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Review article

# The United States Department of Energy's Regional Carbon Sequestration Partnerships Program Validation Phase

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## Abstract

This paper reviews the Validation Phase (Phase II) of the Department of Energy's Regional Carbon Sequestration Partnerships initiative. In 2003, the U.S. Department of Energy created a nationwide network of seven Regional Carbon Sequestration Partnerships (RCSP) to help determine and implement the technology, infrastructure, and regulations most appropriate to promote carbon sequestration in different regions of the nation. The objectives of the Characterization Phase (Phase I) were to characterize the geologic and terrestrial opportunities for carbon sequestration; to identify $CO_2$ point sources within the territories of the individual partnerships; to assess the transportation infrastructure needed for future deployment; to evaluate $CO_2$ capture technologies for existing and future power plants; and to identify the most promising sequestration opportunities that would need to be validated through a series of field projects.

The Characterization Phase was highly successful, with the following achievements: established a national network of companies and professionals working to support sequestration deployment; created regional and national carbon sequestration atlases for the United States and portions of Canada; evaluated available and developing technologies for the capture of $CO_2$ from point sources; developed an improved understanding of the permitting requirements that future sequestration activities will need to address as well as defined the gap in permitting requirements for large scale deployment of these technologies; created a raised awareness of, and support for, carbon sequestration as a greenhouse gas (GHG) mitigation option, both within industry and among the general public; identified the most promising carbon sequestration opportunities for future field tests; and established protocols for project implementation, accounting, and management. Economic evaluation was started and is continuing and will be a factor in project selection.

During the Validation Phase, the seven regional partnerships will put the knowledge learned during the Characterization Phase into practice through field tests that will validate carbon sequestration technologies that are best suited to their respective regions of the country. These tests will verify technologies developed through DOE's core R&D effort and enable implementation of $CO_2$ sequestration on a large scale, should that become necessary. Pilot projects will have a site-specific focus to test technology; assess formation storage capacity and injectivity; validate and refine existing $CO_2$ formation models used to determine the transport and fate of $CO_2$ in the formation; demonstrate the integrity of geologic seals to contain $CO_2$; validate monitoring, mitigation, and verification (MMV) technologies; define project costs and compare costs of alternatives; assess potential operational and long-term storage risks; address regulatory requirements; and engage and evaluate public acceptance of sequestration technologies. Field validation tests involving both sequestration in geologic formations and terrestrial sequestration are being developed.

The results from the Validation Phase will help to confirm the estimates made during the Characterization Phase and will be used to update the regional atlases and NatCarb. Answers to many questions about the effectiveness and safety of carbon sequestration technologies will be instrumental in planning for a Deployment Phase, in which large volume tests will be planned to further sequestration as an option that can mitigate GHG emissions in the United States.


*Keywords:* Carbon; Sequestration; $CO_2$; Carbon dioxide; Regional; Partnerships; Geologic; Terrestrial

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## 1. Introduction

Coal is predicted to continue to dominate power generation for the next 25 years. Power generation from coal is one significant source of carbon dioxide ($CO_2$) emissions, making the effort to reduce these emissions a critical research need (EIA, 2005). The United States has made a commitment to work toward the long-term reduction of $CO_2$ emissions, which in the U.S. originate mainly from the combustion of fossil fuels for energy production, transportation, and other industrial processes, with about one third of U.S. anthropogenic $CO_2$ emissions coming from power plants (EIA, 2005). One promising approach for the reduction of $CO_2$ emissions is carbon capture and sequestration (CCS). The U.S. Department of Energy's (DOE) Carbon Sequestration Program continues to make progress towards the goals of lowering the cost of $CO_2$ capture and ensuring that the $CO_2$ can be safely and permanently sequestered (Klara and Srivastava, 2002; Klara et al., 2003). As sequestration technology has advanced, the topic has attracted the interest of a wide community; but deployment of carbon sequestration throughout the U.S. will require a comprehensive understanding of the requirements for capture, transport, storage, monitoring, and risk mitigation associated with implementation of this technology.

Geographical differences across the U.S. in fossil fuel use and potential sequestration storage sites dictate the use of a regional approach to address carbon sequestration. To accommodate these differences, in 2003 the DOE created a nationwide network of seven Regional Carbon Sequestration Partnerships (RCSP) to help determine and implement the technology, infrastructure, and regulations most appropriate to promote carbon sequestration in different regions of the nation as described in a previous article (Litynski et al., 2006a).

The seven regional partnerships created under the DOE program are (Fig. 1):

- Big Sky Carbon Sequestration Partnership (Big Sky)
- Midwest Geological Sequestration Consortium-Illinois Basin (MGSC)
- Midwest Regional Carbon Sequestration Partnership (MRCSP)
- Plains $CO_2$ Reduction Partnership (PCOR)
- Southeast Regional Carbon Sequestration Partnership (SECARB)
- Southwest Regional Partnership on Carbon Sequestration (SWP)
- West Coast Regional Carbon Sequestration Partnership (WESTCARB)

The Characterization Phase (also referred to as Phase I) of the partnerships initiative ended in September 2005, with a significant list of accomplishments. The Validation Phase (Phase II) began in October 2005 as a four-year effort with an investment of $157 million (including a cost share of $46 million) to conduct geologic and terrestrial sequestration field tests throughout the U.S.

## 2. Characterization Phase accomplishments

Significant Characterization Phase accomplishments (NETL, 2005) are discussed below. In addition, economic evaluations were started and are continuing and will be a factor in project selection for the Validation Phase.

### *2.1. Establishment of a national network to support $CO_2$ sequestration*

For a two-year investment of $19.9 million (including a cost share of $6.9 million) during the Characterization Phase, DOE

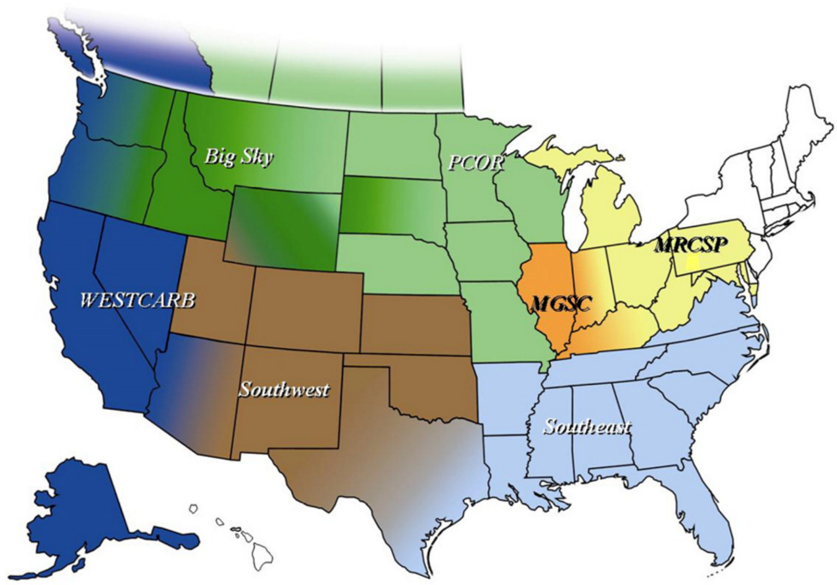


Fig. 1. Regional partnerships.

achieved the active participation in the development of CCS technology of over 500 professionals representing over 300 industrial companies, engineering firms, state agencies, environmental organizations, educational institutions, and other organizations.

### *2.2. Creation of carbon sequestration atlases for the regions and the United States*

An important objective of the Characterization Phase was to establish both regional atlases and a national carbon sequestration atlas containing information on $CO_2$ point sources, potential geologic sequestration sites, terrestrial sequestration opportunities, and the $CO_2$ transportation infrastructure. Each of the seven partnerships has developed an extensive database and geographic information system (GIS) that is used as a decision support system to identify locations where sequestration is most feasible within their regions. The national atlas contains information on over 5500 sources, representing about 45% of total U.S. $CO_2$ emissions. This information includes source location (latitude and longitude), amount of $CO_2$ emitted per year, the $CO_2$ concentration and pressure of the exhaust gas, and other data. The atlas also contains information on potential geologic and terrestrial sinks. For geologic reservoirs, data from

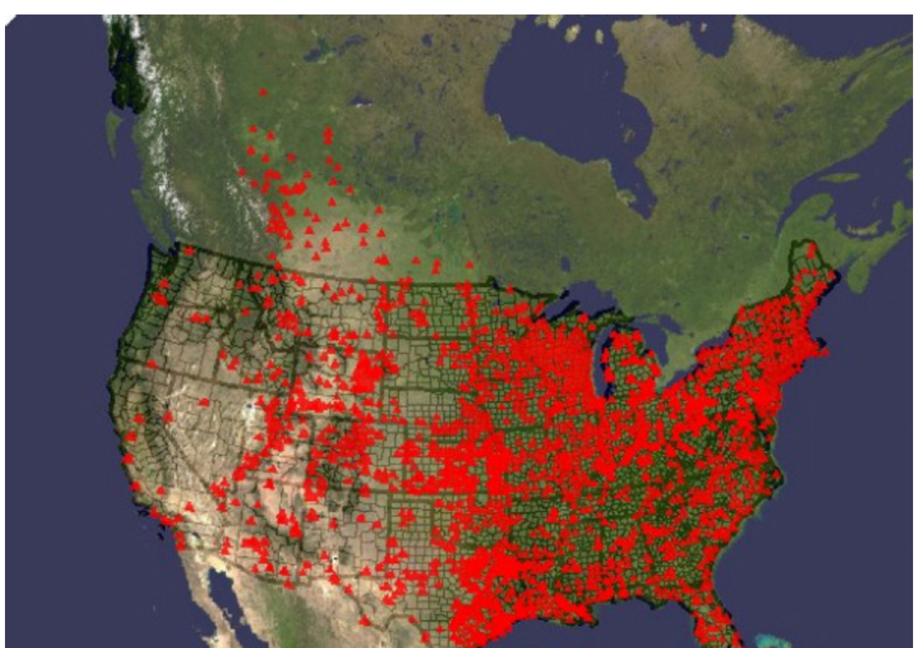

Fig. 2. $CO_2$ point sources.

hundreds of thousands of wells provide information on location, depth, temperature, porosity, and other pertinent information needed to evaluate a reservoir's potential as a $CO_2$ storage site. Data on terrestrial systems includes land use and management, climate (precipitation and temperature), soil properties, and other parameters needed to estimate the potential for increasing annual carbon uptake and long-term storage.

The national atlas is an internet-based portal called NatCarb. NatCarb is a mapping tool through which the partnerships are providing the carbon sequestration picture on a national scale. The NatCarb system was designed in collaboration with, and is similar in design and capabilities to, many of the regional systems.

The NatCarb portal permits exploration of national geologic and terrestrial carbon sequestration opportunities by linking databases from the seven regional partnerships into a single interactive mapping system. NatCarb is not a repository for partnership data. Each regional partnership retains ownership and control of its own data, and highly detailed regional sequestration maps are available through the partnerships. However, NatCarb's ability to link to partnership data and display potential sequestration opportunities on a national scale allows the public to explore options across partnership boundaries. The NatCarb portal is available through a public web site (NatCarb, 2006) that allows visitors to use its interactive mapping system and provides access to up-to-date information collected by the partnerships.

Figs. 2–5 display a series of NatCarb maps detailing $CO_2$ sources and potential geologic sinks (oil and natural gas fields, coal beds, and saline formations). Fig. 2 provides a visual depiction of $CO_2$ point sources across the U.S. and part of Canada. The red areas represent various $CO_2$ point sources, such as power plants, industrial facilities, natural gas processing plants, and other $CO_2$ emitting facilities and operations.

The orange, purple, and bright green areas in Fig. 3 show some of the oil and natural gas fields for the U.S. and a small section of Canada. Fig. 4 depicts coal beds across the U.S., with the various colors indicating coal type (see legend). The map shows significant potential sequestration opportunities associated with large coal beds in the Appalachians, the Southeast and Midwest regions, and the Rocky Mountain region.

Saline formations provide the largest potential for sequestration among the various geologic options. Fig. 5 illustrates the distribution of saline formations, which NatCarb developed using the National Energy Technology Laboratory's (NETL) National Brine Database. The map shows that the vast majority of sequestration opportunities in saline formations exist west of the Mississippi River and in the Gulf Region.

In addition to mapping source and sink information, NatCarb can provide detailed information from partnership databases on individual $CO_2$ point sources and geologic formations. Using NatCarb's polygon feature, a user is able to focus on one or a cluster of point sources or sinks by drawing a polygon around a data point or collection of data points on a map.

The NatCarb mapping system is able to overlay multiple data sets onto a single map. For example, saline formations can be overlaid with $CO_2$ point sources, enabling the user to visualize these two data sets in comparison to one another. In many instances, $CO_2$ point sources are either co-located with, or very near, potential sequestration sites. The ability to match sources and sinks though NatCarb's mapping capabilities provides policymakers and project developers an initial national overview of sequestration opportunities and is a critical first step in identifying possible $CO_2$ sequestration projects.

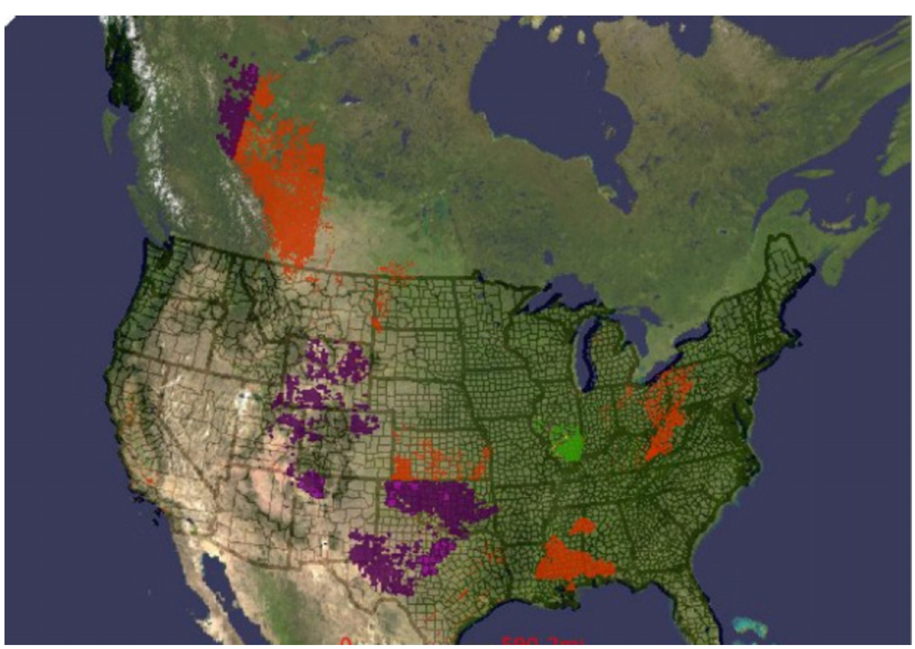

Fig. 3. Oil and natural gas fields.

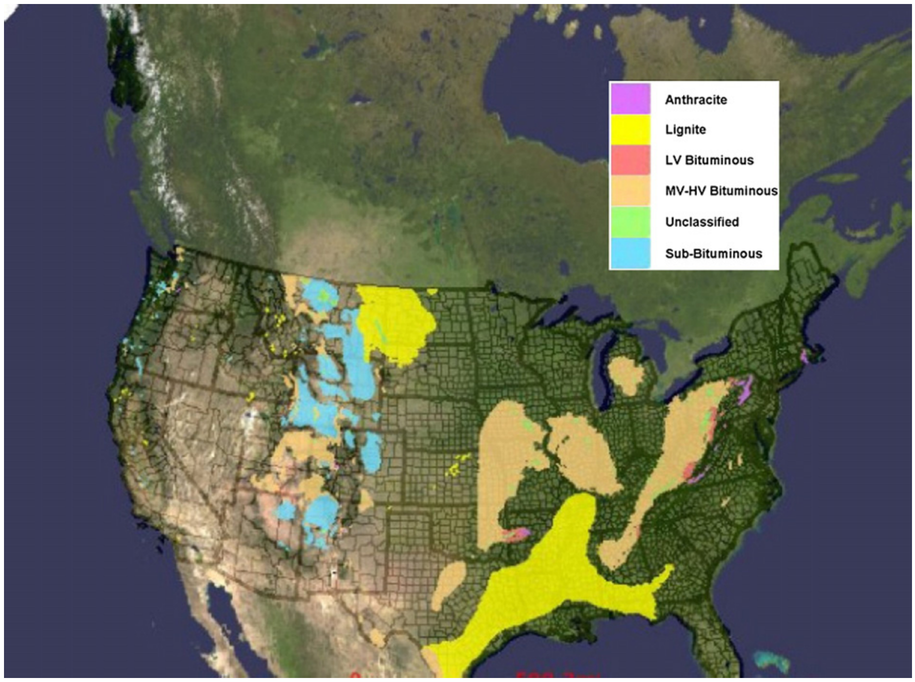


Fig. 4. Coal formations.

### *2.3. Determination of geologic sequestration opportunities*

The regional partnerships collected a significant amount of data on potential sinks in their regions, including information on the physical and chemical parameters of different reservoirs. Data were collected on sinks that had the potential to be suitable storage opportunities and for which characterization data were readily available. For geologic sequestration, information on saline formations, coal seams, oil and natural gas fields, and shales was collected. In addition, specific physical information on the seals which cap these geologic layers was collected to determine if injected $CO_2$ could be contained in the target formation.

### *2.4. Determination of major $CO_2$ point sources and evaluation of $CO_2$ capture technologies*

The partnerships determined that the major point sources of $CO_2$ emissions were power plants, refineries, gas processing plants, iron and steel plants, cement and lime plants, ammonia production, and ethanol production. The exact distribution

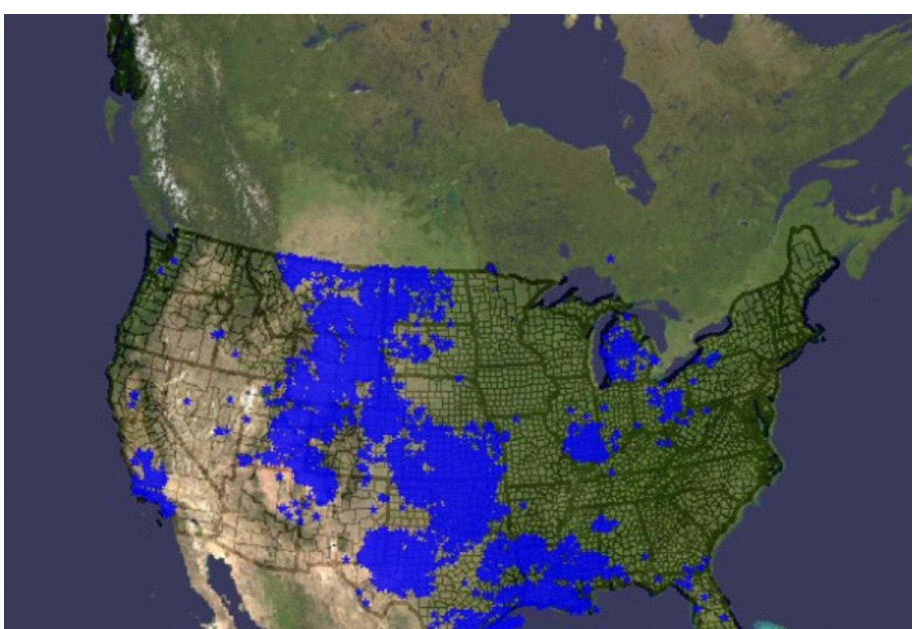

Fig. 5. Saline formations.

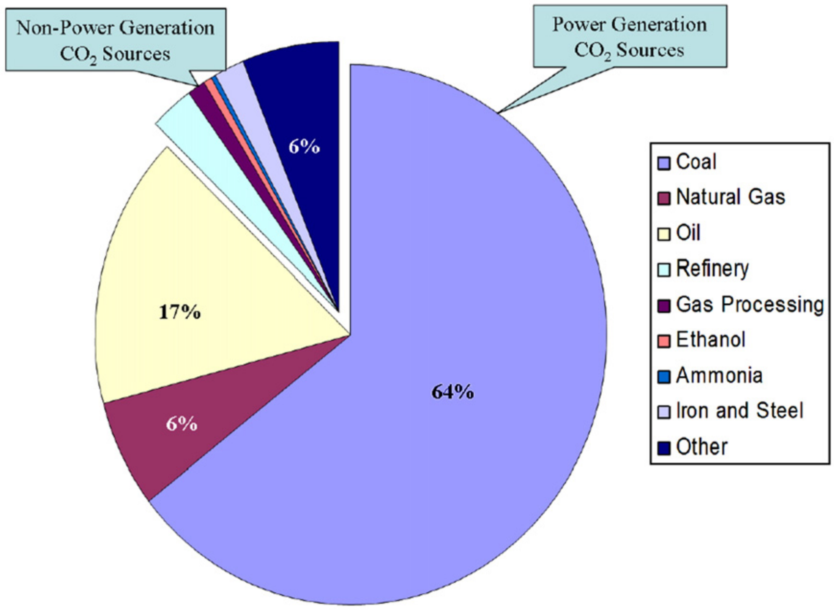


Fig. 6. $CO_2$ emissions profile for regional partnerships.

varied from region to region, but electric power production was a major contributor in all regions. Fig. 6 presents the $CO_2$ emissions profile for the area covered by the U.S. portion of the regional partnerships (Figueroa, 2005); 87% of the $CO_2$ emitted to the atmosphere from point sources is the result of electric power production using fossil fuels. Thus, for geologic sequestration to have a major impact on reducing emissions, capture technology must be developed that is applicable to recovering $CO_2$ from the flue gas from conventional power plants.

$CO_2$ sequestration in geologic formations is a three-step process: capture, transport, and injection. Of these three steps, capture is the most expensive and energy intensive by a large margin (IPCC, 2005). For this reason, development of improved capture processes is critical, if $CO_2$ sequestration is to live up to its potential as a mitigating factor for global climate change. The partnerships evaluated $CO_2$ capture technologies, both commercially available and under development (Klara and Srivastava, 2002; Figueroa, 2005; White et al., 2003). A few processes, such as ethanol production, inherently produce a concentrated stream of $CO_2$, suitable for sequestration. However, the $CO_2$ waste streams from most processes are relatively dilute. For example, the flue gas from a coal-fired power plant is typically at one atmosphere with a $CO_2$ concentration of about 14%. For PC plants, post-combustion $CO_2$ capture using monoethanolamine (MEA) is the most technically and economically viable, but substantial costs are involved due to the large parasitic power load (MGSC, 2005).

The applicability of various commercial and developing $CO_2$ capture technologies to the $CO_2$ sources shown in Fig. 6 are tabulated in Table 1. Fig. 7 shows estimated costs for $CO_2$ capture using the best currently available technologies. On average, using current technology, costs are in the range of \$50/ton of $CO_2$ captured (MRCSP, 2005).

### *2.5. Development of an improved understanding of permitting requirements*

Based on current knowledge, the risks from $CO_2$ transportation and sequestration appear to be small, particularly when

Table 1
Applicability of various $CO_2$ capture technologies (MRCSP, 2005)

| Source type | Point of capture | Amine scrubbing | Ammonia scrubbing | Physical absorption | Gas separation membrane | Gas absorption membrane | Oxyfuel+drying/ compression | Simple drying/ compression |
|---|---|---|---|---|---|---|---|---|
| Power Plants post-combustion | Flue gas | 1 | **2** | – | **2** | **2** | **2** | – |
| Power plants pre-combustion | Shifted syngas | – | – | 1 | **2** | – | – | – |
| Iron/steel facilities | Blast furnace gas (~60–70% of total $CO_2$) | 1 | – | 1 | **2** | 3 | – | – |
| Refineries | Heater/boiler flue gas (~65–85% of total $CO_2$) | 1 | 3 | – | **2** | 3 | **2** | – |
| Cement plants | Kiln flue gas | 1 | 3 | – | 3 | 3 | 3 | – |
| Gas processing plants | Vented $CO_2$ | – | – | – | – | – | – | 1 |

1 — Commercially available; **2** — actively being developed; 3 — very early stage of R&D.

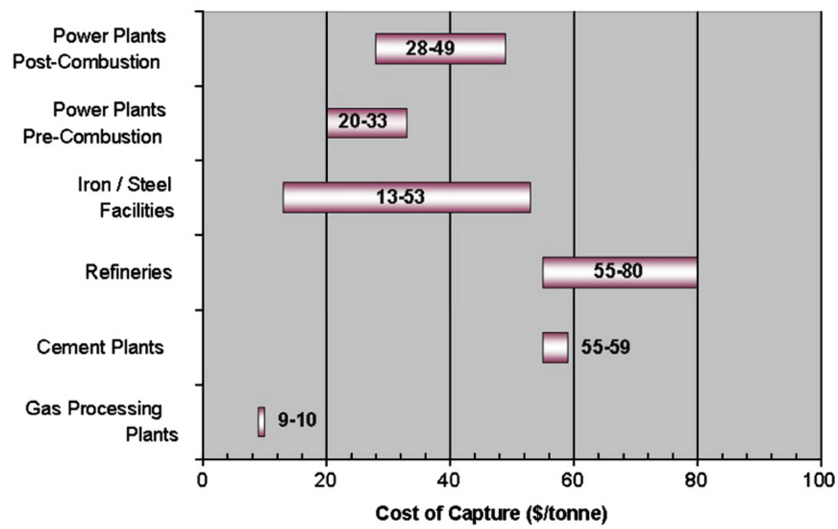


Fig. 7. Estimated cost of $CO_2$ capture (MRCSP, 2005).

compared to the risks associated with hydrocarbon pipelines (IPCC, 2005). Careful design and operation of a $CO_2$ sequestration project will minimize risks, such as high $CO_2$ concentrations resulting from pipeline rupture, leaking well casing, or leaks through faults, but risk cannot be completely eliminated. In order to reduce risk to an acceptable level, it will be necessary to develop safety and environmental regulations that $CO_2$ sequestration projects will be required to meet. Furthermore, proposed projects will have to go through an approval and permitting process.

Working in collaboration with the Interstate Oil and Gas Compact Commission (IOGCC), the partnerships have addressed the question of how future commercial sequestration projects should be permitted. In a report characterizing the current regulatory framework for carbon capture and storage (IOGCC, 2005), the IOGCC notes that most states already have regulations covering many of the issues that will need to be addressed, such as capture, transportation, injection, and post-injection monitoring, and indicates that existing regulations have laid the groundwork for the commercial development of sequestration.

A large body of federal, state, and local laws and regulations controlling emissions are applicable to capture, although only a few state-level regulations target $CO_2$ emissions, but this could change if growing concern with climate change leads to some sort of $CO_2$ limits. For transportation, the rules and regulations governing natural gas pipelining already include $CO_2$ and, because there is a well established pipeline regulatory framework, there is little need for new $CO_2$ transport regulations.

For injection and storage, the regulatory framework is less well defined. Since many states and localities have experience with $CO_2$ EOR, natural gas storage, and acid gas injection, the IOGCC and the partnerships concluded that regulations for $CO_2$ injection and storage should be built upon this existing regulatory framework. However, it may be necessary to make a distinction between injection for EOR and injection for non-EOR, especially injection into saline formations. The regulatory framework also needs to address liability and monitoring, mitigation, and verification (MMV) issues associated with long-term $CO_2$ storage.

### *2.6. Raised awareness and support for carbon sequestration as a greenhouse gas mitigation option*

During the Characterization Phase, the Partnerships focused on developing key messages about carbon sequestration and used community web broadcasts, focus groups, fact sheets, town hall meetings, and a public television documentary on carbon sequestration to convey the science behind these technologies. The Validation Phase will continue these broad outreach activities and focus on education and outreach to the communities in the vicinity of field tests.

### *2.7. Identification of priority opportunities for sequestration field tests*

A major goal of the Characterization Phase was to identify opportunities in the U.S. to test technologies developed in DOE's core sequestration R&D program. An important task for each partnership was to evaluate the enormous number of possibilities with their various pros and cons and select those of highest priority. Another task was to try to find industrial partners who would be willing to participate in the tests.

### *2.8. Establishment of protocols for project implementation*

Carbon sequestration is expected to have little market penetration in the absence of economic incentives that can come in the form of value added benefits from enhanced oil or gas recovery; tax incentives for clean energy projects; and/or in the form of $CO_2$ offsets assigned to the $CO_2$ sequestered in geologic formations or terrestrial ecosystems. Offsets generated from sequestration projects could be traded on commodity exchanges. Documented GHG offsets could then be recorded in voluntary state and federal registries, such as the DOE Energy Information Administration's GHG reporting guidelines, and/or accepted as offsets that could be traded through institutions, such as the Chicago Climate Exchange. Ultimately, some sort of market driven trading system may prove effective in achieving $CO_2$ reductions.

## 3. Field validation tests

Individual partnership databases and GIS's were used as decision support systems to determine the most promising opportunities within each region for sequestration projects. The primary factors influencing this selection include capacity (porosity, depth, chemical composition of fluids), containment (integrity of geologic seal, presence of faults, seismic history), and injectivity (permeability). Other factors influencing site selection include information on historical production records for oil and natural gas fields, whether a coal is mineable or unmineable, or the oil in a reservoir is miscible or immiscible with $CO_2$. The Validation Phase is putting this information into practice through the implementation of a number of field validation tests. These tests will provide the data necessary to verify technologies developed through DOE's core R&D effort and enable implementation of $CO_2$ sequestration on a large scale. Pilot projects will involve a site-specific focus for testing technology, assessing formation storage capacity, defining costs, assessing risks, gauging public acceptance, testing regulatory requirements, and validating MMV methods. Thirty-six tests, involving both geologic and terrestrial sequestration, will be performed. The location and types of these tests are shown in Fig. 8.

### 3.1. Tests in geologic formations

There are several options for storing $CO_2$ in geologic formations, including:

- Injection into oil reservoirs for enhanced oil recovery (EOR) and into natural gas reservoirs for enhanced gas recovery (EGR).
- Injection into unmineable coal seams for enhanced coal bed methane (ECBM) production.
- Injection into saline formations.

More research, specifically field experimentation, is needed to better understand the full suite of potential processes and effects (Klara et al., 2003).

#### 3.1.1. Injection into hydrocarbon reservoirs for EOR and EGR

Depleted oil and natural gas reservoirs provide ideal sites for $CO_2$ sequestration field tests. There are three reasons for this: (1) the fact that these reservoirs have retained hydrocarbon deposits for millions of years demonstrates that they are tight; (2) there is typically a large amount of geologic data pertaining to the site, and (3) there is the potential for increased hydrocarbon production, through the displacement of oil and natural gas, that can help offset sequestration costs. A number of projects will be carried out in the Validation Phase involving EOR and EGR. The partnerships have identified a sequestration potential in depleted oil and natural gas reservoirs of over 82 billion tons of $CO_2$. Table 2 presents a summary of tests

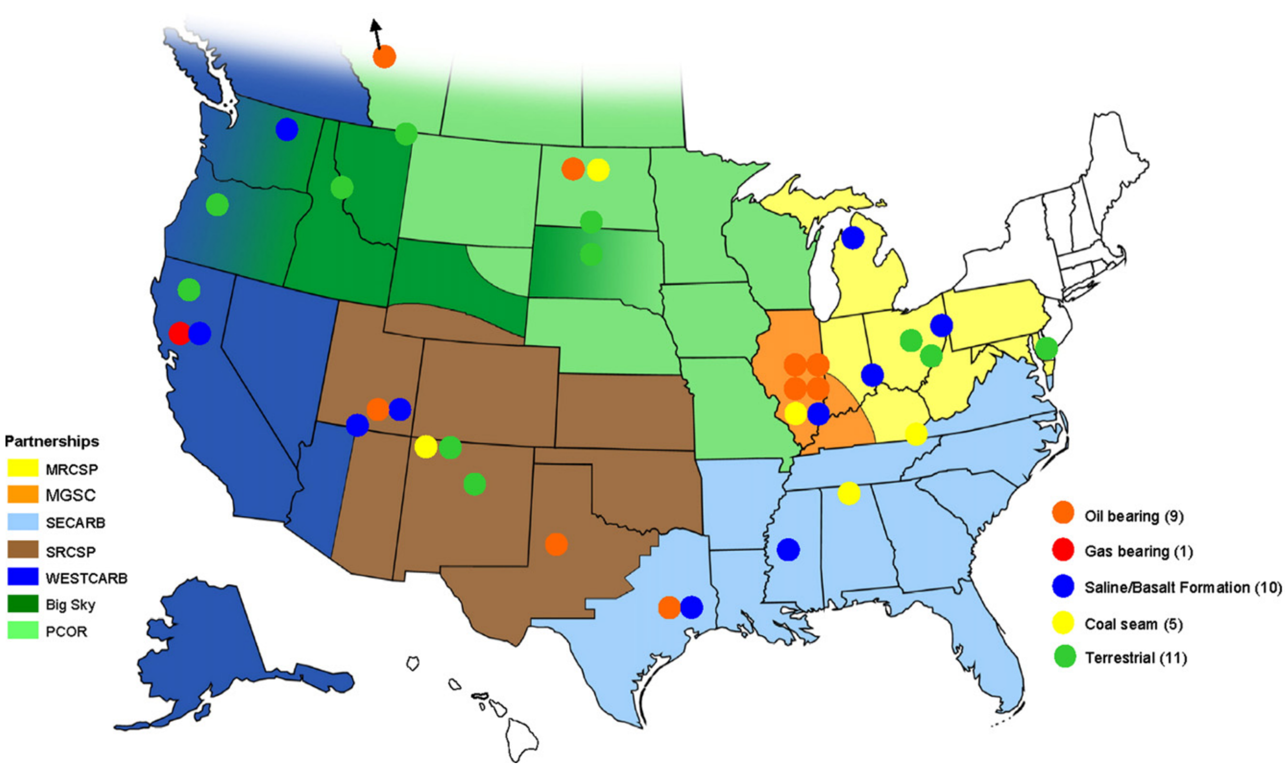


Fig. 8. Map of Validation Phase field test sites.

Table 2
Geologic sequestration field validations tests — EOR and EGR

| Partnership | Formation type — geologic province | Quantity of $CO_2$ injected/stored (tons) | Approximate well depth (ft) |
|---|---|---|---|
| MGSC | Huff n' Puff Test, Illinois Basin, Loudon Oil Field, IL | 300 | 1550 |
| | Well Conversion Test, Illinois Basin, IL | 300 | 1550 |
| | Pattern Flood I Test, Illinois Basin, IL | 300 | 1550 |
| | Pattern Flood II Test, Illinois Basin, IL | 300 | 1550 |
| PCOR | Duperow Formation, Beaver Lodge Oil Field, ND | 5000 | 10,500 |
| | Keg River Formation, Zama Oil Field, Alberta, Canada | 250,000 ($CO_2$) 90,000 ($H_2S$) | 5000 |
| SECARB | Lower Tuscaloosa Formation, MS | 800,000 | 10,000 |
| SWP | Permian Basin, SACROC-Claytonville Oil Field, TX | 900,000 | 5800 |
| | Paradox Basin, Aneth Oil Field, UT | 450,000 | 5800 |
| WESTCARB | Middle Capay Shale, Thornton Gas Field, CA | 500 | 3050 |

aimed at sequestering $CO_2$ in conjunction with EOR and EGR operations.

Because of the economic benefits of increased oil production, EOR projects are likely to provide some of the earliest opportunities for $CO_2$ sequestration. For example, the Permian Basin region of Texas and New Mexico currently injects more than 60 million tons of $CO_2$ per year (IOGCC, 2005). Of the total, about one half is recycled $CO_2$ that is produced with the oil and water from the formation. A natural result of injecting $CO_2$ into a reservoir to stimulate oil production is the retention of some of the $CO_2$. Part of the $CO_2$ dissolves in fluids (oil and water) in the pores of the formation or occupies empty pores as a dense gas (because of the high pressure) and does not migrate to the production well. Thus, part of the injected $CO_2$ remains permanently trapped. $CO_2$ EOR projects are responsible for producing 62 million barrels of oil per year in the U.S. or about 20% of the oil production of the Permian Basin (OGJ, 2004).

The objective of a combined $CO_2$ sequestration/EOR project differs somewhat from that of a typical EOR project. In typical EOR, the objective is to minimize $CO_2$ usage, that is minimize $CO_2$ retained in the formation, to lower costs; whereas, in $CO_2$ sequestration/EOR, the objective is to maximize $CO_2$ retention in the formation. Pilot tests will help determine the best way to modify EOR using $CO_2$ flooding to increase $CO_2$ retention and the effect of the larger amounts of $CO_2$ on phase equilibrium, $CO_2$ migration, injectivity, and interactions with formation minerals.

### 3.1.2. Injection into unmineable coal seams

Another option for geologic sequestration of $CO_2$ is injection into unmineable coal seams. Methane strongly adheres to coal surfaces, but when $CO_2$ is injected into a coal seam, it displaces the methane. Sale of the coal bed methane thus produced can help offset the cost of $CO_2$ sequestration. Laboratory studies indicate that between two and ten molecules of $CO_2$ are adsorbed, depending on coal type, for every molecule of methane released (Stanton et al., 2001; Sudibandriyo et al., 2005). The United States is fortunate to have large deposits of coal, and many of these coals appear to be suitable for geologic sequestration. However, a number of questions must be answered before this technology can be implemented on a large scale. One problem is porosity. Coal seams tend to have low porosity, i.e., few openings for gas flow, so it may be difficult for the injected $CO_2$ to come into contact with the entire coal surface. Also, the potential for the coal to swell when $CO_2$ is injected remains an issue, since swelling may reduce porosity (ECDN, 2005).

Deep coal resources, which cost the most to mine (especially seams greater than 500 ft deep and less than 42 in. thick or greater than 1000 ft deep, which are not accessible with current mining equipment), will be mined last, if at all. Because the methane in these coals has been adsorbed for millennia, it is likely that the $CO_2$ that displaces the methane will also be strongly adsorbed and remain sequestered essentially forever (Klara et al., 2003). Sequestration in coal beds is limited to unmineable seams; since, if the coal were to be mined, the

Table 3
Geologic sequestration field validations tests — saline/basalt formations

| Partnership | Formation type — geologic province | Quantity of $CO_2$ injected/ stored (tons) | Approximate well depth (ft) |
|---|---|---|---|
| MGSC | Saline — Mt. Simon Sandstone, Mattoon and Loudon Oil Fields, IL | 10,000 | 8600 |
| MRCSP | Saline — Mt. Simon Sandstone. KY | 3000 | 3500 |
| | Saline — Bois-Blanc Sylvania Sandstone, Michigan Basin, MI | 20,000 | 3200 |
| | Saline — Appalachian Basin Sandstones, OH | 3000 | 8300 |
| SWP | Saline — Desert Creek and Ismay Zones, Paradox Basin, Aneth Oil Field, UT | 20,000 | 6900 |
| WESTCARB | McCormick Sand Saline Formation, Thornton Gas Field, CA | 1000 | 3500 |
| | Saline — Cedar Mesa Sandstone, Coconino Sandston, Tapeats Sandstone, or Redwall Limestone, Colorado Plateau, AZ | 2000 | 7000 |
| SECARB | Saline — Lower Tuscaloosa Massive Sand Unit, MS | 3000 | 8600 |
| | Saline — Lower Tuscaloosa Formation, MS | 30,000 | 10,300 |
| Big Sky | Columbia River Basalt Group, WA | ~3000 | 3800 |

Table 4
Geologic sequestration field validations tests — coal bed methane

| Partnership | Formation type — geologic province | Quantity of $CO_2$ injected/stored (tons) | Approximate well depth (ft) |
|---|---|---|---|
| MGSC | Pennsylvanian Carbondale Formation, IL | ~750 | 1000 |
| PCOR | Harmon Coal Seam, Williston Basin, ND | <1000 | 1800 |
| SECARB | Appalachian Basin, VA and WV | 1000 | 2300 |
| | Black Warrior Basin, AL | 1000 | 2500 |
| SWP | San Juan Basin, NM | 75,000 | 3000 |

adsorbed $CO_2$ would be released to the atmosphere. Table 4 presents a summary of $CO_2$ sequestration field tests in unmineable coal seams.

Much data gathering and model building is proceeding in laboratories, but these results need to be verified. The tests being performed will provide this verification. Questions that will be answered by field testing include the effect of coal rank, depth, and water content on $CO_2$ adsorption capacity and methane recovery, the mobility and reactivity of supercritical $CO_2$ in coal seams, the phase behavior of binary and tertiary gas mixtures, matrix swelling/shrinking, and macropore/micropore diffusion of gas in coal. There will also be information on the integrity of coal seams for storing $CO_2$.

### 3.1.3. Injection into saline formations

Still another option for geologic $CO_2$ sequestration is injection into a saline formation. The areal extent of saline formations vastly exceeds that of oil and natural gas fields. Thus, the potential for storing $CO_2$ in these formations is very large. However, the chemistry involved is much more complex, and there is less assurance of a tight formation, since a saline formation can exist without an impermeable cap rock. The partnerships have estimated that saline formations have the potential to sequester nearly 7000 billion tons of $CO_2$. Table 3 summarizes field validation tests involving saline formations.

Information that will be generated by field projects that inject $CO_2$ into saline formations includes: 3D seismic surveys to follow the migration of the injected $CO_2$; interactions of $CO_2$ with formation fluids; and interactions of $CO_2$ with the cap rock. There is some indication that precipitation of carbonates in the cap rock may decrease porosity and improve formation integrity (ECDN, 2004). At the scale of testing (a few thousand tons of $CO_2$) being done under the Verification Phase of the partnerships program, many questions related to capacity, injectivity, short-term fate and transport, and site development will be answered. However, there will still be questions that will require large volume injection tests which will be used to answer issues such as feasibility of continuous injection, reservoir management, and long-term fate of the $CO_2$. Answers to these and other issues can only be addressed through scale up of sequestration projects.

If in the future, lack of water and improvements in desalination technology make it desirable to produce water from these formations for agricultural or other purposes, the pressure of $CO_2$ in the formations could aid in lifting the water to the surface, thus lowering costs. $CO_2$ would be flashed off, recovered, and re-injected.

### 3.1.4. Storage in other geologic formations

Flows and layered intrusions of basalt occur globally, with large volumes being present in the U.S., especially in the Northwest. This makes $CO_2$ storage in basalt formations of particular interest to the Big Sky Partnership (Big Sky, 2005). Basalt is typically regarded as a very low-porosity, low-permeability rock and, hence, not suitable for $CO_2$ storage. When permeability is encountered, it is almost always associated with fractures. However, as a result of variations in cooling rates, thermal contraction, degassing, and interactions with water, lava flows may consist of basalt that can be a target for $CO_2$ storage, for example when porous and permeable and confining low-permeability inter-beds occur. Basalt has a higher potential for mineral trapping of $CO_2$ than sedimentary rocks because, under proper condition, the injected $CO_2$ can react with the silicates of the basalt, releasing cations such as calcium, magnesium, and iron that can then precipitate carbonate minerals. Current knowledge of this type of storage is limited, and more research is needed to evaluate the extent and rate at which mineralization of $CO_2$ occurs in basalt, before its storage potential, both in the pore space and through mineralization, can be determined with confidence (McGrail et al., 2003).

## 3.2. Terrestrial sequestration field tests

Terrestrial sequestration relies on a completely different mechanism for storing $CO_2$. It makes use of the fact that plants can absorb $CO_2$ from the atmosphere and convert it to cellulose and other substances that are then preserved in plant tissues or in the soil. Since $CO_2$ is not stored as such, when dealing with terrestrial projects, the usual reference is to carbon sequestration, rather than $CO_2$ sequestration.

Geologic sequestration has great potential for reducing $CO_2$ emissions from large point sources, which are amenable to existing and developing $CO_2$ capture technologies; but no technologies exist for capturing the $CO_2$ produced by dispersed sources, such as gasoline and diesel fueled automobiles and trucks. However, since terrestrial sequestration involves absorption from the air, this approach can help offset $CO_2$ emissions from diffuse sources.

Terrestrial sequestration involves changes in agricultural and forest land management practices to increase the amount of carbon stored in plants and soil. Improved practices include adoption of conservation technologies, such as no-till farming, converting marginal croplands to grasslands and forests, establishing vegetation on mined soil, wetlands restoration, and careful selection of plant species. Although terrestrial projects tend to be relatively short term, compared to geologic sequestration, they have great potential for reducing $CO_2$ buildup in the atmosphere and can bridge the gap until long-term, more permanent solutions are developed and implemented. Table 5

Table 5
Terrestrial sequestration field validation tests

| Partnership | Project title | Test location | Land categorization |
|---|---|---|---|
| Big Sky | Cropland Field Validation Test | North Central MT, Eastern SD, parts of Canada | Agricultural |
| | Rangeland Sequestration Potential Assessment | Region-wide | Rangeland |
| | Forestry Field Validation Test | Region-wide | Forest |
| MRCSP | Terrestrial Sequestration Field Test: Croplands | Region-wide | Agricultural |
| | Terrestrial Sequestration Field Test: Minelands | Region-wide | Mineland |
| | Terrestrial Field Test: Wetland-Blackwater Refuge | Cambridge, MD | Wetlands |
| PCOR | Terrestrial Field Validation Test | Great Plains Wetlands Complex (Prairie Pothole Region) | Wetlands |
| SWP | Southwest Regional Terrestrial Pilot Test | Region-wide | Multiple |
| | Terrestrial Riparian Restoration Project | San Juan Basin Coal Fairway (Navajo City, New Mexico) | Rangeland/Riparian |
| WESTCARB | Shasta County Terrestrial Sequestration Project | Shasta County, California | Forest and Rangelands |
| | Lake County Terrestrial Sequestration Project | Lake County, Oregon | Forest and Rangelands |

summarizes Validation Phase projects that will impact terrestrial sequestration.

## 4. Monitoring, mitigation, and verification (MMV) efforts

If $CO_2$ sequestration is to become an accepted technology for reducing the buildup of greenhouse gases in the atmosphere, then techniques will need to be developed to monitor, mitigate, and verify the sequestered $CO_2$. Unless the general public is convinced that $CO_2$ sequestration is safe and effective, it will not be implemented; and it is MMV technologies that will be most critical in providing this assurance. The goals of MMV for geologic sequestration are to:

- Identify storage processes and confirm their efficiency.
- Evaluate the interactions of $CO_2$ with formation solids and fluids.
- Assess environmental, health, and safety impacts in the event of a leak.
- Evaluate and monitor remediation efforts should a leak occur.
- Assist in mediating legal disputes resulting from any impact of sequestration technology (groundwater impacts, seismic events, crop losses, etc.)

The partnerships are developing tailored and dynamic programs that focus on the greatest potential risks for $CO_2$ leakage from the particular formation into which the $CO_2$ is being injected. Each program will monitor the site before, during, and after $CO_2$ injection; this monitoring will involve the use of multiple techniques to follow $CO_2$ migration.

Each partnership will develop a specific MMV plan for each sequestration site. These plans will take into account the geology and hydrology of the site and the location and nature of other wells in the vicinity of the test. The plan will incorporate a sampling protocol that includes a variety of MMV monitoring techniques, such as remote sensing and aerial surveillance. Novel seismic imaging techniques that may be used include high-resolution 2-D reflection survey and cross-well seismic survey; geophysical techniques include electromagnetic (EM) imaging and electrical resistivity imaging. Seismic technology will be important in leak detection monitoring, for example, where seismic reflection shows the presence of $CO_2$ in a formation above a leaking storage formation but is not able to provide information on the amount of $CO_2$ present. This can be addressed by combining the information from seismic monitoring with EM techniques that are directly sensitive to water saturation. In most cases, the two fluids in the system will be water and $CO_2$; thus, if water saturation is determined, then $CO_2$ saturation is also known. A wide variety of novel techniques are available or are being developed and will be used in the planning and monitoring of the $CO_2$ sequestration pilot projects (Klara et al., 2003).

Although activities for terrestrial sequestration projects will be considerably different than for geologic sequestration, the partnerships will also develop MMV plans for these sites. These plans will include determination of initial carbon levels, measurement of carbon sequestration rates, development of assessment protocols, comparison of results to other projects, and monitoring of methane and nitrous oxide releases (Litynski et al., 2006b).

Various member organizations of the regional partnerships are involved in the development of novel techniques for monitoring the movement of $CO_2$ in geologic formations, determining carbon concentration in soils, and detecting leaks from sequestration sites. They are also active in the development of computer models that can be used to simulate the storage of $CO_2$ and carbon in geologic and terrestrial sites. Such models can help evaluate the permanence of $CO_2$ sequestration at a particular site and the potential for migration into adjacent strata.

## 5. Conclusion

After a highly successful Characterization Phase, which gathered a large amount of data on $CO_2$ sources and potential sinks in the U.S. and assembled this data into a national atlas, the DOE Regional Partnerships program has moved into the Validation Phase. The major objective of this phase is to carry out geologic and terrestrial carbon sequestration pilot projects and to develop the data necessary to design and implement future commercial projects. The geologic projects cover a wide range of geologic strata into which $CO_2$ will be injected. Test sites are chosen by the regional partnerships based on what is most appropriate for their regions. Some partnerships have depleted oil and natural gas fields, others large unmineable coal deposits, still others have extensive saline formations, and some are looking at other options. The same is true for terrestrial projects. In some regions, reforestation is a viable option; in other partnerships with less rainfall, grasslands may be a better choice. The wide variety of tests conducted during the Validation Phase of the RCSP program will greatly increase the knowledge base on carbon sequestration and lay the groundwork for large-scale tests during the Deployment Phase.

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