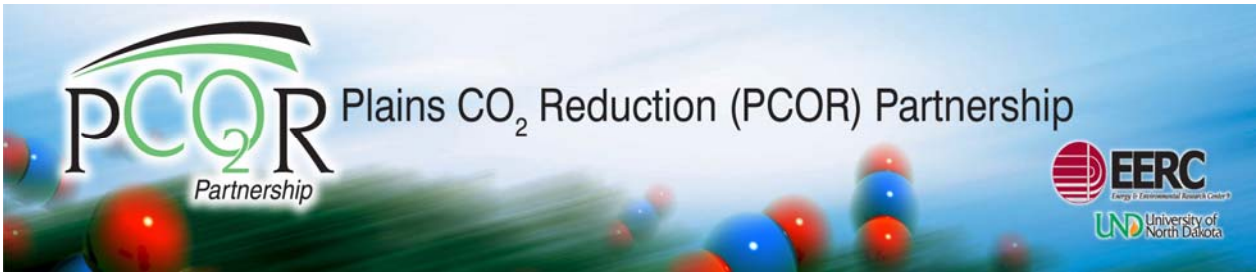

PLAINS CO_2 REDUCTION (PCOR) PARTNERSHIP PHASE II – FINAL REPORT

Final Report

(for the period October 1, 2005 – December 31, 2009)

Prepared for:

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State Capitol, 14th Floor
Bismarck, ND 58505-0840

Contract Nos. FY06-LV-143 and G005-014

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December 2009

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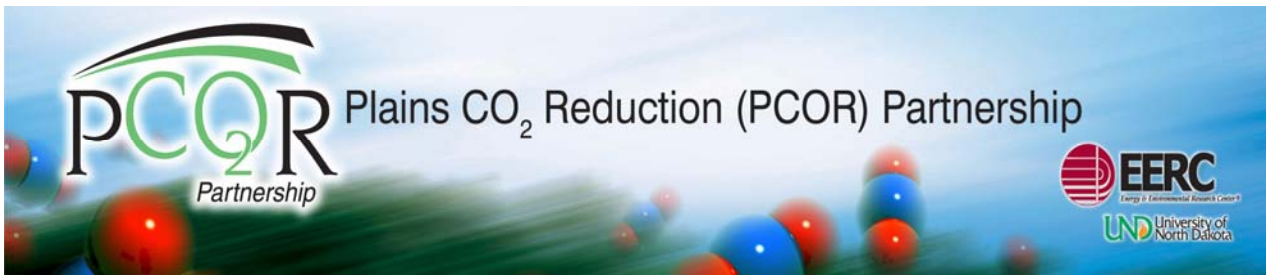

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ABSTRACT

The Plains CO_2 Reduction (PCOR) Partnership is one of seven Regional Carbon Sequestration Partnerships (RCSPs) competitively awarded by the U.S. Department of Energy (DOE) National Energy Technology Laboratory in 2003 as part of a national plan to mitigate greenhouse gas emissions. The PCOR Partnership is led by the Energy & Environmental Research Center at the University of North Dakota in Grand Forks, North Dakota, and includes more than 80 stakeholders from the public and private sector. The PCOR Partnership region includes all or parts of nine U.S. states and four Canadian provinces. Phase II, the validation phase, was an extension of the characterization phase (Phase I, 2003–2005) of the program and covered the period from 2005 through 2009. Phase II activities focused on carbon storage field validation projects that were designed to develop the local technical expertise and experience needed to facilitate future large-scale carbon dioxide storage efforts in the region's subsurface and terrestrial settings. These activities included four field validation tests (three geologic and one terrestrial) along with continued refinement of the regional characterization of sequestration opportunities, elucidation and clarification of the regulatory and permitting requirements for sequestration as well as the identification of commercially available carbon dioxide capture technologies, integration of the regional efforts with the other DOE RCSPs, and continuation of local and regional public outreach initiatives. Results of the Phase II activities indicated that the PCOR Partnership region has tremendous opportunities for carbon sequestration in geologic and terrestrial settings. Total funding for Phase II exceeded $29 million, with 56% of that funding provided by DOE and the balance contributed by industry and other nonfederal partners. This report documents and summarizes all work performed over the course of the Phase II effort and presents the findings, recommendations, and conclusions of this work.

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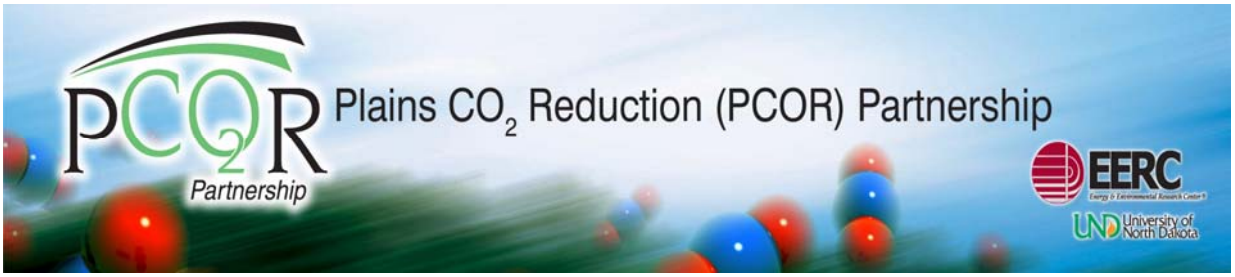

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EXECUTIVE SUMMARY

The Plains CO_2 Reduction (PCOR) Partnership is one of seven Regional Carbon Sequestration Partnerships (RCSPs) competitively awarded by the U.S. Department of Energy (DOE) National Energy Technology Laboratory in 2003 as part of a national plan to mitigate greenhouse gas emissions. The PCOR Partnership is led by the Energy & Environmental Research Center (EERC) at the University of North Dakota in Grand Forks, North Dakota, and includes more than 80 stakeholders from the public and private sector. The PCOR Partnership region includes all or parts of nine U.S. states and four Canadian provinces. Its regional population accounts for approximately 9% of the combined total of Canadian and the U.S. populations (based on 2008 estimates by the U.S. Census Bureau and Statistics Canada). As calculated by the PCOR Partnership Decision Support System (DSS, ©2007 EERC Foundation), the PCOR Partnership regional population is 29.7 million.

Phase II, the validation phase, was an extension of the characterization phase (Phase I, 2003–2005) of the program and covered the period of 2005–2009. Phase II activities focused on carbon storage field validation projects designed to develop the local technical expertise and experience needed to facilitate future large-scale carbon dioxide (CO_2) storage efforts in the region's subsurface and terrestrial settings. These activities included four field validation tests (three geologic and one terrestrial) along with continued refinement of the regional characterization of sequestration opportunities, elucidation and clarification of the regulatory and permitting requirements for sequestration as well as the identification of commercially available carbon capture technologies, integration of the regional efforts with the other DOE RCSPs, and

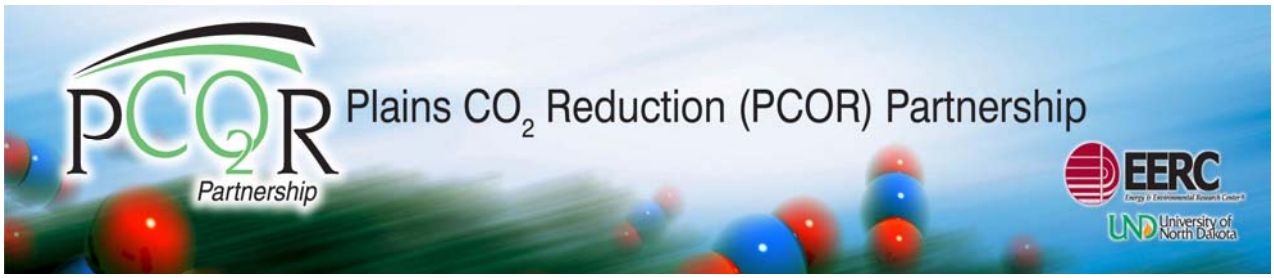
continuation of local and regional public outreach initiatives. Funding for Phase II exceeded $29 million, with 56% of that funding provided by DOE and the balance contributed by industry and other nonfederal partners.

The four field validation tests performed during Phase II were 1) the Zama Field Validation Test, which focused on the injection of acid gas (hydrogen sulfide [(H_2S]-rich CO_2) for the dual purpose of carbon sequestration and enhanced oil recovery (EOR); 2) the Lignite Field Validation Test, which focused on the injection of CO_2 for the dual purpose of carbon sequestration and enhanced coalbed methane (CBM) production; 3) the Williston Basin Oil Field Validation Test, which focused on the injection of CO_2 for the dual purpose of carbon sequestration and EOR; and 4) the Terrestrial Field Validation Test, which focused on the management of Prairie Pothole Region wetlands and the subsequent evaluation of the net reduction in greenhouse gas fluxes of CO_2, CH_4, and N_2O. Based on the results of these Phase II field validation tests, as well as other Phase II activities, it was concluded that the PCOR Partnership region has tremendous carbon storage potential. Tertiary-phase EOR represents the primary near-term opportunity for managing CO_2 in the region, so much so that the EOR demand for CO_2 in the region exceeds the near-term supply. One key near-term source of CO_2 in the region is natural gas-processing facilities. If the CO_2 supply should ever surpass the EOR demand, saline formations are available throughout the region to meet carbon storage needs.

Significant CO_2-based EOR and CO_2 storage opportunities exist within the region, including the pinnacle reef structures that were examined as part of the Zama project and in the deep carbonate systems in the Williston Basin. The former validation test also confirmed the ability to inject and store H_2S-rich acid gas, thereby avoiding the necessity of H_2S removal from the CO_2 prior to storage. The Williston Basin validation test demonstrated the feasibility of EOR/CO_2 storage using the huff 'n' puff approach. It was also determined that unminable lignite may also represent a viable sequestration target for CO_2, although more research is needed prior to implementing large-scale applications of this approach to carbon storage. The assessment of carbon storage in lignite did not support the concept of simultaneously enhancing the production of CBM during CO_2 storage at the particular location studied. Finally, it was determined that the wetlands of the Prairie Pothole Region represent significant targets for terrestrial CO_2 storage and, along with the adjacent agricultural lands, represent a significant potential near-term strategy to offset CO_2 emissions.

The Phase II efforts also demonstrated that monitoring, verification, and accounting programs can be designed and implemented that are technically effective, cost-effective, and unobtrusive to commercial operations. The Phase II program activities continued to confirm the importance of outreach activities to the success of CO_2 storage projects. These outreach activities are most effective when they are conducted at multiple levels, i.e., local community levels to nationwide venues. In addition to outreach, regulatory and legal issues also continued to represent key challenges to the implementation of large-scale CO_2 storage projects, driven largely by uncertainties associated with continually evolving regulatory policies that control the construction, operation, and postoperation monitoring of the various carbon storage strategies.

In the fall of 2007, the PCOR Partnership initiated its 10-year Phase III program, which is focused on implementing two commercial-scale geologic carbon sequestration demonstration projects in the region.



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1.0 BACKGROUND

The Plains CO_2 Reduction (PCOR) Partnership is one of seven regional partnerships operating under the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) Regional Carbon Sequestration Partnership (RCSP) Program. The PCOR Partnership is led by the Energy & Environmental Research Center (EERC) at the University of North Dakota in Grand Forks, North Dakota, and includes over 80 stakeholders from the public and private sector as listed in Table 1-1. The PCOR Partnership region includes all or parts of nine states (Iowa, Minnesota, Missouri, Montana, Nebraska, North Dakota, South Dakota, Wisconsin, and Wyoming) and four Canadian provinces (Alberta, British Columbia, Manitoba, and Saskatchewan), as shown in Figure 1-1.

The RCSP Program comprises a large portion of NETL's Carbon Sequestration Program and is a government–industry effort tasked with determining the most suitable regulatory strategies and technology/infrastructure needs for carbon capture and storage (CCS) on the North American continent. The seven partnerships (see Figure 1-2) that currently form this network encompass over 350 state agencies, universities, and private companies, spanning 43 states, three Native American Organizations, and four Canadian provinces.

The RCSP Program initiative is being implemented in three phases:

- Phase I – Characterization Phase (2003–2005): characterization of opportunities for carbon sequestration

Table 1-1. PCOR Partnership Phase II and III Partners

1)	U.S. Department of Energy National Energy Technology Laboratory
2)	University of North Dakota Energy & Environmental Research Center
3)	Abengoa Bioenergy New Technologies
4)	Air Products and Chemicals
5)	Alberta Department of Energy
6)	Alberta Research Council
7)	ALLETE
8)	Ameren Corporation
9)	American Coalition for Clean Coal Electricity
10)	American Lignite Energy (ALE)
11)	Apache Canada Ltd.
12)	Baker Hughes Oilfield Operations, Inc.
13)	Basin Electric Power Cooperative
14)	Biorecro AB
15)	Blue Source, LLC
16)	BNI Coal, Ltd.
17)	British Columbia Ministry of Energy, Mines and Petroleum Resources
18)	Carbozyme, Inc.
19)	Computer Modelling Group, Inc.
20)	Dakota Gasification Company
21)	Ducks Unlimited Canada
22)	Ducks Unlimited, Inc.
23)	Eagle Operating, Inc.
24)	Eastern Iowa Community College District
25)	Enbridge Inc.
26)	Encore Acquisition Company
27)	Energy Resources Conservation Board/Alberta Geological Survey
28)	Environment Canada
29)	Excelsior Energy Inc.
30)	Fischer Oil and Gas, Inc.
31)	Great Northern Project Development, LP
32)	Great River Energy
33)	Hess Corporation
34)	Huntsman Corporation
35)	Interstate Oil and Gas Compact Commission
36)	Iowa Department of Natural Resources – Geological Survey
37)	Lignite Energy Council
38)	Manitoba Geological Survey
39)	Marathon Oil Company
40)	MEG Energy Corporation
41)	Melzer Consulting
42)	Minnesota Power
43)	Minnkota Power Cooperative, Inc.
44)	Missouri Department of Natural Resources
45)	Missouri River Energy Services
46)	Montana–Dakota Utilities Co.

Continued . . .

Table 1-1. PCOR Partnership Phase II and III Partners (continued)

47)	Montana Department of Environmental Quality
48)	National Commission on Energy Policy
49)	Natural Resources Canada
50)	Nebraska Public Power District
51)	Nexant, Inc.
52)	North American Coal Corporation
53)	North Dakota Department of Commerce Division of Community Services
54)	North Dakota Department of Health
55)	North Dakota Geological Survey
56)	North Dakota Industrial Commission Department of Mineral Resources, Oil and Gas Division
57)	North Dakota Industrial Commission Lignite Research, Development and Marketing Program
58)	North Dakota Industrial Commission Oil and Gas Research Council
59)	North Dakota Natural Resources Trust
60)	North Dakota Petroleum Council
61)	North Dakota Pipeline Authority
62)	North Dakota State University
63)	Otter Tail Power Company
64)	Petroleum Technology Research Centre
65)	Petroleum Technology Transfer Council
66)	Prairie Public Broadcasting
67)	Pratt & Whitney Rocketdyne, Inc.
68)	Ramgen Power Systems, Inc.
69)	RPS Energy Canada Ltd. – APA Petroleum Engineering Inc.
70)	Saskatchewan Industry and Resources
71)	SaskPower
72)	Schlumberger
73)	Shell Canada Energy
74)	Spectra Energy
75)	Strategic West Energy Ltd.
76)	Suncor Energy Inc.
77)	TAQA NORTH, Ltd.
78)	TGS Geological Products and Services
79)	University of Alberta
80)	U.S. Geological Survey Northern Prairie Wildlife Research Center
81)	Weatherford Advanced Geotechnology
82)	Western Governors' Association
83)	Westmoreland Coal Company
84)	Wisconsin Department of Agriculture, Trade and Consumer Protection
85)	Xcel Energy

Figure 1-1. PCOR Partnership region.

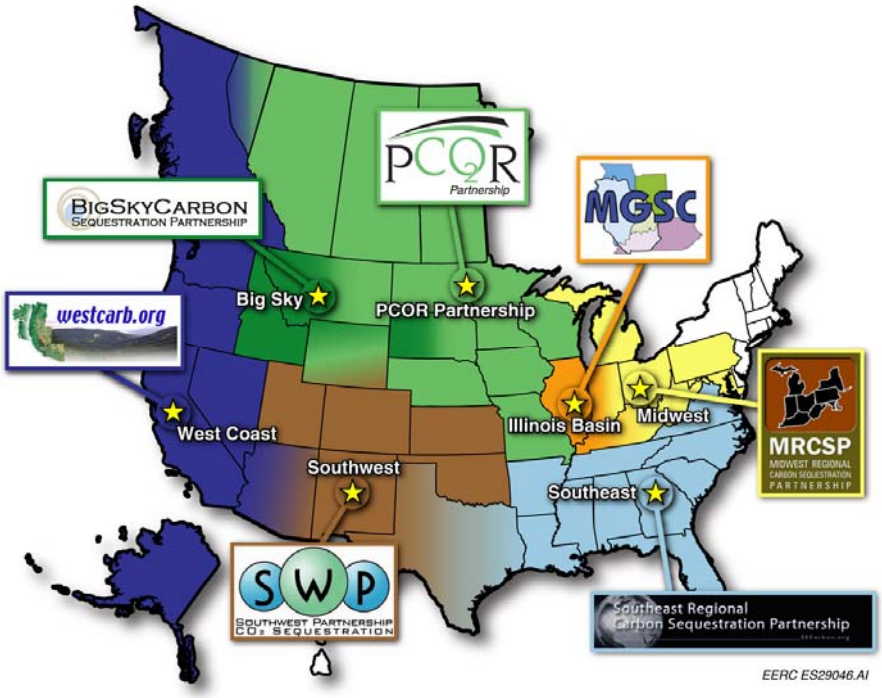

Figure 1-2. RCSP Program partnerships.

- Phase II – Validation Phase (2005–2009): small-scale, carbon storage field validation tests

- Phase III – Development Phase (2007–2017): large-volume carbon storage demonstration tests

The PCOR Partnership's efforts support the following NETL Carbon Sequestration Program goal:

> **"**By 2012, develop fossil fuel conversion systems that offer 90% CO_2 capture with 99% storage permanence at less than a 10% increase in the cost of energy services." (see Figure 1-3).

Attainment of NETL's program goal will be aided by the PCOR Partnership's integrated approach to address a multitude of economic, social, and technical challenges associated with carbon dioxide (CO_2) capture and storage (CCS). Among these challenges are the cost-effective integration of CO_2 capture strategies with fossil fuel conversion systems, then development of accurate and cost-effective CO_2 monitoring, verification, and accounting (MVA) protocols; the demonstration of the permanence of underground CO_2 storage; and the education of the public at large to gain its acceptance of the regulatory and technical strategies for managing CO_2 emissions.

The PCOR Partnership was established in the fall of 2003. Phase I focused on characterizing sequestration opportunities in the region. In the fall of 2005, the PCOR Partnership launched its 4-year Phase II program, which focused on carbon storage field validation projects that were designed to develop the regional technical expertise and experience needed to facilitate future large-scale CCS efforts in the region's subsurface and terrestrial settings.

In the fall of 2007, the PCOR Partnership initiated its 10-year Phase III program, which is focused on implementing two commercial-scale geologic carbon sequestration demonstration projects in the region.

2.0 PCOR PARTNERSHIP PROGRAM GOALS AND OBJECTIVES

The PCOR Partnership is focused on assisting DOE in achieving its goal of "developing, by 2012, fossil fuel conversion systems that offer 90% CO_2 capture with 99% storage permanence at less than 10% increase in the cost of energy service." To that end, the PCOR Partnership is working with a diverse group of public and private sector stakeholders to expand the understanding of CO_2 storage options, facilitate more accurate estimates of CO_2 storage capacity, and establish a regional infrastructure capable of supporting the future deployment of CCS strategies.

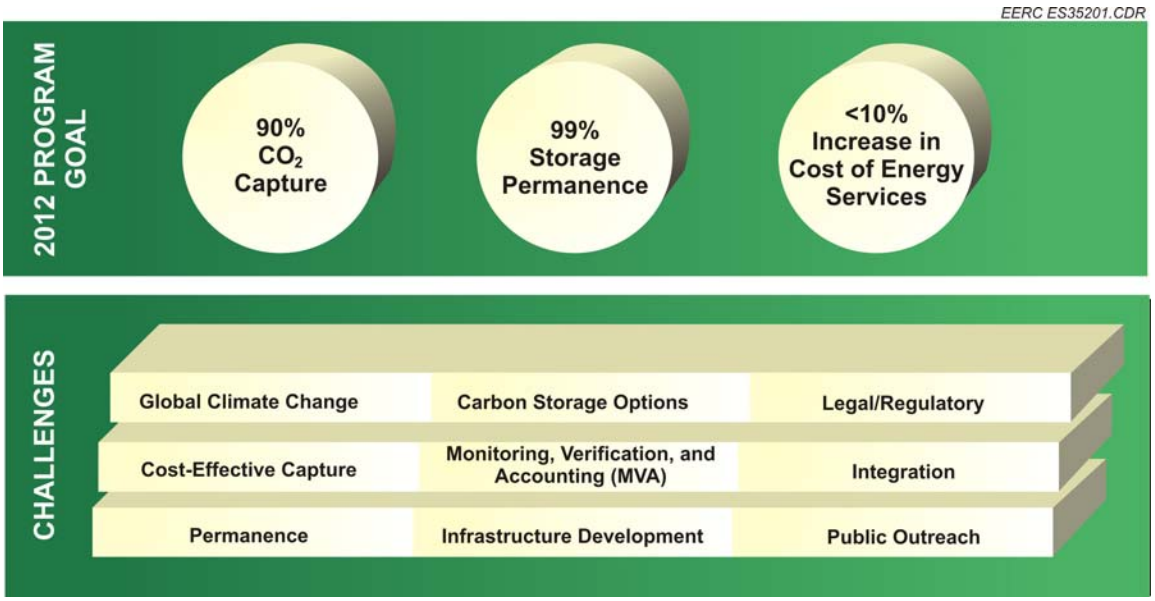

Figure 2-1. NETL Carbon Sequestration Program goal (source: www.netl.doe.gov/ technologies/carbon_seq/overview/program_goals.html [accessed June 2009]).

The PCOR Partnership serves a variety of industries that are located within the region, all of which are sources of CO_2 and/or other greenhouse gases. By conducting strategic regional characterization and validation/deployment field tests with its partners, the PCOR Partnership has identified the most efficient and cost-effective means for achieving reductions in greenhouse gas emissions. At the same time, the PCOR Partnership focuses on minimizing the long-term risk associated with these reduction strategies and maximizing the potential benefits that can be realized by enhancing the production of both oil and coalbed methane (CBM) during carbon storage. This focus on business goals, as well as greenhouse gas reduction goals, ensures that the latter is not achieved at the expense of the former, which is critical to the program's success. The PCOR Partnership designed its Phase II program to demonstrate that these two goals are not mutually exclusive and to set the stage for large-scale deployments of these concepts at commercial scale as part its Phase III efforts.

3.0 INTRODUCTION

The Phase I program activities concluded that there is significant terrestrial and geologic sequestration potential in the PCOR Partnership region. Opportunities for both of these sequestration potentials were identified based on assessments of sources, sinks, and deployment issues including capture and separation technologies and transportation systems. These assessments resulted in the identification of four source–sink combinations for investigation within the PCOR Partnership region during Phase II of the program:

- **Geologic Sequestration:** The best near-term opportunities for geologic sequestration were identified in Montana, Wyoming, North Dakota, Saskatchewan, and Alberta and led to the following three Phase II geologic sequestration projects:

  - Injection of acid gas (70% CO_2 and 30% hydrogen sulfide [H_2S]) from sour gas plants into oil fields for simultaneous sequestration and enhanced oil recovery (EOR) (Zama Keg River F Pool, Alberta, Canada).

  - Injection of CO_2 into economically unminable lignite seams to determine the suitability of these strata for CO_2 sequestration, as well as enhanced CBM production (Williston Basin, North Dakota).

  - Injection of CO_2 in oil fields in the proximity of the existing Dakota Gasification Company (DGC) CO_2 pipeline for simultaneous sequestration and EOR (Williston Basin, North Dakota).

- **Terrestrial Sequestration:** The Phase I assessment of terrestrial sequestration revealed that it represented a significant potential for securing CO_2 offsets. The potential was divided between croplands, forestlands, and grasslands. The analysis further suggested that wetlands and the associated riparian grasslands, in particular, offered significant carbon uptake potential, even though they accounted for a relatively small portion of the actual landscape. For this reason, Phase II validation tests were planned to investigate grasslands and wetland catchments in the Prairie Pothole Region (PPR) of the PCOR Partnership (northeast Montana, northeast and central North Dakota, north and central South Dakota, western and southern Minnesota, and northern Iowa).

Locations of the four field validation tests are shown in Figure 3-1.

Phase I activities also identified key data gaps and other project needs that were incorporated into the design and implementation of the Phase II field validation tests. First, the validation tests were designed to pursue a market-based approach, which attracted broad-based stakeholder involvement. In particular, it was determined that the PCOR Partnership region offered a very significant opportunity for enhanced resource recovery during CO_2 sequestration. Evidence of the importance of this approach is provided by the increase in stakeholders that took place during Phase II (i.e., the number of PCOR Partnership partners increased from 50 to 85 over the period of performance). This involvement is critical to the timely movement of CO_2 sequestration from concept to full-scale deployment. The cost of MVA must also be market-driven to ensure that economical solutions, which can be easily incorporated into existing commercial-scale monitoring programs, result. In tandem with this, public outreach and education are equally important to ensure acceptance of these practices at the full scale. During Phase I, it was also determined that the PCOR Partnership Decision Support System (DSS, ©2007 EERC Foundation) system was a flexible and reliable tool for the regional characterization of CO_2 sources and sinks, which led to multiple updates and refinements of the system during Phase II. Lastly, it appears as if CCS can be readily integrated into the current regulatory framework within the PCOR Partnership region. While regional-scale CO_2 storage

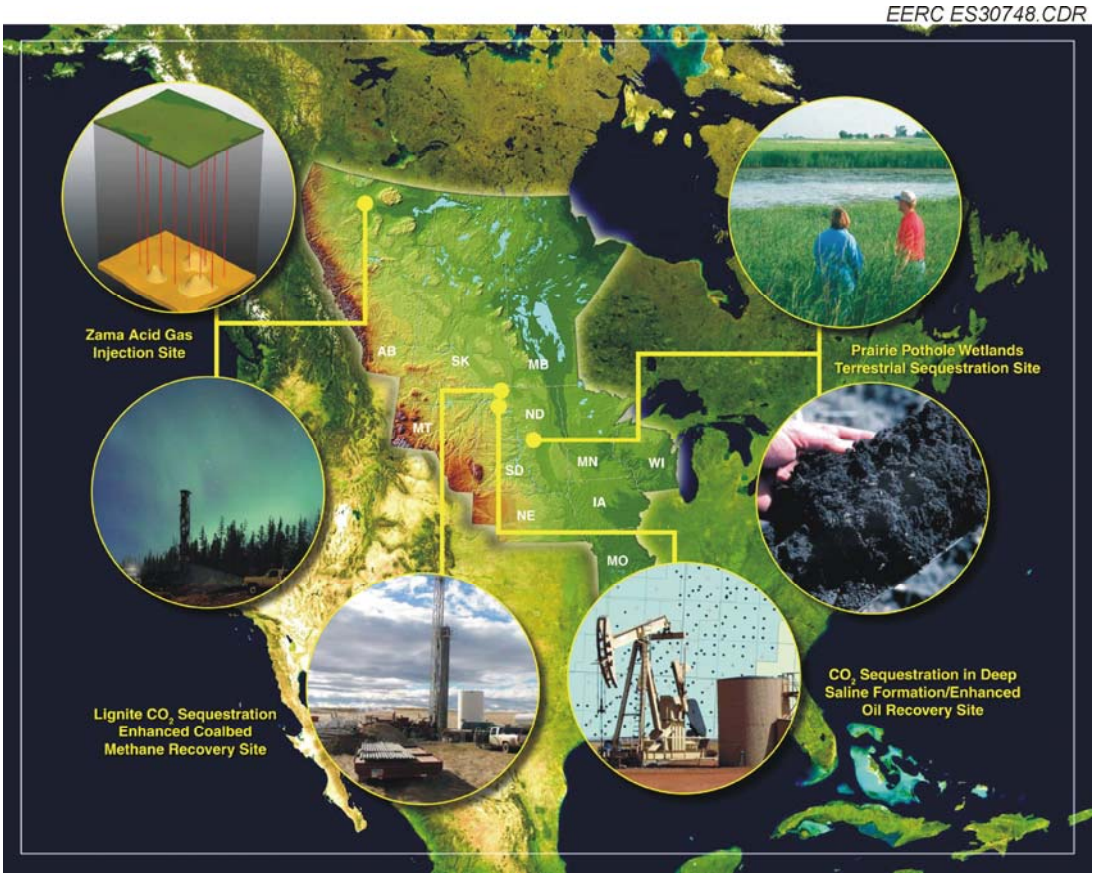

Figure 3-1. Phase II field validation tests.

capacity efforts showed that the region has very significant potential for large-scale CCS projects, judicious site selection and vigorous geologic characterization are key to developing successful CCS projects. Future activities will need to emphasize the development of detailed knowledge of the geologic and hydrodynamic characteristics on local and site-specific scales. At the same time, a common accounting practice is still needed to monetize these carbon credits with the unitization process for oil fields providing a suitable model for such a framework.

4.0 GEOLOGIC FIELD VALIDATION TESTS

Phase II activities included three geologic field validation tests:

- Zama Field Validation Test – This test focused on the injection of acid gas (H_2S-rich CO_2) for the dual purpose of carbon sequestration and EOR.

- Lignite Field Validation Test – This test focused on the injection of CO_2 for the dual purpose of carbon sequestration and enhanced CBM production.

- Williston Basin Oil Field Validation Test – This test focused on the injection of CO_2 for the dual purpose of carbon sequestration and EOR.

4.1 Zama Field Validation Test

Experimental Methods

The primary objective of the Zama Field Validation Test was to demonstrate the safe and cost-effective injection of acid gas into a partially depleted oil field for the simultaneous purposes of acid gas disposal, CO_2 sequestration, and EOR. The reservoirs in the Zama oil field exist in the form of isolated, porous, and permeable pinnacle reefs (carbonate rocks) which are sealed by a thick layer of essentially impermeable anhydrite (Figure 4-1). The CO_2 capture, transportation, and injection processes and subsequent hydrocarbon recovery operations were executed by Apache Canada Ltd. (Apache) at its oil field and natural gas-processing plant locations near Zama, Alberta, Canada (Figure 4-2). The role of the PCOR Partnership was to conduct MVA activities at a specific location/reservoir (referred to as the "F Pool") within the Zama oil field. The MVA activities were designed to be cost-effective and cause minimal disruption to ongoing commercial oil production activities while providing critical data on the behavior and fate of the injected acid gas mixture within the reservoir.

The Zama project was designed with the following objectives:

- To demonstrate that the capture and injection of an acid gas into a properly characterized and carefully selected underground oil reservoir is feasible and safe within existing industry and regulatory standards.

- To design, implement, and demonstrate cost-effective MVA strategies for verifying and validating the containment integrity of the target reservoirs.

- To demonstrate that highly concentrated acid gas (in this case, 30% H_2S and 70% CO_2) can be successfully used for EOR operations and sequestration in this type of geological feature (i.e., carbonate pinnacle reefs).

Specifically, this Phase II validation test was conducted by a multidisciplinary team of engineers, scientists, regulators, and management personnel. The management team for the project included representatives from Apache and the EERC. The primary technical team was comprised of technical professionals from Apache, the EERC, the Alberta Energy and Utilities Board (AEUB), the Alberta Geological Survey (AGS), RPS Energy, Schlumberger Oilfield Services, and Advanced Geotechnology Inc. Effective, frequent communication between all team members was critical to the timely, cost-effective design and implementation of all project activities. To facilitate communication and the appropriate sharing of project data, conference calls were held on at least a quarterly, often monthly, and sometimes weekly basis. A password-protected file transfer portal (FTP) site was established for the sharing of documents and data between members of the technical team. Integration of activities in a cross-disciplinary manner (e.g., data from standard, regulation-required reservoir pressure testing were used to conduct nonstandard pressure studies and geomechanical modeling; nonstandard tracer injection was

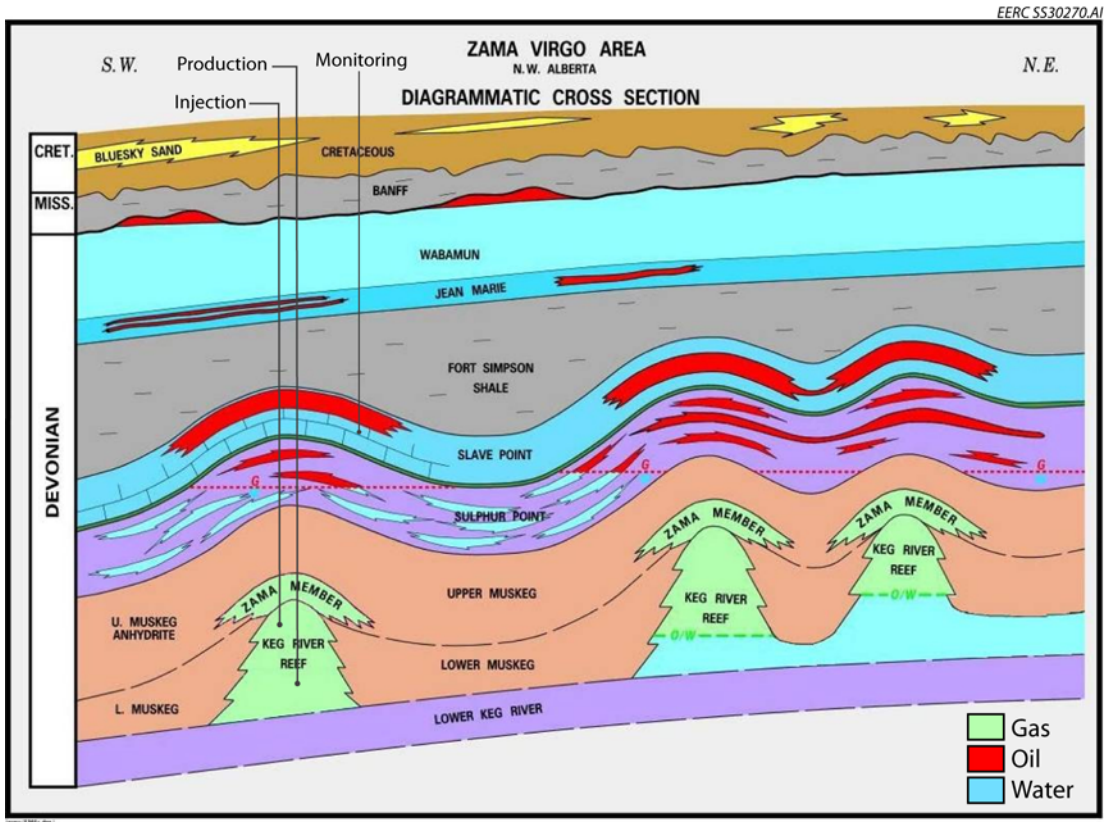

Figure 4-1. Cross section through the Zama area illustrating the isolated nature of Keg River Formation Pinnacle reefs and the encapsulating anhydrite of the Muskeg Formation (figure courtesy of Apache).

coordinated with standard planned maintenance activities, etc.) facilitated efficient implementation of the project plans. Such integration, while effective from a project management and budget standpoint, sometimes blurred the lines between the various elements of the program, which further underscored the need for frequent and diligent reporting of activities and results as well as thoughtful, interpretive discussion between team members.

Development of Validation Test Plan

Early geological sequestration research and demonstration projects deployed MVA strategies that were developed based on a lack of knowledge about the effectiveness and utility of many of the applied technologies. This absence of knowledge required these early projects to gather as much data as possible using a wide variety of techniques. In particular, a desire to monitor the plume of injected CO_2 led to a strong emphasis on the use of geophysical data, especially 3-D and 4-D seismic, to identify and track the plume. While the use of geophysically based approaches and techniques in early projects yielded valuable results that are important to the development of geological sequestration as a CO_2 mitigation strategy, their high costs of deployment and often limited ability to identify CO_2 in many geologic settings suggested their impracticality as the primary basis for the development of MVA plans for future commercial

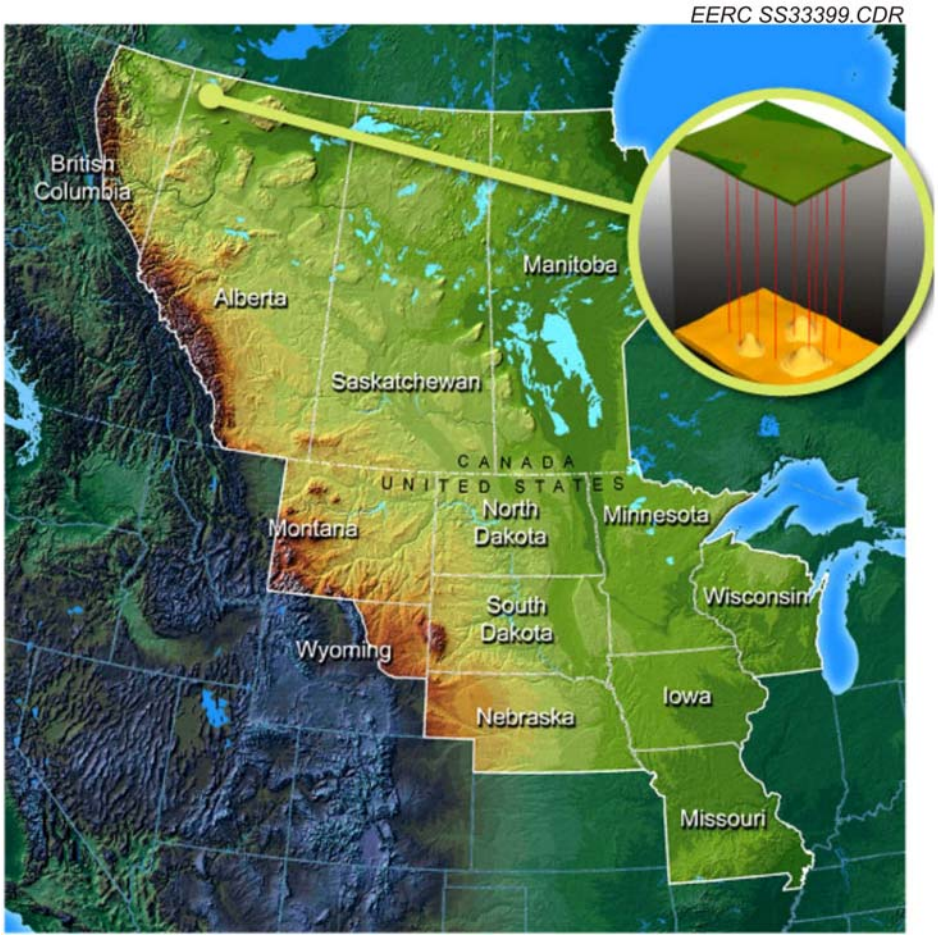

Figure 4-2. Location of the PCOR Partnership–Apache acid gas storage field validation test in the Zama Field of Alberta.

projects. For the implementation of CCS to occur on a large enough scale to mitigate global climate change, economics must be secondary only to health and safety considerations at the earliest stages of project development. At the same time, a detailed understanding and effective demonstration of the technical feasibility with respect to injectivity, capacity, containment, and overall safety is essential for all stakeholders to accept the concept of large-scale CO_2 and/or acid gas injection. This is the context within which the validation test plan for the Zama site was developed.

From a technical perspective, the validation test plan was designed to benefit from a relative wealth of previously generated, readily available subsurface characterization and reservoir production and injection data. These data provided critical, invaluable insight regarding the long-term prospects for the safe injection and storage of the acid gas. From an economic perspective, the validation test plan was able to take advantage of the existing EOR infrastructure, which minimized the start-up costs of the project while simultaneously offering the potential to take advantage of the incremental oil production to offset the costs of capital, operations, and maintenance and, ultimately, bring profitability to the project. The use of this

established hydrocarbon reservoir also provided added benefits because a regulatory framework already existed for permitting and operating many, if not all, of the surface and subsurface operations that were utilized as part of the project.

More specifically, the Zama validation test plan was designed to:

- Maximize the use of previously generated data on the geological, geochemical, and geomechanical characteristics of the formation into which acid gas was to be injected (target injection zone) and the overlying low-permeability rock formations that would serve as seals.

- Minimize, as much as possible, the need to obtain data beyond those which are already collected by the operator as part of the "normal" or "standard" operation of an EOR or acid gas disposal project.

For those elements of the MVA plan that required the use of new or nonstandard testing or technologies in the field, their use was conducted in close consultation with the field managers and operators to ensure that disruption of normal oil field operations was minimized.

The incorporation of these fundamental guiding principles in the validation test plan of the Zama project ensured that the goal of demonstrating the economic feasibility of acid gas injection for simultaneous EOR and CO_2 storage under "real world" technical and economic constraints could be achieved. At the same time, the PCOR Partnership and Apache recognized the value of developing previously unavailable fundamental data sets that could provide new understanding of CCS and guide the direction of future CCS research and deployment. With that in mind, the PCOR Partnership sought and, when appropriate, acted on opportunities to cost-effectively conduct additional activities that were of a more research-oriented nature and which would not typically be part of future commercial EOR and/or CCS projects.

In March 2007, the Zama project was recognized by the Carbon Sequestration Leadership Forum (CSLF) as being uniquely able to fill technological gaps with regard to this approach to geological sequestration of CO_2. The following elements were identified as future areas of focus by the CSLF program:

1. Reservoir engineering – Challenges in dealing with acid gas as a miscible fluid for EOR and the ultimate sequestration of associated CO_2.

2. EOR – Lessons learned at Zama will facilitate the deployment of acid gas injection for EOR at other storage reservoirs. This will become increasingly important as energy needs increase the focus on the more remote, dispersed, and smaller oil pools that do not justify the investment in the infrastructure required for CO_2 capture and injection.

3. Depleted oil and gas fields – The utilization of depleted oil and gas fields for sequestration purposes will be validated by the Zama project. In addition, the lessons learned associated with oil recovery from carbonate pinnacle reefs will also be valuable in applying this approach to other similar reservoirs around the world.

Test Plan Implementation

The validation test consisted of two discrete but related programs: 1) the acid gas injection program and 2) the MVA program. These programs were not necessarily independent of each other, as there were some activities and data sets that were common to both of them. However, each of these portions of the test is presented in this report in independent sections, with each section addressing those activities that were associated with the primary purpose of each program area.

The purpose of the injection program was to 1) ensure the cost-effective injection of acid gas from the Zama gas-processing plant into the Zama F Pool reservoir, 2) facilitate the production of incremental oil from the F Pool reservoir, and 3) support the documentation of effective CO_2 sequestration in the F Pool. Key aspects of the injection program include the CO_2 capture and infrastructure elements of the project, well preparation and maintenance activities, and acid gas injection and EOR operations.

The purpose of the MVA program was to 1) provide a set of baseline conditions upon which the effects of the project can be evaluated both during and after injection operations, 2) generate data sets that demonstrate the safe and secure containment of the acid gas, and 3) establish a technical framework for the creation and ultimate monetization of carbon credits associated with the reduction of emissions and the geological sequestration of CO_2 at Zama. MVA program activities that established the baseline conditions included:

- Geological and hydrogeological characterization at various scales.
- Characterization of the F Pool reservoir.
- Determination of geomechanical and geochemical properties of key rocks in the reservoir/seal system.
- Evaluation of the integrity of existing wellbores.

Field-based elements of the MVA program included the introduction of a tracer into the reservoir and data collection (i.e., formation fluid sampling and analysis, reservoir dynamics monitoring) from the injection, production, and monitoring wells. Other key elements of the MVA program included documentation of the permitting process and regulatory framework for the project, determination of material balance based on the collected field data, and a modeling-based study of historical and new reservoir pressure data in an effort to maximize the use of pressure data as a means of early identification of acid gas leakage. Generally speaking, monitoring activities were focused on the near-reservoir environment, including monitoring for leakage through cap rock, wellbores, and spillpoint breaches (Figure 4-3).

Results and Discussion

The Phase II activities at Zama, Alberta, generated laboratory- and field-based data that were combined with historical information from the site to provide valuable insights regarding the injection of acid gas for CCS and EOR. These insights provide stakeholders and planners of future, similar projects with the ability to make more informed decisions regarding a number of design elements. Project-critical technical areas for which information was compiled include:

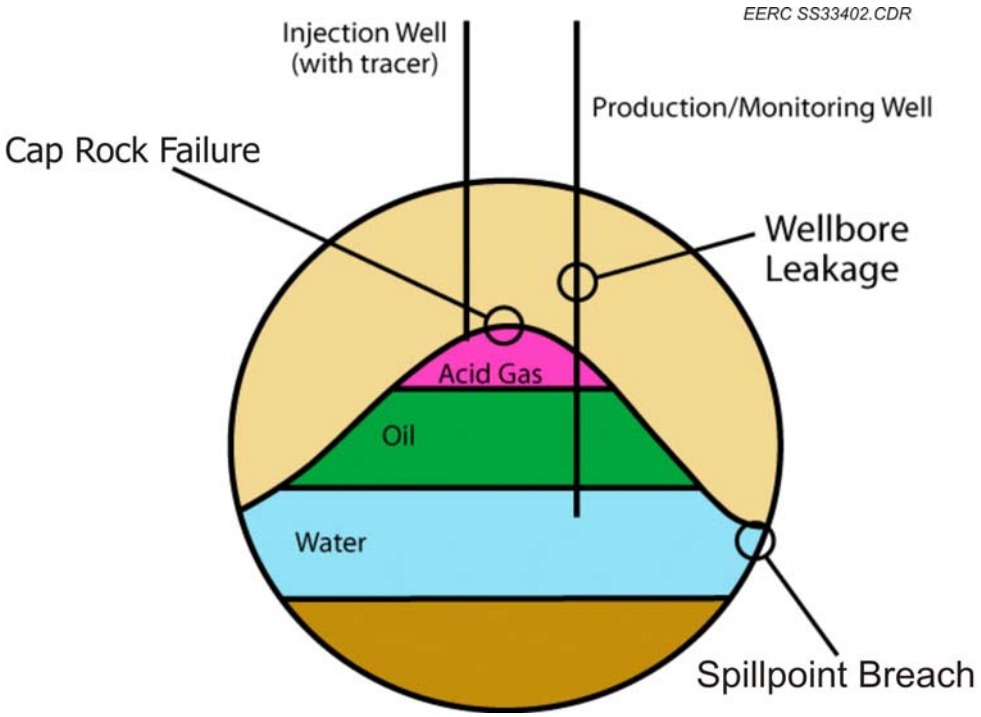

Figure 4-3. Monitoring activities at Zama focused on assessing the potential for leakage out of the reservoir through the cap rock, wellbores, and spillpoint at the base of the structure.

- Baseline geological and hydrogeological characterization.
- Wellbore integrity.
- Geomechanical properties of reservoir and seal rocks.
- Expectations for geochemical interactions.
- Prediction of near- and long-term effects and fate of the injected gases.
- Design and operation of wells and surface infrastructure in the presence of high concentrations of acid gas.

Some of the key observations, challenges, and lessons learned over the course of this acid gas injection field validation test are discussed in this section.

Acid Gas Injection and Oil Production

The injection of acid gas into the Zama Keg River F Pool pinnacle reef was initiated in December 2006. Injection continued into 2009, with some interruption for well maintenance. Apache plans to continue injection beyond 2010. To date, a cumulative total of over 800 million cubic feet (approximately 40,000 tons) of acid gas has been injected into the F Pool, with an average composition of 70% CO_2 and 30% H_2S. This equates to approximately 20,000 net tons of CO_2 stored throughout the operational period. Injection rates throughout this period were relatively stable at approximately 1 million cubic feet per day but generally increased over the past year to meet voidage replacement demands. Oil is currently being produced at an average

rate of 100 barrels per day (Figure 4-4). As of August 30, 2009, 25,000 barrels of oil have been produced from this pinnacle.

Suitability of Pinnacle Reefs for Acid Gas Injection and Long-Term CCS

Based on the available data from the geologic studies, it was concluded that the injection of acid gas into the pinnacle reefs of the Zama Keg River Formation can be done in a safe manner. Over long periods of time, the acid gas will be confined to the injection horizon by the reef structures that originally trapped the oil and gas. There appears to be very minimal potential for acid gas leakage through faults and fractures in the Zama area or for acid gas migration to shallower strata, potable groundwater, or to the surface as a result of flow through naturally occurring permeability streaks or flow paths.

The strength of the reservoir and cap rock formations, as determined by the geomechanical and geochemical evaluations, combined with the closed architecture of the pinnacle structure and the very conservative maximum operating pressures, leave little possibility of lateral migration outside of the reef structures. Further, the results of the regional hydrogeological study indicates that while the potential dispersion beyond the individual pinnacle spill points into the regional aquifer was very small, if such dispersion did occur, it would result in storage occurring in the regional aquifer before the plume had traveled a significant distance, e.g., the maximum velocity of the formation water is sufficiently slow that it would take as much as 800,000 years for a fluid molecule to reach a Keg River Formation outcrop. This period of time is sufficient to assure that mineralogic, geochemical, and physical dispersion of the emplaced CO_2 would mitigate significant leakage potential.

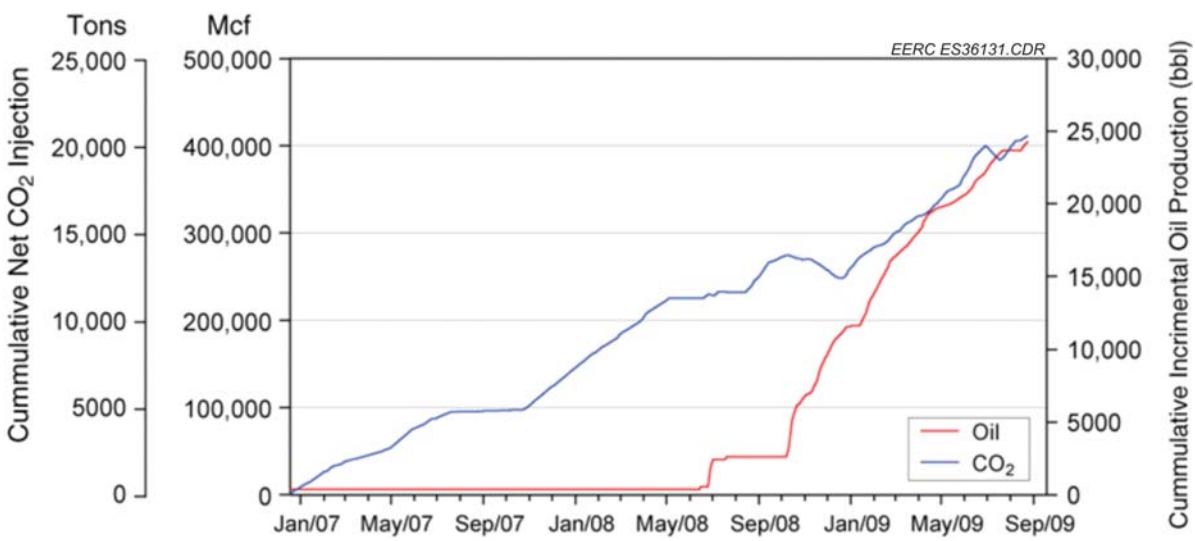

Figure 4-4. Zama acid gas injection profile – cumulative CO_2 injection and incremental oil production.

When combined with data from laboratory pore entry mercury injection pressure tests and mechanical stress testing on similar area cores, as well as log analyses and drilling reports, there is strong evidence that the thick (200 ft [60 m] to 300 ft [90 m]) Muskeg Formation dolomite/anhydrite sequences provide a competent, dense, and essentially impermeable cap rock above the Keg River pinnacles. These data suggest that the F Pool pinnacle integrity far exceeds the current Energy Resources Conservation Board (ERCB) EOR pressure limit, and it is possible that following the completion of the EOR recovery, additional CO_2 and/or acid gas volumes could be stored safely within this pinnacle by increasing the allowable storage pressure beyond the original reservoir pressure.

There are currently known to be over 800 pinnacle reefs in the Zama subbasin of the Western Canadian Sedimentary Basin. There are also known to be countless similar pinnacle reefs in the Williston Basin, Michigan Basin, and Illinois Basin, and other basins worldwide. The geological and hydrogeological studies conducted at Zama provide supporting documentation that these pinnacle reefs represent suitable, and even excellent, sites for CCS and EOR.

Relative Mobility and Fate of CO_2 and H_2S Within Carbonate Reservoirs

One set of questions that was identified early in the Zama project was whether or not the H_2S and CO_2 would undergo separation within the reservoir, if it did occur, the magnitude and timing of that separation and, ultimately, what the effects of any separation would be. The results of geochemical modeling, which used the geochemical and mineralogical properties of the F Pool reservoir, indicated that the leading edge of the acid gas plume is likely to be relatively enriched in CO_2. This observation was in agreement with the results of field- and laboratory-based analytical results as well as other modeling efforts. The relative enrichment is due, at least in part, to the preferential absorption of H_2S into the aqueous phase. However, in the presence of reactive iron-bearing minerals, other processes can contribute to the separation of the two gases. For example, as the acid gas plume reacts with the carbonate minerals, significant amounts of iron and bicarbonate are added to the water. This iron rapidly precipitates as an iron sulfide when H_2S is present in the gas phase. The iron sulfide precipitation produces a significant amount of acid, which drives much of the bicarbonate out of aqueous solution, leading to further CO_2 enrichment in the gas plume.

Current research is being conducted to determine if containment of the acid gas in a geological reservoir may be significantly affected by the capillary properties of the acid gas–brine solution in relation to the capillary pore entry pressure of the brine-saturated cap rock system. In particular, questions will be answered with respect to the maximum reservoir pressure limitation to avoid acid gas leakage through, or imbibition into, the cap rock and whether it may be lower than current pressure limits derived from mechanical stress testing. The designated maximum operating reservoir pressure will be pool-specific. If a lower maximum reservoir pressure limit is necessary, the estimates for storage capacity in each reservoir will require additional review. The impact of this lower maximum reservoir pressure on the gas miscibility with the reservoir oil and the EOR potential of the site will, in turn, need to be investigated.

The results of the acid gas mobility and fate investigations conducted as part of the Zama field validation project may be directly applicable not only to the hundreds of similar pinnacles

in the Zama subbasin, but also to acid gas injection projects, in general, that involve carbonate rock formations.

Effects of Acid Gas on Wellbores and Surface Infrastructure

The selection of corrosion-resistant materials for well completions and surface infrastructure is critical to the long-term operation and maintenance of an acid gas CCS/EOR project. Because of the higher costs of these materials, it is important that they be used judiciously in the design of wells and surface facilities to ensure the proper balance of performance versus cost. For instance, as a result of the significant incremental costs for corrosion-resistant alloy (CRA) pipe, most CO_2 and acid gas injection projects (over 100 in North America) have selected low-alloy carbon steel, protected by coatings or linings, for casing and tubing applications. In some circumstances, it may be satisfactory and more cost-effective to utilize one or two joints of CRA casing within critical wellbore sections rather than throughout the entire length of the well. Smaller equipment items such as packers, flow control devices, and subsurface safety valves are often constructed of nickel-based alloys, as it is more difficult to protect all of the wetted and working surfaces of these items with coatings. This approach has been applied successfully to the design of acid gas injection and sour gas production wells at Zama and, in most cases, can be broadly applied to similar injection schemes wherever they may be planned.

The use of corrosion-resistant cements is also a critical component to maintaining wellbore integrity. In general, recent literature suggests that the proper design of portland-based cements is very CO_2-resistant. In fact, the results of experimental work presented by Duguid (2008) concluded that a properly cemented well with good zonal isolation will be safe for 30,000 to 700,000 years. The literature also consistently shows that while CO_2 and brine mixtures do change the texture and mineralogy of portland cements used in oil wells, those changes do not significantly reduce the hydraulic seal afforded by the cement sheath. Specifically, studies were conducted by the NETL to investigate the degradation of a Class H well cement (with and without fly ash [Type F] admixtures) by CO_2 under geologic sequestration conditions (Kutchko, et al., 2007, 2008, and 2009). Following exposure to both supercritical CO_2 and CO_2-saturated brine, these studies observed alterations of the cement by the former that were similar in process to cement in contact with atmospheric CO_2, i.e., ordinary carbonation, while alteration of cements exposed to the latter was typical of acid attack on cement. Extrapolation of the hydrated cement alteration for 1 year revealed penetration depths of 1.00 ± 0.07 mm and 1.68 ± 0.24 mm, respectively, that are consistent with observations of field samples from an EOR site after 30 years of exposure to CO_2-saturated brine under similar pressure and temperature. These results suggested that significant degradation due to matrix diffusion of CO_2 in intact Class H neat hydrated cement is unlikely on time scales of decades. Following the addition of Type F fly ash, a common additive used in cements for well sealing in oil and gas field operations, the penetration depth after 30 years of exposure to supercritical CO_2 and CO_2-saturated brine was projected to be 170 to 180 mm (two fly ash–cement blends were studied: 35:65 and 65:35). Despite these observed alterations in the fly ash–cement mixtures, the reacted cement remained relatively impermeable to fluid flow after exposure to brine solution saturated with CO_2, with permeabilities well below the American Petroleum Institute-recommended maximum well cement permeability of 200 μD (American Petroleum Institute, 1991). Analyses

of 50:50 fly ash–cement cores from a production well in a sandstone reservoir exhibited carbonation and low permeability to brine solution saturated with CO_2, which is consistent with these laboratory findings.[1]

A review of the integrity of the casing cement and completion of the acid gas EOR/CCS wells in the F Pool indicated that the integrity of the current wells is good. However, to permit the projection of cement–acid gas interactions into the future, the PCOR Partnership is currently planning a similar study, as described above, to examine the interactions of typical wellbore cements with acid gas to determine if the presence of H_2S influences (i.e., exacerbates or diminishes) the alterations in the cement that were observed in the presence of CO_2 alone.

Some site-specific infrastructure challenges were encountered at the Zama facility. Most notably, asphaltines and waxes plugged flowlines, particularly during the winter months of operation. These problems were successfully addressed by Apache through the combined use of heated and/or insulated flowlines and the introduction of chemical additives to prevent the coagulation of those materials. It is important to note that none of the operational challenges presented by the CCS/EOR project at Zama are new to the oil and gas industry and, given time and thoughtful consideration, all of them are manageable and should not threaten the commercial use of acid gas injection for EOR or as a viable CCS strategy.

The Use of Pressure Data and Tracers to Detect Leakage

Routine pressure data that were collected at the Zama facility, both during the preinjection operations of the F Pool as well as during the acid gas injection phase of the CCS/EOR project, were used to assess the potential leakage of acid gas from the pinnacle reef into an overlying formation. In addition, a one-time injection of a unique tracer compound into the acid gas stream was also used for this purpose. This tracer compound was injected during the early stages of the injection phase, after which its presence was monitored in various production and monitoring wells as part of periodic routine sampling and analysis events. Specifically, for the Zama F Pool, an existing gas production well that had been completed into the overlying Slave Point Formation was selected to serve as the monitoring well for both the pressure measurements and tracer analyses. Both of these leak detection strategies were designed to take advantage of data that were already being collected at the facility, i.e., pressure data, to minimize any disruption to the normal operations of the commercial oil field operation.

Historical and current pressure data were gathered for both the Keg River F Pool and the overlying Slave Point FFF Pool. During acid gas injection, initial pressure testing was performed on the Slave Point FFF Pool in April 2008. A further pressure survey and gas-sampling operation was conducted on December 20, 2008. The historical pressure data, combined with these new data, permitted a comparison of the Keg River F Pool and Slave Point FFF Pool pressure histories and indicated that a small 29-psi (200-kPa) increase in pressure had been observed in the Slave Point FFF Pool over the 4-year period of this project. At this point, it cannot be determined if this observation is a result of the influx of water into the formation, the seepage of gas into the formation from the Keg River F Pool, or simply normal fluctuations in the formation

[1] No obvious differences were observed between the 35:65 fly ash–cement blend samples that were exposed to supercritical CO_2 and CO_2-saturated brine.

pressure and/or in the pressure gauge readings. More time-series pressure data are required before it can be determined if this observed pressure change is real and, if so, to what source it can be attributed.

As part of the tracer study, a gas-soluble chemical tracer compound (5.5 kg of Core Labs IGT-1100) was injected into the Keg River F Pool in February 2008. The collection and analysis of fluid samples from the Slave Point FFF Pool for the tracer was conducted on a 6-month schedule. A total of two samples have been taken and analyzed with a third sampling event to take place in early 2010 and, to date, no tracer has been detected in any of the samples.

Generally speaking, tracer and pressure-monitoring activities represent two approaches for leak detection that can be easily implemented in the field. At the Zama facility, their use over a limited period of time suggests that there is no leakage of acid gas occurring from the Keg River F Pool. However, the data are not sufficient to evaluate the effectiveness of these techniques as part of an MVA protocol that is designed to detect leaks that represent an unacceptable risk to human health or the environment. For this reason, these approaches should be studied in more detail in the upcoming Phase III field projects, where sufficient time-series data can be collected and these techniques can be more thoroughly evaluated as elements of an integrated, noninvasive, and cost-effective MVA plan.

MVA and Nontraditional Economic Components

The MVA program associated with the Zama project was designed to provide data that could be used to establish a basis for the creation and eventual monetization of carbon credits associated with the CCS component of the project. Specifically, the MVA activities conducted at Zama were designed to yield data that would demonstrate 1) the containment of the injected CO_2, 2) the mass of CO_2 that was stored, and 3) the long-term protection of human health and the environment. The MVA data generated over the course of the Zama project provided a technically robust, detailed accounting of the mass of CO_2 that was stored and its containment; however, the documentation of the long-term protection of human health and the environment was somewhat limited during this project because of its limited duration relative to the anticipated operations of a full-scale CCS/EOR project. To fully address this last item, it is necessary to construct a model that can predict the future performance of CCS/EOR and/or to collect additional MVA data over the course of a longer-duration Phase III demonstration project involving this approach to carbon sequestration. Moving forward, the PCOR Partnership is considering both of these approaches for addressing the long-term safety and environmental aspects of this carbon sequestration strategy. However, robust carbon credit-trading markets for credits associated with geological storage of CO_2 have been very slow to develop and, to date, the Zama project did not establish any carbon credits associated with the work described herein. While carbon credits have not yet been established for the Zama project, the CCS/EOR project may yield tax credits for Apache in the future. To encourage the development of a CCS industry in Alberta, the provincial government, through the Alberta Department of Energy, has instituted a Royalty Credit Program (Alberta Department of Energy, 2005). This program offers a royalty reduction to companies that use CO_2 in EOR operations and that meet certain qualification criteria. Apache has submitted applications for the F and NNN Pools at Zama based in part on the technical work provided by this project but they have not yet been awarded.

Recommendations and Conclusions

As the demand for natural gas increases, it is likely that more sour gas fields with elevated concentrations of H_2S will be tapped to meet this increase in demand, resulting in additional natural gas-processing facilities that produce offgases consisting of mixtures of CO_2 and H_2S. Injection of this acid gas into the subsurface was investigated at a natural gas-processing plant in Zama, Alberta, to examine the feasibility of simultaneously disposing of the H_2S, sequestering the CO_2 and producing additional hydrocarbon products.

Key conclusions from the research activities performed at Zama are as follows:

- From a hydrogeological perspective, the pinnacle geometry, excellent cap rock, and extremely slow groundwater flow preclude migration. Findings from this research suggest that if leakage were to occur through the cap rock or into the underlying Keg River Aquifer system, it would be a very slow process taking thousands to hundreds of thousands of years and would likely be limited to much less than a kilometer from the site because of dissolution, dispersion, and residual gas trapping along the migration pathway.

- Mechanically, the anhydrite cap rock was investigated using standard oil industry techniques and was found to be ideal for CO_2 storage. Results of laboratory testing of this cap rock material was combined with mechanical testing using wireline techniques and 3-D geomechanical simulations to fully understand the stress–strain relationships of the unique pinnacle geometry as it undergoes injection and production scenarios. All indications are that the combination of safe operating practices (using well-established regulatory frameworks) and a thorough understanding of the mechanical rock properties at Zama will help prevent failure, ensuring containment of injected fluids.

- Reactions of the reservoir and cap rock were evaluated through a laboratory and modeling exercise intended to determine whether injection of acid gas into a carbonate structure would impact the permeability in the system and, ultimately, hamper injectivity and storage potential of the reef. Findings indicate that the reactivity of the reservoir is low with respect to the current composition of acid gas, and that the primary form of acid gas trapping is solution trapping. These results further demonstrate that this is an ideal site for geological storage of CO_2 through acid gas injection.

- Engineering questions at the site have been answered through comprehensive planning using proven oil field practices. Many of the challenges faced in geological storage scenarios can be overcome by turning to the 100 plus years of characterization, drilling, production, and movement of fluids throughout North America and across the globe.

- MVA activities at Zama suggest that the Zama Field is an ideal candidate for consideration as a large-scale CO_2 storage location. Through the 50 years of oil

production and the current research activities at the site, confidence in this system (reservoir and seals) has been assured.

The Zama Field Validation Test demonstrated that acid gas can be safely injected into subsurface pinnacle reef structures while simultaneously sequestering CO_2 and producing additional oil. However, the routine extrapolation of these results to other facilities and geologic formations is not possible at this time because of differences in lithology, pore fluids, and concentrations of injectate. To successfully make this extrapolation, the subsurface injection of acid gas must be examined in the context of reservoir-specific characteristics and a fundamental understanding of some of the critical chemical and geochemical interactions and fate and transport mechanisms in the subsurface. For this reason, there are still several questions that need to be answered to further facilitate large-scale subsurface acid gas injections beyond the Zama site. Some of the more critical of these questions that should be answered are as follows:

1. Are preexisting and current wellbore completion and abandonment techniques satisfactory for acid gas injection sites? Does the acid gas result in the advanced deterioration of wellbore cements and lead to the eventual leakage of gas to the atmosphere? If so, when might this leakage occur and at what rate?

2. Does the acid gas interact with the cap rock, and will these interactions lead to the accelerated degradation of cap rock material?

3. What chemical and geochemical processes control the long-term storage of CO_2 and H_2S and can these processes be adequately modeled to predict the subsurface fate and transport of these gases over time?

4. What monitoring techniques should be used to ensure the cost-effective, early detection of potential gas leaks from the formation and to verify the quantities of CO_2 that are sequestered?

The Zama site is ideal to conduct these additional research activities for the following reasons: 1) an excellent partnership with the field operator, Apache, exists; 2) the unique geological setting with respect to the isolated nature and geometry of pinnacle reef structures ensures containment of the injected acid gas; 3) injection of acid gas is ongoing and will continue to remain active as an EOR scheme; and 4) the lithology is characteristic of many comparable reservoirs in the central interior of North America.

4.2 Lignite Field Validation Test

Experimental Methods

The overall objective of this validation test was to demonstrate the ability to sequester CO_2 in economically unminable lignite coal seams while simultaneously investigating the potential for CO_2-enhanced CBM production. The test consisted of laboratory- and field-based investigations of an unminable lignite coal seam located in Burke County in northwestern North Dakota. More specific project objectives were as follows:

- To demonstrate that CO_2 can be safely injected and trapped in lignite by means of adsorption.

- To assess the feasibility of CO_2-enhanced CBM production from lignite.

- To evaluate a variety of carbon sequestration operational parameters to determine the applicability of these test results to other similar coal seams within the region or beyond.

Several of the studies that were conducted as part of this validation test provided very useful data and were identified as important tools that should be included as part of the planning and implementation of similar projects. These studies examined:

- CO_2 storage capacity and methane content of lignite.

- Features of fluid transport in lignite.

- Stability of CO_2 stored within lignite.

- Factors controlling the success of CO_2 sequestration/CBM production operations in lignite.

- Economics of operation.

Using anthropogenic CO_2 to enhance the production of CBM from unminable lignite coal seams, while sequestering the CO_2 in the coal after the CBM has been produced represents a potential market-driven storage opportunity that may offer both a near-term economic return and a long-term environmental benefit.

Site Selection

The selection of the validation test site was driven by a number of technical and nontechnical factors. The former included the review of geophysical logs from the database of the North Dakota Industrial Commission Division of Mineral Resources, Oil and Gas Division (NDIC OGD), which identified multiple coal seams. Following this reconnaissance effort, water well logs and other available data sets, e.g., gamma ray logs, were examined to identify the water quality, coal characteristics, and baseline geologic settings in these candidate coal seams. State criteria associated with the definition of an unminable coal seam were also used as part of the screening process. These criteria included a minimum coal depth, cumulative coal thickness, individual bed thickness, and overburden thickness as well as a maximum overburden-to-coal stripping ratio. In addition, the availability of mineral rights was also an important screening factor.

Project Permitting

The validation test required the acquisition of a number of federal and state permits. The primary federal environmental statute was the National Environmental Policy Act (NEPA) of 1969, which stipulates specific procedural requirements for federal agency actions. In general, NEPA applies only to those projects where federal funds are used, federal lands are crossed and/or used, or federal permits are required. In this instance, a NEPA review was required because some of the demonstration test funds were provided by DOE.

The North Dakota permitting requirements are embodied in the North Dakota Administrative Code, which contains general rules and regulations that were adopted by NDIC to conserve and govern the natural resources of the state. Each of these environmental statutes was reviewed to determine the permitting requirements for this validation test.

Well Drilling, Logging, Completion, and Development

In August 2007, five wells were drilled in a modified five-spot configuration within a 160-acre spacing unit (designated as Wells 36-9, 36-10, 36-15, 36-15C [injector well], and 36-16). Figure 4-5 displays a map of the well locations. A summary of the sampling and logging activities that were performed on each of these wells are provided in Table 4-1. More details regarding each of these activities follows.

Figure 4-5. Map of injection and monitoring well locations.

Table 4-1. Summary of Sampling and Logging Activities for the Injection and Four Monitoring Wells

Well Designation	36-9	36-10	36-15	36-15C	36-16
Total Depth, ft	1242	1274	1643	1246	1211
Drilling Cutting Samples	X	X	X	X	X
Core Collection				X	
Platform Express Logging Suite	X	X	X	X	
Sonic Scanner Log				X	
Cement Bond Log	X	X	X	X	X
Cased-Hole Neutron Log				X	X

Throughout the drilling, a two-person geological team collected drill cutting samples and recorded mud gas concentrations from near surface to total depth, 24 hours a day. Drill cuttings were collected at 10-foot sample intervals during the drilling of the first two wells (36-15 and 36-15C) and at 30-foot intervals during the drilling of the remaining wells (36-9, 36-10, and 36-16). The depths of the samples were noted and they were cleaned, dried, and described.

In addition to collecting drill cuttings from each well, a single core was collected from the injection well (36-15C). The coring program was designed to collect the targeted coal seam and a few feet of representative clay from above and below it. Only a limited amount of core was cut to ensure the coal would not lose inherent porosity and permeability as a result of the compression caused by pressures associated with coring excessive intervals of sediment above and below the coal seam. A 20-foot core was cut from the depth interval extending from 1070 to 1090 feet.

The wells were logged immediately after drilling using the Schlumberger Platform Express logging suite. A Schlumberger Sonic Scanner log was also run in the injector well (Well 36-15C). These logging techniques were easily implemented (one exception was monitoring well [36-16] where an assumed sediment bridge prevented open-hole logging of the well) and provided valuable information for the test.

Well completion and development for the validation test were somewhat unique, as the well-drilling program was designed based on the need to collect petrophysical data. This required drilling below the injection zone to accommodate the logging tools. The zone of interest then needed to be isolated to ensure injection control. This led to a completion program where the entire wellbore was cased and cemented, followed by perforation of the injection zone.

Development of the wells was accomplished by applying different stimulation techniques, in stages, with the intent, if possible, of avoiding the use of more aggressive techniques that had the potential to negatively influence the injection zone and complicate the interpretation of postinjection monitoring. The techniques employed during the validation test, in order of application, included swabbing, sonic hammer, nitrogen N-fit test (i.e., minifrac), and acid treatment.

Laboratory Tests

Numerous laboratory studies were conducted on the core from Well 36-15C. These tests included coal compositional analyses (i.e., proximate and ultimate analyses, maceral analysis, and vitrinite reflectance), canister gas desorption studies, methane and CO_2 sorption isotherms, and permeability tests. These small-scale tests, using only small quantities of coal, provided useful information regarding the potential to move CO_2 through the formation and the ability of the coal to adsorb both CO_2 and methane and subsequently release them from the coal bed.

CO_2 Injection

Approximately 90 tons of CO_2 was injected over a roughly 2-week period into a 10–12-ft-thick lignite coal seam at a depth of approximately 1100 feet. A total of nine distinct phases of CO_2 injection were investigated during this time. Throughout each phase, different injection strategies were employed in an attempt to maximize the rate of CO_2 injection into the formation. The strategies investigated were 1) CO_2 injection at the maximum acceptable pressure for the formation (i.e., 780 psig), 2) CO_2 injection cycling near an average of 720 psig, and 3) CO_2 injection at various combinations of temperature and pressure to vary the density of the gaseous CO_2 and/or the proportion of liquid and gaseous CO_2 from 100% of either phase to a mixture of the phases. Because of the properties of the reservoir, the majority of the CO_2 injection was conducted in cycles, which began with the buildup of the bottom hole pressure to a predefined threshold of 780 psig, followed by a slow decline. On average, each injection cycle took about 40 minutes. The bottom-hole temperature varied from 50°F (10°C) to 62.5°F (17°C).

A summary of the key characteristics of these nine phases of CO_2 injection is provided below:

- The duration of the injection phases ranged from as few as 6 to as many as 76 hours of operation.
- The pressure swings ranged from a low of 605 psia to a high of 770 psia.
- The average CO_2 flow rate ranged from 0.13 to 1.45 gpm.
- The volume of CO_2 injected ranged from 308 to 6660 gallons, depending on the injection cycle.

MVA Measurements

MVA measurements at the Burke County site included 1) direct measurements, which provided information directly related to the fluid pathways or the shape of space occupied by fluids, and 2) indirect measurements, which provided data regarding certain parameters that characterized the fluid movement at discrete points of the formation. More specifically, the methods used during this demonstration test included the following:

- RST (reservoir saturation tool).

- Cross-well seismic measurements.

- Surface sensors for measurement of temperature, pressure, and flow rate.

- Downhole sensors for measurement of temperature, pressure, conductivity, and pH.

- Gas sampling at wellheads to measure methane, CO_2, and oxygen concentrations and periodic gas chromatography analyses, which included the measurement of a fluorocarbon-based tracer that was injected with CO_2 at the beginning of the test.

- Microseismic measurements, which included both geophones and tiltmeters.

Because of the low injection rates, many of the monitoring techniques chosen could not verify CO_2 injection and/or detect CO_2 plume movement. Higher injection rates may provide better results for some of the techniques used. After analysis of all gathered data, it was determined that a combination of seismic image tomography and RST measurements was found to provide the best depiction of CO_2 movement at the site. This combination permitted the verification of the CO_2 injection into the targeted depth interval through the RST measurements. However, no extrapolation to reconstruct the plume geometry could be done from the RST measurements alone, since the injected CO_2 did not reach the monitoring wells in amounts that could be registered with the RST. Thus cross-well seismic tomography was used to bridge the gap and provide valuable missing information regarding the plume extent.

Downhole sensors recorded a pressure front in Monitoring Wells 36-15 and 36-9 approximately 9 days after injection had commenced. These results provided real-time data with regard to the movement of fluids within the targeted reservoir.

Results and Discussion

Consistent with the project goals, this demonstration test revealed both what works and what does not work when attempting to store CO_2 in an unminable coal seam. To some degree, the knowledge gained may be site-specific; however, more generic conclusions can be drawn that can serve as the basis for refining the design of future projects of this type.

Site Selection

The site selection process led to the identification of an area in Burke County in northwestern North Dakota as the general location of the demonstration test site. Eventually, a mineral lease was obtained for Section 36, T159N, R90W in the southeast corner of Burke County and served as the location for the validation test.

Project Permitting

The NEPA review indicated that neither a NEPA Environmental Assessment nor an Environmental Impact Statement (EIS) was required for the demonstration test because it

qualified for a categorical exclusion. The exclusion was determined based on the information that had been provided to DOE as part of a project questionnaire.

The North Dakota permitting requirements for the demonstration test, while state-specific, are more than likely quite similar to those that now exist, or will exist, in most oil- and gas-producing states. The North Dakota requirements included a well-spacing exemption, drilling permits, an injection application, an aquifer exemption, and the submission of numerous well reports and Sundry Notices. These requirements are representative of the types of activities that would likely be required to initiate most CO_2 sequestration operations in North Dakota. While they are test- and state-specific, they are probably not unlike what may be encountered in other states where unminable coal seams are being targeted for CO_2 sequestration.

Well Drilling, Logging, Completion, and Development

Five wells were drilled in a modified five-spot configuration within a 160-acre spacing unit (designated as Wells 36-9, 36-10, 36-15, 36-15C [injector well], and 36-16). A freshwater/native mud system was employed to drill both the conductor/surface hole and test/production hole for all five wells. Mud weights were designed to be as low as possible to avoid fluid invasion and subsequent formation damage at depth. Throughout the drilling, a 24-hour/day, two-person geological well site team collected drill cutting samples and recorded mud gas concentrations from near surface to total depth. A Pason (P3) gas detector with chromatograph was used to monitor and record total mud gas and document the gas composition. Additional facts on the drilling and mud systems can be found in the PCOR Partnership Phase II Deliverable D53: CO_2 Sequestration Test in a Deep, Unminable Lignite Seam in Western North Dakota Regional Technology Implementation Plan (RTIP) (Botnen, L., et al., 2009).

Core Recovery

There was 100% recovery of the single core that was retrieved during the drilling of Well 36-15C; however, coal was present in only the last 4 feet of the core, indicating that the entire coal seam of interest, as well as the lower clay interval, had not been captured during the coring process. The partial collection of core from the zone of interest occurred as a result of the methods used to terminate the coring process and the lack of an absolute stratigraphic control while coring. In addition, when the core barrel retrieval began, little to no increase was noted in the string weight. Because of the possibility that the core catcher had not closed, it was decided to slowly retrieve the core to minimize the chance of losing it. The time loss because of this process was significant, and there may have been a significant amount of gas lost from the coal during this retrieval process. This fact is important as it affects the estimates of the recoverable CBM as determined from the laboratory experiments that were conducted on the core (see Laboratory Tests section).

Well Logging

The open-hole logs assisted in the selection of the CO_2 injection interval and highlighted the presence of a bifurcated coal seam. It also provided valuable insight regarding the possible lack of a cleat system in the coal and a relatively homogeneous stress field, which ultimately

contributed to limiting the CO_2 injection rate. Numerous visual displays of log descriptions and analysis can be found in the RTIP (Botnen, L., et al., 2009).

Well Development

Field operations focused on development of the wells to determine hydrogeologic properties of the formation. During the initial stages of well development, none of the wells drilled into the lignite seam yielded substantial fluid volumes. Development of the wells was conducted by employing different stimulation techniques in stages, with the desire to avoid using the more aggressive techniques that had the potential to negatively influence the injection zone and complicate the interpretation of postinjection monitoring data. These techniques included swabbing, sonic hammer, nitrogen N-fit test (i.e., minifrac), and acid treatment.

The results of the N-fit tests indicated that the coal formation was significantly underpressured, with an actual reservoir pressure of about 345 psia versus an expected formation pressure of approximately 470 psia. This underpressured situation was not anticipated, and as a result, well drilling, completion, and development activities were greatly affected. Additionally, the underpressured zone and lack of hydraulic conductivity precluded the use of a pump test to evaluate the "aquifer," which would have led to a better understanding of the hydrodynamics of the injection zone. A complete review of well development techniques and activities can be found in the RTIP (Botnen, L., et al., 2009).

Laboratory Tests

While it is difficult to scale up these laboratory results to the field scale, the conduct of these laboratory tests is recommended as part of the planning and design of carbon sequestration projects in unminable lignite coal seams. Assembling these laboratory data using field samples will improve the ability to predict field performance. It will also permit the investigation of correlations between the coal properties and the sorption and release of CO_2 and methane, both of which are critical variables that govern the economic success of this sequestration approach as well as its acceptance by the public. Furthermore, these data are needed for the development of fate and transport models that are required to project the future subsurface movement of the CO_2. An in-depth discussion of laboratory results and findings can be found in the RTIP (Botnen, L., et al., 2009).

CO_2 Injection

Although the short durations of these individual injection phases made it difficult to reach any firm conclusions, the data did suggest that some improvements in injection rates could be achieved by heating the CO_2 and injecting it in a purely gaseous state at fairly high pressures. Details on injection regimes implemented during the project can be found in the RTIP (Botnen, L., et al., 2009).

MVA Measurements

Because of the low CO_2 injection rates, many of the MVA monitoring techniques that were used were not able to verify CO_2 injection and/or detect CO_2 plume movement. Higher injection rates would likely provide better results for some of the techniques that were used.

After analysis of all of the MVA data, it was determined that a combination of seismic image tomography and RST measurements provided the best MVA data/information at the site. This combination permitted the verification of the CO_2 injection into the targeted depth interval; however, no extrapolation to reconstruct the plume geometry could be done from the RST measurements alone, since the injected CO_2 did not reach the monitoring wells in amounts that could be registered with the RST. Thus cross-well seismic tomography was used to bridge the gap and provide valuable missing information regarding the plume extent. Using the four monitoring wells to acquire two 2-dimensional surveys with high vertical and horizontal resolution that crossed at or near the injection well, it was possible to calibrate the response at the wells with the RST and then fill in the gaps between the wells with the cross-well seismic data. The RST and cross-well seismic measurements provided the best MVA data/information by providing the best depiction of the CO_2 movement at the site. These results are also generally supported by pressure data collected from Monitoring Wells 36-15 and 36-9.

Recommendations and Conclusions

The validation test for the sequestration of CO_2 in unminable lignite coal in Burke County, North Dakota, affirmed that CO_2 can be safely injected and stored in an unminable lignite seam. At the same time, the feasibility of recovering methane was not demonstrated because of the very low methane content of the targeted coal seam. It is believed that the low methane content of this coal seam was directly related to atypical reservoir characteristics, i.e., an underpressured reservoir. In addition, the limited duration of this validation test did not permit the development of an optimal CO_2 injection strategy, the development and verification of a subsurface fate and transport model for CO_2, or the definition of an optimal and effective MVA protocol.

It is recommended that a longer-duration test be conducted to permit the optimization of this CO_2 sequestration strategy, the development and verification of a CO_2/methane subsurface fate and transport model, and the definition of an MVA protocol. The suite of laboratory tests that were conducted on the core samples provided valuable information for the validation test and should be conducted as part of future demonstrations but with the goal of streamlining them to provide a design support experimental protocol.

Any future test of this sequestration strategy should focus on the investigation of alternative CO_2 injection strategies. The results of this validation test suggested that the injection of gas-phase CO_2 represented the optimal injection strategy for this coal seam. If this is the case at other coal seams, it would severely limit the amount (i.e., mass) of CO_2 that could be injected into the coal over time. To overcome this limitation, long horizontal wells could be used along with larger-diameter wells. Alternatively, more aggressive completion techniques could be employed, such as cavitation or hydraulic fracturing, to provide greater permeability for CO_2

injection. This design element is critical to the full-scale deployment of this strategy and should be investigated in more depth as part of any future field test.

As a general statement, this validation test demonstrated the overall feasibility of injecting CO_2 into coal seams at the field scale. It was safely executed, suggesting that similar equipment could be deployed and similar operations could be successfully implemented at other field sites. A follow-on, longer-duration field test should be implemented with the intent of 1) optimizing the carbon storage and enhanced CBM production operations; 2) developing, calibrating, and verifying a CO_2/methane fate and transport model; and 3) evaluating the economics of this carbon storage/enhanced CBM production option. At the same time, a more streamlined MVA strategy can also be developed, applied, and validated as part of further field testing.

4.3 Williston Basin Oil Field Validation Test

The PCOR Partnership Phase I studies indicated that the Williston Basin oil fields may have the capacity to store over 500 million tons of CO_2 as part of CO_2 flood EOR operations. While the CO_2-based EOR operations at the Weyburn and Midale Fields in Saskatchewan are good examples of economically and technically successful injection of CO_2 for simultaneous sequestration and EOR, the depths of injection and, therefore, reservoir conditions in those fields are relatively shallow (ca. 4600 ft) and not necessarily representative of many large Williston Basin oil fields. To evaluate this CCS and EOR potential, the PCOR Partnership conducted a Phase II field validation test in a deep carbonate reservoir at the Northwest McGregor oil field in Williams County, North Dakota. The CO_2 huff 'n' puff (HnP) field validation test was conducted on a well (formally named the E. Goetz #1 well) that is currently producing oil from an interval of the Mississippian-age Madison Group at a depth of approximately 8050 ft in the Northwest McGregor oil field. Unique elements of the Madison Group within the Northwest McGregor oil field with respect to the application of a CO_2 HnP operation, as compared to other HnP operations in the literature, include the following:

- It was among the deepest applications, at a depth of 8052 ft, and it was operated at among the highest pressures (3000 psig) and temperatures (200°F), as well.

- It was conducted in a carbonate (limestone) reservoir as compared to most HnPs in the literature, which have been conducted in clastic reservoirs.

The specific goals of the field-based activities at Northwest McGregor were to 1) evaluate the technical and economic viability of CO_2 injection in carbonate oil reservoirs at depths greater than 8000 ft, 2) determine the effectiveness of the CO_2 HnP approach to stimulate oil recovery from individual mature wells in the Williston Basin as well as the overall PCOR Partnership region, and 3) test the ability of Schlumberger's RST and Vertical Seismic Profile (VSP) to serve as MVA tools with respect to the identification of relatively small amounts of CO_2 in a deep carbonate reservoir. To achieve these goals, approximately 440 tons of CO_2 was injected into a single well and allowed to "soak" for 2 weeks, after which time the well was brought back into production, allowing the flow of incremental oil, water, and gas (primarily CO_2). The results of this field validation test provide stakeholders and CCS operators with previously unavailable information to support the deployment of CO_2 HnP as a means of improved oil recovery in the

Williston Basin and throughout the PCOR Partnership region as well as the deployment of RST and VSP technologies as part of an MVA strategy.

Experimental Methods

Technical Approach for Field Validation Test

A CO_2-based HnP operation is a well stimulation or EOR technique that is typically conducted on a single well that is not part of a secondary or tertiary oil recovery operation. CO_2-based HnP operations have been conducted at hundreds of individual well locations all over the world, and there is a wealth of published information on the effectiveness of this technique for the stimulation of mature wells in a variety of different reservoir settings. Over the course of a typical HnP operation, the producing oil well will be put through three phases (Hyne, 1991). During the huff (injection) phase, CO_2 is injected into the reservoir through the well for a period of days to weeks. Following the injection is the soak, or shut-in, phase, during which the well is shut in for several days to weeks to allow the CO_2 to dissipate in the reservoir and dissolve into the oil thereby causing it to swell and become less viscous. During the puff (production) phase of the operation, the CO_2-affected oil is produced from the well (Hyne, 1991). Because the HnP operation conducted by the PCOR Partnership included a variety of non-industry-standard characterization and testing activities as part of the project, the field-based work conducted at the E. Goetz #1 oil well was classified into six distinct phases, as presented below:

- Preinjection Phase – The preinjection phase included the gathering of readily available historical reservoir and production data, primarily in the NDIC Department of Mineral Resources well files, that would support the development of an effective injection and monitoring plan. The preinjection phase also included field-based well preparation activities (i.e., swabbing, inspection of tubing and rods, and casing tests, etc.) that were necessary for preparing the well for CO_2 injection. Field-based characterization site activities were also conducted in the preinjection phase, including the application of ultrasonic logging to determine the preinjection condition of the well casing and cement, the deployment of the RST and VSP technologies to obtain baseline fluid saturation conditions in the reservoir, and the collection of downhole and near-surface fluid samples to determine baseline geochemical conditions. The overall preinjection phase lasted several weeks, although the field-based components were conducted over a period of approximately 2 weeks.

- Injection Phase – The injection phase primarily included the mobilization and setup of the CO_2 and CO_2-pumping unit at the E. Goetz #1 well location and the injection of CO_2 into the well. The injection phase also included the simultaneous injection of a perfluorocarbon tracer into the well to serve as an additional means of monitoring the movement and fate of the CO_2. The injection phase occurred over the course of approximately 1 week.

- Postinjection Phase – The postinjection phase was the period of time immediately after the injection of CO_2. During this phase, initial postinjection pressure and temperature data were obtained, downhole temperature and pressure sensors/recorders

(commonly referred to in the oil field industry as "bombs") were installed in the well to record those parameters during subsequent soak and production phases, and one downhole geophysical logging event (using the RST) was conducted. The size and nature of the RST allowed for its deployment into the well in such a manner that there was no loss of pressure in the well and, therefore, no effect on the CO_2 in the reservoir. It was not possible to run the downhole portion of the VSP technology into the well without fully opening the well and losing reservoir pressure; therefore, the VSP was not deployed during this phase of the operation. The postinjection phase was conducted over the course of less than 1 week after the end of the injection.

- Soak Phase – The soak phase was the time during which the E. Goetz #1 well was undisturbed and CO_2 was allowed to soak into the reservoir. Monitoring of pressure at the surface was the only activity conducted during this time. The duration of the soak period is determined by the nature of fluids that are produced within 24 hours of first reopening the well. If only CO_2 is produced, then the well is shut in again and allowed to soak for a longer period of time. If oil is produced, then the soak period is considered to be over, and the production phase is begun. While the literature suggests that the soak period for HnP operations can last anywhere from two to several weeks, the soak period for the E. Goetz #1 HnP was approximately 2 weeks.

- Production Phase – The production phase is the period of time during which the well produces oil at a rate that is greater than the preinjection rate. The literature indicates that this can last anywhere from weeks to several months, depending on a variety of reservoir-specific factors. During the production phase, oil, gas, and water production data were obtained and surface samples of fluids from the E. Goetz #1 and the E.L. Gudvangen #1 wells were collected and analyzed periodically. Fluid samples were also collected from shallow groundwater wells in the vicinity of the E. Goetz #1 well and analyzed for CO_2, tracer, and other standard parameters, including ions and metals. For the purposes of the PCOR Partnership Phase II program, the production phase was considered to have lasted approximately 3 months. Actual improved oil productivity was still occurring after this time, but the Phase II schedule dictated that postproduction activities be conducted before the E. Goetz #1 well had returned to its preinjection productivity.

- Postproduction Phase – In addition to the routine surface pressure monitoring and fluid sampling from the E. Goetz #1 and E.L. Gudvangen #1 wells, the postproduction phase of the PCOR Partnership Phase II Northwest McGregor HnP project included a final round of downhole fluid sample collection and analysis; application of the ultrasonic, caliper, and RST logging technologies; and acquisition of VSP data. The postproduction phase was conducted over the course of approximately 2 weeks.

Key commercial partners in the CO_2 HnP field validation test included Eagle Operating, Schlumberger Carbon Services, and Praxair. The technical team was led by the EERC. Eagle Operating provided access to the site (which is owned and operated by Eagle) and conducted all operational and maintenance activities related to the well. CO_2 was purchased from Praxair, which also designed and conducted the injection process in close collaboration with the EERC.

The EERC and Schlumberger conducted characterization activities to develop data on baseline conditions and determine the effects of CO_2 on the reservoir during and after the injection phase. The dynamic response of the injection zone was evaluated for changes over the course of the project using a variety of downhole logging tools and the monitoring of pressure in the injection well and another nearby producing well that provided limited service as an observation.

Using a petrophysical model of the Northwest McGregor oil field, preinjection predictions regarding the nature of CO_2 in the target reservoir during and after injection were compared to actual postinjection reservoir conditions as monitored over the duration of the study period. The alignment of the preinjection modeling predictions with the field observations was evaluated. The RST and VSP results provide previously unavailable insight regarding the fate of injected CO_2 within a relatively deep carbonate target reservoir, particularly with respect to the penetration of CO_2 away from the borehole and into the reservoir. Broadly stated, goals of the field demonstration were to provide stakeholders with key information regarding 1) the viability of CO_2-based HnP operations as an option for improved oil recovery in deep carbonate oil reservoirs and 2) the consideration of deep carbonate oil reservoirs as reasonable targets for large-scale CO_2 storage.

MVA Plan

The CO_2 MVA activities at the site were jointly designed and implemented by the EERC and Schlumberger Carbon Services. The purpose of the MVA program was to 1) provide a set of baseline conditions upon which the effects of the injection can be compared to data gathered during and after injection operations; 2) generate data sets that demonstrate the security of the injection program from the perspectives of containment and safety; and 3) establish a technical framework for the determination of the effectiveness of Schlumberger's RST and VSP technologies as a means of identifying and monitoring the plume of injected CO_2 in a deep carbonate reservoir setting. MVA program activities that resulted in the determination of baseline conditions included geological and hydrogeological characterization at various scales, characterization of the Northwest McGregor reservoir, the determination of geomechanical and geochemical properties of key rocks in the reservoir/seal system, and evaluation of wellbore integrity issues. Field-based elements of the MVA program included the introduction of a tracer and data collection (i.e., formation fluid sampling and analysis, reservoir dynamics monitoring) from the injection/production well and monitoring wells.

Other key elements of the MVA program included documentation of the permitting process and regulatory framework for the project, determination of material balance based on the collected field data, and an observational study of the effectiveness of CO_2-based HnP with respect to improving oil productivity. Generally speaking, monitoring activities were focused on the near-reservoir environment, including monitoring for leakage through cap rock, migration away from the intended zone of influence within the reservoir, and wellbore leakage. However, shallow groundwater wells in the vicinity of the Northwest McGregor HnP test were tested before injection, during the operational phase of the project, and at the end of the project performance period to ensure that the CO_2 injection program did not impact local groundwater resources.

Routine Monitoring

Monitoring at the Northwest McGregor oil field was conducted primarily through the E. Goetz #1 well, the E.L. Gudvangen #1 well (serving as a deep reservoir observation well while still actively operated as an oil and natural gas production well), and a shallow groundwater well in the vicinity of the E. Goetz #1 well. The monitoring program included the use of relatively routine monitoring techniques such as the periodic measurement of the wellhead pressure of the E. Goetz #1 and E.L. Gudvangen #1 wells (Figure 4-6), and the periodic analysis of fluid (oil, water, and gas) samples from all of the wells for a perfluorocarbon tracer introduced during the injection operation and/or other CO_2-related parameters. These monitoring activities were conducted to provide a timely and effective means of informing the operator and other potentially affected stakeholders of potential impacts should the injected CO_2 migrate out of the intended zone. From a technical standpoint, with respect to the fate of CO_2 and HnP effectiveness, these monitoring techniques also provided a means by which to determine the fate of the CO_2 through the use of mass balance calculations.

Specialized Geophysical Characterization Techniques

The Northwest McGregor HnP test site offered a chance to test two specialized geophysical characterization technologies in a deep reservoir environment. While the application of these technologies is not a necessary component to the operation of a HnP-based oil recovery project, their use as a means of identifying and qualitatively or semiquantitatively monitoring

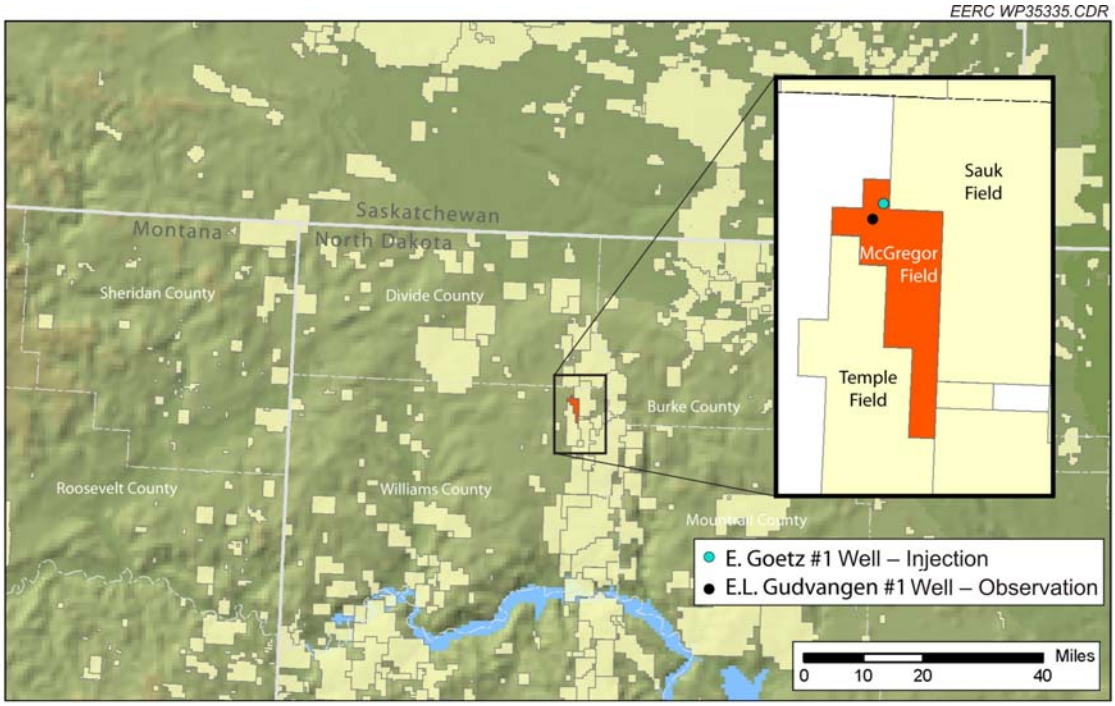

Figure 4-6. Map view of Northwest McGregor oil field with relative locations of the injection and observation wells.

CO_2 in the context of CCS may be quite appropriate and valuable. The RST and VSP technologies, both owned and operated by Schlumberger Oilfield Services, were deployed at the Northwest McGregor site in close collaboration between Schlumberger Carbon Services and the EERC, both before and after CO_2 injection operations. The Northwest McGregor field allowed for testing of these technologies under conditions that are relatively unique. The depth of the reservoir meant that the downhole components of the technologies would be subjected to higher reservoir pressures and temperatures than are usually encountered for a CO_2 storage project. Also, the heterogeneity of the carbonate and evaporite beds within the Mission Canyon Formation added a level of complexity to the system that further tested the ability of both the field-based components of the technology and the office-based processing and interpretation of the raw data generated in the field. The relatively small amount of CO_2 injected into the reservoir and small footprint of the plume also pushed the documented lower threshold of CO_2 detection for the RST and VSP technology, which is useful when trying to delineate the edges of large plumes created by large-scale CCS projects.

Application of RST – The RST is a downhole geophysical tool that is deployed into the target well using a truck-mounted wireline system. For the E. Goetz #1 well, application of the RST took a crew of two people approximately 4 to 6 hours. While the raw RST data for each run were provided to the EERC in the field immediately upon completion, final processing of the raw data into an interpretive format was conducted by Schlumberger personnel in Houston, Texas, over the course of approximately 2 weeks. The RST technology was deployed in the E. Goetz #1 well three times over the course of the Northwest McGregor HnP project: 1) approximately 6 weeks before injection to establish baseline saturations of oil, water, and gas in the near-wellbore reservoir environment; 2) approximately 72 hours after injection to determine the occurrence of CO_2 when it was at its maximum saturation in the near-wellbore reservoir environment; and 3) at the end of the production phase of the project, 129 days after the well was brought back into production.

The RST was considered appropriate for this application for two significant reasons. First, the small diameter of the tool, 1 11/16 inches, was ideal for deployment within the production tubing of this well. This offered a significant opportunity to log the hole immediately after injection ceased to determine saturations and extent of vertical migration within the reservoir. Second, the cased-hole utility of this tool allows for longer-term monitoring of fluid saturations in the near-wellbore environment which can be used, coupled with VSP findings, in the dynamic simulation of reservoir performance and lateral migration of CO_2.

Application of the VSP Technology – The VSP technology couples the use of a downhole wireline acoustic monitoring tool with surface seismic sources to generate 2-D seismic maps of the target reservoir. In the case of the Northwest McGregor project, the seismic sources were provided by two vibe trucks located on opposite ends of a line approximately 3000 ft from the target well. Each VSP survey event was conducted using multiple lines in different orientations (e.g., north–south, east–west) to facilitate the development of a 3-D view of the reservoir and the plume. The survey events required a minimum of a four-person crew and approximately 10 to 12 hours to conduct. The VSP technology was deployed by Schlumberger Carbon Services twice over the course of the Northwest McGregor HnP project: 1) approximately 6 weeks before injection to establish baseline saturations of oil, water, and gas

in the reservoir environment and 2) at the end of the production phase of the project, 129 days after the well was brought back into production. Raw data were sent to Schlumberger offices in Houston, Texas, for processing. Largely because of the complex and heterogeneous nature of the carbonate- and evaporite-dominated rocks that make up the Mission Canyon Formation, processing of the raw data into formats that allowed for interpretation required approximately 6 weeks.

CO_2 Injection and Incremental Oil Production

The injection of CO_2 into the Mission Canyon reservoir of the Northwest McGregor oil field was initiated on June 25, 2009, and completed on June 26, 2009. The total amount of CO_2 injected was 440 tons, and the time required to inject that volume was 36 hours. The operational parameters of the injection are provided in Table 4-2. The CO_2 used in the injection was of a food-grade purity (>99% CO_2). It was purchased from Praxair, which shipped it by rail from its gas plant in Wyoming to a rail yard in Stanley, North Dakota, from which it was then transported by tanker truck to the Northwest McGregor injection site. The pumping unit and technical support to conduct the injection were also provided by Praxair. Figure 4-7 is a photograph of the pumping unit that was used to pressurize the CO_2 and the piping and valve system that was used to deliver the pressurized CO_2 to the wellhead. The pressure of the CO_2 was maintained in a manner to ensure the CO_2 was injected into the reservoir in the supercritical state but did not exceed the reservoir fracture pressure. Upon completion of the injection, the E. Goetz #1 well was shut in.

After the injection phase of the HnP operation, the E. Goetz #1 well was shut in and the injected CO_2 allowed to soak for a period of 2 weeks. The soak period allows the injected CO_2 time to dissolve into the oil, causing it to simultaneously expand and undergo a reduction in viscosity which, in turn, allows it to flow more freely. Oil recovery is also stimulated by the localized increase in reservoir pressure that was caused by the injection operation. On July 6, 2009, the E. Goetz #1 well was opened to determine if the well was ready to be brought back into production. The review of documented HnP results in the literature indicated that a useful rule of thumb for determining if the soak period was finished was the nature of fluid production in the first 24 to 48 hours (depending on the size of injection) after the well was opened. In general, if only CO_2 is produced within the first 24 to 48 hours, then the well should be shut in again and the CO_2 allowed to soak for another week to 2 weeks. If oil is produced within the first 24 to 48 hours, then the well is ready to be brought back into production.

Table 4-2. Operational Parameters for the Injection of CO_2 into the E. Goetz #1 Well

Total Mass of CO_2 Injected	440 tons
Maximum Allowable Injection Pressure Based on Fracture Gradient	5100 psig
Average Injection Rate	12.2 tons/hour
Average Injection Pressure (surface)	2900 psig
Average Injection Pressure (bottomhole)	5000 psig
Average Injection Temperature (bottomhole)	190°F
Wellhead Pressure at End of Injection	3500 psig
Length of Injection Period	36 hours

Figure 4-7. Pumping unit and pipe and valve system used to inject CO_2 into the E. Goetz #1 well.

Results and Discussion

The activities conducted at the Northwest McGregor oil field as part of the PCOR Partnership Phase II field demonstration project yielded previously unavailable insight regarding 1) the effectiveness of small-scale CO_2 injection using the HnP approach to stimulate improved oil recovery from a mature oil well in a deep carbonate reservoir; 2) the effective combined use of historical and newly acquired geological, geochemical, and geomechanical data sets to develop the petrophysical and dynamic simulation models necessary to predict and history-match CO_2 injection and oil production; and 3) the effectiveness of the RST and VSP geophysical characterization technologies to identify and delineate the occurrence of CO_2 in a deep carbonate oil reservoir. Key findings include the following:

- The effective and iterative use of historical and newly acquired data sets is critical to the baseline characterization aspect of MVA. This was demonstrated in the Northwest McGregor HnP project through the development and application of new fracture analysis data and fracture distribution models based on thorough evaluation of historical well logs and core samples. These models were critical to understanding the movement of CO_2 within the reservoir and history-matching both the oil production data and the data from the third RST logging event.

- RST and VSP were demonstrated to have the ability to provide valuable views of the specific location of injected CO_2 within a deep carbonate reservoir environment. The

application of these tools, combined with robust modeling, may be very effective MVA technologies for CCS in deep carbonate reservoirs.

- The improved oil productivity that was observed during this project suggests that the application of CO_2-based HnP may be a viable approach to improved oil recovery from mature wells in not only the Williston Basin, but other mature oil-producing areas of the PCOR Partnership region. Phase I characterization activities demonstrated that there are many oil fields in the PCOR Partnership region that may be suitable for the application of large-scale CO_2 injection for EOR operations, with those fields having the potential to produce approximately 3.4 billion barrels of incremental oil (Smith et al., 2005). At a price of $70/barrel (price of oil on New York Mercantile Exchange, November 2, 2009), that oil resource is worth over $238 billion. The use of CO_2 for HnP on individual wells in the region may yield additional economically attractive opportunities, making the size of the prize even larger and providing further incentive for the creation of a regionally extensive CO_2 distribution infrastructure.

The results of the monitoring activities demonstrated that no statistically significant changes in monitored parameters were observed over the course of the project at the E.L. Gudvangen #1 well or any of the shallow groundwater wells. Figure 4-8 is a graph of CO_2 measurements in gas samples from the E.L. Gudvangen #1 well which demonstrates that there has been no change in CO_2 content in the gas stream for that well, while Table 4-3 presents water quality data from the shallow groundwater well, demonstrating no change in water quality for those resources. Figure 4-9 shows a comparison of results from those RST logging events.

The results indicate that the RST logging tool is able to clearly identify the zones within the near-wellbore reservoir into which CO_2 was injected and subsequently migrated. In the case of the Northwest McGregor reservoir, it appears that after injection the CO_2 plume largely moved upward until it was blocked by the impermeable anhydrite bed at a depth of approximately 7930 ft. Some residual gas saturation appears to have migrated into and remained at levels below the perforated zone. This is interesting because it matches well with the vertical geometry of the plume that was predicted by the dynamic simulation that included the fracture network as part of the geologic model. These results indicate that the RST is capable of operating effectively in deep carbonate reservoir environments. Such results can be useful when determining the vertical migration of CO_2 in a reservoir. Additionally, when interpreted in conjunction with ultrasonic imager (USI) logs, caliper logs, and other wellbore integrity-related logs, these results may be particularly useful in identifying locations in the wellbore that may be acting as points of leakage.

Figures 4-10 and 4-11 provide a comparison of results from those VSP deployment events. Close examination of the raw VSP data generated by the two surveys showed that there was an observable difference in seismic reflectance in the reservoir between the baseline and postinjection runs. In particular, there was a noticeable difference in the common depth point (CDP) maps for the north and east offsets. The processed VSP results indicated that the lateral component of the injected CO_2 plume spread out primarily in an easterly direction, with CO_2 saturation seen approximately 300 ft from the E. Goetz #1 well along the eastern transect and approximately 50 ft along the northern transect. The results indicate that the VSP surveying

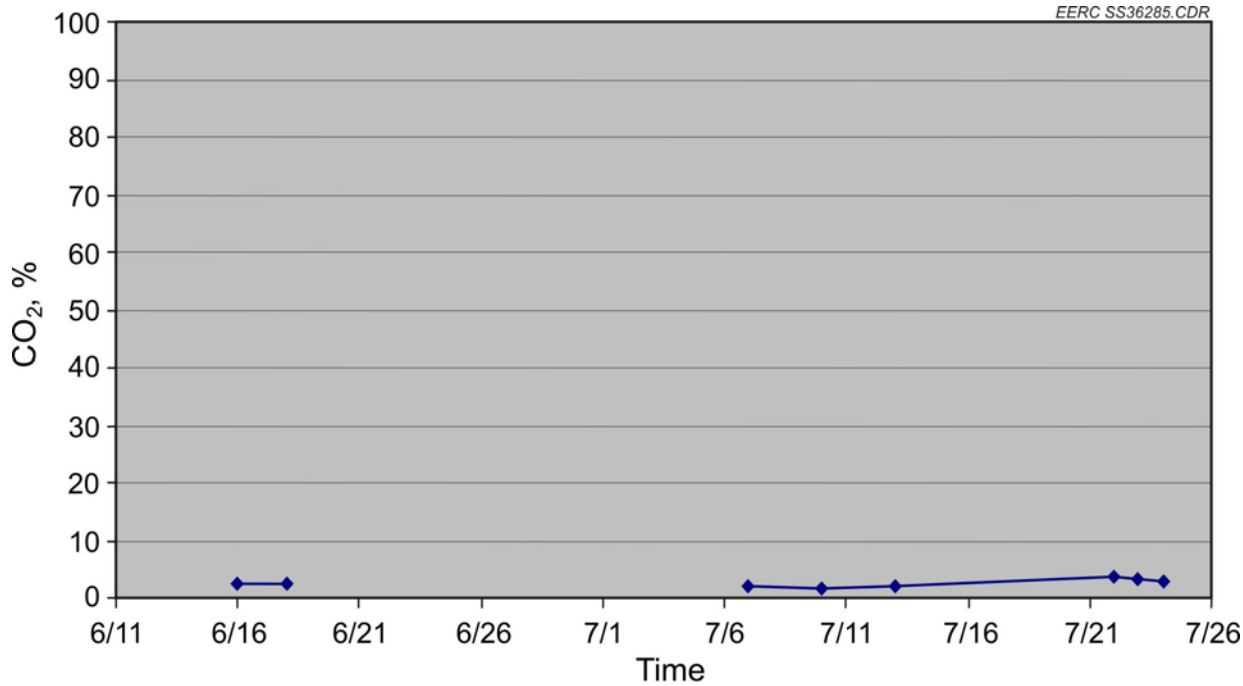

Figure 4-8. CO_2 content measured in the E.L. Gudvangen #1 gas stream.

Table 4-3. Results of Water Quality Tests on Water from Shallow Goundwater Wells in the Vicinity of the E. Goetz Well

	Well #1 Before	Well #2 After
pH	7.4	7.8
Bicarbonate, mg/L	1530	1464
Ca, mg/L	270	248
TDS,[1] mg/L	4910	5100
Conductivity, ohm-m	1.66	1.74
Perfluororcarbon	Nondetected	Nondetected

[1] Total dissolved solids.

technology is able to identify the zones into which CO_2 was injected and subsequently migrated a distance of 300 to 1200 ft away from the wellbore. These results indicate that the VSP is capable of operating effectively in deep carbonate reservoir environments. Such results can be useful when determining the horizontal and vertical migration of CO_2 in a reservoir. When interpreted in conjunction with RST logs these results may be particularly useful in delineating the vertical and horizontal extent of a CO_2 plume. In the case of the Northwest McGregor injection, the VSP results showed the plume as largely being at a depth of a little more than 7900 ft, and are entirely consistent with the RST results showing the greatest saturation of CO_2 at approximately 7930 ft. It is also worth noting that its ability to detect the small amount of CO_2 (approximately less than 300 tons distributed over an area of approximately an acre) that was in the Northwest McGregor Mission Canyon reservoir after 115 days of production suggests that the VSP may be an effective means of identifying the edge of larger plumes such as would occur at large-scale commercial CCS injection projects.

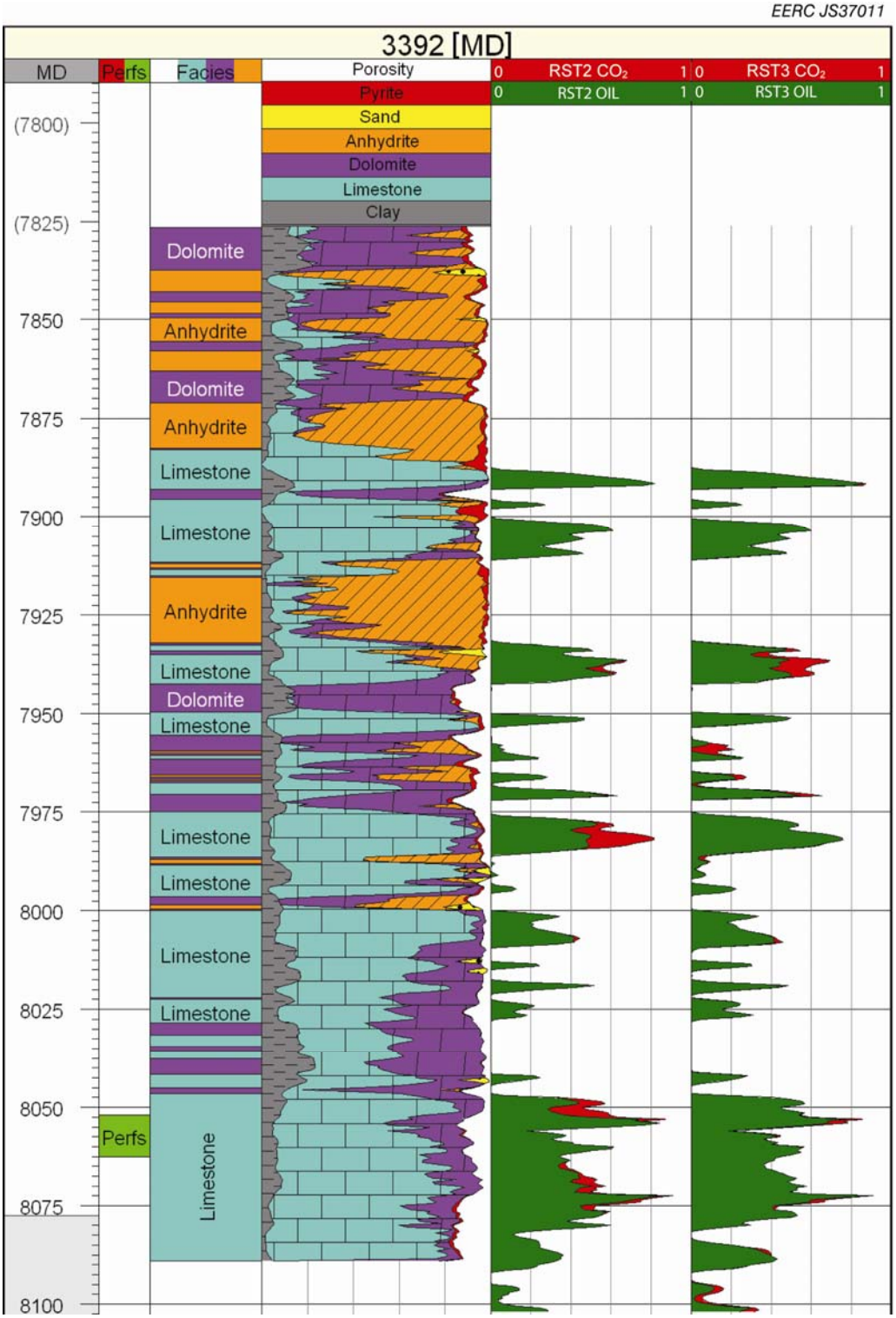

Figure 4-9. Comparison of results of two of the Northwest McGregor RST logging events, with the RST log on the left representing the fluid saturation conditions approximately 48 hours after injection and the RST log on the right representing conditions approximately 3 months later. CO_2 saturation is represented by red, while oil saturation is represented by green.

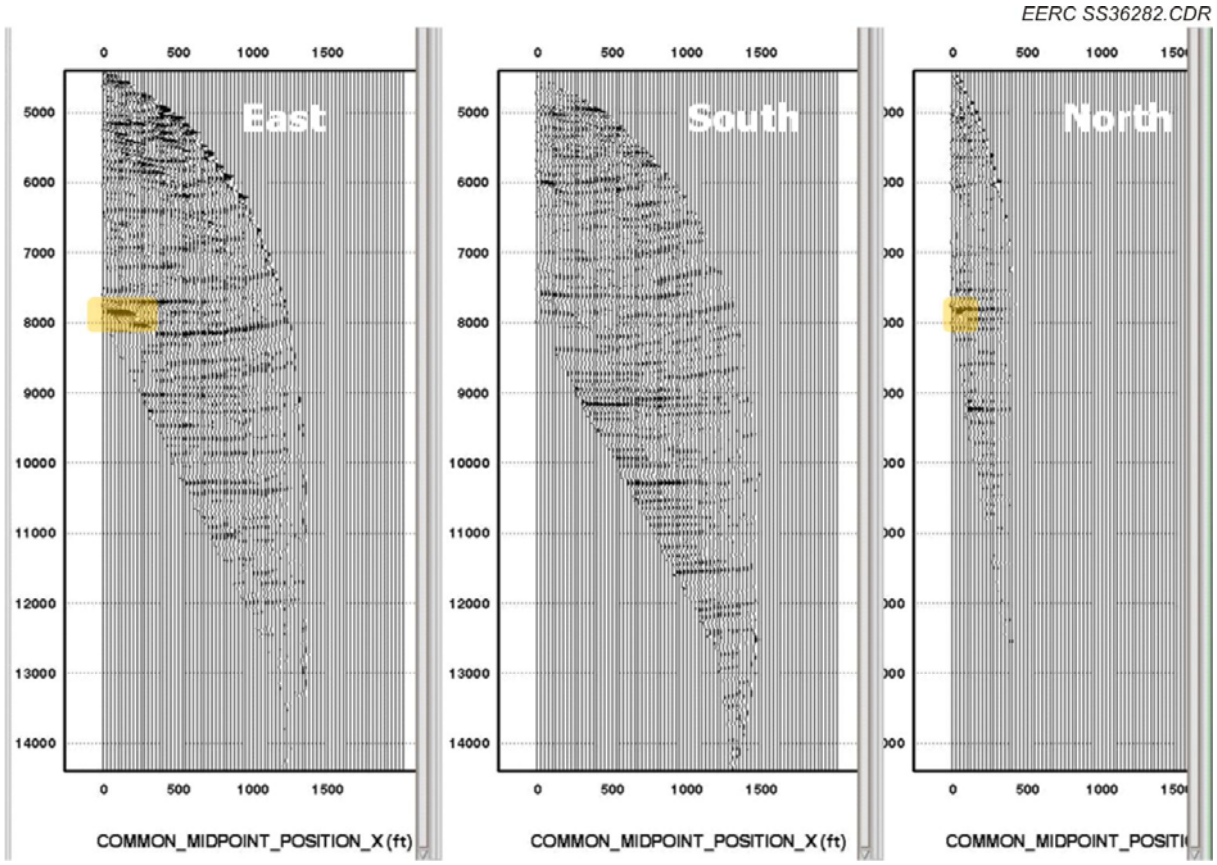

Figure 4-10. Difference CDP maps showing comparison of results from the VSP surveying events. The areas highlighted in yellow indicate zones that have been interpreted to represent a change in density that is indicative of an increase in CO_2 saturation within that portion of the reservoir.

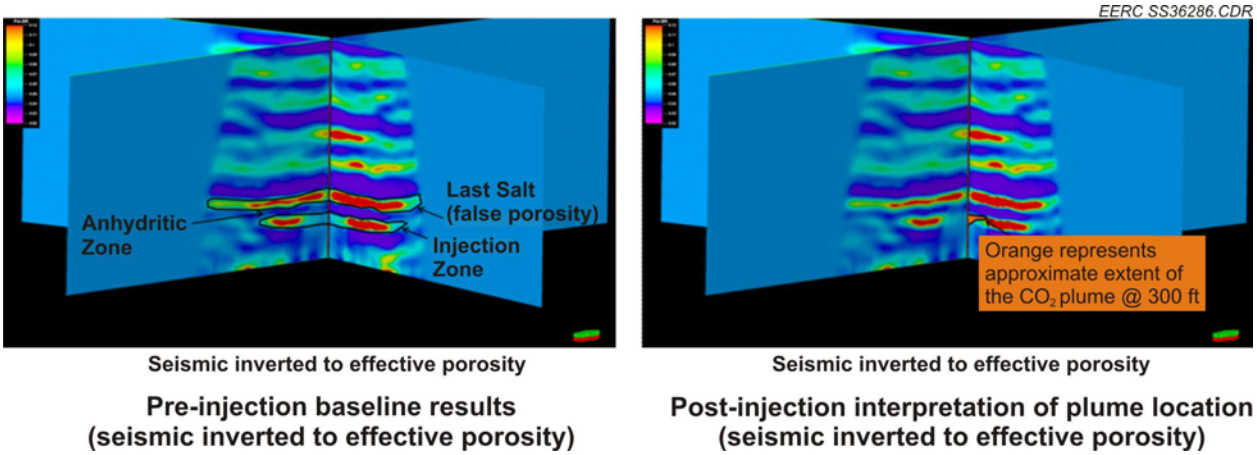

Figure 4-11. Interpreted comparison of VSP survey pre- and post-injection results.

In the case of the Northwest McGregor HnP operation, the E. Goetz #1 well produced exclusively gas for approximately 2 hours before producing oil and water at a rate approximately 10 times greater than baseline. This high production, with a peak production rate of 20 barrels of oil per day, continued over the course of 5 days, during which the well was free-flowing (i.e., not on any type of pump). Oil and water production during this period flowed directly into mobile oil–water separation tanks. These mobile separation tanks were larger than the on-site separation tanks and had been brought to the site to handle the higher rates of production that were anticipated during the early days of the production phase. The use of these larger separation tanks allowed for the constant unrestricted flow of fluid from the well. Because of scheduling conflicts on the part of the service rig providing support to the HnP project and uncertainty regarding its later availability, the decision was made to install a pump into the producing well prior to the departure of the service rig on July 13, the sixth day into the production phase. Unfortunately the installation of the pump significantly restricted the flow of oil and water from the well, and while average daily production rates were two to three times higher than the original baseline production rate of 1.5 barrels of oil per day, oil production did not approach the very high rates achieved in the first few days of the production period. Figure 4-12 is a graph showing oil and water production over the course of the production period (July 6, 2009, through November 10, 2009). Tables 4-4 and 4-5 provide key production statistics for the same period of production.

Recommendations and Conclusions

The establishment of carbon credits associated with geologic storage of CO_2 will require a robust yet cost-effective MVA plan for each injection project. The activities and results of the Northwest McGregor HnP project made several valuable contributions to the baseline characterization and monitoring components of MVA. With respect to baseline characterization, the project demonstrated that historical geological, production, and operational information, obtained from the NDIC OGD well file database and the archives of the North Dakota Geological Survey Core Library, can provide a tremendous amount of critical data with respect to the baseline conditions of both oil field reservoirs and individual wells. With respect to monitoring, the Northwest McGregor HnP project yielded previously unavailable field-based data on the effectiveness of using Schlumberger's RST and VSP technologies to develop a qualitative view of the vertical and horizontal nature of the injected CO_2 within a deep carbonate reservoir. The ability of these technologies to "see" the effects of the small-volume plume of CO_2 (<300 tons) at a depth greater than 8000 ft, as demonstrated at the Northwest McGregor field 3 months after injection, indicates that these technologies should be considered to be valuable additions to the MVA toolbox for future large-scale CCS projects.

The PCOR Partnership region includes hundreds of large stationary sources of CO_2, many of which are located in close proximity (within 100 miles) to oil fields that are suitable for CO_2-based EOR operations. The size of the potential oil resource in the PCOR Partnership region that may be associated with CO_2-based EOR is over 3.4 billion barrels of oil (Sorensen et al., 2006). At a price of $70/barrel this resource could have a value over $238 billion. These economics provide a substantial incentive to develop large-scale CCS projects for some of those close-proximity sources. Many, if not most, of the oil fields in the region are in close proximity to saline formations that may also be suitable targets for large-scale CO_2 storage. Under these

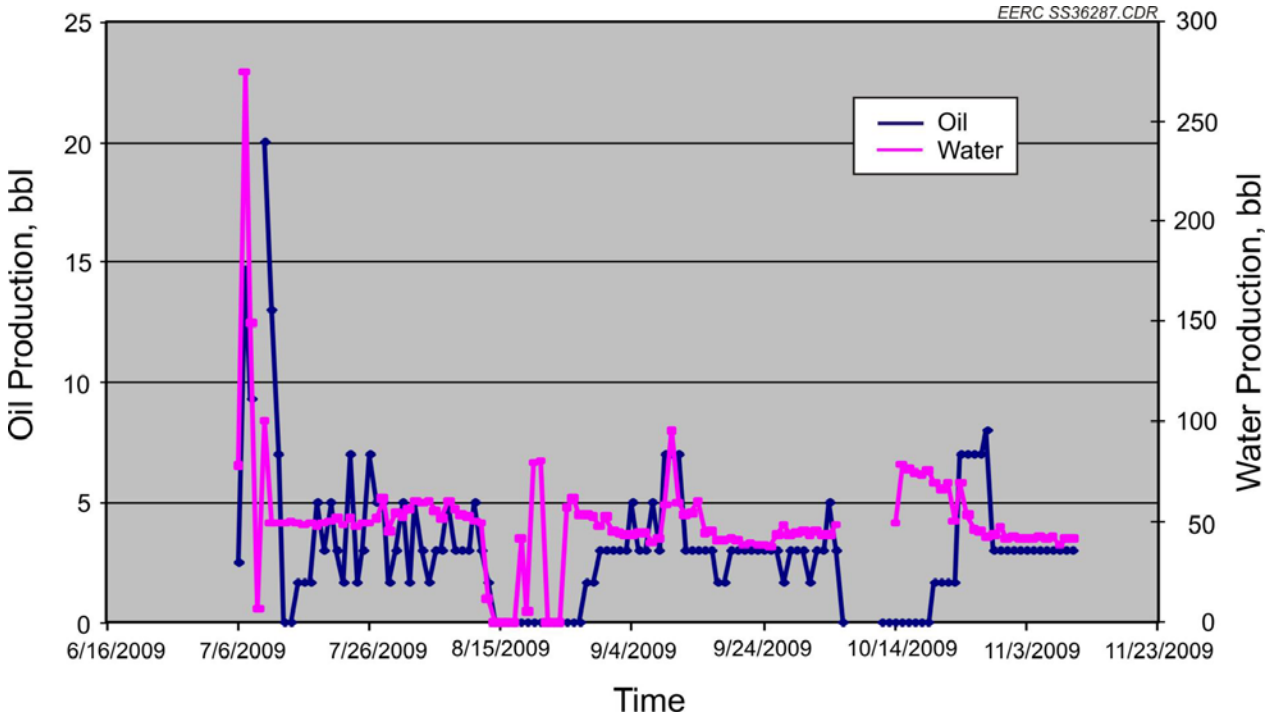

Figure 4-12. Oil and water production data for the Northwest McGregor HnP, summer and fall of 2009.

Table 4-4. Key Production Statistics for the Northwest McGregor HnP Operation

	E. Goetz Baseline Production Statistics	HnP Production Statistics (averages) (July 6 through November 10, 2009)	Improved Recovery to Date
Oil Production Rate (not including down time)	1.5 BOPD[1]	3.3 BOPD	2.2X
Oil Cut, %	2.8	6	2.1X
% of Injected CO_2 Produced Back	NA	30	NA

[1] Barrels of oil per day.

Table 4-5. Production Totals for the Northwest McGregor HnP Operation from July 6 Through November 10, 2009

Days on Production	Oil	Water	Gas (CO_2)
115	377 bbl	6100 bbl	2222 Mcf (130 tons)

circumstances, it is logical to envision the implementation of large-scale CCS in the region as developing over the course of two main phases.

We envision the first phase of CCS implementation will exploit the sale of incremental oil from CO_2-based EOR projects to offset some of the capital required to construct the capture, compression, and transportation elements of large-scale CCS. The effectiveness of large-scale CO_2 flood operations in the Williston Basin has previously been, and continues to be, demonstrated at the Weyburn and Midale oil fields in Saskatchewan. The results of the Northwest McGregor HnP project suggest that smaller-scale CO_2-based HnP operations may also be a viable means of improving the oil productivity of mature wells in the PCOR Partnership region, especially the Williston Basin. While the volumes of CO_2 that would ultimately be stored by HnP operations would be relatively small compared to a CO_2 flood, the use of CO_2 for HnP on individual wells may yield further economically attractive opportunities in the region, which will provide additional incentive for the creation of a CO_2 distribution infrastructure in the oil-producing areas of the PCOR Partnership region.

Over time, as carbon management becomes a greater component of mainstream society, carbon credit-trading markets will evolve and provide additional economic incentives for conducting large-scale CCS projects. Once oil resources at injection locations have become depleted, the development of robust carbon credit-trading markets will facilitate and ultimately support continued injection into saline formations as the second phase of CCS implementation.

5.0 TERRESTRIAL VALIDATION TEST

The PCOR Partnership region is home to a variety of land use options that present an opportunity for terrestrial carbon sequestration. Many of the region's important and highly productive ecosystems have been altered by agricultural and commercial development. Terrestrial carbon sequestration on these diminished lands can be enhanced by implementing practices such as introducing cover crops on fallow land, the conversion from conventional tillage to conservation tillage, and the restoration and/or preservation of grasslands and seasonal wetlands. Landowners adopting these practices can generate a new source of income while at the same time revitalizing a suite of ecosystem functions that were either nonexistent or greatly reduced.

As part of Phase I activities, the PCOR Partnership identified cost-effective CO_2 terrestrial sequestration solutions for the region and developed methods to facilitate and manage the validation and deployment of these technologies. In Phase II, the PCOR Partnership partners characterized the technical, scientific, and administrative issues inherent to terrestrial offsets. The Partnership also worked to enhance the public's understanding of CO_2 sequestration, identifying the most promising opportunities for sequestration in the region, demonstrating technologies, and detailing an action plan for the implementation of regional CO_2 sequestration projects.

Experimental Methods

The objective of the Phase II terrestrial field validation test was to develop the technical capacity to systematically identify, develop, and apply alternate land use management practices for greenhouse gas (GHG) reductions in the PPR (Figure 5-1) at both local and regional scales. This Phase II test focused on terrestrial sequestration opportunities in the grasslands and wetland catchments of the region. The goal of this project was to monetize terrestrial carbon credits in these two areas. Project partners also developed and refined the business processes necessary to create terrestrial carbon credits that can be transacted in voluntary or mandatory regional, national, or international carbon markets.

The Phase II terrestrial validation test emphasized work on the following subtasks:

- Compilation of design criteria
- Field site identification and sampling
- Data compilation and analysis
- Identification of land use management practices that increase soil organic carbon (SOC)

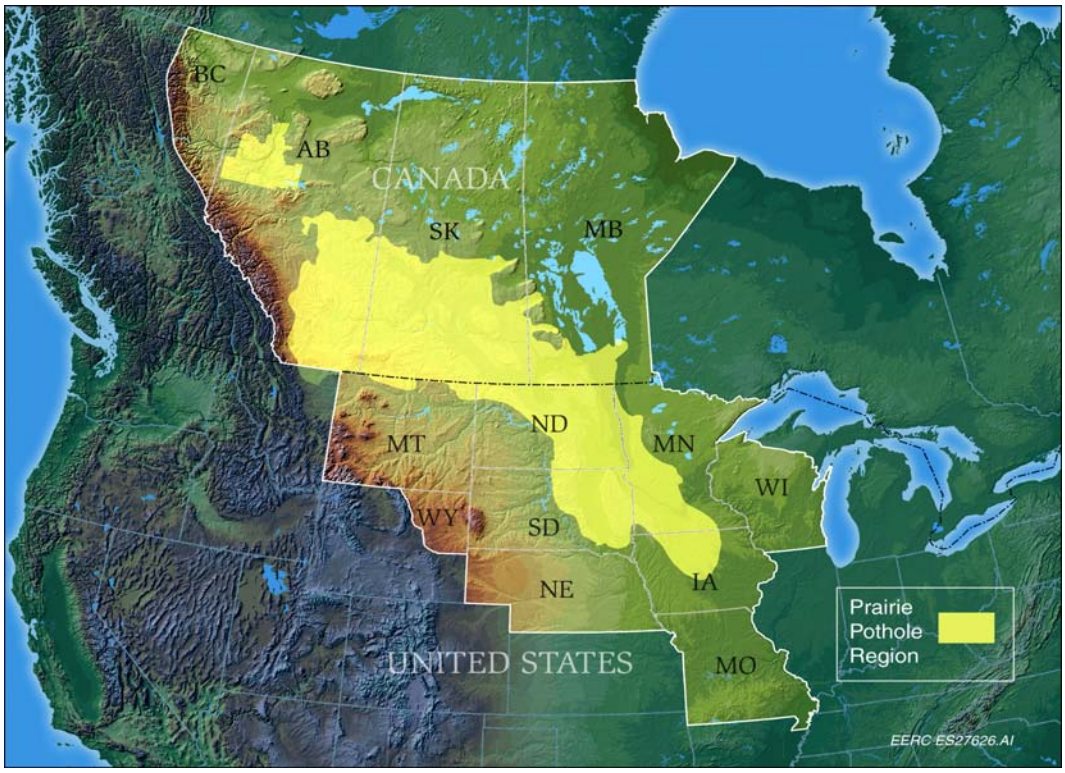

Figure 5-1. The PPR and regional project area for the
Phase II Terrestrial Field Validation Test.

- Development and implementation of a Web-based landowner outreach strategy

- Geographic information system (GIS) modeling for extrapolation of site-specific information to the region

- Business process for carbon credit trading

While the objectives of the Terrestrial Field Validation Test remained the same for the duration of the project, there were adjustments made to some subtasks related to the development of the business processes. This was dictated by the fluctuating carbon market conditions, including development and release of new carbon standards and protocols, the launch of new state and regional GHG programs, and the passage of the American Clean Energy and Security Act by the U.S. House of Representatives in June 2009. The initial validation test focused on grassland restoration while, for many of the aforementioned reasons, avoided grassland conversion became the most operational best management practice under current market conditions.

Compilation of Design Criteria

GIS and empirical data were compiled to determine sample location, distribution and strata within the region. These activities were coordinated with, and supported by, ongoing field research that was being performed by the U.S. Geological Survey Northern Prairie Wildlife Research Center (USGS NPWRC) and Ducks Unlimited Canada (DUC). Each sample location was reviewed with respect to the following:

- Soil type and soil bulk density
- Climatological patterns of the study area
- Native grasslands
- Cropland and tillage practice
- Restored grasslands and wetlands
- Site topography
- Vegetation characteristics and species
- Management prescriptions

Actual sample locations for both grasslands and wetlands were selected in proximity to existing and future monitoring and research stations.

Field Site Identification and Sampling

Both grasslands and wetlands were sampled throughout Montana, North and South Dakota, Minnesota, and Iowa to obtain quality field data for meeting the test objectives. In an effort to realize the true net carbon benefit, samples were collected not only to determine carbon uptake and storage, but also to quantify methane (CH_4) and nitrous oxide (N_2O) gas fluxes. This test also evaluated the effects of specific land management practices (e.g., grazing, haying, restoration) on the global warming potential (GWP) of all major GHGs (i.e., CO_2, CH_4, and

N_2O) simultaneously with carbon sequestration potential in both wetlands and associated upland catchments.

Grasslands

Grassland sampling focused on previously cropped acres that had been restored (reseeded) to tame or native grasses. The U.S. Department of Agriculture's (USDA's) Conservation Reserve Program (CRP) is the most common form of grassland restoration, but other grassland restorations (e.g., federal, state, and private wildlife areas) were also sampled. Since these grasslands were restored over a number of years, they provided time-series data that were useful for measuring carbon sequestration rates as a function of the age of the reseeding. Sample sites were selected based on the criteria of grassland age, soil productivity class, and current land management. Soil sampling took place on 14,250 acres and occurred in the summer/fall of three consecutive years starting in 2006 (Cihacek, 2009a).

Restored grasslands of varying ages (vintages) were sampled to determine the rate of carbon sequestration relative to cropland and undisturbed grassland. A spatial GIS and empirical data were compiled to determine sample location, distribution, and strata. These data included information such as soil type, existing land use, and crop history, to name a few. PCOR Partnership members obtained or developed spatial layers for soils, native grasslands, cropland, wetlands, and other land cover classifications for the subject area of the test (Figure 5-2).

Each sampling point was established at a location that was typical for the soil type, landscape, and vegetation type found in that area. Once the sampling point was established, a handheld probe was advanced to collect five sample cores to a depth of 30 cm (12 inches). The five cores were sampled within a 5-meter radius around the initial point. Sample cores were separated into two samples, one including soil from the surface to a depth of 15 cm and the other including the core segment from 15–30 cm of depth. The same intervals for each of the five samples were composited in separate plastic bags for transport to the laboratory (see Figures 5-3 and 5-4).

In the laboratory, the two composited samples were weighed and subsampled for moisture content to permit a determination of the soil bulk density. The remainder of the sample was air-dried for approximately 4 days, crushed to pass a 2-mm screen, and stored in soil sample bags. Approximately 10–12 grams of thoroughly mixed soil was milled to pass a 100-mesh screen for carbon analysis. Total carbon was determined by high-temperature combustion (~1000°C). Inorganic carbon was determined by the release of CO_2 following acid addition to the sample. Organic carbon was then calculated from the difference between total carbon and inorganic carbon.

Carbon sequestration rates were determined by regression analysis using carbon in the cropland as the beginning state before restoration (0 years) and carbon in the native grassland as the desired end state (Cihacek, 2009b).

Figure 5-2. Dr. Larry Cihacek collecting deep cores with a truck-mounted soil probe.

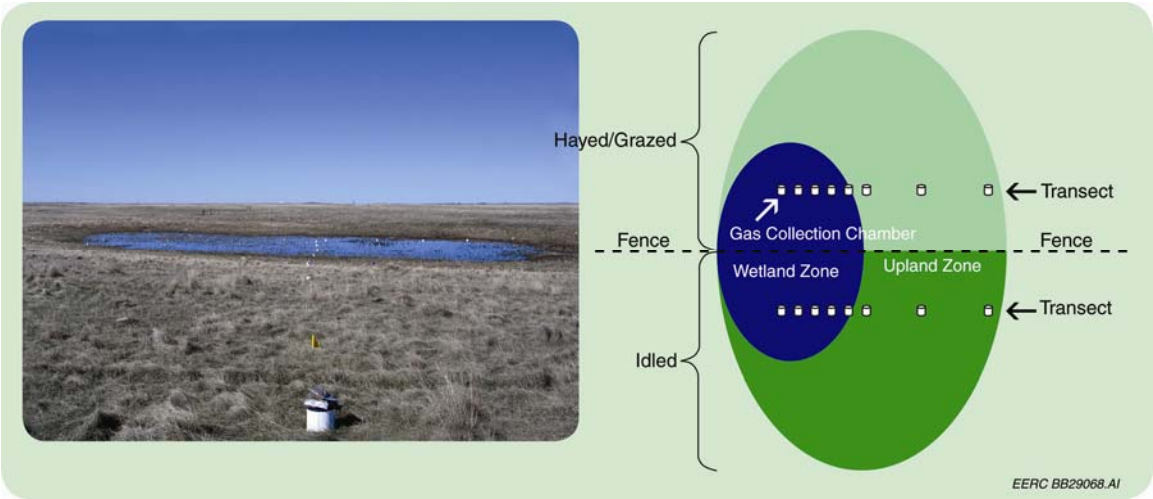

Figure 5-3. Typical sample chamber layout in seasonal wetland.

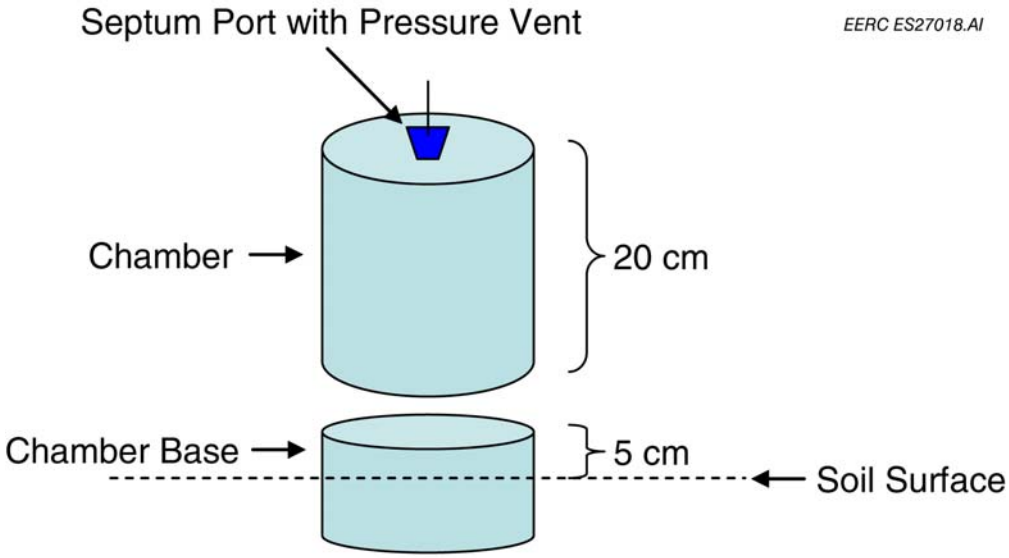

Figure 5-4. Gas flux sample chamber design.

Wetlands

GHG fluxes were monitored in wetland catchments located in north-central South Dakota. Restored, native, and cropland wetlands selected for monitoring were representative of wetland types most commonly targeted for restoration. To reduce background variation among wetland replicates, sites were targeted that exhibit similar water regimes, size, cropping and restoration history, and soil type. Three restored, three native, and three cropland wetlands were monitored. Wetland sites were instrumented to monitor fluxes of GHG emissions (i.e., CO_2, CH_4, N_2O) from the wetlands themselves and surrounding uplands following standard protocols developed by USGS NPWRC (Gleason and Tangen, 2009a).

A reference-based approach was used to compare GHG (N_2O, CH_4, and CO_2) fluxes from restored grassland catchments (three hayed and three nonhayed) to native prairie (three grazed and three nongrazed) and cropland (three nondrained) reference conditions. Wetland catchments, which included wetland and surrounding uplands, were located in north-central South Dakota. Static (non-steady state) chambers (Coolman and Robarge, 1995; Livingston and Hutchinson, 1995) were used to monitor GHGs during the growing seasons (circa March–September) of 2007 and 2008. Data collected included biweekly measurements of GHG fluxes, soil temperature, and soil moisture (%) at eight landscape positions (five wetland and three upland) within each catchment. Additionally, soil samples were collected during 2007 for determination of physical characteristics (e.g., bulk density), SOC, total nitrogen, and nitrate (NO_3). Soil moisture, bulk density, and particle density were used to calculate the fraction of the pore space that was filled with water, i.e., the water-filled pore space (WFPS) (Gleason and Tangen, 2009b).

To complement this effort, microbiologist Dr. Dingyi Ye of the EERC performed laboratory-based and in situ microcosm studies on microbial cycling of CO_2, CH_4, and N_2O in a wetland environment. The objectives of the laboratory microcosm study were 1) to verify and

evaluate the potential of wetland restoration to sequester CO_2, 2) to clarify the effects of the restoration on CH_4 and N_2O emissions, and 3) to examine the effects of wetland restoration on soil microbial community structure and population dynamics, especially those populations involved in the production and consumption of CH_4 and N_2O. The in situ microcosm study was an effort to explore a methodology that may provide accurate estimation and prediction of changes in major GHG budgets by wetland restoration. This task consisted of two on-site column experiments. One to quantitate changes in CO_2, N_2O, and CH_4 fluxes from the investigated wetlands "before" and "after" restoration, while the other examined the in situ effects of N-fertilizers on CO_2, N_2O, and CH_4 emissions from terrestrial ecosystems.

Identification of Land Use Management Practices that Increase SOC

The diversity of landscapes and land uses in the PCOR Partnership region offers many opportunities for terrestrial carbon sequestration. To achieve maximum sequestration results, it is important that best management practices (BMPs) be implemented. Successful management plans require shifting land uses from those with low or negative sequestering capabilities to those with large sequestering and storage capabilities (e.g., grassland protection and restoration, wetland restoration and enhancement, or afforestation). However, a portfolio of more incremental management practices (e.g., conservation tillage) is available that, when aggregated over the hundreds of millions of private hectares in the region, has significant carbon-sequestering potential.

The process of evaluating regional opportunities for carbon sequestration and/or the possibility of prescribing management practices that mitigate emissions of GHG requires an understanding of the economic trade-offs associated with land management and land use alternatives. As part of this task, an economic analysis was performed that focused on the economic competitiveness of land use change associated with wetland restoration on currently farmed cropland by comparing the economic returns from crop production to potential revenues from restoration. The intent was to provide insight into the range of economic returns that must be generated from restoration projects to compete favorably with existing crop production.

Three different restoration configurations were modeled. Each configuration was based on an 80-acre site with varying percentages of site acreage in catchment and wetland areas. A plausible range of per-acre values for components of revenues and restoration expenses was used for each configuration and compared to expected agricultural revenues in 15 separate areas within the PPR of North Dakota, South Dakota, Minnesota, and Iowa.

Development and Implementation of a Web-Based Landowner Outreach Strategy

This task was originally intended to serve as the reference resource and primary communications outlet to inform, engage, and solicit participation in the carbon offset price discovery element of this project. However, it was determined that price discovery was better established by carbon market price signals and economic analysis of alternative land uses rather than by survey. Feasibility was determined by completing a trend analysis on past and current

land use practices and establishing the costs for effecting land use change on privately owned properties through risk analysis and modeling.

GIS Modeling for Extrapolation of Site-Specific Information to the Region

Land values and rental rates vary markedly across the PCOR Partnership region. Thus, from an economic standpoint, carbon sequestration potential must be balanced with the cost of easement acquisition and grassland/wetland restoration expense and the risk of conversion. To evaluate this trade-off, spatial data were obtained and analyzed to develop models to predict the risk of loss of a particular piece of native grassland. The risk of loss modeling was essential to the development of the methodology contained in the Climate, Community, and Biodiversity Standard (CCBS) Avoided Grassland Loss Project (Climate, Community, and Biodiversity Standard, 2008). This modeling is critical to the development of future offset methodologies.

The economic feasibility of increasing and maintaining existing soil carbon at the landscape level was assessed for the avoided conversion of native grasslands. The financial competitiveness of BMPs against existing crop practices was assessed across the U.S. and Canadian portion of the PPR. Variations in commodity prices, farm support payments, and carbon payments were used to model the probability of transition from one land use to another (Rashford, 2009).

Business Process for Carbon Credit Trading

From beginning to end, many implementation steps must occur between carbon market participants to complete a terrestrial offset transaction. The basis of any scalable terrestrial project is active participation by private landowners. As landowners weigh the benefits of enrolling in a carbon program, the returns of doing so will have to compete with other land uses and income opportunities. Aggregators and project developers play an important role as intermediaries between offset buyers and landowners, minimizing the risk of both parties as well as maximizing the benefits of a mutually beneficial carbon program. Among the services that aggregators and project developers provide are risk mitigation solutions that would be too great for landowners or buyers to assume on their own. Finally, and perhaps most importantly, several legal instruments must be prepared to ensure clear ownership of credits and transparency during the sales transaction (Renner et al., 2009). The terrestrial field validation test provided the framework necessary for the development of business process and carbon program methodologies (Botnen, B., et al., 2008).

Results and Discussion

Field Site Identification

The seven monitoring sites were identified for characterization within the PCOR Partnership Region. These sites are located in Montana, Minnesota, Iowa, North Dakota, and South Dakota, as shown in Figure 5-5.

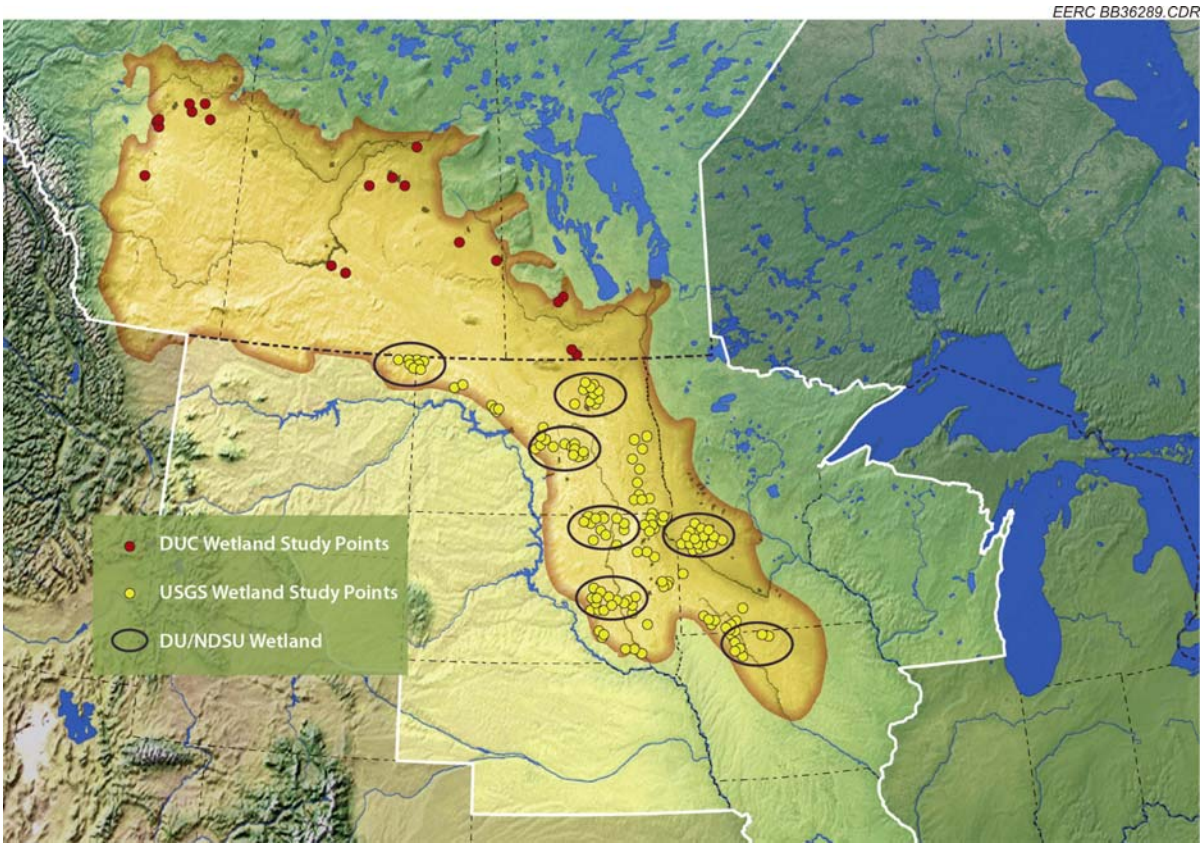

Figure 5-5. Study site locations.

Field Data Compilation and Analysis

Grassland Sampling

A summary of the number of grassland samples collected in each sampling area and the total number of samples are shown in Table 5-1. A total of 2850 samples (1425 0–15-cm samples and 1425 15–30-cm samples) were collected as part of this project. In total, approximately 22.3 square miles of land area was sampled. The estimated annual carbon sequestration rates for each sampling area are shown in Table 5-2 (ranked from highest to lowest rate). The estimated soil carbon sequestration rate across all sampling areas is also shown in Table 5-2.

Soil carbon was highest in the cooler and drier portion of the region, and it tended to be lowest in the warmer and moister part of the region. The western Minnesota site appeared to be near equilibrium, perhaps because of its cool, moist conditions. The estimated sequestration rates appeared to be comparable to recently published rates for restored grasslands of 0.94±0.86 Mg C/ha/year (Liebig et al., 2005). Short-term changes in the local climate may impact the annual rate of carbon sequestration during the growing season. During the sampling process, it was observed that the northern and central South Dakota sampling areas were in the second season of droughtlike conditions. Many of the grasslands were being hayed for livestock forage for the

Table 5-1. A Summary of the Number of Sites and Acres Sampled Within Each Sampling Area

Sampling Area	Sample Number	Acres Sampled
Northeastern Montana	174	1740
Northeastern North Dakota	138	1380
Central North Dakota	208	2080
Northern South Dakota	191	1910
Central South Dakota	257	2570
Western Minnesota	217	2170
Southern Minnesota/Northern Iowa	240	2400
Total	1425	14,250

Table 5-2. A Summary of Estimated Carbon Sequestration Rates by Sampling Area and Across the Combined Sites

Sampling Area	Annual SOC Sequestration Rate
	Mg/ha/30 cm depth[1]
Northeastern Montana	0.45 ± 2.10
Central North Dakota	0.43 ± 1.96
Central South Dakota	0.41 ± 1.52
Northern South Dakota	0.35 ± 1.69
Southern Minnesota/Northern Iowa	0.31 ± 2.10
Northeastern North Dakota	0.23 ± 2.14
Western Minnesota	–0.05 ± 2.10
All Sites Combined	0.23 ± 2.33

[1] The ± the range in values that can be expected.

second year in a row. It is likely that only small amounts of carbon are being sequestered when land is hayed during a dry growing season. Dry weather in these sampling areas is usually accompanied by high daily temperatures. It is conceivable that haying the land removes the shading soil cover provided by the grass, allowing the soil temperatures to increase, thereby stimulating microbial oxidation of soil carbon (Cihacek, 2009a).

Wetland Catchment Gas Flux Sampling

Based on seasonal means, CO_2 fluxes were lower in cropland than restored and native catchments (both upland and wetland zones) during both years. Upland zones were dominated by negative CH_4 fluxes, with native sites exhibiting greater seasonal average uptake rates, expressed as g CH_4-C ha^{-1} day^{-1}, during 2007 and 2008 (–9.23, –7.75, respectively) than restored (–0.38, –1.64) and cropland (–1.04, –3.14). Within wetland zones during 2008, CH_4 flux also was lower in native sites (–5.89) than restored (39.99) and cropland (61.22). Nitrous oxide fluxes, expressed as g N_2O-N ha^{-1} day^{-1}, during 2008 from upland and wetland zones were highest in cropland (2.30, 8.86, respectively) sites, followed in descending order by restored (1.42, 5.96) and native sites (1.03, 2.04). During 2007, mean seasonal fluxes of N_2O in upland and wetland zones, and CH_4 from wetland zones, did not significantly vary by land use.

No consistent trends emerged when comparing mean seasonal flux of GHGs between native grazed and nongrazed catchments and between restored hayed and nonhayed sites. Regardless of land use, CO_2 contributed the most to overall GWP in uplands and wetlands. However, since measurements were performed using opaque chambers, CO_2 fluxes did not include photosynthesis, and fluxes represent only respiration of plants and soil biota (i.e., community respiration) rather than net ecosystem exchange of carbon. Excluding the contribution of CO_2 and considering only the GWP contribution of N_2O and CH_4, N_2O contributed the most to GWP in the uplands for both years; the GWP of CH_4 was negative for uplands. In contrast, within the wetland zones, CH_4 contributed the most to overall GWP during 2007, whereas during the drier 2008 season, N_2O was the dominant contributor to GWP (Gleason and Tangen, 2009b).

Overall, restored catchments exhibited N_2O and CH_4 fluxes that were statistically similar to or lower than those observed in cropland sites. Both CH_4 and N_2O fluxes showed a positive relation with WFPS ($r^2 = 0.54$, 0.36, respectively), with native catchments exhibiting the lowest average WFPS during the study. Nitrous oxide flux also showed a positive relation ($r^2 = 0.38$) with soil NO_3 concentration, which was highest in croplands, followed in decreasing order by restored and native catchments. Consequently, higher CH_4 and N_2O fluxes in cropland and restored sites relative to native sites, were associated with differences in WFPS and NO_3 soil concentration. Vegetation on restored sites was reestablished recently (2005–2006), and these catchments tended to exhibit NO_3 concentrations and soil moisture conditions intermediate to that observed in native and cropland catchments; the residual effects of agriculture on soil NO_3 concentration should decrease over time (Gleason and Tangen, 2009a).

The results of the laboratory-based and in situ microcosm studies on microbial cycling of CO_2, CH_4, and N_2O in a wetland environment showed that by restoring currently farmed wetlands, thereby cutting off N-fertilizer inputs, the following can be achieved: 1) a reduction of CO_2 flux and increased storage and 2) reduction of emissions. Additionally, restoration activities do not promote a dramatic increase in population sizes of the microorganisms that produce N_2O and CH_4. These results demonstrate that wetland restoration will significantly reduce the overall GWP budget (Ye et al., 2009).

Identify Land Use Management Practices that Increase SOC

Two fact sheets were developed during Phase II as part of this task. These fact sheets summarized the regional potential for sequestering CO_2 through habitat restoration as well as the best practices for terrestrial carbon sequestration in the PPR:

- "CO_2 Sequestration Through Habitat Restoration – Defining Best Terrestrial Sequestration Practices for Landowners"

- "Best Management Practices for Terrestrial Carbon Sequestration on Private Lands in the Prairie Pothole Region"

Other benefits that result from agricultural land restoration, such as water quality, erosion control, flood buffering, and recreational and wildlife benefits, were also determined as part of

this effort and were summarized in a Fact Sheet entitled "Cobenefits of Terrestrial Carbon Sequestration in the PCOR Partnership Region."

Overall, the economics of terrestrial sequestration projects generally improved with decreases in land productivity, increases in carbon prices, reductions in restoration costs, and increases in revenues from grassland rents. However, even under the most positive scenarios for wetland restoration, only a few situations resulted in the net present value (NPV) of wetland revenues exceeding agricultural revenues when easement payments were excluded.

Given the current understanding of the economic trade-offs, wetland restoration on farmed cropland does not appear to be a land use change that is cost-competitive with other terrestrial GHG abatement options. Even at the highest carbon price evaluated ($125/MT), few situations result in wetland restoration revenues exceeding future crop returns. These results are in contrast to results from other studies that suggest afforestation and conversion of cropland to perennial grasses become competitive at those carbon prices. It would appear the best way to classify carbon sequestration from wetland restoration is that the value of sequestered carbon represents a cobenefit to the restoration project (Bangsund and Leistritz, 2009).

Developing and Implementing a Web-Based Landowner Outreach Strategy

Printed and electronic communications were developed and used to stimulate landowner interest in adopting land use management practices for carbon offsets. The Web site outreach component of this task provided information to landowners on the options for sequestration, the carbon sequestration potential of each practice, and BMPs for retaining sequestered carbon. The site also provided information for investors seeking to purchase aggregated volumes of carbon offsets. A mapping tool was also developed for tracking property and land cover types under option contracts for carbon GHG rights pending aggregation and future sales (Ducks Unlimited, 2009).

GIS Modeling to Extrapolate Site-Specific Information to the Region

Landowners in the PPR are increasingly aware of possible income opportunities from terrestrial carbon sequestration projects. However, the success of any terrestrial carbon program will depend on the willingness of private landowners to adopt land uses and management practices that sequester carbon or reduce GHG emissions and the economic returns of these practices relative to alternative land uses, namely crop agricultural production. In economic theory, landowners are assumed to convert land to the use that maximizes the present discounted value of an infinite stream of net return less conversion costs. Assuming that landowners base their expectations of future net returns on current or historical returns, the landowner's decision rule is to choose the use with the highest expected one-period net return.

This project has focused on wetland ecosystems, riparian areas, and associated grasslands to evaluate terrestrial carbon sequestration opportunities in the northern Great Plains. Wetland and grassland ecosystems are inherently heterogeneous, meaning that land management and land use decisions are dependent upon the influences of site-specific attributes. Recently, participation in government programs, such as the CRP and Wetland Reserve Program and other programs has

resulted in the conversion of marginal croplands to perennial grasses. However, the enthusiasm for participation in long-term cropland retirement has diminished as economic returns from those programs have not kept pace with economic returns from traditional crop production. To spatially identify land classes, land uses, and the necessary financial incentives to spur adoption, a spatial econometric model of land use change in the PPR was developed as part of Phase II PCOR activities. Results will be used to identify land use conversion rates for the Avoided Grassland Conversion project and in the targeting of program activities.

Future economic returns, usually represented by an annual value, can be discounted and summed to produce net present values. A net present value approach provides considerable flexibility to place different revenue streams into a common metric for direct comparison.

While the net present value approach allows for comparison of nonuniform economic returns over time among various activities, it is problematic for policy makers to expect wholesale land use changes based on potentially small differences in net present values. There are likely to be a range of economic returns over which landowners will be indifferent to alternative activities. The extent that future economic returns need to exceed current returns for an alternative action to be acceptable is difficult to predict, and subject to individual landowner and producer preferences, behavior, and perceptions. Regardless of those caveats, comparisons of net present value of various alternatives (e.g., retaining current land use versus implementing grassland and/or wetland restoration) provide a valuable benchmark to begin evaluating the economic viability of terrestrial carbon sequestration activities.

The PPR of the United States was divided into 16 subregions. Those subregions were created to represent areas with similar overall crop rotations, soil productivity, and production characteristics. Crop rotations in each subregion were estimated based on crop acreage from 2006 through 2008. Seven years of revenues and expenses were compiled for the predominate crops in eight regions of North Dakota and Minnesota. Because of data limitations, a 3-year average of returns was developed for crop-producing regions in South Dakota and Iowa. In North Dakota and Minnesota, an Olympic average of crop returns was generated. The Olympic average for crop returns was then combined with crop rotation percentages to generate composite acre values. Average composite acre returns were then differentiated into three levels of producer profitability. The three levels of producer profitability represent the starting points for examining the economics of alternative wetland management. The premise is that widespread changes in land management and land use will require economic returns to be roughly equivalent to or exceed those of existing activities.

Revenues are likely to be a function of net gain in carbon sequestration rates (i.e., those greater than what might exist with current land use and management), anticipated carbon prices, payments for ecosystem services, hunting leases, easement payments, grazing and/or forage revenues. Costs could include grass establishment, tree plantings, weed control, haying and forage collection expenses, and expenses related to changes in water conveyance (e.g., plugging tiles, altering ditches). Assuming a standard set of parameters (e.g., regional values for sequestration, carbon price sets, forage values) for the proposed activity, net present value of the two alternatives can be compared. Changes in some parameters allow various “what if” questions to be examined. As an example, if the net benefits from the wetland restoration are substantially

below current economic returns, the activity(s) are not likely to be implemented. If the difference is slight, perhaps changes in project design or enhancement might provide sufficient economic return to entice greater landowner participation. In other cases, projects may not be attractive to landowners until carbon prices exceed a certain threshold. Additionally, some activities in some regions may not be economically feasible over any reasonable range of carbon prices or forage values. The key variable in the analysis is the economic benchmark for existing land use, which provides the necessary starting point to examine the likelihood of widespread landowner participation in a host of wetland and grassland restoration projects.

Previous studies have found that carbon prices will have to reach $10/ton C ($2.73/MTCO2e) for conservation tillage and $25/ton C ($6.83/MTCO2e) for afforestation to become economically attractive to landowners in the Great Plains region (Lewandarski et al., 2004). As carbon prices rise, terrestrial sequestration practices will face competition among each other, with afforestation providing the greatest per acre carbon benefit and highest potential return at higher carbon prices.

Recently, interest in corn-based ethanol as a fuel alternative has put strong upward pressure on agricultural land prices, expanding corn production into historically unprofitable areas. However, not all agricultural activities preclude long-term terrestrial sequestration. In much of the PCOR Partnership area, grass-based economies dominate the landscape with activities such as haying and grazing to support livestock production. Research has shown that haying and grazing activities can continue without detrimentally impacting soil carbon sequestration rates or storage (Liebig et al., 2005).

The model developed by Dr. Ben Rashford at the University of Wyoming allows for predictive land use changes given changing land use returns in response to rising crop returns or carbon incentives, providing for prescriptive analysis of land use change (Figure 5-6). Results have found the probability of grassland conversion highest in areas of higher soil quality and, therefore, a higher opportunity cost of remaining in grassland. Probability conversion risk displays a high degree of spatial variability, but with higher probabilities generally found in the Minnesota and Iowa portions of the PPR. In absolute acres converted per county, the number of acres initially in a grassland use can lead to large conversions, even for relatively low conversion probabilities.

Business Process for Carbon Credit Trading

The validation test results supported the development of protocols for terrestrial carbon credit development and trading, which are intended to serve as a model to promote and implement terrestrial sequestration across the PPR. These protocols were the basis for a partnership between Ducks Unlimited, Inc. (DU), and a joint venture of private equity groups and offset brokers. Through this DU Carbon Credit Program, the monetization of carbon credits for grasslands was realized. This program provided landowners with a revenue stream novel to the agricultural economy of the plains, i.e., sequestered carbon. Through this program, landowners sign perpetual grassland easements while, at the same time, they are conveying carbon rights to be bundled and sold on the open market. In addition to providing the basic science, the results from this test have provided the business process framework that is needed

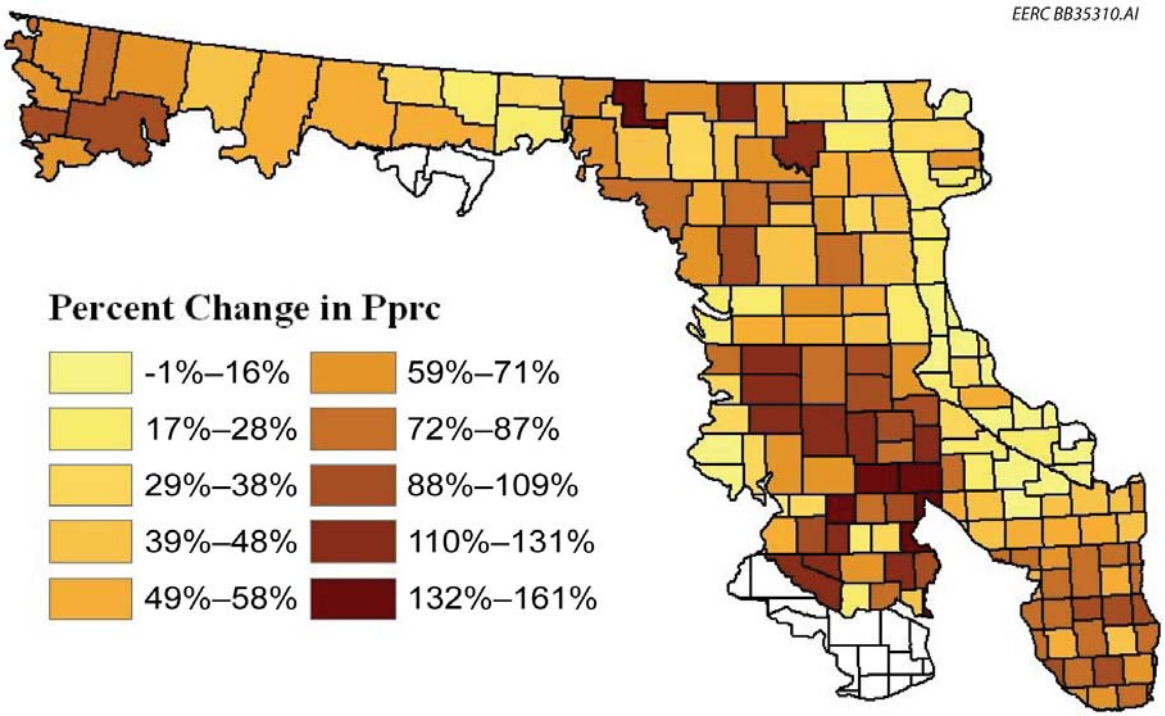

Figure 5-6. Predicted percent change in the probability of transitioning from pasture/rangeland to cultivated crops between 2006 and 2011.

for project developers and investors to advance emission reduction targets as well as achievefinancial returns in this rapidly emerging market. While credits for wetlands have not yet been realized, it is anticipated that the results of this project will contribute to the development of methodologies that can be used for this purpose in the near future.

An overview of the business processes required for developing and transacting carbon offsets in the PCOR Partnership region is provided in Figure 5-7. These processes are detailed in the PCOR Partnership topical report, "Market Development for Terrestrial Sequestration on Private Lands" (Botnen, B. et al., 2009a) and in the PCOR Partnership plan, "Terrestrial Field Validation Test Regional Technology Implementation Plan" (Botnen, B. et al., 2009b). Many carbon market stakeholders are involved in bringing terrestrial offsets to end users, including those involved in financing, producing, generating, providing, aggregating, and/or marketing GHG emission reductions. The terrestrial field validation test results also supported the accreditation of an a avoided grassland conversion project based on the CCBS (Climate, Community, and Biodiversity Standard, 2008). This validation test was the first to be certified by the standard in the United States and is the first avoided grassland conversion project in the world.

Recommendations and Conclusions

The results of this validation test indicate that there is great potential for carbon sequestration in grassland and wetland catchments located throughout the PCOR Partnership

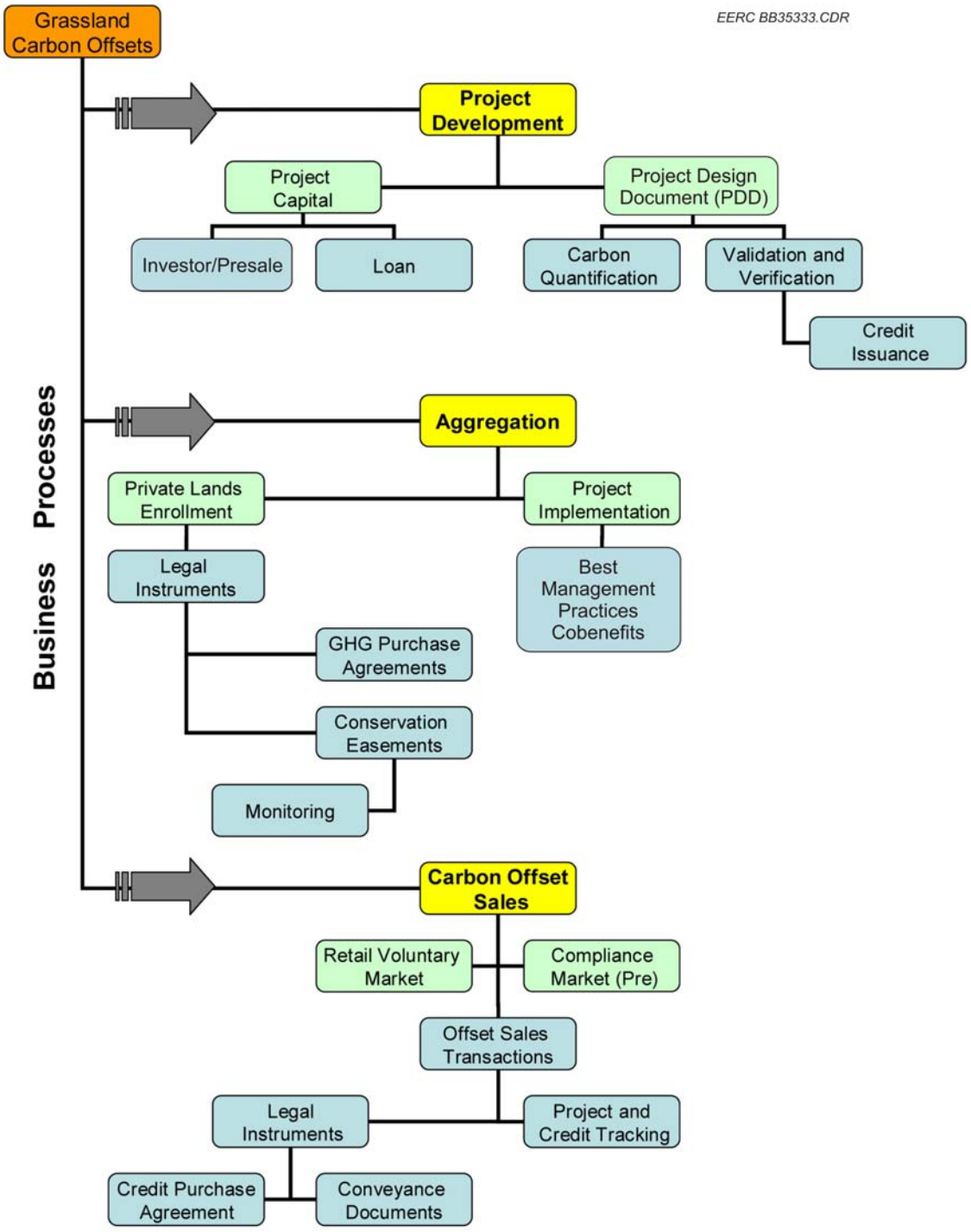

Figure 5-7. Flowchart depicting the business processes to follow for implementing terrestrial carbon sequestration projects.

region. The sequestration rates in the various vintages of grasslands that were sampled were all comparable to recently published rates and it was concluded that GHG emissions from wetland catchments would not offset potential soil carbon sequestration benefits associated with restored wetlands. On the basis of information developed in this test, approximately 130,000 tons of native grassland carbon offsets was generated in the PCOR Partnership region and sold in September 2008; negotiations are currently under way to transact an additional 600,000 tons. The legal instruments and database tools developed during this validation test were used to ensure a smooth transaction, transparency, and efficient reporting (Botnen, B., et al., 2008).

Terrestrial sequestration in the PCOR Partnership region has many opportunities to benefit from carbon market finance with the development of federal climate legislation that includes a robust offset program. Results from this validation test will continue to be instrumental in the future development of methodologies and protocols to further advance terrestrial offsets in regulated and voluntary carbon markets. However, there are still challenges that should be addressed as these markets evolve, including refining the science and economic valuation of ecosystem services. Studies should be conducted to assign carbon sequestration values and metrics to terrestrial ecosystems, which will be an integral part of the rule-making process for offsets under federal climate legislation. These rules ultimately affect the financial viability and competitiveness of all biological offset projects. Other implementation issues that should be addressed include uncertainties about tax implications for carbon revenue mechanisms, the assignment of risk and the release of liabilities among parties, and the role of public incentive programs in climate mitigation and carbon sequestration. These studies are necessary to assist the voluntary carbon market to find a successful trade-off between transparent and verifiable carbon quantification and cost-effectiveness. Currently, compliance with more stringent voluntary carbon offset standards appears to be extremely cost-prohibitive to the average offset buyer, and general market uncertainty in the initial stages of market development has further hampered project development.

Additional standards and protocol development are also needed to gain full traction in future voluntary and/or regulatory markets. This development will rely heavily on carbon model development. The greatest impediment to advanced carbon sequestration model development is the lack of monitoring and the understanding of terrestrial carbon cycling in various ecosystems. Because of the amount of research on forest–carbon dynamics, forestry offsets are the most commonly recognized terrestrial offset. If the carbon values of other ecosystems are to be fully recognized, greater amounts of research into the carbon cycles within each of these will need to be conducted. In summary, future research efforts should focus on:

- The development of improved MVA systems, methods, and protocols. This will include the refinement of direct measurement technologies for critical GHGs and address leakage concerns.

- An analysis of the impacts of bioenergy production and markets on terrestrial carbon sequestration.

- The development of process-based biogeochemical models that can be used to forecast the influence of climate and land use change scenarios on GWP and associated

ecosystem services (e.g., wildlife habitat, water quality, soil erosion, floodwater storage).

- An extensive analysis and comparison of GHG flux and carbon uptake and storage between native grasslands and agricultural lands. This may lead to certifiable CH_4 and N_2O credits.

- An expansion of existing grazing and haying studies to broaden the understanding of their respective impacts on carbon uptake and storage.

- The continuation of sampling at current sites to establish long-term trends in carbon storage and GHG flux. This will allow us to refine current BMPs for sequestering CO_2 in prairie wetlands and grasslands and will lead to the development of more robust models.

- The development of carbon market policies and protocols that improve the recognition and marketability of prairie grassland carbon credits in the voluntary and future regulated markets in the United States.

6. 0 OTHER PROGRAMMATIC ACTIVITIES

6.1 Characterization of Regional Sequestration Opportunities

A necessary step toward the deployment of CCS in the PCOR Partnership region is the development of an understanding of the magnitude, distribution, and variability of the region's major stationary CO_2 sources and potential sequestration targets. This task focused on developing that understanding using the regional characterization efforts of the Phase II project activities. Key steps in these efforts included the following:

- The identification of major data elements required to assess the region's CO_2 production, geologic and terrestrial sequestration capacity, existing transportation systems, infrastructure, and regulatory framework.

- The collection of information from multiple sources, including agencies governing oil and gas exploration, regulatory agencies, industrial partners, and publicly available databases.

- Analyzing, reviewing, and assembling the data into a usable format.

- Establishing formal arrangements with the Iowa Geological Survey in order to leverage local expertise with regard to subsurface geology.

- Dissemination of the data to DOE and its partners through the PCOR Partnership DSS, a database-driven Web site containing both traditional Web pages and an interactive GIS.

The data/information that were collected during Phase II of the project were used to update and expand similar data/information that had been collected during Phase I.

The PCOR Partnership DSS

Data gathered through the regional characterization effort, as well as other information generated by the Phase II field validation tests, were compiled and disseminated to the PCOR Partnership partners through the project DSS. This password-protected Web-based platform contains tools and capabilities that are designed to deliver functional and dynamic access to the data. Much of the data are housed in a relational database and accessed through the map-based portion of the Web site. Conventional Web pages provide access to relatively static data, such as links to reports, CO_2-related Web sites, terrestrial maps, and snapshots of regional data.

A Web-based GIS interface is also part of the DSS. This interface provides several analysis methods, allowing partners and research teams to browse, query, analyze, and download data regarding CO_2 generation and sequestration in the PCOR Partnership region. For example, the GIS application can be used to:

- Examine attributes of individual features or groups of features and their spatial relationships to other features.

- Query the underlying data to analyze the region and export selected data for manipulation in other software.

- Explore the nature of the data through thematic maps.

The original DSS site was launched in 2004 and went through some changes over the following few years. However, growth and exposure of the PCOR Partnership made it obvious that the site was somewhat dated and inefficient in disseminating the large volume of information that was being generated by the PCOR Partnership. Therefore, as part of the Phase II activities, the non-GIS portion of the DSS site was redesigned to achieve the following objectives:

- Increase site traffic
- Improve site functionality through consistent navigation
- Expand access to timely information
- Provide a more uniform and modern appearance

A redesign team was assembled to create the new DSS site. This team consisted of the project manager for regional characterization, an EERC marketing research specialist, several database and Web site programmers, and an EERC graphic designer. The redesign of the DSS site was initiated in September of 2008 and was conducted in five phases.

Phase 1 – Evaluation of the Original DSS Site

To assess the use of the original DSS site, Web-tracking software was used to determine the extent to which the original DSS site was being used by DOE and PCOR Partnership partners (EERC users were not considered in the evaluation). Based on these findings, the redesign team determined what content was no longer valuable to members and what content was most important. On this basis, some of the content from the original site was updated and transferred to the new site.

Phase 2 – Development of a New DSS Site Prototype

To accommodate the new content and enhancements to the site, a completely new site framework was required. The redesign team reviewed other award-winning Web sites and took various components from other sites to create a unique prototype for the new DSS site. The new design (Figure 6-1) contains the following major categories in a left-hand navigation pane that would expand when selected to offer more options:

- Interactive Maps
- Learn about Carbon Management
- Field Validation Tests
- Demonstration Projects
- Regulations
- Carbon Markets
- Products Database

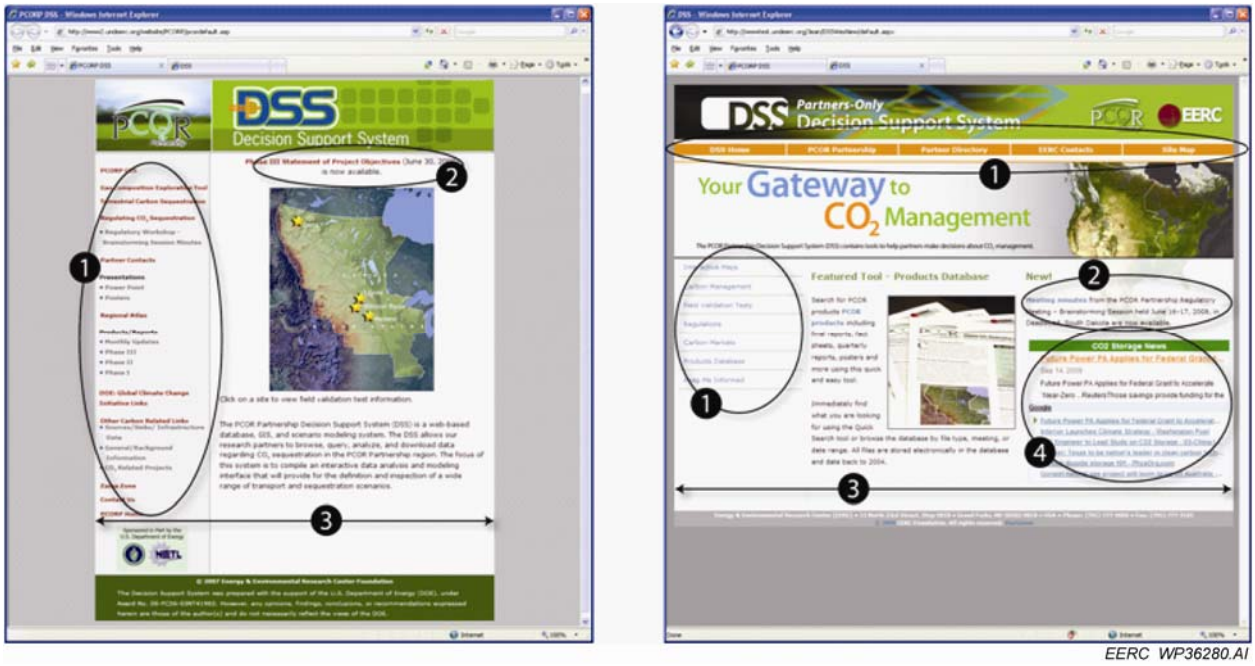

Figure 6-1. Screen captures comparing the original and new DSS home pages.

In addition to the flexible left-hand navigation pane, a top navigation bar provides quick and easy access to key pages, including the following:

- DSS Home
- About PCOR Partnership
- EERC Contacts
- Partner Directory
- Site Map

The content for the site was created through collaboration between EERC education and outreach professionals and PCOR Partnership technical researchers.

Phase 3 – Internal Review of the DSS Prototype

The working prototype of the new DSS site was distributed for review by PCOR Partnership technical researchers and management team. Reviewers were asked to consider the usability, look and, most importantly, content of the site.

Phase 4 – Revision of Prototype Based on Internal Review

The only major revision to the original prototype was the addition of a new section called "Keep Me Informed." The purpose of this section is to display timely information, such as meeting notices, announcement of completed reports, and industry news. Although this information could be stored elsewhere on the site (e.g., Products Database), there needed to be a page to draw attention to all new and time-sensitive information.

Phase 5 – Launched and Maintained Site

The new site was put online at the end of September 2009. A DSS Site Manager has been dedicated to maintaining the site and will obtain new site content through the following mechanisms:

- Review of monthly, quarterly progress, and topical reports
- Participation in PCOR Partnership meetings
- Conduct of periodic status update meetings with the management team and task leaders
- Conduct of annual formal review meetings with the management team and task leaders

The PCOR Partnership Atlas

The PCOR Partnership regional atlas, which was initially created and published during Phase I of the project, was revised twice during the Phase II project period (Figure 6-2). With each revision, the atlas became a stronger document for the dissemination of the underlying CCS

Figure 6-2. Cover of the PCOR Partnership Atlas 2nd Edition, revised.

concepts as well as the steps that the PCOR Partnership was taking to address the CCS issues in the region.

The atlas discusses the concept of global warming, the nature of CO_2, the DOE RCSPs, and the concepts of CCS before providing a geographic-based CO_2 source and sink profile of the PCOR Partnership region. The document also provides brief descriptions of the practical approaches the project is taking to address CO_2 storage options in the region.

Over 1800 copies of the 54-page atlas were printed and distributed to educators, businesses, and policy makers during Phase II of the project. In addition to the printed copies, the atlas was also made available as a pdf document through the PCOR Partnership public and members-only Web sites.

Regional/Local Sink Assessments

In Phase I of the project, broad scale geologic sequestration assessments were conducted on various saline formations, oil fields, and lignite seams in the PCOR Partnership region. As part of Phase II, this assessment work continued, but focused on smaller geographical areas.

These smaller areas showcase the application of more sophisticated geologic models by integrating detailed localized data. One of the regional assessments focused on a series of stacked saline formation horizons in the Williston Basin. A separate assessment looked at EOR potential at an oil field level, also in the Williston Basin.

Washburn Study Area

In many sedimentary basins, there may be more than one potential subsurface target horizon for CO_2 storage, each with an appropriate seal to ensure safe, long-term storage. A great example of stacked target horizons can be found in the North Dakota portion of the Williston Basin (Figure 6-3).

The area of investigation encompasses 6100 square miles in west-central North Dakota, which is underlain by over 9800 ft of sedimentary rock. It was selected because of its proximity to seven large coal-fired industrial sources of CO_2. By using publicly available well file information, a map-based approach was used to develop reconnaissance-level petrophysical

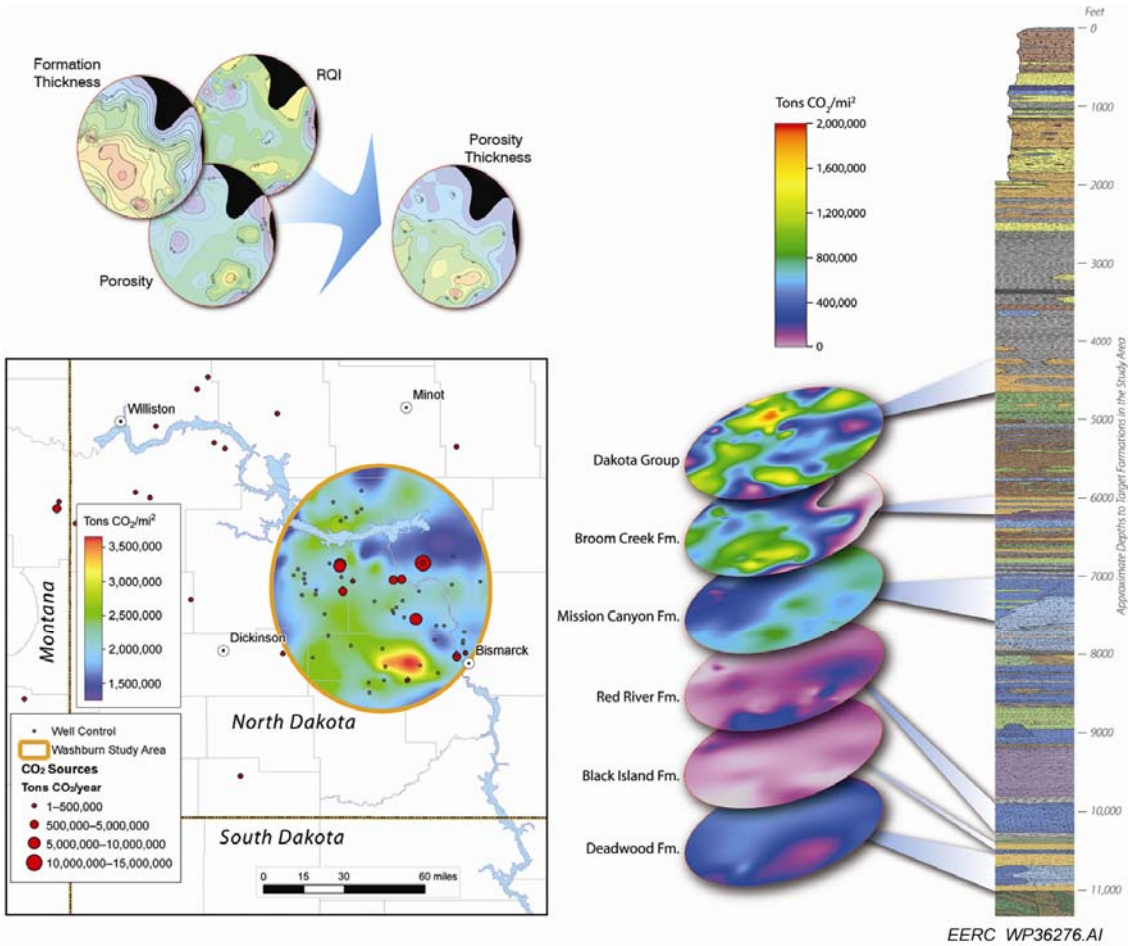

Figure 6-3. Depiction of potential storage capacity for stacked brine formations in west central North Dakota.

model of a sequence of stacked brine-saturated formations. The methodology employed used digital well logs from over 50 wells to identify zones of porosity in the stacked sequence of rock and then created maps depicting the areal distribution of the thickness and porosity values of these rock formations.

A reservoir quality index (RQI) was calculated for each target horizon based on the thickness of each formation and a designated criteria. Specifically, the RQI is the thickness of an interval that meets a specified cutoff criteria for volume of shale (Vsh) and/or porosity (φ), divided by total interval thickness (H). For example, base-case RQI = thickness >0.06 φ/total interval thickness. An RQI value allows the modeler to account for poor-quality rock that, because of high clay content and/or low porosity, has low permeability and would not contribute to CO_2 storage capacity. The resulting petrophysical models provided the basis for estimating CO_2 storage capacity of 11 potential target injection intervals in seven different formations within four distinct regional aquifer systems as classified by the USGS Groundwater Atlas. The total CO_2 storage capacity in these brine-saturated formations in this area of the Williston Basin was estimated to be about 13 billion tons.

Rival Field

In Phase I, the potential CO_2 storage capacity of numerous oil fields was calculated based on some primary, publically available data. The calculation of more exact storage capacities for a reservoir requires a systematic analysis, including detailed geologic characterization, production history, and modeling efforts. This type of activity was conducted on the Rival acid gas field in north-central North Dakota as part of the Phase II activities. These Phase II calculations suggest that nearly 10 million barrels of incremental oil could be produced from this field while simultaneously storing nearly 5 million tons of CO_2 from a nearby gas-processing plant.

Iowa

In an effort to expand coverage of the PCOR Partnership region at the state and/or province level, a subcontract was established with the Iowa Geological and Water Survey (IGWS) to obtain local expertise and to secure base-level geological characterization of the state.

This reconnaissance level investigation was based on existing information and local staff expertise and focused on the following:

- Paleozoic sandstone and carbonate strata, which are unused mineralized aquifers in the southwestern part of the state.
- Precambrian-age clastic rocks associated with the Mid-Continent Rift.
- Pennsylvanian strata and associated coals located in the southern part of the state.

A particular challenge in characterizing Iowa's sequestration potential, particularly with quantitative estimates, is the relative lack of deep wells, core tests, geophysical logs, surface geophysics, and other data commonly generated in areas with oil, gas, or CBM resources,

particularly those which supply data on unit porosity and permeability. While a limited amount of oil and gas exploration has occurred in Iowa, the data density and detail are far less than are available in areas of significant hydrocarbon production. Existing geologic data, modeling, and extrapolation of available data allowed for characterization of the geometry of the target units and the preparation of preliminary estimates of their sequestration potential. These initial sequestration estimates can be improved as future data on porosity and permeability are generated.

Iowa Saline Formations

Carbon sequestration within saline aquifers is considered a possibility for several Paleozoic aquifer systems in the Forest City Basin. Five aquifer systems were examined, with the Cambro-Ordovician and Mt. Simon Aquifers representing the best targets for further investigation. These two aquifers both contain intervals of high porosity (>20%–25%) and high permeabilities (>500–1000 millidarcies), and both are bounded by effective confining beds. Because these two aquifers are in the deeper part of the stratigraphic section, they also have the widest geographic distribution at appropriate depths.

Although there are sufficient data available to provide basic information on the porosities and matrix permeabilities of each of these five major individual aquifers, as well as the 3-D distribution and stratigraphic container for each of them, existing data suggest that dissolved solids concentrations are below 10,000 mg/L across most of the aquifer volume. These low-TDS values put these aquifer systems in the protected classification and would require an exemption from the U.S. Environmental Protection Agency (EPA) to be used as a target for CO_2 storage.

Iowa Coal

Virtually the entire 24-county study area of southwestern Iowa (Figure 6-4) is underlain by coal-bearing Pennsylvanian strata at relatively shallow depths. The burial depth of Pennsylvanian coal-bearing strata varies between 0 and about 1900 feet, with most at depths less than 1000 feet. Most of the coal seams range in thickness from a few inches to 1 to 2 feet. In rare cases, coals of 4 to 5 feet in thickness were identified. The potential for CBM and carbon sequestration within this coal-bearing strata have not yet been adequately evaluated, but because the area contains significant cumulative thicknesses of coal, further study is warranted.

The Midcontinent Rift System (MRS) in Iowa

The MRS of North America is a failed rift that formed in response to regionwide stresses associated with the Grenville Orogeny about 1100 million years ago. The MRS in Iowa is buried by thick sequences of Paleozoic and Mesozoic sedimentary rocks and Quaternary glaciogenic deposits, ranging in thickness from about 1700 feet near the Minnesota border to in excess of 5000 feet in southwest Iowa. The Midcontinent Rift System (MRS) in Iowa

The MRS is of interest as a possible repository for stored CO_2 because of its exceedingly thick sequences of clastic sedimentary rocks (sandstones, siltstones, and shales) and depth of

Figure 6-4. 24-county study area of southwestern Iowa.

burial. MRS clastic rocks underlie over 16,000 square miles of Iowa (about 28% of the state), with the vast majority of these rocks lying below the 2700-foot optimal sequestration depth.

Many of the rock sequences encountered in the extremely limited number of penetrations of MRS clastic rocks in Iowa would fit the requirements as potential cap rock, but no units with sufficient porosity or permeability for CO_2 sequestration have yet been encountered. However, it is important to note that all of the information about the geotechnical characteristics of the MRS clastic rocks in Iowa came from only four wells, one deep penetration and three closely spaced, very shallow penetrations, of a sequence of rocks that cover 16,000 square miles of Iowa.

NATional CARBon (NATCARB) Sequestration Database and GIS Support

Through the course of characterizing CO_2 sources and potential storage opportunities in the PCOR Partnership region, a large quantity of data have been compiled. One of the core responsibilities of the project is to support the national carbon infrastructure of NATCARB, the national online atlas, and the development of DOE's National Carbon Atlas. NATCARB serves as a centralized point of data exchange for information generated and compiled by the RCSP entities. The PCOR Partnership provided support for these efforts by preparing maps and data for the analog atlas and by processing, storing, and presenting digital data for the Web-based atlas.

Regional CO_2 Sources

A discussion of the approach and results associated with the development and analysis of large stationary CO_2 sources (Figure 6-5) in the PCOR Partnership region can be found in the

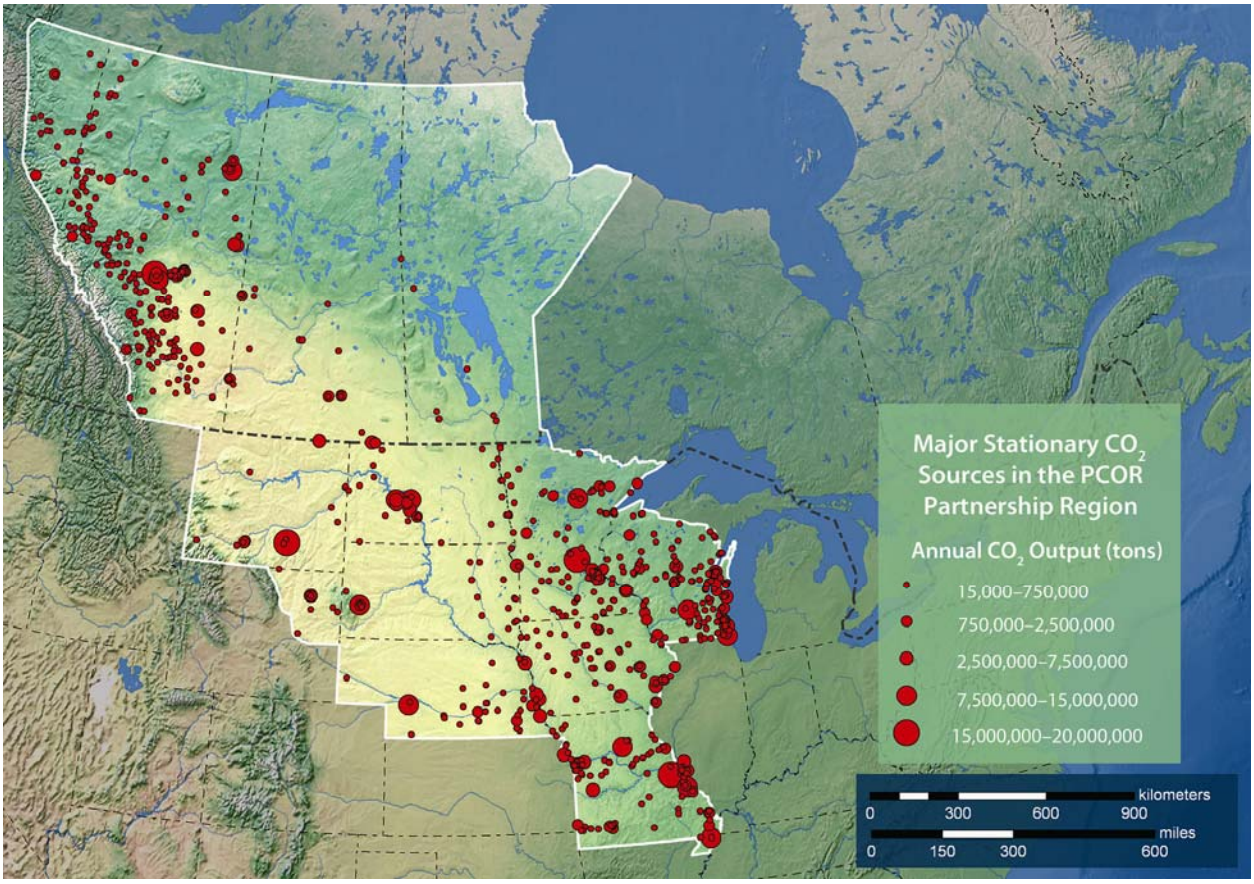

Figure 6-5. Map showing the stationary sources of CO_2.

discussion of the Phase II activities entitled "Identification of the Commercially Available Sequestration Technologies Ready for Large-Scale Deployment."

Recommendations and Conclusions

Regional characterization activities will continue to play an important role in the PCOR Partnership Program. The wealth of data developed or obtained through the first two phases of the program are providing the PCOR Partnership with the information necessary for defining and assessing regional sequestration opportunities. The data are compiled, stored, and managed in the DSS as a means to deliver knowledge of the character and spatial relationship of sources, sinks, and infrastructure to the PCOR Partnership members. Partners who utilize the DSS also provide the PCOR Partnership with valuable input regarding key data elements and sources of information for further characterization. This effort was showcased in the formal working agreements that were established with the Iowa Geological Survey in Phase II and are in place with the Missouri Department of Natural Resources for the Phase III efforts of the project. Future regional characterization efforts will strive to expand the areas of broad geologic review while also integrating more subregional investigations that will carry higher levels of confidence.

6.2 Research Safety, Regulatory, and Permitting Issues

The objective of this task was to identify and track new and existing regulations as they relate to CCS deployment within each of the PCOR Partnership states and provinces. Additionally, outcomes of this task were designed to be incorporated into the goals and objectives of other Phase II activities as part of the regulatory permitting action plans that were generated for each field validation test.

The identification and tracking of the federal, state, and provincial regulatory developments were accomplished using a variety of techniques and relying on a variety of sources. For example, the regulatory action plans that were developed for each validation test included an in-depth review of the state/province regulations that were applicable to the project. Additionally, both federal regulations in the United and States and Canada were reviewed as part of this process, when dictated by the initiatives of the state and/or province, i.e., the recently proposed EPA rules for CO_2 geologic sequestration wells.

At the same time, reviews were conducted of the activities of the three primary regional GHG initiatives in the United States (i.e., Regional Greenhouse Gas Initiative [RGGI], which originated in December 2005; Midwest Greenhouse Gas Reduction Accord [MGGRA], which originated in November 2007; and the Western Climate Initiative (WCI), which originated in February, 2007), selected states (i.e., Missouri, Montana, Nebraska, North Dakota, South Dakota, Wisconsin, and Wyoming) and selected Canadian provinces (i.e., British Columbia, Alberta, Manitoba, and Saskatchewan) as well as the Interstate Oil and Gas Compact Commission (IOGCC), including its recently formed Pipeline Transportation Task Force. Finally, the PCOR Partnership received significant input regarding regulatory developments from its partners through frequent contact via e-mail and telephone conversations as well as during a workshop that was held in Deadwood, South Dakota, in June 2009.

Regulatory Permitting Action Plans

The PCOR Partnership prepared regulatory permitting action plans as part of each of its Phase II field validation tests. These plans were required to comply with relevant regional, state/provincial, and federal regulatory agency requirements. The permitting action plans that were developed as part of these efforts provided a road map to assist those conducting the tests in meeting their respective regulatory requirements. The action plans provided background information on each project and described the regulatory and permitting steps taken by the EERC and its partners to conduct each of the four field validation tests. Additionally, relevant federal, state, and provincial regulatory summaries were included as part of the plan.

EPA Proposed Rules for CO_2 Geologic Sequestration Wells

In July 2008, EPA issued federal requirements for CO_2 geologic sequestration wells as part of a proposed rule under the Underground Injection Control (UIC) Program. The regulation was proposed under the authority of the SDWA (Safe Drinking Water Act), and its scope is limited to groundwater protection. The proposed rules would establish a new injection well class, Class VI. The rules also list technical criteria for geologic site characterization, area of review and

corrective action, well construction and operation, mechanical integrity testing and monitoring, well plugging, postinjection site care, and site closure. Because of limitations under the SDWA, the proposed rules do not address long-term stewardship issues beyond the postclosure period, nor do they address property rights issues.

A notable activity of the partnership in the regulatory context during Phase II of the program was the preparation of comments on EPA's Proposed Rules for Regulating Geological Sequestration under the UIC Program. Draft comments on EPA's proposed rules were developed and submitted to an ad hoc committee of PCOR Partnership members. As input from this committee was received, the comments were refined. The document was then distributed to the entire PCOR Partnership membership for final comment. Staying abreast of the latest regulatory developments is of the utmost importance for the PCOR Partnership. As various rule-making processes advance, the outcomes of these efforts can greatly affect the CO_2 sequestration initiatives of the PCOR Partnership partners and the advancement of CCS as a whole.

IOGCC

The PCOR Partnership staff has been intimately involved with the activities of the IOGCC, and participation in its current activities is ongoing. The scope of these activities is described in more detail as follows.

The IOGCC Geological CO_2 Sequestration Task Force, working with member states and others, was given the task of developing regulatory guidelines for CO_2 sequestration. The primary objective of the task force was to examine the technical, policy, and regulatory issues related to safe and effective storage of CO_2 in the subsurface (oil and natural gas fields, coal beds, and saline formations), whether for storage, alone, or in combination with enhanced hydrocarbon recovery. A final report was produced that contained an assessment of the current regulatory framework that would likely be applicable to geological CO_2 sequestration as well as recommended regulatory guidelines and guidance documents.

Additionally, the task force developed a model statute and regulations that deal with site licensing, well operation, well/site closure, and long-term sequestration of CO_2. The statute and regulations were released to the public at the end of September 2007 and provided guidance to states as they began the develop their own statutes and regulations to deal with the geologic storage of CO_2. The final report, entitled "CO_2 Storage: A Legal and Regulatory Guide for States," was released in January 2008.

Recently, IOGCC formed a Pipeline Transportation Task Force to identify barriers and opportunities for wide-scale deployment of a CO_2 pipeline transportation system. The task force intends to educate decision makers as to the policy, legal, regulatory, and liability frameworks for CO_2 transportation and to facilitate cooperation among key stakeholders regarding pipeline planning and development. John Harju represents the PCOR Partnership on this Task Force.

Regional Initiatives

The PCOR Partnership reviewed the three regional GHG initiatives that are now in place to reduce CO_2 emissions through the adoption of cap-and-trade programs and the implementation of complementary processes focused on topics such as energy efficiency, low-carbon transportation fuels, and renewable electricity production, to name a few. As listed below, the first of these initiatives was established at the end of 2005, while the other two were put in place during calendar year 2007:

- RGGI (December 2005)
- MGGRA (November 2007)
- WCI (February 2007)

These initiatives now include 23 states as full members and nine states as observers. These states span the entire United States, including representation from the West Coast, northern plains, Rocky Mountains, Midwest, mid-Atlantic, and East Coast. The initiatives also include six of the ten Canadian provinces, four as full members and two as observers. Observers from six Mexican border states are also involved in the WCI. Table 6-1 provides a summary of each of these initiatives, providing the date of formation; the participants of the initiative, including both members and observers; the industry sectors that are addressed; and the original goals and mandates of each effort. These initiatives have developed processes to create regional markets that utilize cap-and-trade, along with the trading of emission allowances, as their primary operating mechanism.

State/Provincial Activities

State and provincial activities related to CCS were updated by PCOR Partnership staff as part of a PCOR Partnership-sponsored Regulatory Brainstorming Workshop (June 16 and 17, 2009, Deadwood, South Dakota). During the workshop, regulatory authorities provided their perspective regarding their regulatory authority as it related to CCS. Updates from those entities in attendance are provided. While many states appear to be waiting for the conclusion of EPA's rule-making process (see the previous section on EPA Proposed Rules), others are moving forward with the development of their own regulations for CCS projects, as shown in Table 6-2.

Alberta

In January 2008, the Alberta Climate Change Strategy was announced. Components of the strategy included a commitment to CCS development activities and provided for the formation of the Alberta Carbon Capture and Storage Development Council. This council released an interim report entitled "Accelerating Carbon Capture and Storage in Alberta" in December 2008. For Alberta to excel at advancing CCS technology implementation, the report recommends a "robust fiscal framework, a clear regulatory framework, and a comprehensive research and development and technology development program" (Alberta Carbon Capture and Storage Development Council, 2009). To that end, the province has committed $2 billion to fund CCS projects.

Table 6-1. Overview of GHG Regional Initiatives[1]

Initiative	Date Formed	Participants		Industry Sectors	Goals/Mandates
		Members	Observers		
RGGI	December 2007	**States** Connecticut, Delaware, Maine, Massachusetts, Maryland, New Hampshire, New Jersey, New York, Rhode Island, and Vermont	**States** Pennsylvania **Canadian Provinces** New Brunswick, Ontario, and Quebec	Power plants	• Implement the first cap-and-trade program for CO_2. • Establish CO_2 emission cap from power plants and allow sources to trade emission allowances. 1. Initially, cap CO_2 emissions at 2009 levels. 2. Reduce emissions by 10% by 2019.
MGGRA	November 2007	**States** Illinois, Iowa, Kansas, Michigan, Minnesota, and Wisconsin **Canadian Provinces** Manitoba	**States** Indiana, Ohio, and South Dakota **Canadian Provinces** Ontario	Multisector	• Long-term target: 60% to 80% decrease in CO_2 from current emission levels by 2050. • Develop multisector cap-and-trade system. • Develop GHG emission-tracking system. • Develop other policies to aid in reducing emissions, such as low carbon fuel standards. • Addresses GHGs as defined by United Nations Framework Convention on Climate Change (i.e., CO_2, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride).

Continued . . .

Table 6-1. Overview of GHG Regional Initiatives (continued)

Initiative	Date Formed	Participants		Industry Sectors	Goals/Mandates
		Members	Observers		
WCI	February 2007	**States** Arizona, California, Montana, New Mexico, Oregon, Washington, and Utah **Canadian Provinces** British Columbia, Manitoba, Ontario, and Quebec	**States** Alaska, Colorado, Idaho, Kansas, Nevada, and Wyoming **Canadian Provinces** Nova Scotia and Saskatchewan **Mexican Border States** Baja California, Chihuahua, Coahuila, Nuevo Leon, Sonora, and Tamaulipas	2012: Focus on electricity generation and large industrial and commercial sources 2015: Include transportation and other residential, commercial, and industrial fuel use.	• Establish regional emission target and market-based system, such as a cap-and-trade program, covering multieconomic sectors to achieve target. 1. Announced regional, economywide GHG emission target of 15% below 2005 levels, or approximately 33% below "business-as-usual" levels, by 2020 (August 2007). 2. Released design recommendations for cap-and-trade program: a) beginning in 2012, program will cover emission from electricity generation and large (>25,000 metric tons a year of CO_2 equivalents) industrial and commercial sources and b) effective in 2015, emissions from transportation and other residential, commercial, and industrial fuel use will be included. • Mandatory reporting is required in early 2011 for calendar year 2010. Reporting threshold is 10,000 metric tons of direct emissions. • Third-party verification on reporting data required for facilities over the 25,000-metric-ton threshold. • Addresses GHG as defined by United Nations Framework Convention of Climate Change (i.e., CO_2, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride)

[1] Information in this section is summarized from the Pew Center on Global Climate change (accessed 2009) and the Snow and Graves ECOS Green Report (2007).

Table 6-2. Listing of State/Provincial CCS Rule-Making Activity

Province/State	CCS Rules/Regulations In Place or under Development
Alberta	X
British Columbia	X
Iowa	
Manitoba	
Minnesota	
Missouri	
Montana	X
Nebraska	
North Dakota	X
Saskatchewan	X
South Dakota	
Wisconsin	
Wyoming	X

While minor modifications may be needed in existing legislation to clarify disposal and tenure rights for long-term CO_2 storage, the ERCB of Alberta is currently prepared to accept applications for CCS projects. The ERCB plans to regulate CCS activities under existing regulations that focus on general technical requirements and evaluations of each individual CCS application. Based on these evaluations, the ERCB may apply "approval conditions" on the proposal that would necessitate additional regulatory requirements intended to manage the unique aspects of a specific project (Alberta Carbon Capture and Storage Development Council, 2009).

British Columbia

The province of British Columbia is in the process of addressing the issue of CO_2 injection for non-EOR-related activities. The update received at the regulatory brainstorming session indicated that existing legislation will be modified slightly to accommodate non-EOR injection and regulatory authority for those initiatives would lie with the British Columbia Oil and Gas Commission.

Missouri

Missouri currently does not have regulations directly related to geologic carbon sequestration. The state has a new governor, and the Department of Natural Resources has a new department head; therefore, future policy initiatives are only just now being formulated.

Montana

In May 2009, the governor of Montana signed Senate Bill 498 which gives authority to regulate CCS projects to the Board of Oil and Gas Conservation. The bill gives the Board the

authority to seek primacy from EPA for CCS projects, and a majority of the legislation is not in effect until this primacy is granted to the state. Primacy requirements for geologic sequestration wells have not been finalized as of this writing. Additionally, further development of rules is expected to hinge on primacy designation. The bill does state that pore space ownership resides with the surface owner if no one else "owns" it.

Nebraska

Nebraska Public Power, which is publicly owned, has expressed interest in geologic sequestration of CO_2. While Nebraska does not have legislation or regulations in place for CCS, it is anticipated it would follow IOGCC recommendations.

North Dakota

The North Dakota Legislature has passed, and the governor has signed, two bills related to the geologic sequestration of CO_2. The first deals with pore space ownership and specifies that the surface owner is the pore space owner, while preserving the mineral owners' dominance. Additionally, it does not allow for separation of pore space ownership and surface ownership. The second bill is the CCS bill. It assigned regulatory authority for CCS projects to NDIC's Division of Mineral Resources, the regulatory body that oversees oil and gas activities. The bill defines CO_2 sequestration projects as separate from EOR projects but provides for the conversion of an EOR project to a sequestration project. It also allows NDIC to certify storage that occurs during EOR projects and for liability transfer to the state after the closure period of the project. Formal rule making is expected to begin in late 2009.

Saskatchewan

The 2009–2010 Plan for the Ministry of Energy and Resources in Saskatchewan calls for the ministry to support ongoing projects related to CCS. The ministry staff is reviewing existing regulations to determine what changes may be necessary to accommodate CO_2 injection for non-EOR-related projects. Ownership of the pore space is one of the current focus areas.

South Dakota

Currently, South Dakota does not have CO_2 sequestration regulations. Various legislators have expressed an interest in CCS; therefore, the South Dakota Department of Environmental Quality is conducting relevant research activities that would allow for the possibility of the introduction of legislation during the next session. However, this past spring saw the signing into law of House Bill 1129 that requires the Public Utilities Commission to regulate CO_2 pipelines.

Wyoming

Wyoming has passed five bills in the last 2 years that cover the general legislative framework for CCS, pore space ownership, and unitization. Issues related to long-term stewardship are still in development and are expected to be considered by the legislature in 2010. Development of comprehensive rules is also under way, including conducting public meetings,

with the process expected to be completed by December 2009. Wyoming is unique in the PCOR Partnership region in that it has split the regulatory authority governing CO_2 injection activities. While authority for CO_2 injection for EOR projects resides with the Wyoming Oil and Gas Conservation Commission, the authority for non-EOR injection falls under the Wyoming Department of Environmental Quality (DEQ). Additionally, because of the vast amount of federal lands in the state, it is anticipated that following the postclosure period for storage projects, liability will not transfer to the state.

Recommendations and Conclusions

A variety of regulations will be used to ensure that the sequestration of CO_2 is conducted in a manner that is fair, responsible, and in the public interest. Additionally, rules will be generated to protect the physical, biological, and chemical quality of our nation's resources from the irresponsible application of sequestration strategies. The PCOR Partnership developed permitting action plans for each of the Phase II field validation tests to ensure that each test complied with the current rules and regulations for these operations. These plans represent prototypes that can be used to guide future projects, recognizing that the rules and regulations are continually evolving over time. In particular, a great deal of development has occurred at the regional, state/provincial, and federal levels with regard to CCS policy that may affect the way similar projects will be permitted in the future.

CCS technology and policy development are taking a prominent position in the climate change debate occurring in the U.S. Congress and in state/provincial legislatures. This debate has spurred federal and state/provincial agencies to start their CCS rule-making activities. In addition, various regional initiatives have been fashioned across the United States and Canada to develop GHG emission strategies in which CCS will likely play a role as an offset option. As these activities evolve, it is important for the PCOR Partnership to continue to utilize the program results and findings to help inform the policy debate so that policy decisions do not unknowingly restrict or constrain the full-scale deployment of carbon sequestration strategies. With this in mind, a thorough review of the Phase I and Phase II project findings as they relate to the current and evolving federal, state, and provincial regulatory frameworks for carbon sequestration is recommended. The results of this technical/policy review will provide an ongoing basis for preparing both informal and formal comments to significant proposed rules and regulations.

6.3 Public Outreach and Education

At the outset of the Phase I PCOR Partnership program in 2003, geologic CO_2 sequestration was "an unknown" not only in the PCOR Partnership region but at the national and international level. Except for a core technical and policy community, this lack of knowledge was essentially universal, including the great majority of policy developers, opinion leaders, NGOs (nongovernmental organizations), educators, and the general public. Recognizing this situation, DOE charged the RCSPs with developing and implementing a program of outreach and education concerning the concept of sequestration, and, in particular, geologic sequestration. Overall, DOE called for activities that would:

- Raise the awareness of the general population in the PCOR Partnership region regarding sequestration.

- Provide focused outreach to audiences in areas where sequestration validation or long-term demonstration tests would be occurring.

- Provide focused outreach to key global/regional audiences, such as legislators and educators.

- Promote collaboration among partners and other partnerships, and transfer lessons learned to the RCSP program and the larger community.

To accomplish this, DOE requested that the partnerships launch public Web sites and collaborate within the overall RCSP program; however, the remainder of the outreach program was left to the discretion of individual partnerships. In response to this request, the 2-year Phase I PCOR Partnership outreach effort launched a public Web site, produced a half-hour documentary broadcast for public television, broadly distributed DVDs of the television documentary, created a general public PowerPoint presentation, and prepared a half dozen fact sheets. The Phase II effort, which was initiated in the fall of 2005, built upon and expanded this basic outreach and education effort.

Characteristics of Region

The PCOR Partnership's outreach and education activities were focused on an international region that consists of four Canadian provinces and parts or all of nine U.S. states (accounts for 17% of the combined land mass of the United States and Canada) and contains nearly 10 million households (Figure 6-6). The U.S. portion of the region contains about 22 million inhabitants and accounts for 8% of the U.S. population. The Canadian portion of the region contains about 6 million inhabitants and accounts for 17% of the Canadian population. Altogether, the region accounts for about 2.5% of the earth's land area, 3% of the earth's anthropogenic carbon emissions, and 3% of world gross domestic product.

During the Phase II outreach planning and assessment, the overall partnership region was divided into two parts, Outreach Regions A and B, based on selected demographic and carbon sequestration project criteria (Figure 6-6). The regions were characterized as follows:

- Outreach Region A: Includes the Canadian provinces of British Columbia, Alberta, and Saskatchewan, as well as all or portions of the U.S. states of North Dakota, Montana, and Wyoming. These areas produce fossil energy, export energy resources (and electricity in some cases), and are suitable for both terrestrial and geologic sequestration. Further, Outreach Region A coincides with areas where people "live with" energy resource extraction, refining, and conversion activities. Outreach Region A contains the sites for the three geological CO_2 sequestration Phase II verification tests, as well as the candidate sites for the Phase III commercial-scale demonstration projects. This region contains half of the PCOR Partnership region's land area and about 20% of the PCOR Partnership region's population.

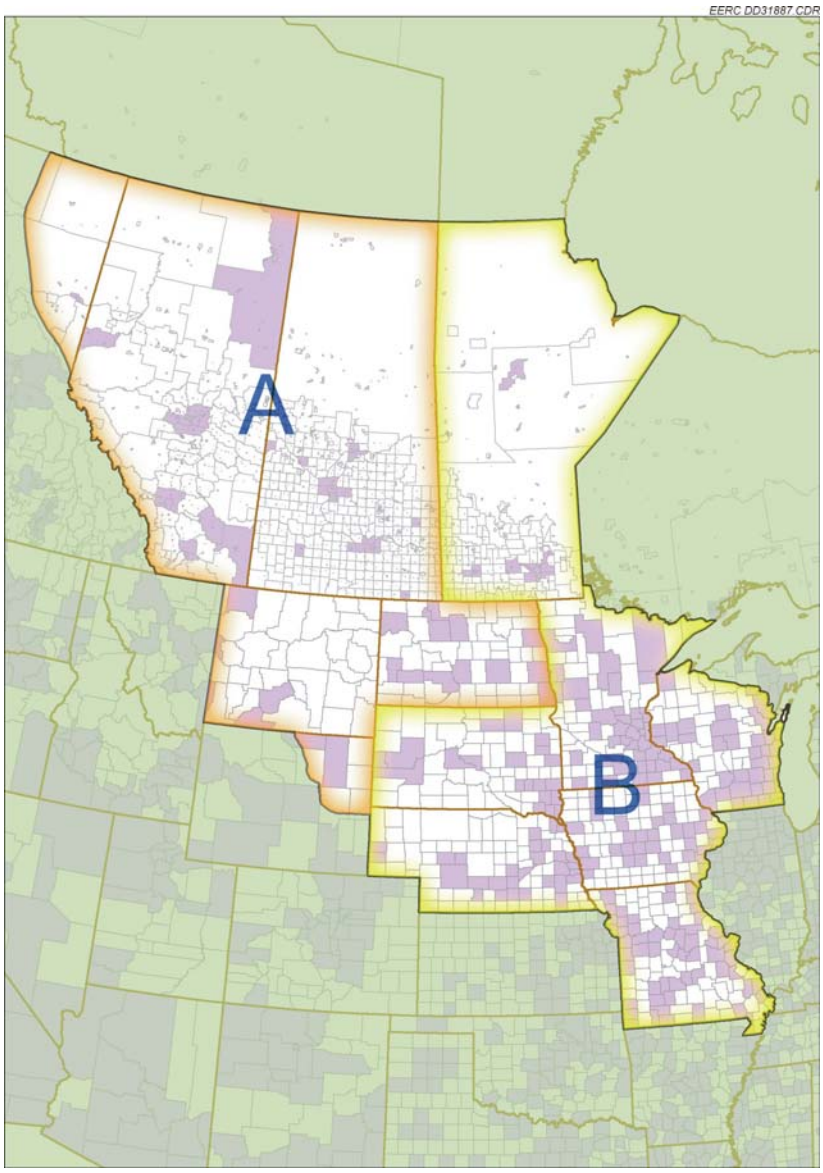

Figure 6-6. Map of populations by county (municipality in Canada) in the PCOR Partnership region showing Regions A and B (shaded areas have populations over 10,000).

- Outreach Region B: Includes the U.S. states of Minnesota, Wisconsin, Iowa, Missouri, Nebraska, and South Dakota, as well as the Canadian province of Manitoba. Outreach Region B is an importer of energy resources (as well as electricity in some cases), and although it contains major CO_2 sources, it has fewer possibilities for local geologic sequestration. The Phase II terrestrial verification test was cited in this region (South Dakota). This region accounts for half of the PCOR Partnership region's land area and over 80% of its population. This region also contains the bulk of the urban population and the bulk of the gross national product generated within the overall PCOR Partnership region.

Approach

The Phase II outreach plan was designed to extend the four basic objectives of the outreach program to the next level. To accomplish this, the overall program approach was modified in the following way.

- General outreach was undertaken throughout Outreach Regions A and B but focused outreach in the latter was postponed for Phase III efforts.

- Focused outreach to critical audiences was initiated regarding field verification tests to ensure support for these larger-scale field projects.

- Collaboration and integration were expanded to include not just the other partnerships in the RCSP program but other groups such as the International Energy Agency (IEA) and other projects such as the Weyburn–Midale program.

In addition, outreach activities were focused on raising awareness and encouraging communication among key audiences, particularly the "influencers" among the general population as well as current and prospective partners (target audiences and the respective messages for each of them are addressed in Appendix A). As part of Phase II, the Phase I outreach activities were continued as outreach was provided to decision makers and opinion leaders, including lawmakers, partners, technical audiences, and educators. This outreach also included the distribution of products to raise the awareness of the general public across the region through television broadcasts and a public Web site. The Phase II approach featured a multidisciplinary outreach team who developed a variety of outreach products and plans for general and project-related outreach. The outreach activities were conducted by the outreach team, the EERC's PCOR Partnership Program team, and the PCOR Partnership partners. Standards and quality assurance/quality control (QA/QC) procedures to ensure the quality of the outreach materials used by these groups were developed based upon existing in-house EERC capabilities, standards, and QA/QC practices that were developed during Phase I of the project.

Phase II outreach activities relied upon the outreach materials that were developed during Phase I; the new materials that were developed in Phase II; and materials from partners, the other DOE partnerships, and DOE, as appropriate. Outreach often utilized in-place networks, including partner networks. Table 6-3 summarizes the outreach products that were developed and made available. Table 6-4 provides an overview of the outreach approach by showing the outreach strategies and products with respect to the different target audiences.

Public Web Site

The PCOR Partnership public Web site is currently available to approximately 7 of the 10 million households in the region, as well as through public venues like schools and libraries. Assuch, the public Web site is the center of the outreach capability for the PCOR Partnership regional outreach effort. The Web site address is listed on all outreach materials, and audiences are directed to the Web site for additional information.

Table 6-3. Outreach Materials Available at the Close of Phase II

Designation	Product
Fact Sheet 1	What Is CO_2 Sequestration?
Fact Sheet 2	CO_2 Sequestration – Controlling CO_2 Emissions to the Atmosphere Through Capture and Long-Term Storage
Fact Sheet 3	The Weyburn Oil Field – A Model for Value-Added Direct CO_2 Sequestration
Fact Sheet 4	Wetland Carbon Sinks in the Glaciated North American Prairie
Fact Sheet 5	Identifying CO_2 Sequestration Opportunities
Fact Sheet 6	PCOR Partnership Phase II
Fact Sheet 7	Site G2 – Pinnacle Reef/Acid Gas Sequestration Verification Test
Fact Sheet 8	Site T1 – Wetland CO_2 Sequestration Verification Test
Fact Sheet 9	Site G3 – Deep Oil Field CO_2 Sequestration Verification Test
Fact Sheet 10	Site G1 – Unminable Lignite CO_2 Sequestration Verification Test
Documentary 1	"Nature in the Balance – CO_2 Sequestration"
Documentary 2	"Reducing Our Carbon Footprint—The Role of Markets"
Documentary 3	"Out of the Air, Into the Soil: Terrestrial Sequestration"
Documentary 4	"Managing Carbon Dioxide: The Geologic Solution"
Documentary 5	"Carbon Footprint: One Size Does Not Fit All"
Article 1	Controlling Carbon Dioxide Emissions and Still Providing Affordable Energy
Article 2	An Introduction to Storage of Carbon
Article 3	The Capture and Long-Term Storage of Carbon Dioxide
Atlas	PCOR Partnership Atlas
Public Web Site	PCOR Partnership public Web site (www.undeerc.org/pcor)
PowerPoint	PCOR Partnership public outreach PowerPoint presentation
Display Booth	PCOR Partnership public outreach display booth

The basic public Web site that premiered as part of Phase I underwent three significant updates during Phase II. The first update occurred in the spring of 2006 and added seven major sections, streaming video, 50 primary pages (as well as additional links and supplementary pages), and a sequestration news section that was updated monthly. The second update, in the fall of 2008, modified the format to allow easier reading, reorganized the content to allow for better navigation, and added additional information on verification tests and other sequestration activities in the region. The third and final update, in August of 2009, used an Abobe Flash multimedia program to help show the breadth of the site content as well as video clips to supplement information on key sequestration topics.

Currently, the public Web site features background information on sequestration, information on regional sequestration activities involving the partnership as well as activities by others, and information on the partnership itself. The site also features announcements, press releases, and all of the outreach products. The documentaries and video clips are available in streaming format, and all print products can be downloaded. Materials such as documentary DVDs and hard copies of print products can also be ordered online. The site also features links to partner Web sites, DOE and other Partnership sites, and a variety of other program and technical sites. The site also contains pages for educators, children, and homeowners.

The PCOR Partnership has tracked page views and visits to the public Web site since July 1, 2006. As shown in Table 6-5, annual visits to the Web site have increased since Phase II began and remain substantial.

Table 6-4. Outreach Strategies and Products by Primary Intended Audience

	Primary Audience					
				Science Educators	County Extension Agents	EERC Communications Staff
	Partners	Demo Site	Public	Youth	Landowners	Select Public
OUTREACH STRATEGIES						
One-on-One Meetings	x	x				
Presentations	x	x		x	x	
Annual Meeting	x					
Outreach Networks (reach a broader audience through their efforts)				x	x	x
Public Relations (includes press releases)	x	x	x	x	x	x
Keystone K–12 Curriculum				x		
Mass Media–Public TV	x	x	x	x	x	x
OUTREACH PRODUCTS						
Fact Sheets						
Technical	x					
Nontechnical			x	x	x	x
Demonstration Site Specific		x				
Documentaries	x	x	x	x	x	x
Newspaper Articles	x	x	x	x	x	x
Regional Atlas	x	x	x	x	x	x
Web Site						
Public			x		x	x
Partners Only	x					
Kids Only (part of public Web site)				x		
PowerPoint Presentation	x	x	x			
Display Booth	x	x	x			

Mass Media – Public Television

The broadcast of 30-minute original documentaries on public television are the secondary means of general outreach in the PCOR Partnership region. Four documentaries (Figure 6-7) were produced and broadcast during Phase II.

Reducing Our Carbon Footprint: The Role of Markets – This original 30-minute feature production provides information on anthropogenic (human) CO_2 emissions; the relationship between energy, the economy, and human CO_2 emissions; strategies for controlling human CO_2 emissions; the role of markets in helping to finance carbon reductions; the basic

Table 6-5. Page Views, Visits, and Average Visit Time for the PCOR Partnership Public Web Site for the Period July 1, 2006, to June 30, 2009

Period	Page Views[1]	Visits[2]	Average Visit Time[3, 4]
July 06 – June 07	6038	4413	95 seconds
July 07 – June 08	14,416	10,011	109 seconds
July 08 – June 09	32,111	8872	72 seconds

[1] A single Web page viewed through a browser.
[2] A visit begins when a visitor enters the site. Visitors may click one or more page views. The end of the visit is signaled by exit click or 10 minutes of inactivity.
[3] Average duration of all visits. Sum of all visits in seconds divided by the total number of visits, not including single event visits.
[4] In "visit days" the equivalent for Period 1 equals 291; Period 2 equals 757; and Period 3 equals 443.

Figure 6-7. The four PCOR Partnership documentaries.

approaches to carbon markets; the types of projects that are being undertaken in developing economies; and the way that geologic CO_2 sequestration fits into the picture. This documentary was premièred on Prairie Public television on April 17, 2008, and has received a Communicator Award of Excellence. The communicator Award is the leading international award program honoring creative excellence for communications professionals and is one of the largest awards of its kind in the world.

Out of the Air—Into the Soil: Land Practices that Reduce Atmospheric Carbon – This original 30-minute feature production shows examples from North and South America where effective landscape management is helping plants to absorb carbon as a first step toward reducing our carbon footprint. Topics include rainforest restoration in Brazil; Mississippi

bottomland forest restoration in Arkansas and Louisiana; fuel reduction, reforestation, and forest management techniques in California; and grassland and wetland restoration and no-till agriculture in the northern Great Plains. The documentary was premiered on Prairie Public Television on September 26, 2008, and subsequently received a Communicator Award of Excellence and a Gold Aurora Award. The Aurora Award is an international competition designed to recognize excellence in the film and video industries.

Managing Carbon Dioxide: The Geologic Solution – This original 30-minute feature production tells the story of how the discovery of natural CO_2 in underground geologic formations came to be used to help recover more oil from reservoirs in West Texas and how this led scientists and engineers to begin work on practical ways of permanently storing CO_2 from fossil fuel-fired power plants and other large stationary sources in natural sealed containers deep underground in a practice called geologic sequestration, a key part of CCS. This documentary was premiered on Prairie Public Television on November 10, 2009.

Carbon Footprint: One Size Does Not Fit All – This feature (currently in production) tells the story of the variations in energy use from society to society and how carbon management actions play out across the societies. The fact that different countries have different starting points and different considerations when it comes to reducing emissions is illustrated by visiting families in the United States (postindustrial society), India (rapidly industrializing society), and Cameroon (preindustrial society). Through the families, key topics are discussed including energy use (type, amount, source), carbon emissions associated with each activity, and what would have to happen to reduce (or keep low) CO_2 emissions. The family experience is put into the greater context of how energy is created, supplied, and used in each society. A release date of spring 2010 is anticipated.

Several public television stations provide full coverage across the region as listed in Table 6-6. Prairie Public Broadcasting, the coproducer of the four Phase II documentaries, did an initial broadcast of the documentaries in its market (North Dakota, Manitoba, and northwestern Minnesota) and then took the lead in making the documentaries available to the other public television stations in the PCOR Partnership region and the 350 markets outside of the region.

Using the national viewing average of 1.5% for public television, the broadcast of each of the four documentaries was viewed in an estimated minimum of 150,000 households in the PCOR Partnership region. Information to date suggests that the documentaries have been broadcast in at least a third of the public broadcasting markets in the United States and Canada, including major East and West Coast markets.

Public Relations, Outreach Networks, and External Media

A total of four news releases for the PCOR Partnership were developed in consultation with the Communications Director of the EERC, and then distributed by the EERC to regional TV stations, radio stations, newspapers, and/or magazines. In addition, an interview was given by PCOR Partnership personnel regarding sequestration and a newspaper article was written.

Table 6-6. Public Television Stations in the PCOR Partnership Region

Primary Coverage Area	Public Television Station	Location
North Dakota	Prairie Public Broadcasting	Fargo, North Dakota
South Dakota	South Dakota Public Television	Vermillion, South Dakota
Nebraska	NET1	Lincoln, Nebraska
Iowa	Iowa Public Television/IPTV	Johnston, Iowa
Minnesota Southeast	Twin Cities Public Television	Minneapolis, Minnesota
Minnesota Northeast	WDSE/Channel 8	Duluth, Minnesota
Minnesota South	Pioneer Public TV	Appleton, Minnesota
Minnesota Northwest	Lakeland Public Television	Bemidji, Minnesota
Wisconsin	Wisconsin Public Television	Madison, Wisconsin
Missouri East	KETC/Channel 9	St. Louis, Missouri
Missouri West	Kansas City Public Television	Kansas City, Missouri
Missouri South	Ozarks Public TV	Springfield, Missouri
Missouri North	KMOS Missouri	Warrensburg, Missouri
Montana	Montana PBS	Bozeman, Montana
Wyoming	KCWC/Channel 4	Riverton, Wyoming
Alberta	KSPS	Spokane, Washington
Manitoba	Prairie Public Broadcasting	Fargo, North Dakota
Saskatchewan	Detroit Public Television	Detroit, Michigan

The PCOR Partnership utilized a number of print and electronic outreach networks in the region. Many of these are maintained by partners or by groups with whom the outreach team or partners are working. Utilizing these existing outreach networks increased the ability of the PCOR Partnership to make an outreach impact with efficiency and consistency.

In addition, a number of magazine articles, newspaper articles, online articles, and newsletter articles were published in the region that featured the PCOR Partnership or spoke about sequestration. A summary of articles in these external media from North Dakota and other select areas is included in Table 6-7; a detailed listing is provided in Appendix A.

One-on-one outreach was limited to members or for technical audiences. PCOR Partnership management and technical personnel handled one-on-one communications with environmental groups, NGOs, and key officials using materials developed by the Outreach Team. Over 2500 copies of the PCOR Partnership regional atlas, 3100 DVDs of documentaries, and numerous fact sheets were distributed as part of these interactions.

Table 6-7. A Summary of External Coverage of PCOR Partnership and PCOR Partnership Region Sequestration Activities (April 1, 2006, to September 30, 2009)

Coverage Type	Total	Primary	Secondary
Magazine	5	1	4
News Release	5	4	1
Newspaper	37	1	36
Online	20	6	14
TV/Radio	7	1	6
Newsletter	7	3	4

Presentations and Event Participation

Presentations and event participation applied to all key audiences. Presentations were done for partners and with partners. PCOR Partnership staff members participated in events where they made technical presentations and hosted the PCOR Partnership booth. Members of the outreach team gave presentations to meetings and events held by partners as well as external groups. As part of this activity, presentations were made to North Dakota educator groups each year, most notably, at the statewide teacher meetings, as well as educator workshops hosted by the North Dakota Petroleum Council and the North Dakota Lignite Energy Council. Over 1500 copies of the PCOR Partnership regional atlas and 1500 DVDs of documentaries were distributed, mainly in packets that supplemented the public event presentations.

Outreach for Validation Test Activities

Outreach for the four field validation tests was led by either the validation test partner and/or or by the PCOR Partnership. The outreach team developed validation test outreach plans, and outreach was supported by the development and distribution of fact sheets, PowerPoint materials, and Web pages.

Best Practices Manual

A Best Practices Manual for Outreach was prepared by the outreach team in the spring of 2009 (Daly et al., 2009). The manual outlined 20 outreach best practices and was used as a model in the preparation of the RCSP Outreach Working Group (OWG) Best Practices Manual during the summer of 2009.

RCSP Activities

The outreach team aided project integration and efficiencies in the RCSP program by taking part in the activities of the OWG. These activities are summarized in Table 6-8.

Recommendations and Conclusions

During Phase II, the outreach task responded to DOE's mandate for outreach at the regional level and to project sites as well as addressed key audiences and contributed to a stronger outreach effort within the RCSP program as a whole and to the growing sequestration

Table 6-8. PCOR Partnership Outreach Team Contribution to Outreach Working Group Activities

Activity or Product	PCOR Partnership Contribution/Involvement
Intra-Project Communications and Lessons Learned	• Project updates during monthly OWG conference calls • Lead role in the development of an outreach presentation for the annual DOE sequestration meeting • Contributed to the development of the Best Practices Manual for sequestration outreach by taking part in report preparation and by providing the PCOR Partnership Outreach Best Practices Manual as a model framework for the OWG report
Outreach for the RCSP Program	• Active role in the development of a DOE RCSP video for Greenhouse Gas Control Technologies 2009 (GHGT-9) regarding the RCSP program • Lead role in the development of a DOE RCSP general information video for sequestration
Contributing to General State of Sequestration Outreach Knowledge	• Review of internal DOE reports • Review of external reports

outreach community. At the regional level, information on sequestration reached an estimated 1.6%, or 150,000 households, for the public television broadcasts of each of the four original documentaries, broad view of messages were viewed during the 8 to 10,000 annual visits to the PCOR Partnership Web site that is available in three quarters of the households in the region as well as schools and offices, and press releases supplemented the regional outreach in media in the North Dakota region. The public PowerPoint along with the expanded tool kit were used in annual presentations to educators as well as in other presentations to teachers, 7–12 and university students, and project communities in the case of the lignite verification test. Collaboration with peers and communication of "lessons learned' was accomplished through participation in the activities of the OWG, including the preparation of the RCSP's Outreach Best Practices Manual, as well as serving in an advisory capacity for the Weyburn–Midale project and select projects of the Petroleum Technology Research Center and IEA forums.

On the basis of Phase II activities and experiences, we recommend the following:

- Continued strengthening of outreach efforts in our region by drawing on the expertise developed by outreach programs and partners in other regions, including presentations at partnership events and collaboration on outreach projects.

- Carrying lessons learned to external groups by participation in advisory groups to project or regional outreach initiatives and groups on the international stage as a means of helping to ensure technically sound messaging and communications frameworks.

- Greater resources toward native populations and other groups who are often underserved by mainstream information channels.

- Improved feedback and tracking capability to determine exposure to messages as well as to aid in planning for more effective outreach activities.

- Improved capacity to take advantage of in-place networks like the Web, including social networking, magazines, and the education system, to broaden and strengthen outreach capabilities and improve the ongoing deliverability of messages regarding sequestration.

6.4 Identification of the Commercially Available Sequestration Technologies Ready for Large-Scale Deployment

The primary goal of this task was to identify sequestration technologies and approaches that are suitable and available for large-scale deployment in the PCOR Partnership region and to evaluate their economic viability. Task activities also included an investigation of the use of wind power to offset at least a portion of the energy penalty associated with the electricity that is needed to operate CO_2 compressors. Lastly, the PCOR Partnership assisted Excelsior Energy in the preparation of a carbon management plan for a planned integrated gasification combined cycle (IGCC) facility in northern Minnesota.

The primary task goal was met by maintaining a current CO_2 emissions database; appropriately matching CO_2 sources, CO_2 capture/separation technologies, and geologic sinks; and estimating, as accurately as possible, the costs of CO_2 capture, compression, and transportation to sequestration sites within the region.

CO_2 Source Identification, Emission Estimation, and Location Verification

The PCOR Partnership maintains a database of CO_2 emissions from electric-generating and industrial point sources within the region. The point sources were identified primarily by searching databases of EPA and Environment Canada (EC) (U.S. Environmental Protection Agency, 2009a, b, c; Environment Canada, 2009) although some ethanol plants were found by searching the database of the Renewable Fuels Association (Renewable Fuels Association, 2009). Gas-processing facilities that were not included in either the EPA or EC data sets were identified by purchasing the *Oil and Gas Journal* Worldwide Gas-Processing 2008 data set.

Whenever possible, actual measured CO_2 emission rates were included in the PCOR Partnership CO_2 emissions database. The measured emission rates were found in EPA Clean Air Markets (U.S. Environmental Protection Agency, 2009b), e-GRID (U.S. Environmental Protection Agency, 2009c), and EC (Environment Canada, 2009) databases. When actual CO_2 emission rates could not be found, the emissions were estimated using either the methodologies outlined by Pavlish (Pavlish et al., 2009), or, for gas-processing facilities, using data from the *Oil and Gas Journal* Worldwide Gas-Processing 2008 data set and making the assumption that the CO_2 concentration in the raw, produced natural gas is 4% by volume (Metz et al., 2005). To be on par with the data generated by the other DOE RCSPs, an average of 75% CO_2 removal and subsequent venting of that CO_2, was also assumed (DOE RCSP Capture and Transportation Working Group, 2008). Equation 1 shows the calculation used to estimate the amount of CO_2 captured and subsequently emitted in short tons/yr.

$$CO_2 \text{ emitted} = g \times 0.04 \times \frac{10^6 \frac{ft^3}{d}}{\frac{MMft^3}{d}} \times \frac{365\ d}{yr} \times \frac{lbmol}{379\ ft^3} \times \frac{44\ lb}{lbmol} \times \frac{1\ ton}{2000\ lb} \times 0.75 \qquad \text{[Eq. 1]}$$

where g is the natural gas throughput in $MMft^3/d$, and the gas stream is assumed to be at oil and gas industry standard conditions of 60°F and 1 atm.

Location coordinates for the CO_2 emission sources were visually verified or corrected using the Google Earth satellite maps. In some instances, the resolution of the Google Earth imagery was not sufficiently high to see a facility. At other times, the facility was built after the satellite images were taken. Occasionally, the location of an older facility could not be verified but a better location could not be determined through a search of the company's Web pages or other Web-based information. In those cases, the location coordinates were left as they appeared in the database and were flagged for further review during the next QA/QC check of the database.

Matching Protocol: Source–Capture Technology–Storage Site

Sources of CO_2 were matched with capture technologies that are considered the most likely to be applicable to the source based on the volume and characteristics of the CO_2 stream. For example, ethanol plants produce a very pure stream of wet CO_2 and typically would require only dehydration prior to compression and transport. Gas-processing facilities often use amine scrubbing to remove CO_2 from the natural gas stream, and gasification systems would probably employ physical sorption systems such as Selexol™ or Rectisol®. The current thinking for electric utilities is that the likeliest capture technologies would be one of the variations of the amine- or ammonia-scrubbing technologies.

To match a particular source with a secure geological storage site, the PCOR Partnership DSS was employed. A map of sinks (i.e., saline formations, unminable coal deposits, and depleted oil fields) was overlain with the source location. Sinks that also had the potential to produce a usable product and reduce the cost of carbon sequestration, such as EOR or enhanced CBM recovery, were given priority over other potential sinks for a given source.

Pipeline Routing

Potential pipeline routes and distances were estimated using a GIS-based model for CO_2 pipeline transport that was developed at the Massachusetts Institute of Technology (MIT) (Herzog, 2006; Massachusetts Institute of Technology, 2007). The MIT model calculates the pipeline diameter and identifies the least-cost path connecting a CO_2 source to a given sink. The model implements obstacle grid layers (at a 1-km × 1-km scale) in which local terrain, crossings, protected areas, and populated places are assigned relative cost factors to permit the determination of a least-cost route between a single CO_2 source and a geologic sink. The model also estimates the capital and operating costs of the pipeline, which includes the costs of obstacles identified during its routing through federal or protected land or through populated areas. Obstacles can increase the cost for the length of pipeline that is routed through an obstacle

from roughly 3 times (highway or railroad crossing) to 30 times (national park crossing) (Massachusetts Institute of Technology, 2007). Pipelines were routed so as to include as many sources as possible. The pipeline diameter changed at various points along the route as sources were picked up by the pipeline.

Capture, Compression, and Transportation Infrastructure Cost Estimation

Capture and compression costs were estimated using the Integrated Environmental Control Model (IECM) (Carnegie Mellon University Department of Engineering and Public Policy, 2007). The IECM is a tool for calculating the performance, emissions, and cost of a fossil fuel-fired power plant, including the base plant, pollution control devices, CO_2 capture facilities, compression, and pipeline construction. A methodology was developed to enable the use of the IECM to estimate the power requirement and costs of drying and compression for ethanol and gas-processing plants that did not require capture of the CO_2. Pipeline costs were typically calculated using the MIT pipeline-routing software described previously.

CO_2 Emissions Database

The PCOR Partnership DSS CO_2 emissions database was updated twice during Phase II. These updates, which included the identification of new sources and the updating of emission values, were accomplished using various updated databases from the EPA, EC, and industry groups. In addition, duplicate sources were eliminated and the locations of all sources were verified to the extent possible using the satellite imagery available on Google Earth. There are currently 927 point sources in the PCOR Partnership region that each produce at least 15,000 short tons CO_2/yr. Total CO_2 emissions in the PCOR Partnership region are about 562 million short tons CO_2/yr.

Sixty-two CO_2 point sources are shared by the PCOR Partnership and the Big Sky Carbon Sequestration (Big Sky) Partnership. Efforts were undertaken with personnel from the Big Sky Partnership to ensure that the names, locations, and CO_2 emission levels of these sources were identical in both Partnerships' databases. While both partnerships include these sources, the NetCarb national repository for these data only includes the information once.

The methodologies used to estimate the CO_2 emissions were collated into a single document, which was submitted to the DOE. DOE integrated the information in this document with similar documents from the other six RCSPs (U.S. Department of Energy Regional Carbon Sequestration Partnerships Capture and Transportation Eorking Group, 2008). The PCOR Partnership also prepared a similar but more detailed document for the PCOR Partnership members (Pavlish et al., 2009).

Source–Capture Technology–Geological Sink Matching

Upon the request of various partners and/or in support of other PCOR Partnership task activities, CO_2 sources were matched to suitable capture technologies and geological sinks. Matching the various point sources with appropriate capture methods required an understanding of the state of the art of capture technologies, which was developed through searches of the

literature and Web sites. This state of the art survey of capture technologies was summarized in an interactive table of over 40 technologies, which was included on the PCOR Partnership partners-only Web site. This same information will also be compiled and included in a value-added topical report that summarizes current CO_2 capture technologies at all levels of development, from laboratory-scale to commercially available. This report will be completed and submitted as part of the PCOR Partnership Phase III Infrastructure activities.

Matching sources to geological sinks was also investigated. In these instances, the critical variables were the volume and purity of the CO_2 as well as the storage capacity and location of geological sinks that were capable of accepting the CO_2.

Infrastructure Cost Estimation

Employing CO_2 capture on a regional scale will require considerable energy and financial resources. The cost of capture required for the initial deployment of carbon sequestration in the PCOR Partnership region was estimated. Capture and compression costs and power requirements for ethanol plants, gas-processing facilities, and electricity-generating facilities were estimated using the IECM, a desktop computer model that was developed at Carnegie Mellon University with funding from DOE NETL. The route and cost of a regional pipeline network required for implementation of a regional sequestration program was estimated using a pipeline-routing model developed by MIT. The regional pipeline network that resulted from this effort is shown in Figure 6-8. All of these costs were summarized and the estimation methodologies explained in a Best Practices Manual (Jensen et al., 2009). In summary, the total cost of capture, drying/compression, and pipeline transportation within the PCOR Partnership region was estimated to range from $1.8 billion/yr for the CO_2 produced during fermentation at the region's ethanol plants to $25.8 billion/yr for the ethanol plants' fermentation-related CO_2 plus 90% of the CO_2 produced by the region's electricity-generating plants that are at least 100 MW in size. These efforts would reduce the PCOR Partnership region's point-source CO_2 emissions by 3% and 57%, respectively.

Excelsior Energy Carbon Management Plan

The PCOR Partnership performed a study for Excelsior Energy to identify the various options for management of CO_2 that will be produced by the Mesaba Energy Project that is currently under development. Mesaba Energy Project sites under consideration are in the Iron Range of Minnesota, and sequestration sinks were evaluated that are within approximately 500 miles of that location. The first phase of the Mesaba project (Mesaba One) will be constructed as "capture-ready," meaning that it will be built to accommodate the addition of a CO_2 capture technology at a later date. Excelsior Energy has chosen an activated methyldiethanolamine (aMDEA) chemical absorption system to capture the CO_2. When constructed, the aMDEA system will capture up to 30 wt% of the CO_2 generated by the plant during gasification and will produce about 4500 tons/day of a high-purity CO_2. Carbon management strategies that were considered focused on geologic sequestration, especially EOR opportunities that might offer a chance to sell the CO_2. Pipelines are probably the most cost-effective means of transporting the CO_2 produced by the Mesaba Energy Project, although they represent a substantial capital investment.

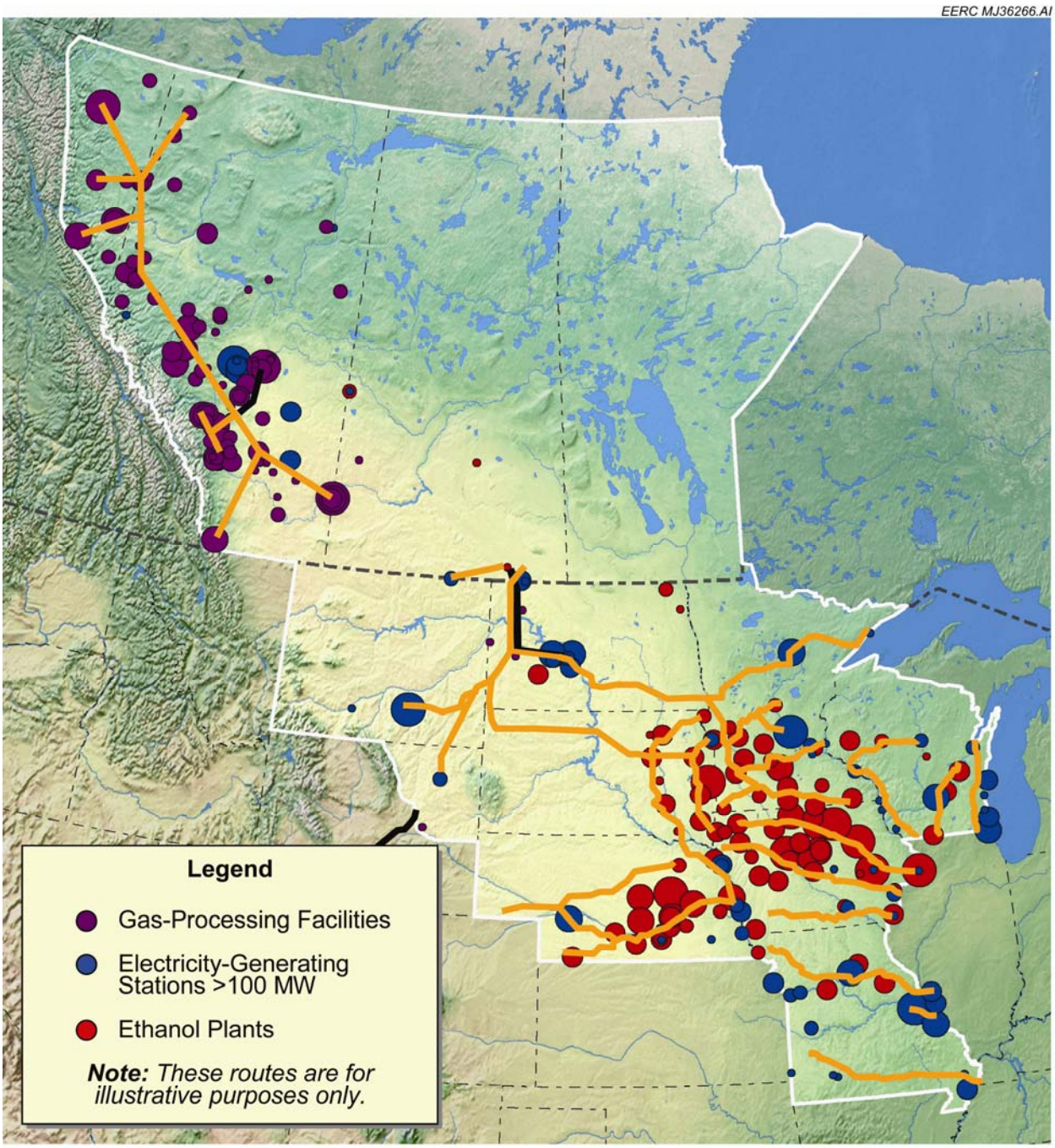

Figure 6-8. The PCOR Partnership pipeline network route. Blue dots represent CO_2 sources. Yellow lines show the pipeline network routes calculated as part of the PCOR Partnership study. Fuchsia lines represent existing or planned CO_2 pipelines.

Carbon markets may offer the Mesaba Energy Project another way to realize a return on the investment associated with CO_2 capture. Significant possibilities exist in the region for both terrestrial and geologic sequestration and trading of carbon offsets as significant features of a carbon management strategy. However, North American carbon markets are in their infancy, and

the exact type of market structure and associated value of credits have not been sufficiently defined to incorporate them into the planning of this project.

Using Wind Resources to Offset the Power Requirements of Geological Storage Activities

A best practices manual was developed to illustrate the steps required to assess the applicability of using wind resources to offset some of the fossil fuel-generated electricity needed for CO_2 geologic sequestration activities. The power generated could be fed directly to a transmission line or used directly for the sequestration activities. Geologic sequestration of CO_2 requires substantial energy for capture, separation, compression, and injection. The most likely process operations for which power from wind resources could be used are the compression and injection steps. When fossil fuel-produced electricity is used for these processes, it reduces the GHG emission reductions realized by CCS and the amount of power that is available to be transmitted to the grid. Wind power could eliminate some of this energy penalty by providing cost-effective energy for some of the equipment needed for sequestration.

A case study investigating the use of wind energy to replace lignite-produced electricity for CO_2 compression was completed and estimated a potential revenue of $3.2 million annually (carbon credits and electricity savings) and a 13-year simple payback. Eighteen 1.5-MW wind turbines would be needed to match the 27-MW demand of the compressors for a CO_2 pipeline located in western North Dakota. The capital investment for turbine installation was estimated to be $40.5 million to generate approximately 70,800 MWh annually, with interest estimated at $1.5 million annually, assuming a 6% loan. Utilization of wind energy in this case study could generate 86,400 short tons of carbon credits. The potential revenue from these carbon credits was estimated to be $350,000 annually using an average price of $4.05 per short ton CO_2. Other income or savings include the production tax credit ($1.3 million) and electricity savings from utilizing wind energy ($3.0 million). Economic viability was based on a 20-year service life for the wind turbines.

Recommendations and Conclusions

Current cost estimates for the capture, compression, and pipeline transportation network required for the effective implementation of CCS are significant, leading to the conclusion that additional research is needed to identify more cost-effective capture and compression technologies. Related to this research need, larger- and longer-duration demonstration tests for the integrated capture, compression, transportation, and injection of CO_2 are needed to not only verify the ability to safely store CO_2 on a large scale, but to provide robust economic data that can be used to generate more accurate estimates of the cost of their implementation.

Most industries will need to plan their carbon management strategies to be prepared for a carbon-constrained future. Regional decision makers should consider the overarching issues such as how best to implement a carbon management strategy that will minimize the carbon intensity of their products through alternative fuel sources such as wind and biomass as well as through the use of both terrestrial and geologic sequestration and trading of carbon offsets. Even though the North American carbon markets are in their infancy and the exact type of market structure

and associated value of credits have not been determined, parametric and statistical studies are recommended to bound the problem and to identify the plausible combination of approaches that would be candidates for achieving the mandated and/or desired targets.

6.5 Program Management and Regional Partnership Program Integration

The EERC PCOR Partnership Program Manager (PM) for Phase II activities provided leadership in fully coordinating and integrating the activities of the PCOR Partnership. The PCOR Partnership leadership team focused on providing completion of milestones, quality deliverables, and accurate and timely program reports. Annual project review meetings between representatives of the PCOR Partnership, the PCOR Partnership management team, and DOE project managers were held to ensure that program goals were being met. The timely dissemination of the PCOR Partnership's technical results through attendance of and presentations at technical meetings, distribution of technical support materials, posting of technical materials on the Web, and regular communication with other RCSP groups and related programs ensured that the CO_2 sequestration community was informed of the PCOR Partnership accomplishments and activities.

A kickoff meeting for Phase II activities was held at Xcel Energy Corporate Headquarters in Minneapolis, Minnesota, November 1–2, 2005. Annual meetings were held to report progress of activities in conjunction with workshops on topics of interest to the PCOR Partnership partners.

September 13–15, 2006 – The Annual Meeting was held at Delta Bow Valley Hotel in Calgary, Alberta. Two workshops were also held: "Practical Aspects of CO_2 EOR" and "CO_2 Capture, Separation, and Compression."

October 18–19, 2007 – The Annual Meeting was held at the EERC in Grand Forks, North Dakota, along with a PCOR Partnership Geologic Working group meeting.

September 16–18, 2008 – The Annual Meeting was held at the Holiday Inn Hotel & Suites in Maple Grove, Minnesota. Two workshops were also held: "CO_2 Capture, Separation, and Compression" and "Carbon Market Trading." The PCOR Partnership Geologic Working group also held a meeting during this time.

December 1–3, 2009 – The Annual Meeting was held at the Hyatt Regency in St. Louis, Missouri. Two workshops were also held: "Effective Outreach and Communication – Best Practices and Real-World Experiences" and "Carbon Management Strategies."

An abundance of products were developed under Phase II and are enumerated in Appendix B. These products are available to all PCOR Partnership partners through the DSS.

EERC PCOR Partnership representatives participated in and/or presented at a large number of meetings or conferences during the Phase II period of performance. A listing of these meeting/conferences can be found in Appendix C.

Under the umbrella of DOE's RCSP Program, the PCOR Partnership worked together with the other Regional Partnerships to bring value to public and private sector partners by sharing lessons learned and valuable information on regional sequestration activities. The PCOR Partnership was and will continue to be active in the following working groups:

- Public Outreach
- Capture and Transportation
- Geologic and Infrastructure
- GIS and Database
- Monitoring
- Simulation and Risk Assessment
- Regulatory
- Water
- North American Energy
- North American Carbon Atlas Partnership

The PCOR Partnership hosted the 3rd Annual Regional Partnerships' Capture and Transportation Working Group Workshop at the EERC, Grand Forks, North Dakota, June 18–20, 2007. The Regional Partnerships' Capture and Transportation Working Group workshop is an annual event held to offer the CO_2 capture leads from each of the Regional Partnerships the opportunity to discuss their activities and to learn more about a particular topic of interest by attending presentations by invited speakers.

The PCOR Partnership was awarded IOGCC's Annual Chairman's Stewardship Award. IOGCC is a multistate government agency that promotes the conservation and efficient recovery of domestic oil and natural gas resources while protecting health, safety, and the environment. The award represents IOGCC's highest honor for exemplary efforts in environmental stewardship. The award was presented on Monday, November 17, 2008, during the general session of IOGCC's Annual Meeting in Santa Fe, New Mexico.

Ed Steadman and John Harju received the "Distinguished Service – Research and Development Award" from the North Dakota Lignite Energy Council because of their leadership and counsel on CO_2 storage projects involving the lignite industry. The awards were presented on October 8, 2009, in Bismarck, North Dakota.

7.0 PHASE II CONCLUSIONS

The Phase II programmatic efforts of the PCOR Partnership included the completion of four field validation tests (three geologic and one terrestrial) as well as parallel investigations of the CO_2 sequestration potential of the region, of commercially available sequestration technologies for large-scale deployment in the region, and of the regulatory and permitting issues associated with this deployment. In addition, the outreach efforts begun in Phase I were expanded and continued, interacting with multiple levels of the public and project stakeholders.

Based on these Phase II activities, it was concluded that the PCOR Partnership region has tremendous carbon storage potential. Tertiary-phase EOR, where CO_2 storage and EOR are simultaneously achieved, represents the primary near-term opportunity for storing CO_2 in the region, so much so that the regional EOR demand for CO_2 exceeds the near-term supply. The PCOR Partnership region includes hundreds of large stationary sources of CO_2, many of which are located in close proximity (within 100 miles) to oil fields that are suitable for CO_2-based EOR operations. The size of the potential oil resource in the PCOR Partnership region that may be associated with CO_2-based EOR is over 3.4 billion barrels of oil (Sorensen et al., 2006). At a price of $70/barrel, this resource could have a value over $238 billion. These economics provide a substantial incentive to develop large-scale CCS projects for some of those close-proximity sources.

Once the EOR opportunities are exhausted, substantial saline formation capacities that are both stratigraphically and geographically proximal can be utilized. This staged EOR/sequestration to sequestration approach has the added advantage of being accompanied by a significant economic incentive, which has the potential to drive the large-scale deployment of this carbon sequestration strategy. One key near-term source of CO_2, which is somewhat unique in its scale in the PCOR Partnership region, is the natural gas-processing industry. Approximately 68 gas-processing facilities have been identified in the region, with the potential to provide over 11.4 million tons of CO_2 for CCS on an annual basis.

7.1 Field Validation Tests

Two categories of EOR opportunities within the region that have significant CO_2 storage potential are the pinnacle reef structures that were examined as part of the Zama Field Validation Test and the deep carbonate formations that were investigated in the Williston Basin. The former validation test also confirmed the ability to safely and effectively inject and store H_2S-rich acid gas, thereby avoiding the need to remove the H_2S from the CO_2 prior to storage; the latter validation test demonstrated the feasibility of EOR/CO_2 storage using HnP techniques at significant depths (i.e., ~8000 feet). Additionally, the lignite field validation test revealed that unminable lignite may also represent a viable sequestration target for CO_2 although more research is needed prior to large-scale deployment of this approach to carbon storage. The field test data did not support the concept that the commercial production of CBM would be enhanced during CO_2 storage in these coals. Finally, a terrestrial field validation test determined that the wetlands of the PPR represent significant targets for terrestrial CO_2 storage and, along with the adjacent agricultural lands, may represent a key near-term strategy to offset CO_2 emissions.

CCS MVA Protocols

The Phase II efforts also demonstrated that MVA programs can be designed that are technically effective, cost-effective, and unobtrusive to commercial operations. A variety of monitoring tools were investigated and proved to be effective for the different validation tests. Specifically at the lignite field site, it was determined that a combination of seismic image tomography (i.e., cross-well seismic tomography) and RST measurements provided a valuable depiction of CO_2 plume movement at the site, while downhole sensors greatly augmented those observations. This combination of tools permitted the verification of the CO_2 injection into the

targeted depth interval as well as an assessment of the plume extent. In the deep carbonate formations (~8000 feet) of the Williston Basin, it was determined that relatively small amounts of CO_2 could be identified using Schlumberger's RST and VSP as MVA tools. Lastly, tracer and pressure-monitoring efforts were used as part of an MVA strategy during the Zama Field Validation Test. While we suggest that these approaches should be studied in more detail in the future, they were shown to be effective elements of an integrated, noninvasive, and cost-effective MVA strategy.

Terrestrial Field Test

The results of this validation test indicate that there is great potential for carbon sequestration in grassland and wetland catchments located throughout the PCOR Partnership region. The sequestration rates in the various grasslands that were sampled were all comparable to recently published rates, and it was concluded that GHG emissions from wetland catchments would not offset potential soil carbon sequestration benefits associated with restored wetlands. As a direct result of this test, approximately 130,000 tons of native grassland carbon offsets were generated in the PCOR Partnership region and were sold in September 2008; negotiations are currently under way to transact an additional 600,000 tons. The legal instruments and database tools developed during this validation test were used to ensure a smooth transaction, transparency, and efficient reporting.

Terrestrial sequestration in the PCOR Partnership region has many opportunities to benefit from carbon market finance with the development of federal climate legislation that results in a robust offset program. Results from this validation test will continue to be instrumental in the future development of methodologies and protocols to further advance terrestrial offsets in regulated and voluntary carbon markets (Botnen, B., et al., 2008).

Regulatory and Permitting Issues

The PCOR Partnership developed permitting action plans for each of the Phase II field validation tests to ensure that each test complied with the current rules and regulations for these operations. These plans represent prototypes that can be used to guide future projects, recognizing that the rules and regulations continue to evolve over time. In particular, a great deal of development has occurred at the regional, state/provincial, and federal levels with regard to CCS policy that may affect the way similar projects will be permitted in the future. To stay current with these policy and regulatory developments, the PCOR Partnership benchmarked the regulatory and policy status of the primary governing bodies within the region by a conducting a workshop in Deadwood, South Dakota, in June 2009. It was concluded from this workshop that both state and provincial legislatures are continuing to take the initiative to establish their CCS rules. In addition, various regional initiatives continue to evolve across the United States and Canada to develop GHG emission strategies in which CCS will likely play a role as an offset option.

Regional Characterization

Regional characterization activities continued to play an important role in the PCOR Partnership Program during Phase II. The wealth of data developed or obtained through the first two phases of the program has provided the PCOR Partnership with the information necessary to define and assess regional sequestration opportunities. The data have been compiled, stored, and managed in the DSS as a means to deliver knowledge of the character and spatial relationship of sources, sinks, and infrastructure to the PCOR Partnership members. Partners who utilize the DSS also provide the PCOR Partnership with valuable input regarding key data elements and sources of information for further characterization. As part of Phase II, this effort was showcased in the formal working agreements that were established with the Iowa Geological Survey as well as those that were put in place with the Missouri Department of Natural Resources for the Phase III efforts of the project. Real value has been added to the program by focusing the regional characterization efforts on the expansion of the broad geologic view of the region while also integrating the data from more subregional investigations, which typically are associated with higher levels of confidence.

Commercial Availability of Sequestration Technologies for Large-Scale Deployment

Current cost estimates for the capture, compression, and pipeline transportation network required for the effective implementation of CCS are significant, leading to the conclusion that additional research is needed to identify more cost-effective capture and compression technologies. Related to this research need, larger- and longer-duration demonstration tests for the integrated capture, compression, transportation, and injection of CO_2 are needed to not only verify the ability to safely store CO_2 on a large scale but to provide robust economic data that can be used to generate more accurate estimates of the cost of their implementation.

All industries will need to evaluate carbon management strategies that will minimize the carbon intensity of their products through the use of alternative fuel sources, such as wind and biomass, as well as through the use of both terrestrial and geologic sequestration and trading of carbon offsets. Even though the North American carbon markets are in their infancy and the exact type of market structure and associated value of credits have not been determined, parametric and statistical studies are recommended to bound the problem and to identify the plausible combination of approaches that would be candidates for achieving the mandated and/or desired targets.

Public Outreach

It became even more evident during Phase II that outreach activities are critical to the success of the large-scale deployment of CO_2 storage projects. It was determined that these outreach activities are most effective when they are conducted at multiple levels, i.e., local community levels to nationwide venues. Moving forward, the previously successful outreach efforts will continue to be strengthened by drawing on the expertise developed by outreach programs and partners in other regions, including presentations at partnership events and collaboration on outreach projects. Lessons learned will be communicated to external groups by

participation in outreach advisory groups (i.e., project and regional groups as well as groups on the international stage). Finally, greater resources will be focused toward native populations and other groups which are often underserved by mainstream information channels. At the same time, improved feedback and tracking capabilities will be implemented to aid in planning for more effective outreach activities and the capacity will be increased to take advantage of in-place networks like the Web, including social networking, magazines, and the education system, to broaden and strengthen outreach capabilities and improve the ongoing deliverability of messages regarding sequestration.

7.2 Suggestions for Further Study

The Phase II program results did not answer all of the technical, regulatory, or economic questions related to the full-scale deployment of the various carbon storage strategies. Some of these outstanding questions and what should be done to address them are provided as follows.

Acid Gas Injection/EOR

There are still several questions that need to be answered before large-scale subsurface acid gas injection can be deployed at an international level. Some of the more critical of these questions, which should be answered as part of the Phase III program (either in the laboratory or in the field), are as follows:

1. Are preexisting and current wellbore completion and abandonment techniques satisfactory for acid gas injection sites? Does the acid gas result in the advanced deterioration of wellbore cements and lead to the eventual leakage of gas to the atmosphere? If so, when might this leakage occur and at what rate?

2. Does the acid gas interact with the cap rock, and will these interactions lead to the accelerated degradation of cap rock material?

3. What chemical and geochemical processes control the long-term storage of CO_2 and H_2S, and can these processes be adequately modeled to predict the subsurface fate and transport of these gases over time?

4. What monitoring techniques should be used to ensure the cost-effective, early detection of potential gas leaks from the formation and to verify the quantities of CO_2 that are sequestered?

We suggest that the Zama site is ideal to conduct a research program aimed at answering the questions above for the following reasons: 1) an excellent partnership with the field operator, Apache, exists; 2) the unique geological setting with respect to the isolated nature and geometry of pinnacle reef structures ensures containment of the injected acid gas; 3) injection of acid gas is ongoing at the site and will continue to remain active as an EOR scheme; and 4) the lithology is characteristic of much of the central interior of North America.

The Zama Field Validation Test demonstrated that acid gas can be safely injected into subsurface pinnacle reef structures while simultaneously sequestering CO_2 and producing additional oil. In order to extrapolate these results to other facilities and geologic formations, one must carefully consider the particular lithology, pore fluids, and concentrations of injectate at the site being considered. For each site considered, one must strive to develop a fundamental understanding of the critical chemical and geochemical interactions, along with the fate and transport mechanisms that are likely to control the eventual size, shape, and makeup of the CO_2 plume.

Lignite Field Test

While the field validation test did indicate that lignites may be suitable targets for CCS in the future, the limited duration of this Phase II validation test did not permit the robust development of an optimal CO_2 injection strategy or the development and verification of a subsurface fate and transport model for CO_2. Further testing and demonstration will be required to provide the definition of an optimal and effective MVA protocol that could be broadly applied. These data gaps could be further resolved in future work by conducting a longer-duration test that would permit the optimization of this CO_2 sequestration strategy, the development and verification of a CO_2/methane subsurface fate and transport model, and the definition of a streamlined MVA protocol. The suite of laboratory tests that were conducted on the core samples provided valuable information for the validation test and should be conducted as part of this future demonstration test but with the goal of streamlining them to provide a more efficient system design support tool.

Williston Basin – EOR

The activities and results of the Northwest McGregor HnP project made several valuable contributions to the baseline characterization and monitoring components of MVA. With respect to baseline characterization, the project demonstrated that historical geological, production, and operational information obtained from the NDIC OGD well file database and the archives of the North Dakota Geological Survey Core Library can provide a tremendous amount of critical data with respect to the baseline conditions of both oil field reservoirs and individual wells. With respect to monitoring, the Northwest McGregor HnP project yielded previously unavailable field-based data on the effectiveness of using Schlumberger's RST and VSP technologies to develop a qualitative view of the vertical and horizontal nature of the injected CO_2 within a deep carbonate reservoir. The ability of these technologies to "see" the effects of the small-volume plume of CO_2 (<300 tons) at a depth greater than 8000 ft, as demonstrated at the Northwest McGregor field 3 months after injection, indicates that these technologies should be considered to be valuable additions to the MVA toolbox for future large-scale CCS projects.

The results of the Northwest McGregor HnP project suggest that smaller-scale CO_2-based HnP operations may be a viable means of improving the oil productivity of mature wells in the PCOR Partnership region, especially the Williston Basin. While the volumes of CO_2 that would ultimately be stored by HnP operations would be relatively small compared to a more conventional CO_2 flood, the use of CO_2 for HnP on individual wells may yield further

economically attractive opportunities, which will provide additional incentive for the creation of a CO_2 distribution infrastructure in the oil-producing areas of the PCOR Partnership region.

Terrestrial

Additional standards and protocol development should be developed in order for grassland- and wetland-based terrestrial sequestration to gain full traction in future voluntary and/or regulatory markets. This development will rely heavily on carbon model development. The greatest impediment to advanced carbon sequestration model development is the lack of monitoring and the understanding of terrestrial carbon cycling in various ecosystems. Because of the amount of research on forest–carbon dynamics, forestry offsets are the most commonly recognized terrestrial offset. If the carbon values of other ecosystems are to be fully recognized, further research efforts should emphasize research into the carbon cycles within each of other ecosystems. In summary, additional research efforts should focus on:

- The development of improved MVA systems, methods, and protocols. This will include the refinement of direct measurement technologies for critical GHGs and address leakage concerns.

- An analysis of the impacts of bioenergy production and markets on terrestrial carbon sequestration.

- The development of process-based biogeochemical models that can be used to forecast the influence of climate and land use change scenarios on GWP and associated ecosystem services (e.g., wildlife habitat, water quality, soil erosion, floodwater storage).

- An extensive analysis and comparison of GHG flux and carbon uptake and storage between native grasslands and agricultural lands. This may lead to certifiable CH_4 and N_2O credits.

- An expansion of existing grazing and haying studies to broaden the understanding of their respective impacts on carbon uptake and storage.

- The continuation of sampling at current sites to establish long-term trends in carbon storage and GHG flux. This will allow us to refine current BMPs for sequestering CO_2 in prairie wetlands and grasslands and will lead to the development of more robust models.

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APPENDIX A

EXTERNAL COVERAGE OF PCOR PARTNERSHIP AND PCOR PARTNERSHIP REGION SEQUESTRATION ACTIVITIES

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Table A-1. External Coverage of PCOR Partnership and PCOR Partnership Region Sequestration Activities (April 1, 2006, to September 30, 2009; primary coverage shaded)

Date	Headline	Media Organization/Publication	Journalist, Author, or Source	Type
Apr-06	Second phase of the Weyburn CO_2 Monitoring and Storage Project initiated	NETL Accomplishments FY2005	U.S. Department of Energy National Energy Technology Laboratory	Magazine article
7/17/2006	Carbon sequestration partnerships begin next phase of injection tests	GHG Transactions/Technologies	Staff Report	Newsletter article
11/2/2006	EERC receives $67 million for carbon dioxide project	Grand Forks Herald	Susanne Nadeau	Newspaper article
11/17/2006	EERC looks to develop sequestration method	Dakota Student	Dan Rudy	Newspaper article
Winter 2006/2007	Carbon dioxide sequestration communications supported by GIS	ArcNews Online	Staff Report	Online article
Jan-07	PCOR partnership moves into Phase III of carbon sequestration	Partners for Affordable Energy	Staff Report	Magazine article
Feb-07	Minnesota utilities involved in regional carbon sequestration field tests	Partners for Affordable Energy	Staff Report	Online article
2/28/2007	Gerald Groenewold and John Harju interview: EERC's CO_2 program	KVLY-TV 11	Neil Carlson	Television
6/18/2007	PCOR brings together U.S., Canadian partners for CO_2 sequestration initiatives	energyevolution	Staff Report	Online article
8/1/2007	EERC to drill in Burke County to evaluate carbon dioxide sequestration potential	Burke County Tribune	Staff Report	Newspaper article
8/10/2007	Burke sites to test carbon dioxide storage	Bismarck Tribune	Associated Press	Newspaper article
8/10/2007	Drilling begins in N.D. county to test carbon dioxide storage	The Fargo Forum	Associated Press	Newspaper article
8/10/2007	Drilling starts in Burke County to study carbon dioxide storage	Dickinson Press	Associated Press	Newspaper article
8/15/2007	EERC conducting tests in Burke County on unminable coal seams for CO_2 storage	Bowbells, Burke Co. Tribune	Jackie D. Johnson	Newspaper article
10/9/2007	DOE awards first three large-scale carbon sequestration projects	United States Department of Energy Office of Public Affairs	Megan Barnett	News release
10/10/2007	EERC-led project lands $67 million to study carbon capture, storage	Grand Forks Herald	Staff Report	Newspaper article

10/11/2007	UND leading carbon capture study	KFYR-TV	Staff Report	Television
10/11/2007	UND leading a carbon capture study	KVLY-TV 11	Neil Carlson	Television
10/15/2007	DOE pledges nearly $200M to first large-scale carbon-capture projects	Inside Energy with Federal Lands	Alexander Duncan	Magazine article
10/15/2007	Coal wins round versus gas with government sequestration funding	Natural Gas Week	Greg Couturier	Newsletter article
11/3/2007	Can we bury CO_2 in North Dakota prairie?	Star Tribune	Bill McAuliffe	Newspaper article
12/20/2007	Million tons of CO_2 will be injected under Illinois	Environment News Service	Staff Report	Online article
Jan-08	Gas and go: states test stashing CO_2 underground	Governing Magazine	Josh Goodman	Magazine article
Jan-08	PCOR announces two CO_2 storage projects for Phase III	Partners for Affordable Energy, ND Energy Watch Update	Staff Report	Newsletter article
Jan-08	PCOR announces two CO_2 storage projects for Phase III	Partners for Affordable Energy, MN Energy Watch Update	Staff Report	Newsletter article
1/22/2008	Researchers seek better ways to deal with CO_2	Bismarck Tribune	Tony Spilde	Newspaper article
1/23/2008	Researchers study ways to store carbon dioxide	Grand Forks Herald	Associated Press	Newspaper article
1/23/2008	Researchers studying ways to store carbon dioxide in N.D.	Minot Daily News	Associated Press	Newspaper article
1/23/2008	Storing carbon dioxide being studied	Devils Lake Journal	Associated Press	Newspaper article
1/23/2008	Researchers studying ways to store carbon dioxide in ND	Williston Daily Herald	Associated Press	Newspaper article
1/23/2008	Researchers studying ways to store carbon dioxide in N.D.	Jamestown Sun	Associated Press	Newspaper article
1/23/2008	Researchers study ways to store carbon dioxide in N.D.	Dickinson Press	Associated Press	Newspaper article
1/25/2008	North Dakota: Commission OKs grants for oil, CO_2 research	Grand Forks Herald	Janell Cole	Newspaper article
4/4/2008	Informational meeting on carbon sequestration project set for April 15, 2008	EERC	Derek Walters	News release
4/9/2008	Informational meeting on carbon sequestration project set for April 15	Bowbells, Burke Co. Tribune	Staff Report	Newspaper article

4/14/2008	The EERC's second major carbon sequestration documentary premieres on Prairie Public Television Thursday, April 17, 2008	EERC	Derek Walters	News release
4/16/2008	EERC's carbon sequestration documentary premieres April 17	University Letter	EERC	Newsletter article
4/17/2008	EERC's carbon sequestration documentary to air	The Chokio Review	Staff Report	Newspaper article
4/30/2008	PCOR continues carbon dioxide sequestration in Burke County	Bowbells, Burke Co. Tribune	Jackie D. Johnson	Newspaper article
6/2/2008	International partnership evaluates feasibility of major carbon capture and storage project in British Columbia, Canada	Interest Alert	Newswise	Online article
6/3/2008	International partnership evaluates feasibility of major carbon capture and storage project in British Columbia, Canada	EERC	Derek Walters	News release
6/3/2008	International partnership evaluates feasibility of major carbon capture and storage project in British Columbia, Canada	Environmental News Network	EERC	Online article
6/3/2008	International partnership evaluates feasibility of major carbon capture and storage project in British Columbia, Canada	Newswise (Charlottesville, VA)	EERC	Online article
6/3/2008	Large scale carbon capture studied	North Denver Tribune (CO)	EERC	Online article
6/3/2008	International partnership to conduct CCS project	Power Engineering (Tulsa, OK)	Penn Well Corporation	Online article
6/4/2008	International partnership evaluates feasibility of major carbon capture and storage project	University Letter	EERC	Newsletter article
6/10/2008	Hawaii joins DOE's carbon sequestration regional partnership program	Raging Bull Message Boards (Andover, MA)	Staff Report	Online article

8/4/2008	State partners with electric utilities on CO2 capture projects	Valley City Times-Record	Staff Report	Newspaper article
8/4/2008	State partners with electric utilities on CO2 capture projects	Valley City Times-Record	Staff Report	Newspaper article
8/8/2008	EERC's Plains CO_2 Reduction Partnership and Ducks Unlimited announce carbon credit program	EERC	Derek Walters	News release
8/8/2008	EERC's Plains CO_2 Reduction Partnership and Ducks Unlimited announce carbon credit program	Newswise	EERC	Online article
8/8/2008	EERC's Plains CO_2 Reduction Partnership and Ducks Unlimited announce carbon credit program	Environmental News Network	EERC	Online article
8/9/2008	Partnership protects ducks by cutting greenhouses gases	The Forum	Blake Nicholson	Newspaper article
8/9/2008	EERC partnership, DU set up carbon credit program	Grand Forks Herald	Staff Report	Newspaper article
8/9/2008	New carbon credit program aims to help ducks	Minot Daily News	Blake Nicholson	Newspaper article
8/9/2008	New program to aid number of ducks	Tribune Chronicle	Blake Nicholson	Newspaper article
8/10/2008	Program aims to help ducks	Jamestown Sun (Weekend Edition)	Blake Nicholson	Newspaper article
8/13/2008	EERC and Ducks Unlimited announce carbon credit program	University Letter	EERC	Newsletter article
8/13/2008	EERC's Plains CO_2 Reduction Partnership and Ducks Unlimited announce carbon credit program	E-Wire	EERC	Online article
9/15/2008	EERC announce partnership for program	Barnesville Record-Review	Staff Report	Newspaper article
1/16/2009	EERC awarded for CO_2 sequestration	Dakota Student	Michael Thomas	Newspaper article
1/17/2009	Bill seeks to regulate CO_2 storage	Minot Daily News	Gwen Bristol	Newspaper article
1/17/2009	Bills put N.D. in front on storage of CO_2	Grand Forks Herald	Janell Cole and the Associated Press	Newspaper article
1/17/2009	Bill seeks to regulate CO_2 storage	Minot Daily News	Gwen Bristol	Online article
2/26/2009	CO_2 storage rules are proposed	Williston Daily Herald	Dale Wetzel	Newspaper article

3/10/2009	CO_2 storage project starts in Burke County	AP State Online North Dakota	Associated Press	Online article
3/10/2009	CO_2 storage project starts in Burke County	KXNet.com	Associated Press	Online article
3/11/2009	CO_2 storage project starts in Burke County	Jamestown Sun	Associated Press	Newspaper article
3/11/2009	CO_2 storage project starts in Burke	The Bismarck Tribune	Associated Press	Newspaper article
3/11/2009	CO_2 storage starts in Burke County	Williston Daily Herald	Associated Press	Newspaper article
3/11/2009	DOE regional partnership initiates CO_2 injection in lignite coal seam	Green Car Congress	Staff Report	Online article
3/13/2009	CO_2 storage project	Grand Forks Herald	Staff Report	Newspaper article
4/1/2009	Capturing CO_2: membrane systems move forward	Chemical Engineering Progress	Suzanne Shelley	Magazine article
4/2/2009	Sequestering carbon dioxide	KXMA-TV Channel 2	Staff Report	Television
4/2/2009	Sequestering carbon dioxide	KXMB-TV Channel 12	Staff Report	Television
4/2/2009	Sequestering carbon dioxide	KXMD-TV Channel 11	Staff Report	Television
4/2/2009	Sequestering carbon dioxide	KXMC-TV Channel 13	Staff Report	Television
5/23/2009	DOE regional partnership begins core sampling for large-volume carbon sequestration test	Green Car Congress	Staff Report	Online Article
5/23/2009	DOE regional partnership begins core sampling for large-volume carbon sequestration test	Green Car Congress	Staff Report	Online article
8/5/2009	Carbon capture and storage is a necessary action	Grand Forks Herald	Ed Steadman	Newspaper article
8/17/2009	Restored wetlands lead to increased terrestrial CO_2 sequestration	Partners for Affordable Energy	Steve Van Dyke	Online article

APPENDIX B

PHASE II PCOR PARTNERSHIP PRODUCTS

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PHASE II PCOR PARTNERSHIP PRODUCTS

Table B-1. Phase II: Project Deliverables

Title/Description	Completion Date
Zama Field Validation Test Experimental Design Package (D4)	2/28/06
Zama Field Validation Test NEPA Compliance Document (D5)	12/21/05
Zama Field Validation Test Site Health and Safety Plan (D10)	3/31/06
Zama Field Validation Test Regulatory Permitting Action Plan (D11)	3/28/06
Zama Field Validation Test Outreach Action Plan (D15)	4/28/06
Zama Field Validation Test Sampling Protocols (D18)	6/29/06
Zama Acid Gas Project (Fact Sheet 7) (D20)	7/28/06
Zama Field Validation Test Regional Technology Implementation Plan (D52)	9/30/09
Lignite Field Validation Test NEPA Compliance Document (D24)	10/13/06
Lignite Field Validation Test Experimental Design Package (D26)	2/28/07
Lignite Field Validation Test Site Health and Safety Plan (D27)	3/29/07
Lignite Field Validation Test Regulatory Permitting Action Plan (D28)	3/30/07
Lignite Field Validation Test Outreach Action Plan (D29)	4/27/07
CO_2 Sequestration Validation Test in a Deep, Unminable Lignite Seam in Western North Dakota (Fact Sheet 10) (D31)	5/31/07
Lignite Field Validation Test Sampling Protocols (D32)	6/29/07
Lignite Field Validation Test Regional Technology Implementation Plan (D53)	9/30/09
CO_2 Sequestration Validation Test in a Deep Oil Field in the Williston Basin (Fact Sheet 12) (D37)	10/30/07
Williston Basin Field Validation Test NEPA Compliance Document (D41)	12/03/08
Williston Basin Field Validation Test Regulatory Permitting Action Plan (D40)	12/11/08
Williston Basin Field Validation Test Site Health and Safety Plan (D43)	12/23/08
Williston Basin Field Validation Test Experimental Design Package (D42)	12/31/08
Williston Basin Field Validation Test Outreach Action Plan (D45)	2/27/09
Williston Basin Field Validation Test Sampling Protocols (D46)	4/30/09
Williston Basin Field Validation Test Regional Tech. Implementation Plan (D55)	12/29/09
Terrestrial Field Validation Test Site Health and Safety Plan (D12)	2/2/06
Terrestrial Field Validation Test NEPA Compliance Document (D7)	2/14/06
Terrestrial Field Validation Test Experimental Design Package (D6)	2/28/06
Terrestrial Field Validation Test Regulatory Permitting Action Plan (D13)	3/27/06
Terrestrial Field Validation Test Outreach Action Plan (D16)	4/28/06
Terrestrial Field Validation Test Sampling Protocols (D19)	6/21/06
CO_2 Sequestration Through Habitat Restoration – Defining Best Terrestrial Sequestration Practices for Landowners (Fact Sheet 8) (D25)	12/29/06
Terrestrial Field Validation Test Regional Technology Implementation Plan (D54)	7/30/09
First Regional Characterization Data Gap Assessment (D8)	2/28/06
Denver–Julesberg Basin EOR Potential Report (D33)	4/30/07

Continued . . .

Table B-1. Phase II: Project Deliverables (continued)

Title/Description	Completion Date
Regional Characterization Data Gap Assessment Update (D36)	10/31/07
Road Map Document (D50)	6/30/09
Regional Atlas (D49)	9/21/09
Regional CO_2 Sequestration Potential – Field Validation Tests (Fact Sheet 6) (D2)	12/29/05
Outreach Action Plan – Carbon Sequestration (D9)	2/28/06
PowerPoint Presentation: General Audience CO_2 Sequestration Outreach (D17)	5/31/06 2/28/07 5/30/08 12/31/08
Best Practices Manual: Outreach (D48)	5/29/09
Documentary: Carbon Trading (D35)	9/28/07
Documentary: Terrestrial CO_2 Sequestration (D39)	4/30/08
Documentary: Managing Carbon Dioxide: The Geologic Solution (D47)	5/29/09
Documentary: Carbon Footprint – One Size Does Not Fit All (D51)	12/29/09
Best Practice Manual: Using Wind Power to Offset the Energy Requirements of CO_2 Compression for Sequestration (D23)	10/31/06
Best Practice Manual: Excelsior Energy (D38)	11/30/07
Best Practice Manual: Regional Sequestration Opportunities (D44)	7/31/08
Regional Partnership Integration Plan (D21)	7/18/06
Project Management Plan (D1)	12/30/05
Quarterly Progress Report (D3)	1/30/06 4/28/06 7/26/06 10/31/06 1/31/07 4/25/07 7/25/07 10/31/07 1/31/08 4/30/08 7/31/08 10/31/08 1/30/09 4/30/09 7/31/09 11/02/09
Semiannual Report (D14)	4/28/06 10/31/06 4/30/07 10/31/07
Phase II Continuation Application/Progress Report (D34)	7/31/07
Phase II Final Report (D56)	12/29/09

Table B-2. Phase II: Value-Added Products

Title/Description	Date Completed
Carbon Dioxide Storage Capacity in Upper Cretaceous – Tertiary Ardley Coals in Alberta	10/5/06
Evaluation of Sink Options for Excelsior Energy's Proposed Plant	6/29/07
Unitization of Geologic Media for the Purpose of Monetizing Geologic Sequestration Credits	12/13/07
Estimates of CO_2 Storage Capacity in Selected Oil Fields of the Northern Great Plains Region of North America	12/14/07
Black Island Formation Outline	1/11/08
Broom Creek Formation Outline	1/11/08
Deadwood Formation Outline	1/11/08
Duperow Formation Outline	1/11/08
Red River Formation Outline	1/11/08
Winnipegosis Formation Outline	1/11/08
Cobenefits of Terrestrial Carbon Sequestration in the PCOR Partnership Region (Fact Sheet 9)	5/23/08
Carbon Dioxide Storage Capacity in Upper Cretaceous–Tertiary Ardley Coals in Alberta	9/12/08
Market Development for Terrestrial Sequestration on Private Lands	10/9/08
Carbon Dioxide Storage Capacity in Uneconomical Coal Beds in Alberta: Potential and Site Identification	5/20/09
CO_2 Emissions in the PCOR Partnership Region: Characterization and Calculation Methodologies	6/8/09
Carbon Dioxide Storage in Uneconomical Coal Beds in Alberta: Potential and Site Identification	5/20/09

APPENDIX C

NOTABLE PHASE II MEETINGS AND CONFERENCES ATTENDED OR PRESENTED AT BY PCOR PARTNERSHIP REPRESENTATIVES

NOTABLE PHASE II MEETINGS AND CONFERENCES ATENDED OR PRESENTED AT BY PCOR PARTNERSHIP REPRESENTATIVES

- Minneapolis, Minnesota, PCOR Partnership Phase I Wrap-Up/Phase II Kickoff Meeting (November 2005)

- Bismarck, North Dakota, meeting with the North Dakota Industrial Commission (NDIC) Lignite Research Council and the NDIC Oil and Gas Division (November 2005)

- Montreal, Quebec, Canada, meeting with Cansolv Technologies and the 11th Annual United Nations Climate Change Conference (December 2005)

- Bismarck, North Dakota, meeting with Ducks Unlimited (DU), Inc.; the EERC; and U.S. Geological Survey members of the terrestrial field validation test (December 2005)

- Sao Paulo and Rio de Janeiro, Brazil, production of PCOR Partnership Carbon Market Trading Video (January 2006)

- Fort Totten, North Dakota, Meeting with Spirit Lake Tribal Nation (January 2006)

- Grand Forks, North Dakota, Meeting with Ramgen Power Systems, Inc. (January 2006)

- Grand Forks, North Dakota, Meeting with Lignite Energy Council (February 2006)

- Houston, Texas, Petroleum Technology Transfer Council Workshop – DOE CO_2 Enhanced Oil Recovery Preproposal (February 2006)

- Columbus, Ohio, Geologic Working Group (March 2006)

- Calgary, Alberta, Canada, Calgary Chapter of the Society of Petroleum Engineers (March 2006)

- Madison, Wisconsin, Midwestern Association of State Departments of Agriculture Round-Table on Carbon Sequestration Meeting (March 2006)

- Bismarck, North Dakota, North Dakota State Teacher's Meeting (March 2006)

- Fargo, North Dakota, F-M Engineers Club – North Dakota Society of Professional Engineers (March 2006)

- Grand Forks, North Dakota, meeting with Suncor Energy, Inc. (March 2006)

- Palo Alto, California, Partnership Capture and Transportation Working Group Workshop (March 2006)

- Calgary, Alberta, Canada, Workshop on Public Communications for the Final Phase of the International Energy Agency Greenhouse Gas Weyburn Midale CO_2 Monitoring and Storage Project (April 2006)

- Calgary, Alberta, Canada, International Energy Agency (IEA) Greenhouse Gas (GHG) Research & Development Programme's Weyburn Midale CO_2 Monitoring and Storage Project Workshop on Communications, Outreach, and Regulatory Issues (April 2006)

- Western Interstate Energy Board Meeting, via conference call (April 2006)

- Phoenix, Arizona, 48th Cement Industry Technical Conference (April 2006)

- Valley City, North Dakota, North Dakota Academy of Science 96th Annual Meeting (April 2006)

- Billings, Montana, Interstate Oil and Gas Compact Commission (IOGCC) 2006 Midyear Meeting (May 2006)

- Calgary, Alberta, Canada, meeting with Alberta Energy and Utilities Board (EUB) and Apache Canada Ltd. (Apache) to discuss Zama Field trial (May 2006)

- Alexandria, Virginia, 5th Annual Conference on Carbon Capture & Sequestration (May 2006)

- Minot, North Dakota, Williston Basin Petroleum Conference (May 2006)

- Fargo, North Dakota, Farmer's Union press conference (May 2006)

- Trondheim, Norway, Greenhouse Gas Control Technologies Conference (GHGT-8) (June 2006)

- London, England, and Trondheim, Norway, interviews for Carbon Markets Documentary (Video 2) (June 2006)

- Grand Forks, North Dakota, PCOR Partnership Annual Terrestrial Working Group Meeting, EERC (June 2006)

- Bismarck, North Dakota, meeting with State Lands Board for easement (June 2006)

- Lawrence, Kansas, Geographic Information System (GIS)/Outreach/Geological Workshop (July 2006)

- South Dakota, meeting with Robert Gleason to view DU sites (July 2006)

- Mandan, North Dakota, attended Northern Great Plains Research Laboratory's Friends and Neighbors Day (July 2006)

- Zama, Alberta, Canada, meeting with Apache to tour Zama Field validation test site and film documentary footage (August 2006)

- San Diego, California, Sixth Annual Environmental Systems Research Institute (ESRI) Education User Conference (GIS-related) (August 2006)

- Pittsburgh, Pennsylvania, attended U.S. Environmental Protection Agency (EPA)/DOE Technical Meeting (August 2006)

- Calgary, Alberta, Canada, PCOR Partnership 2006 Annual Meeting (September 2006)

- Calgary, Alberta, Canada, participated in acid gas injection field trip being conducted by EUB and Alberta Research Council (September 2006)

- Pittsburgh, Pennsylvania, Regional Carbon Sequestration Review Meeting (October 2006)

- Denver, Colorado, Western Fuels Symposium (October 2006)

- Lawrence Berkeley National Laboratory, IEA 2nd Risk Assessment Network Meeting (October 2006)

- Regina, Saskatchewan, Canada, Saskatchewan and Northern Plains Oil and Gas Symposium (October 2006)

- Bismarck, North Dakota, GIS User Group Meeting (October 2006)

- Grand Forks, North Dakota, met with Lynn Helms, Ed Murphy, and David Hvinden from NDIC to discuss ongoing projects and opportunities (November 2006)

- Fargo, North Dakota, documentary interview with Mary Jo Roth (Great River Energy) at Prairie Public Broadcasting studios and follow-up discussions on draft video track (November 2006)

- Chicago, Illinois, and Washington, D.C., documentary interviews (November 2006)

- Calgary, Alberta, Canada, Zama Project Meeting (December 2006)
- Bismarck, North Dakota, Meeting with DU (December 2006)
- Houston, Texas, Society of Petroleum Engineers CO_2 Workshop (December 2006)
- Washington, D.C., North American Carbon Markets (January 2007)
- Tucson, Arizona, Electric Utilities Environmental Conference (January 2007)
- San Antonio, Texas, Ground Water Protection Council Regulatory Workshop on Geologic Sequestration of CO_2 (January 2007)
- Bismarck, North Dakota, meeting with DU to discuss terrestrial field demonstration (January 2007)
- Goebel Ranch, South Dakota, meeting to discuss terrestrial field demonstration with DU (February 2007)
- Houston, Texas, ESRI Petroleum Users Group Annual Meeting (February 2007)
- Bismarck, North Dakota, Public Service Commission talk about sequestration (February 2007)
- Calgary, Alberta, Canada, Zama Field Validation Demonstration Meeting (March 2007)
- Pittsburgh, Pennsylvania, The Capture and Transportation Model Seminar (March 2007)
- St. Paul, Minnesota, meting with Minnesota Geological Survey and Excelsior Energy to discuss Phase III (March 2007)
- Grand Forks, North Dakota, meeting to discuss terrestrial field demonstration (March 2007)
- Paris, France, Carbon Sequestration Leadership Forum (CSLF) Meeting (March 2007)
- Washington, D.C., Point Carbon North American Carbon Markets Conference (March 2007)
- Long Beach, California, American Association of Petroleum Geologists Annual Conference (April 2–4, 2007)

- Pittsburgh, Pennsylvania, discussion of Phase III activities with Headquarters and other RCSP Partnerships (April 11–12, 2007)

- Regina, Saskatchewan, Canada, Williston Basin Symposium (April 29 – May 1, 2007)

- Regina, Saskatchewan, Canada, participated in Western Canada Sedimentary Basin Working Group Meeting (May 2, 2007)

- Point Clear, Alabama, IOGCC (May 6–8, 2007)

- Pittsburgh, Pennsylvania, Sixth Annual Conference on Carbon Capture & Sequestration (May 7–10, 2007)

- New York, New York, Carbon Finance and Investment Summit (May 21–23, 2007)

- Bismarck, North Dakota, Meeting with Lignite Energy Council and regional utility companies to discuss Phase III (May 22, 2007)

- Calgary, Alberta, Canada, Zama Quarterly Meeting (June 5–8, 2007)

- Clearwater, Florida, 32nd International Technical Conference on Coal Utilization & Fuel Systems (June 10–15, 2007)

- San Diego, California, ESRI International Users Group Meeting (June 18–22, 2007)

- Beulah, North Dakota, toured the Dakota Gasification Company's Great Plains Synfuels Plant (June 18, 2007)

- Grand Forks, North Dakota, Carbon Capture, Separation, and Transportation Working Group Workshop at the Energy & Environmental Research Center (EERC) (June 19–20, 2007)

- Pittsburgh, Pennsylvania, Capacity Working Group Meeting (subgroup to Capacity Working Group) (June 21, 2007)

- Bismarck, North Dakota, Oil and Gas Research Council Meeting (June 25–26, 2007)

- Bismarck, North Dakota, meeting with NDIC and North Dakota Geological Survey to discuss the gas analysis project (July 24, 2007)

- Williston, North Dakota, meeting with Hess Corporation to discuss Phases II and III (August 2, 2007)

- Washington, D.C., Office of Science Review (August 14, 2007)
- Dickinson, North Dakota, American Petroleum Institute meeting (August 16–20, 2007)
- Houston, Texas, Capacity Working Group Meeting (August 23, 2007)
- Grand Forks, North Dakota, Missouri River Energy Meeting (Phase II membership discussion), EERC (August 28, 2007)
- Calgary, Alberta, Canada, Zama Quarterly Meeting (September 4–7, 2007)
- Johannesburg, South Africa, 24th Pittsburgh Coal Conference (September 10–14, 2007)
- Pittsburgh, Pennsylvania, Peer Review of the CS Program (September 17–20, 2007)
- Medora, North Dakota, North Dakota Petroleum Council 26th Annual Meeting (September 18–20, 2007)
- Arlington, Virginia, International Conference on Air Quality VI (September 24–26, 2007)
- Williston, North Dakota, North Dakota Association of Oil and Gas Counties Annual Meeting (September 27, 2007)
- San Antonio, Texas, Society of Exploration of Geophysicists Post Convention Workshop on "CO_2 Sequestration Monitoring" (September 28, 2007)
- Grand Forks, North Dakota, PCOR Partnership Annual Meeting, EERC (October 18–19, 2007)
- Bismarck, North Dakota, DU Carbon Kickoff Meeting (October 25–26, 2007)
- Washington, D.C., Senate Energy Staff Briefing on the Phase III Carbon Sequestration Partnerships Project Awards (October 26, 2007)
- Tampa, Florida, National Conference of State Legislatures Advanced Coal Technologies Energy Institute (October 31 – November 1, 2007)
- Calgary, Alberta, Zama Quarterly Meeting (November 5, 2007)
- Edmonton, Alberta, International Energy Agency (IEA) Meeting (November 6–8, 2007)

- San Francisco, California, Clean Power in the West Summit (November 7–9, 2007)

- Anaheim, California, Society of Petroleum Engineers Annual Technical Conference (November 11–14, 2007)

- Houston, Texas, Carbon Reduction Project Development and Finance (November 14–16, 2007)

- Grand Forks, North Dakota, presented to a graduate chemical engineering class at the University of North Dakota (November 28, 2007)

- Washington, D.C., Carbon Capture Status and Outlook Conference (December 3–5, 2007)

- New Orleans, Louisiana, POWER-GEN International (December 11–13, 2007)

- Pittsburgh, Pennsylvania, Regional Carbon Sequestration Partnership Review Meeting (December 12–13, 2007)

- Bismarck, North Dakota, presented at the Energy Generation Conference (January 30, 2008)

- Moorhead, Minnesota, presented to a group of college science students at the campus of Minnesota State University (February 2008)

- Missouri River Energy Services Board Meeting (February 14, 2008)

- Houston, Texas, attended the Environmental Systems Research Institute GIS Petroleum Users Group meeting (February 25–27, 2008)

- Houston, Texas, ESRI Petroleum User's Group Meeting (February 25–27, 2008)

- Arlington, Virginia, EPA's second public workshop to discuss the development of proposed regulations for the underground injection of carbon dioxide for geologic sequestration under the Safe Drinking Water Act (February 26–27, 2008)

- Phoenix, Arizona, attended a training class for developing GIS applications using .NET in GIS Server 9.2 (February 26–29, 2008)

- Minot, North Dakota, EmPower North Dakota Meeting (February 27, 2008)

- Bismarck, North Dakota, Industrial Commission Meeting (to vote on PCOR Partnership Phase III funding request) (February 29, 2008)

- Washington, D.C., The Edison Foundation's Carbon Capture and Storage: Key Issues and Challenges (March 3–4, 2008)

- Washington, D.C., World Resources Institute CCS Stakeholder Workshop (March 12–13, 2008)

- Washington, D.C., Office of Science Basic Energy Sciences Annual Geosciences Symposium, Courtyard Marriott Gaithersburg Washingtonian Center, Maryland, (March 12–14, 2008)

- Washington, D.C., 2008 RCSP Peer Review (IEA GHG Review) (March 25–28, 2008)

- Minot, North Dakota, North Dakota Science Teacher Meeting (March 28, 2008)

- Minneapolis, Minnesota, attended the Geologic Characterization Meeting (April 17, 2008)

- San Antonio, Texas, AAPG Convention & Exhibition (April 20–24, 2008)

- Minot, North Dakota, 16th Williston Basin Petroleum Conference & Expo (April 27–29, 2008)

- Pittsburgh, Pennsylvania, 7th Annual Carbon Capture & Sequestration Conference (May 5–8, 2008)

- New York, New York, Carbon Finance North America 2008 – Risk and Opportunities in Emissions Markets (June 4–6, 2008)

- Bismarck, North Dakota, Teachers Seminar (June 9–12, 2008)

- Fargo, North Dakota, SharePoint Seminar (June 10, 2008)

- New Mexico and Texas, Documentary filming (June 15–20, 2008)

- Winnipeg, Manitoba, Western Canadian Sedimentary Basin Geologic Working Group (June 18–19, 2008)

- Orlando, Florida, 4th International Symposium on Energy, Informatics and Cybernetics: EIC '08 (June 29 – July 2, 2008)

- Calgary, Alberta, meeting with partners to discuss Phase III demonstration and Zama project (July 7–11, 2008)

- Calgary, Alberta, Computer Modeling Group Ltd. Technical Symposium (July 8–11, 2008)

- San Diego, California, attended the ESRI International Users Conference (August 4–8, 2008)
- Louisville, Kentucky, Coal-Gen (August 13–15, 2008)
- Baltimore, Maryland, attended the Power Plant Air Pollutant Control "Mega" Symposium (August 25–28, 2008)
- Maple Grove, Minnesota, PCOR Partnership Annual Meeting (September 16–18, 2008)
- Cincinnati, Ohio, UIC and CO_2 Geosequestration Seminar (September 24, 2008)
- Chicago, Illinois, attended EPA public meeting on proposed rules for geologic sequestration (September 30, 2008)
- Pittsburgh, Pennsylvania, Pittsburgh Coal Conference (September 29 – October 2, 2008)
- Calgary, Alberta, met with Spectra Energy regarding the progress of the Fort Nelson project (January 6–9, 2009)
- Bismarck, North Dakota, project Meetings (January 13–16, 2009)
- San Antonio, Texas, Ground Water Protection Council & UIC Conference (January 26–28, 2009)
- Phoenix, Arizona, EUEC Conference (February 1–5, 2009)
- Bismarck, North Dakota, North Dakota Petroleum Council Board Room Meeting & Legislative Reception (February 3, 2009)
- Bismarck, North Dakota, Oil and Gas Research Council Meeting (February 4, 2009)
- Orleans, France, CO_2 Geological Storage Modeling Workshop (February 7–13, 2009)
- Minneapolis, Minnesota, meeting with Cargill (February 10, 2009)
- Pittsburgh, Pennsylvania, meeting with the U.S. DOE (February 11, 2009)
- Sioux Falls, South Dakota, presented to the Board of Directors of MRES (February 12, 2009)

- San Diego, California, Hydrogen Works: The Premier Professionals Training Course (February 17–19, 2009)

- Fargo, North Dakota, met with Prairie Public Broadcasting for Geologic Documentary (February 18, 2009)

- Crookston, Minnesota, presented to faculty and students at the University of Minnesota (February 19, 2009)

- Fargo, North Dakota, documentary Editing (March 9, 2009)

- Kansas City, Kansas, Ash Grove Cement Company – 2009 Plant Managers' Meeting/AGem Expo (March 11–13, 2009)

- Bismarck, North Dakota, project meetings (March 15–19, 2009)

- Menlo Park, California, EPRI CO_2 Transportation Workshop (March 16–18, 2009)

- San Francisco, California, 1st International Gas Symposium (March 22–26, 2009)

- Pittsburgh, Pennsylvania, Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting (March 23–26, 2009)

- Fargo, North Dakota, documentary editing (March 25, 2009)

- Gaithersburg, Maryland, Workshop on Future Large CO Compression Systems (March 30–31, 2009)

- Rockford, Illinois, presented at the 43rd Annual Meeting for Geological Society of America (GSA) and 2009 North-Central GSA Section Meeting (April 1–3, 2009)

- Rockford, Illinois, participated in the Roy J. Shlemon Mentor Program in Applied Geoscience Luncheon (April 3, 2009)

- Fargo, North Dakota, participated in a geologic sequestration (D46) documentary edit session at PPB studios (April 2, 9, 14, 21, 24, and 28, 2009)

- Bozeman, Montana, presented at the U.S. Department of Interior, Fish and Wildlife Service, Bozeman Fish Technology Center (April 15–17, 2009)

- Regina, Saskatchewan, Canada, attended the 17th Annual Williston Basin Petroleum Conference (April 26–29, 2009)

- Victoria, British Columbia, Canada, attended the Latitude Geographics GeoCortex User Conference (April 26 – May 1, 2009)

- Arlington, Virginia, attended the National Rural Electric Cooperative Association Cooperative Research Network CO_2 Capture & Utilization Symposium (April 30, 2009)

- Minneapolis, Minnesota, filming for the Carbon Footprint Documentary (D51) (May 2–8, 2009)

- Fargo, North Dakota, participated in a geologic sequestration (D46) documentary edit session at PPB studios (May 2, 7, 12, 17, 20, 23, and 28, 2009)

- Pittsburgh, Pennsylvania, attended and participated in the 8th Annual Conference on Carbon Capture & Sequestration (May 4–7, 2009)

- Moorhead, Minnesota, presented general PCOR Partnership information at the Moorhead Rotary Club (May 19, 2009)

- Delhi, India, filming for the Carbon Footprint Documentary (D51) (May 22 – June 2, 2009)

- Bismarck, North Dakota, attended meetings with DU and the U.S. Geological Survey (June 8–12, 2009)

- Ikata, Muyuka, Buea, Yaounde, Kribi, and Douala, Republic of Cameroon, West Africa, filming for the Carbon Footprint Documentary (D51) (June 12–23, 2009)

- Pittsburgh, Pennsylvania, met with National Energy Technology Laboratory personnel to design collaborative experiments on CO_2 sequestration under geological conditions (June 23, 2009)

- Washington, D.C., attended and participated in U.S.–Canada Clean Energy Dialogue Round-Table on Carbon Capture and Storage (June 29–30, 2009)

- Bismarck, North Dakota, attended the International Climate Stewardship Solutions Conference (June 29–30, 2009)

- Washington, D.C., attended Outreach Working Group Workshop (July 13–16, 2009)

- Fargo, North Dakota, attended editing session for geologic sequestration documentary at Prairie Public Broadcasting studios (August 27, 2009)

- Medora, North Dakota, attended the North Dakota Petroleum Council Annual Meeting (September 1–3, 2009)

- Fargo, North Dakota, attended editing sessions PPB at their offices (September 2, 4, 15, and 25, 2009)

- Bismarck, North Dakota, attended meetings with DU (September 9–11, 2009)

- Minneapolis, Minnesota, traveled to complete filming for the Carbon Footprint documentary (September 14–18, 2009)

- Pittsburgh, Pennsylvania, attended the 26th Annual International Pittsburgh Coal Conference (September 21–24, 2009)

- Kenmare, North Dakota, traveled for site sampling to the Lignite field site and Northwest McGregor field site (September 28 – October 2, 2009)

- Grand Junction, Colorado, presented at the 2009 Geology and Resources Conference American Institute of Professional Geologists annual meeting (October 4–6, 2009)

- Tioga, North Dakota, traveled for a site visit to the Northwest McGregor field site (October 5–7, 2009)

- Tioga, North Dakota, traveled for site sampling to the Northwest McGregor field site (October 6–10 and 19–23, 2009)

- Arlington, Virginia, presented at the EERC Air Quality VII Conference (October 24–29, 2009)

- New Town, North Dakota, presented "Opportunities for the Utilization of CO_2 in North Dakota" (October 28–30, 2009)

- Fargo, North Dakota, traveled for a documentary edit session to Prairie Public Broadcasting offices (October 30, 2009)

- Fargo, North Dakota, traveled for a documentary edit session to PPB offices (November 3, 13, 16, 18, and 25, 2009)

- St. Louis, Missouri, participated in the PCOR Partnership annual meeting and workshops (November 30 – December 3, 2009)

- Fargo, North Dakota, travel to an editing session at PPB (December 8, 11, 13–14, 2009)