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Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations

NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

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Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations

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List of Acronyms and Abbreviations

Acronym/Abbreviation	Definition
2-D	Two-Dimensional
3-D	Three-Dimensional
4-D	Four-Dimensional
AC	Accumulation Chamber
ADRS	Amargosa Desert Research Site
ANSI	American National Standards Institute
AoR	Area of Review
API	American Petroleum Institute
Ar	Argon
ARI	Advanced Resources International
ASTM	American Standard Test Method
BEG	Bureau of Economic Geology
BGS	British Geological Survey
Big Sky	Big Sky Carbon Sequestration Partnership
BLM	Bureau of Land Management
BNL	Brookhaven National Laboratory
C	Carbon
Ca	Calcium
CASSM	Continuous Active Seismic Source Monitoring
CBL	Cement Bond Log
CBM	Coalbed Methane
CCS	Carbon Capture and Storage
CCX	Chicago Climate Exchange
CES	Clean Energy Systems
CGM	Craig-Geffen-Morse Water Flooding Model
CH_4	Methane
CIR	Color Infrared
Cl	Chlorine
CL	Cathodoluminescense
cm	centimeter(s)
CMG	Computer Modeling Group
CO_2	Carbon Dioxide
CO2CRC	Cooperative Research Centre for Greenhouse Gas Technologies
CRT	Cathode Ray Tube
CSLF	Carbon Sequestration Leadership Forum
DIAL	Differential Absorption LIDAR
DOE	U.S. Department of Energy
DTPS	Distributed Thermal Perturbation Sensor
EC	Eddy Covariance
EDS	Energy Dispersive X-Ray Spectroscopy
ECBM	Enhanced Coalbed Methane
EELS	Electron Energy Loss Spectroscopy
EMIT	Electromagnetic Induction Tomography
EOR	Enhanced Oil Recovery
EPMA	Electron Probe Microanalyzer
EM	Electromagnetic
EPA	U.S. Environmental Protection Agency
ERT	Electrical Resistivity Tomography

Acronym/Abbreviation	Definition
ES&H	Environmental, Safety, and Health
ft	Feet
FE	DOE's Office of Fossil Energy
FLOTRAN	Flow and Transport Simulator
g	Gram(s)
GFZ	GeoForschungsZentrum
GHG	Greenhouse Gas(es)
GIS	Geographic Information System
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GS	Geological Storage/Sequestration
H/H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen Sulfide
H_2SO_4	Sulfuric Acid
He	Helium
HC	Hydrocarbon
HCl	Hydrogen Chloride
HVAC	Heating, Ventilation & Air Conditioning
Hz	Hertz
IEA GHG	IEA Greenhouse Gas Programme
in	Inch(es)
IR	Infrared
IRGA	Infrared Gas Analyzer
IEA	International Energy Agency
IOGCC	Interstate Oil & Gas Compact Commission
IP	Induced Polarization
ISO	International Organization for Standardization
IPCC	Intergovernmental Panel on Climate Change
km	Kilometer(s)
Kr	Krypton
KHz	Kilohertz
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LCD	Liquid Crystal Display
LEERT	Long Electrode Electrical Resistance Tomography
LIDAR	Light Detection and Ranging
LLNL	Lawrence Livermore National Laboratory
LVST	Large Volume Sequestration Test
mD	Millidarcy
MDT	Modular Dynamic Tester
m	Meter(s)
mi	Mile(s)
mg	milligram(s)
Mg	Magnesium
MGSC	Midwest Geological Sequestration Consortium
MIT	Mechanical Integrity Test
MVA	Monitoring, Verification, and Accounting
MRSCP	Midwest Geological Carbon Sequestration Consortium
NaCl	Sodium Chloride

Acronym/Abbreviation	Definition
N	Nitrogen
Ne	Neon
NETL	National Energy Technology Laboratory
NNSA	National Nuclear Security Administration
O/O_2	Oxygen
ORD	NETL's Office of Research and Development
ORNL	Oak Ridge National Laboratories
OST	DOE's Office of Science and Technology
P	Pressure
PC	Pulverized Coal
PCOR	Plains CO_2 Reduction Partnership
PFC	Perfluorocarbon(s)
PFT	Perfluorocarbon Tracers
PNC	Pulsed Neutron Capture
ppm	Parts per Million
ppmv	Parts per Million by Volume
psi	Pounds per Square Inch
PTRC	Petroleum Technology Research Centre
QC	Quality Control
R&D	Research and Development
RCSP	Regional Carbon Sequestration Partnership
RGGI	Regional Greenhouse Gas Initiative
Rn	Radon
RST	Reservoir Saturation Tool
S	Sulfur
SAPT	Standard Annular Pressure Test
SAR	Synthetic Aperture Radar
scfd	Standard Cubic Feet per Day
SDWA	Safe Drinking Water Act
SECARB	Southeast Regional Carbon Sequestration Partnership
SF_6	Sulfur Hexafluoride
SNL	Sandia National Laboratory
SO_4	Sulfate
SP	Self-Potential/Spontaneous Polarization
STEM	Scanning Transmission Electron Microscope
SWP	Southwest Regional Partnership
T	Temperature
TAME	The Andersons Marathon Ethanol (Plant)
TDS	Total Dissolved Solids
USDW	Underground Sources of Drinking Water
UIC	Underground Injection Control
USGS	U.S. Geological Survey
USIT	Ultrasonic Imaging Tool
VDL	Variable Density Log
VSP	Vertical Seismic Profile
WestCarb	West Coast Regional Carbon Sequestration Partnership
Xe	Xenon
ZEPP-1	Zero-Emissions Power Plant
ZERT	Zero Emission Research and Technology

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Executive Summary

This document should be of interest to a broad audience interested in reducing greenhouse gas (GHG) emissions to the atmosphere. It was developed for regulatory organizations, project developers, and national and state policymakers to increase awareness of existing and developing monitoring, verification, and accounting (MVA) techniques. Carbon dioxide (CO_2) sinks are a natural part of the carbon cycle; however, natural terrestrial sinks are not sufficient to absorb all the CO_2 emitted to the atmosphere each year. Due to present concerns about global climate change related to GHG emissions, efforts are underway to assess CO_2 sinks, both terrestrial and geologic, as a form of carbon management to offset emissions from fossil fuel combustion and other human activities. Reliable and cost-effective MVA techniques are an important part of making geologic sequestration (sometimes referred to as GS) a safe, effective, and acceptable method for GHG control.

MVA of GS sites is expected to serve several purposes, including addressing safety and environmental concerns; inventory verification; project and national accounting of GHG emissions reductions at GS sites; and evaluating potential regional, national, and international GHG reduction goals. The primary goal of the U.S. Department of Energy's (DOE) Carbon Sequestration and MVA Programs is to develop and demonstrate a broad portfolio of Primary, Secondary, and Potential Additional technologies, applications, and accounting requirements that can meet DOE's defined goals of demonstrating 95 percent and 99 percent retention of CO_2 through GS by 2008 and 2012, respectively. The 95 percent and 99 percent retention levels are defined by the ability of a GS site to detect leakage of CO_2, at levels of 5 percent and 1 percent of the stored amount of CO_2, into the atmosphere.

The MVA Program employs multiple Primary, Secondary, and Potential Additional Technologies (see Appendices I, II, and III for definitions) in several GS injection projects worldwide. Each GS site varies significantly in risk profile and overall site geology, including target formation depth, formation porosity, permeability, temperature, pressure, and seal formation. MVA packages selected for commercial-scale projects discussed are tailored to site-specific characteristics and geological features. The MVA packages for these projects were selected to maximize understanding of CO_2 behavior and determine what monitoring tools are most effective across different geologic regimes (as opposed to tailoring a site-specific MVA package). As defined in this report, available Primary technologies are already fully capable of meeting and exceeding monitoring requirements and achieving the MVA goals for 2008. It is believed that by 2012, modifications and improvements to monitoring protocols through the development of Secondary and Potential Additional technologies will reduce GS cost and enable 99 percent of injected CO_2 to be credited as net emissions reduction.

In the outlined approach, prior to operation, site characterization and associated risk assessment play a significant role in determining an appropriate monitoring program. Accredited projects are assumed to require a robust overall monitoring program for inventory verification for accounting of GHG emissions and GHG registries. The overall goal for monitoring will be to demonstrate to regulatory oversight bodies that the practice of GS is safe, does not create significant adverse local environmental impacts, and is an effective GHG control technology. In general, the goals of MVA for GS are to:

- Improve understanding of storage processes and confirm their effectiveness.
- Evaluate the interactions of CO_2 with formation solids and fluids.
- Assess environmental, safety, and health (ES&H) impacts in the event of a leak to the atmosphere.
- Evaluate and monitor any required remediation efforts should a leak occur.
- Provide a technical basis to assist in legal disputes resulting from any impact of sequestration technology (groundwater impacts, seismic events, crop losses, etc.).

As outlined in this report, GS of CO_2 requires pre-operation, operation, closure, and post-closure monitoring activities at the storage site, as well as risk assessment and development of flexible operational plans, and mitigation strategies that can be implemented should a problem arise. Effective application of monitoring technologies ensures the safety of carbon capture and storage (CCS) projects with respect to both human health and the environment and provides the basis for establishing accounting protocols for GHG registries and carbon credits on trading markets for stored CO_2, if necessary.

Since its inception in 1997, DOE's Carbon Sequestration Program – managed within the Office of Fossil Energy (FE) and implemented by the National Energy Technology Laboratory (NETL) – has been developing both core and supporting technologies through which CCS can become an effective and economically viable option for reducing CO_2 emissions from coal-based power plants and other sources. Successful research and development (R&D) will enable CCS technologies to overcome various technical, economic, and social challenges, such as cost-effective CO_2 separation and transport, long-term stability of CO_2 storage in underground formations, monitoring and verification, integration with power generation systems, and public acceptance.

In July 2008, the U.S. Environmental Protection Agency (EPA) proposed Draft Federal requirements under the Safe Drinking Water Act (SDWA) for the underground injection of CO_2 for GS purposes. EPA is tracking the progress and results of national and international GS research projects. DOE leads experimental field research on GS in the United States through the Regional Carbon Sequestration Partnerships (RCSP) Program. EPA is using the data and experience developed in the Core R&D Program, international projects, and RCSP Program to provide a foundation to support decisions for development of an effective regulatory and legal environment for the safe, long-term underground injection and GS of GHGs. Furthermore, information gained from the RCSPs' large- and small-scale geologic injection projects is predicted to provide the technical basis to account for stored CO_2 in support of any future GHG registries, incentives, or other policy instruments that may be deemed necessary in the future. Once the additional regulatory framework at the Federal and state levels is completed, based in part on the monitoring technologies and operational procedures employed by the demonstration projects undertaken by the RCSPs, proper standards will be in place to ensure a consistent and effective permitting and monitoring system for commercial-scale GS projects.

The life cycle of a GS project involves four phases. Monitoring activities will vary among these phases:

1. **Pre-Operation Phase:** Project design is carried out, baseline conditions are established, geology is characterized, and risks are identified.
2. **Operation Phase:** Period of time during which CO_2 is injected into the storage reservoir.
3. **Closure Phase:** Period after injection has stopped, during which wells are abandoned and plugged, equipment and facilities are removed, and agreed upon site restoration is accomplished. Only necessary monitoring equipment is retained.
4. **Post-Closure Phase:** Period during which ongoing monitoring is used to demonstrate that the storage project is performing as expected and that it is safe to discontinue further monitoring. Once it is satisfactorily demonstrated that the site is stable, monitoring will no longer be required except in the very unlikely event of leakage, or legal disputes, or other matters that may require new information about the status of the storage project.

Each monitoring phase (Pre-Operational, Operational, Closure, and Post-Closure) of a GS project will employ specialized monitoring tools and techniques that will address specific atmospheric, near-surface hydrologic, and deep-subsurface monitoring needs.

DOE-sponsored RCSP projects will move CCS from research to commercial application. Such demonstrations are necessary to increase understanding of trapping mechanisms, to test and improve monitoring techniques and mathematical models, and to gain public acceptance of CCS. Testing under a wide range of geologic conditions will demonstrate that CCS is an acceptable GHG mitigation option for many areas of the country, and the world.

Modeling and monitoring R&D targets for RCSP projects include:

- Assessing the sweep efficiency as large volumes of CO_2 are injected to better quantify CO_2 storage capacity.
- Quantifying the pressure effects and brine movement though heterogeneous rock to better understand the significance of these effects on capacity and monitor pressure and brine migration.
- Quantifying inter-well interactions as large plumes develop, focusing on interaction of pressure, heterogeneity, and gravity as controls on migration.
- Better understanding pressure and capillary seals.
- Developing and assessing the effectiveness of existing and novel monitoring tools.
- Assessing how these monitoring tools can be used efficiently, effectively, and hierarchically in a mature monitoring environment.

As outlined in this report, critical components of a robust MVA program include evaluating and determining which monitoring techniques are most effective and economic for specific geologic situations and obtaining information that will be vital in guiding future commercial projects. The monitoring programs of five selected GS projects taking place in the United States are provided. Each project is sited in an area considered suitable for GS and employs a robust monitoring program (for research purposes) to measure physical and chemical phenomena associated with large-scale CO_2 injection. The five projects discussed in this report are:

1. **Gulf Coast Mississippi Strandplain Deep Sandstone Test (Moderate Porosity and Permeability):** GS test located in the southeast portion of the United States will be conducted in the down dip "water leg" of the Cranfield Unit in Southwest Mississippi. Large volumes of CO_2 from a natural source will be delivered by an established pipeline.
2. **Nugget Sandstone Test (High Depth, Low Porosity and Permeability):** Large volume sequestration test (LVST) in the Triassic Nugget Sandstone Formation on the Moxa Arch of Western Wyoming. The source of the CO_2 is the waste gas from a helium (He) and methane (CH_4) production facility.
3. **Cambrian Mt. Simon Sandstone Test (Moderate Depth, Low Porosity and Permeability):** A large-scale injection test in Illinois is being conducted in the Midwest Region of the United States. The main goal of this large-scale injection will be to implement geologic injection tests of sufficient scale to promote understanding of injectivity, capacity, and storage potential in reservoir types having broad importance across the Midwest Region.
4. **San Joaquin Valley Fluvial-Braided Deep Sandstone Test (High Porosity and Permeability):** Large-scale injection of CO_2 into a deep saline formation beneath a power plant site (the Olcese and/or Vedder sandstones of the San Joaquin Valley, California).
5. **Williston Basin Deep Carbonate EOR Test:** CO_2 sequestration and enhanced oil recovery (EOR) in select oil fields in the Williston Basin, North Dakota. A minimum of 500,000 tons per year of CO_2 from an anthropogenic source (pulverized coal [PC] plant) will be injected into an oil reservoir in the Williston Basin.

Each site varies significantly in overall site geology, including target formation depth, formation porosity, permeability, temperature, pressure, and seal formation. The MVA packages for these case studies were selected to maximize understanding of CO_2 behavior and determine what monitoring tools are most effective across different geologic regimes, as opposed to tailoring a site-specific MVA package.

The complete version of this report is available at:
http://www.netl.doe.gov/technologies/carbon_seq/refshelf/MVA_Document.pdf

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