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U.S. DEPARTMENT OF ENERGY

Quadrennial Technology Review 2015

Carbon Dioxide Storage Technologies

Chapter 4: Technology Assessments

Overview of CO_2 storage technologies

Development of a successful CO_2 storage industry will require effective storage which is both safe and permanent. As the state-of-the-art technology for CO_2 storage has advanced, the number of CO_2 injection projects has increased. The development of such sustained million tonne/year CO_2 saline injection projects in the US and globally provides initial tests of advanced storage technologies and advances understanding of geological storage characterization. CO_2 storage research and design leverages decades of experience related to geologic characterization, modeling, and monitoring tools. Durable, robust, and cost-effective technologies are needed for geologic storage of CO_2, and field tests will help validate these technologies. Field tests will improve our ability to address critical challenges such as improving long-term wellbore integrity, furthering our understanding of geomechanics (for example stress states), and developing adaptive control of fluid flow and pressure management. They will also lead to higher-resolution characterization and mapping of the subsurface to identify fractures and faults that are natural or a result of other subsurface activity, and model the heterogeneities in the geology that can dominate the flow of the CO_2. In addition, improved tools will enhance our ability to monitor and verify permanent storage of CO_2, while also mitigating potential risks and increasing storage efficiency. Through a combination of large-scale field demonstrations, as well as research and design of new technologies, carbon storage technologies are being developed to improve wellbore integrity, increase storage efficiency, improve simulation of subsurface processes, mitigate potential risks, and increase certainty associated with long-term storage operations. The current focus of the program is on broadening the understanding of geologic formations appropriate for CO_2 storage, improving the understanding of the behavior of CO_2 stored in geologic formations, and validating simulation, risk assessment, and monitoring tools and methodologies.

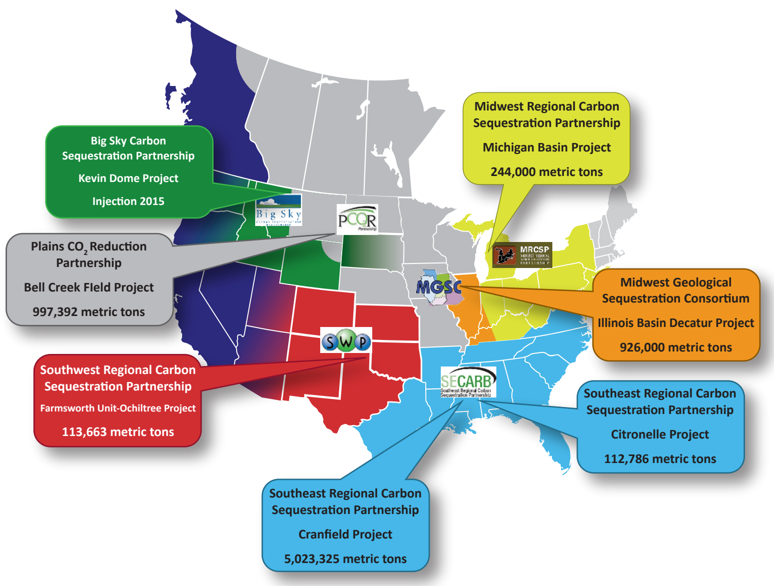
These R&D challenges are closely aligned with those faced by other sectors that utilize the subsurface for energy production and storage. With that in mind, a DOE crosscutting technology team has identified four 'pillars' as key technology areas requiring research in order to address the grand challenge of achieving Adaptive Control of Subsurface Fractures and Fluid Flow. These pillars are: (1) wellbore integrity; (2) subsurface stress and induced seismicity; (3) permeability manipulation; and (4) new subsurface signals. The Chapter 7 Supplemental Information on *Subsurface Science and Technology* appendix provides more details. Technologies are being validated at large-scale field projects throughout the United States and as part of international projects throughout the world.

Development of a successful domestic CO_2 storage industry will require an effective storage infrastructure. DOE's Regional Carbon Sequestration Partnership (RCSP) Initiative, launched in 2003, is a government/industry cooperative effort tasked with testing and validating storage and monitoring technologies that inform the development of best practices, regulations, and infrastructure needs for CCS in different regions of the U.S. and Canada. The RCSP Initiative is comprised of seven Partnerships encompassing 43 states, four Canadian Provinces, and over 400 organizations, as indicated in Figure 4.F.1.[1] The regional focus of the partnerships fosters the understanding of many different geological storage options and expands the options for siting cost-effective CCS projects. Through investments of the US DOE under the CCS Core Storage R&D Program and the Regional

Carbon Sequestration Partnership Initiative, over 10 million tonnes of CO_2 have been stored to date, and that amount is increasing every day.

Activities such as the Regional Carbon Sequestration Partnerships (RCSP) conduct large-scale field demonstrations for different storage types in various formation classes, distributed over different geographic regions, to provide a sound basis for commercial-scale CO_2 storage projects. The RCSP has 7 partnerships encompassing 43 states, 4 provinces, and over 400 organizations. Over 10 million metric tons of CO_2 have been injected as part of DOE's Clean Coal Research, Development, and Demonstration Programs.

Figure 4.F.1 Regional Carbon Sequestration Partnerships Development Phase Project and Injection Totals, January 2015 as Reported by the Partnerships to NETL



International projects also continue to advance the knowledge base. NETL maintains a database of CCS projects worldwide. As of November 2014, the database contained 274 projects, including 69 capture, 60 storage, and 145 for capture and storage in more than 30 countries across 6 continents.[2] The 22 countries of the Carbon Sequestration Leadership Forum[3] (CSLF) are engaged in activities to demonstrate sizeable storage in a wide range of national and geological settings. These activities serve to validate monitoring technologies in large-scale storage projects and qualify and commercialize these technologies for commercial use. Mitigation and remediation methods for potential leaks are also developed and validated, and upscaled for use in commercial scale storage projects. Activities recognized by CSLF further develop the understanding of fundamental processes, thereby advancing the simulation tools regarding the effects and fate of the stored CO_2. Under the auspices of CSLF, consistent methods for evaluating CO_2 storage capacity at various scales are agreed upon and developed, and geographic maps of national and global distribution of this capacity are produced.[4] Table 4.F.1 lists Regional Carbon Sequestration Partnership projects that are currently injecting or have injected carbon. This work is establishing detailed localized data and is building a technical knowledge base.

Additionally, in November 2014, President Obama and Chinese President Xi jointly announced that the United States and China will lead a major new carbon storage project based in China, recently identified as the project site in Yan'an-Yulin, Shan'xi Province, China, operated by Shan'xi Yanchang Petroleum,[5] and work together on a new Enhanced Water Recovery (EWR) pilot project to produce fresh water from saline water displaced by CO_2 injection into deep saline reservoirs.

The following sections highlight the key challenges of advanced CO_2 storage technology and identify what we've learned of the technology challenges and needs, current research and development, and future directions to move towards an effective clean power options. The foremost technical issues for carbon storage are in extending the understanding of geologic formations, improving the tools to monitor and verify permanent storage, and

Table 4.F.1 Regional Carbon Sequestration Partnerships Injecting CO_2

Regional Carbon Sequestration Partnerships injecting CO_2	
Plains CO_2 Reduction Partnership (PCOR)	For the Bell Creek large-scale project, the PCOR Partnership is working with Denbury Onshore LLC to develop robust, practical, and targeted support programs to study incidental CO_2 storage associated with a commercial-scale enhanced oil recovery operation.
Midwest Geological Sequestration Consortium (MGSC)	MGSC has partnered with Archer Daniels Midland (ADM) Company and Schlumberger Carbon Services to conduct a large-volume, saline reservoir storage field project at ADM's agricultural products processing complex in Decatur, Illinois. The project is injecting 1 million metric tons of CO_2 over three years into a deep saline formation in the Illinois Basin.
Midwest Regional Carbon Sequestration Partnership (MRCSP)	MRCSP's large-volume CO_2 injection and storage test is focused on the Niagaran Reef Complex located in Ostego County in northern Michigan. The site is managed by MRCSP's partner, Core Energy, and is in the vicinity of natural gas processing plants that provide CO_2 for the enhanced oil recovery operations.
Southeast Regional Carbon Sequestration Partnership (SECARB)	SECARB, working with partner Denbury, is completing two large-volume injection field projects – one in lower Tuscaloosa Formation at the Cranfield site, and one in the Paluxy Formation at the Citronelle site. These formations are key components of a larger, regional group of similar formations, called the Gulf Coast Wedge.
Southwest Regional Partnership on Carbon Sequestration (SWP)	SWP is characterizing, modeling, monitoring, and tracking at least one million metric tons of CO_2 at an ongoing oil recovery operation in Ochiltree Country in northern Texas. The primary target reservoir is the Pennsylvanian-age Morrow Sandstone Formation within the Farnsworth Unit of the Anadarko Basin.

developing and demonstrating technologies which enable economic management of the subsurface storage resource. These advancements will reduce uncertainty through demonstration. They will also provide tools necessary to build the confidence and public acceptance needed to enable widespread adoption and contribute to broader international goals of establishing CCS.[6] Three broad categories of critical RD&D efforts are:

- **Establish Field Projects** to broaden the understanding of geologic formations appropriate for CO_2 storage both onshore and offshore, improve understanding of the behavior of CO_2 stored in geologic formations, and validate simulation, risk assessment, and monitoring tools and methods.
- **Develop improved Monitoring Tools** to diagnose and verify permanent storage of CO_2 in the subsurface.
- **Develop New Technologies** to improve wellbore integrity, increase storage efficiency, improve simulation of subsurface processes, mitigate potential risks, and increase certainty associated with long-term storage operations.

Field projects

Field projects broaden the understanding of geologic formations appropriate for CO_2 storage both onshore and offshore. Specifically they improve understanding of the behavior of CO_2 stored in geologic formations, and validate simulation, risk assessment, and monitoring tools and methods. These larger scale field projects contribute towards establishing CCS technology to meet global environmental goals.

While great progress has been made in saline formation storage over the past decade, much useful work remains to be done. In particular, there are relatively few large-scale CO_2 storage projects in saline formations. These field projects are important for identifying and resolving the technical challenges associated with satisfying the evolving storage regulatory environment. In addition to enabling the technical viability of CO_2 storage, successful RD&D is anticipated to provide a cost benefit. For example, cost reductions are expected from a number of R&D projects that integrate detailed characterization, operational, monitoring, and laboratory data with reservoir simulation models. Such integrated frameworks can be used to optimize injection patterns and improve the placement of monitoring equipment so as to increase storage capacity, reduce the size of the CO_2 plume and lower monitoring costs. Table 4.F.2 describes the challenges and desired outcomes of CCS field projects, and Table 4.F.3 examines the state of the art, current R&D, and research opportunities and pathways forward.

Table 4.F.2 Challenges and Desired Outcomes of Carbon Storage Field Projects

Goal: Develop, conduct, and evaluate carbon storage field projects to broaden the understanding of geologic formations appropriate for CO_2 storage both onshore and offshore, improve understanding of the behavior of CO_2 stored in geologic formations, and validate simulation, risk assessment, and monitoring tools and methods.

Major R&D Challenges

- Developing the capability for safe, permanent, and cost-effective storage for all storage types both onshore and offshore
- Identifying adequate CO_2 storage resources both onshore and offshore
- Developing cost effective integrated technologies for storage and monitoring its state over time, both onshore and offshore, that meet requirements for safety and permanence, and that satisfy regulations
- Developing technologies to utilize CO_2 as a resource for enhanced oil recovery (EOR) and for other purposes,[7] and to cost-effectively treat water extracted from deep saline reservoirs when managing pressures resulting from carbon injection (see Technical Assessment 4.C on *Carbon Dioxide Capture and Storage Value-Added Options* for further detail)
- Addressing, in addition to technical R&D challenges, non-technical issues associated with CCS large-scale deployment, such as effective public outreach and providing information to regulators, legislators, and financiers.

Desired Outcomes:

- Offshore carbon storage reservoirs identified and characterized to provide options for future field tests and integrated CCS projects Offshore carbon storage reservoirs identified and characterized to provide options for future field tests and integrated CCS projects
- Storage permanence validated through targeted field projects

Table 4.F.3 Technical Assessment and Opportunities of Carbon Storage Field Projects

Goal: Develop, conduct, and evaluate field projects to broaden the understanding of geologic formations appropriate for CO_2 storage both onshore and offshore, improve understanding of the behavior of CO_2 stored in geologic formations, and validate simulation, risk assessment, and monitoring tools and methods.		
State of the Art	Current R&D	Opportunities and Future Pathways
■ Over 10,000,000 metric tons of CO_2 was safely stored in North American large-scale field projects as of April 22, 2015. ■ Field projects have shown that:[8] (1) depositional features within a formation can lead to development of preferred flow paths in the reservoir, which can reduce storage efficiency. (2) flow channeling in some formations can require more than 100,000 metric tons of injected CO2 for successful application of timelapse 3D vertical seismic profiles (VSPs) for plume tracking. (3) above zone monitoring interval (AZMI) pressure approach has merit in assessing storage permanence. (4) permanent installation of downhole geophone arrays enabled acquisition of high quality microseismic data, which is important for monitoring of induced seismicity. (5) integrated instrument packages are valuable for maximizing monitoring data obtained from wellbores. ■ Combined regional assessments show a large storage resource (between roughly 2,300 and over 20,000 billion metric tons) in multiple regions, including saline formations, depleted oil/gas reservoirs, and un-mineable coal.[9] ■ Initial field testing of formations pressure has been conducted in 19 small-scale field projects representing 11 depositional environments with validation of simulation tools for predicting CO_2 movement and storage efficiency and tools and methods for monitoring.[10] ■ Public awareness has been raised through successful interactions between RCSPs and multiple stakeholder groups, and the development of Best Practice Manuals.[11]	■ Deploying near term "first-mover" and longer-term "broad deployment" storage projects, supported by RCSP, to conduct large-scale field validation testing of storage and monitoring technologies in regionally significant storage formations. This work includes: advancing understanding of methods for characterizing the storage and confining zones, designing injection strategies, and modeling plume movement; and validating seismic and non-seismic monitoring tools. Validating integrated processes and risk management and depositional environments. ■ Small-scale field validation testing is being done in additional regionally significant storage formations to augment RCSP small-scale field validation testing and to confirm injectivity of the reservoir, validate simulation models and monitoring tools, and confirm integrity of confining formations. ■ Conducting field characterization of potential storage formations to evaluate injectivity and available storage resource and storage permanence of potential onshore and offshore storage complexes across the range of heterogeneous depositional environments. ■ Engaging multiple stakeholder groups through RCSP initiative to increase public awareness and inform the development of an effective regulatory and legal framework for safe injection and long-term geologic storage. ■ The 22 countries of the Carbon Sequestration Leadership Forum (CSLF) are engaged in an initiative[12] to identify potential test sites for saline injection of CO_2. ■ Working with international partners on sharing information and data from existing RD&D efforts, and seeking opportunities for collaboration. For example, working with Shell Quest on field testing and validation of DOE-funded, advanced MVA technologies. ■ In November 2014, President Obama and Chinese President Xi jointly announced that the US and China will lead a major new carbon storage project based in China, and work together on a new Enhanced Water Recovery (EWR) pilot project to produce fresh water from CO_2 injection into deep saline reservoirs.	■ Completion of the RCSP large-scale field projects could, with some projects extended, address high-priority research targeted at specific technical barriers such as improved methods to interpret AZMI signals, induced seismicity, and associated storage in residual oil zones (ROZ). ■ Assessment of offshore storage resource, including identification of potential risks and field validation of storage and monitoring technologies, could help address specific technical issues for future offshore storage, including offshore infrastructure, monitoring at the seafloor and water column and geomechanics of poorly consolidated reservoirs. ■ Fit-for-purpose field validation testing could address key technical research issues involved with engineering the subsurface, including geo-steering to protect against induced seismicity and/or leakage; and demonstrating net carbon negative storage with enhanced hydrocarbon recovery. ■ Next-generation pre-commercial scale site characterization, including collection and analysis of data sufficient for permitting, could support future integrated carbon capture and storage projects. ■ Through international partnerships, the further development of protocols to exchange data and information on carbon storage efforts, and seek opportunities for collaborative research which could accelerate CCS technology, evaluation, and validation.

Monitoring tools

Technologies to diagnose and verify permanent storage of CO_2 in the subsurface are an important aspect for meeting regulatory and GHG accounting goals. Table 4.F.4 describes some of the challenges and desired outcomes for monitoring tools, and Table 4.F.5 provides an assessment of the state of the art, current R&D, and research opportunities for these tools.

Table 4.F.4 Challenges and Desired Outcomes for Carbon Capture and Storage Monitoring Tools

Goal: Develop improved tools to monitor and verify permanent storage of CO_2 in the subsurface

Major R&D Challenges

- Detecting and quantifying leakage to the surface.
- Detecting and quantifying leakage out of the storage unit
- Developing improved integrated tools and systems for improved, long-term monitoring.
- Developing improved tools and techniques to map the CO_2 plume, physical property changes, and potential migration pathways in the storage reservoir
- Developing and validating technologies to meet regulatory objectives to document storage permanence and isolation from USDW

Desired Outcomes:

- Develop and integrate advanced monitoring tools for verification of CO_2 storage that can withstand long-term exposure to subsurface conditions
- Develop novel seismic and non-seismic technologies that can be integrated into high-resolution, robust and permanently installed autonomous monitoring systems for CO_2 storage

Table 4.F.5 Technical Assessment and Opportunities for Carbon Storage Monitoring Tools

Goal: Develop improved tools to monitor and verify permanent storage of CO_2 in the subsurface		
State of the Art	Current R&D	Opportunities and Future Pathways
■ Research related to monitoring to determine storage permanence, has provided insight concerning: (1) key measurements needed, (2) interpretation of measurements, and (3) specific tools to use in order to distinguish a possible leakage signal from background natural variations. ■ A new method—satellite-based ground displacement—is being used to monitor subsurface pressure changes due to CO_2 injection. ■ Improved understanding of the resolution of geophysical (to include pulsed neutron capture logs, electrical resistivity tomography, gravity), seismic techniques, and improvements in analysis and interpretation of seismic for monitoring the CO_2 plume have been developed and applied. ■ New understanding of tracers for monitoring CO_2 behavior has been developed and applied in the field. ■ Borehole tools incorporating multiple measurement tools have been developed and applied in the field.	■ Developing diagnostics, such as Light Detection And Ranging (LIDAR) systems for spatial mapping of CO_2 at the surface, for verifying that there is no surface leakage of CO_2 from the subsurface. ■ Developing real-time near-surface monitoring systems to protect ground water and reduce cost. ■ Developing fiber-optic based sensor systems for enhancing near surface and deep subsurface monitoring. ■ Improving seismic monitoring technology, including use of combined multicomponent seismic technology and rock physics modeling to reduce uncertainty in plume monitoring; developing sparse arrays for seismic monitoring of the plume. ■ Developing non-seismic subsurface monitoring techniques to reduce their cost and to verify storage permanence, including Controlled Source Electromagnetic Methods, a pressure-based inversion and data assimilation system, methods to characterize the geomechanical properties, and use of isotopes and perfluorocarbon tracers. ■ Improving analysis and modeling to verify storage permanence, including a stochastic joint inversion toolbox linking reservoir process simulations with dynamic monitoring and measurement inversion.	■ Development of advanced manufactured sensors could provide more precise well and reservoir monitoring. ■ Design of high-resolution, robust, permanently installed monitoring networks could reduce cost and verify permanent storage. ■ Creation of lower-cost tools with higher resolution, including novel geophysical and tracer technologies, is needed to determine storage permanence in wells and to measure emissions from the natural system. ■ Formulation of advanced analysis and modeling methods could enhance monitoring and verification of storage permanence. ■ Integration of advanced monitoring tools into intelligent monitoring systems with advanced data management software could improve accuracy and optimize the verification of storage permanence.

New technologies and tools

Technologies and tools to improve wellbore integrity, increase storage efficiency, improve simulation of subsurface processes, mitigate potential risks, and increase certainty associated with long-term storage operations are important for further reducing costs and improving security of carbon storage.

The ability to have real-time control or "mastery" of the subsurface could have a transformative effect on numerous industries and sectors, impacting the strategies deployed for subsurface energy production and storage. Improved control of the subsurface requires efforts to address the following key challenges to optimize CO_2 storage, energy production, and waste storage/disposal:

- **Discovering, characterizing, and predicting:** Efficiently and accurately locating target subsurface geologic environments; quantitatively inferring their evolution under future engineered conditions; and characterizing the subsurface at a relevant scale;
- **Accessing:** Safe and cost-effective drilling or mining with properly managed reservoir integrity;
- **Engineering:** Creating the desired conditions in challenging high-pressure/high-temperature environments;

- **Sustaining**: Maintaining these conditions over long time frames throughout complex system evolution; and
- **Monitoring**: Improving observational methods and advancing understanding of the microscopic basis of macroscopic complexity throughout system lifetimes.

Table 4.F.6. describes the challenges of and desired outcomes for the development of advanced technologies and tools to address these issues, and Table 4.F.7 examines the state of the art, current R&D, and research opportunities and pathways forward for them.

Table 4.F.6 Challenges and Desired Outcomes for Advanced Technologies and Tools

Goal: Develop new technologies and tools to improve wellbore integrity, increase storage efficiency, improve simulation of subsurface processes, mitigate potential risks, and increase certainty associated with long-term storage operations.

Major R&D Challenges

- Ensuring wellbore integrity for long-term containment of CO_2 in the reservoir
- Ensuring that possible release of CO_2 through natural or man-made pathways can be sealed effectively
- Understanding CO_2 plume and brine pressure front movement, stabilization, and impacts, and sealing capability of caprocks, in order to increase certainty in long term containment of CO_2 in the reservoir and make efficient use of reservoir storage space
- Understanding the potential for geomechanical deformation of the injection zone, confining zone, and wellbore as a result of CO_2 injection, and be predictive of future geomechanical "events" such as induced seismicity
- Understanding geochemical processes associated with CO_2 injection, and how these chemical reactions may impact physical processes in the storage formation, the caprock, the wellbore, and along potential release pathways
- Developing risk assessment strategies in order to identify potential site issues, both technical and non-technical, and implement immediate mitigation procedures

Desired Outcomes:

- Develop advanced risk assessment and geologic storage technologies addressing technical barriers to first mover projects
- Advance fluid flow models to increase accuracy and decrease uncertainty of the simulations used to optimize injection efficiency
- Integrate fluid flow models with complex risk assessment tools and methods

Table 4.F.7 Technical Assessment and Opportunities for Advanced Technologies and Tools

Goal: Develop new technologies to improve wellbore integrity, increase storage efficiency, improve simulation of subsurface processes, mitigate potential risks, and increase certainty associated with long-term storage operations.		
State of the Art	Current R&D[13]	Opportunities and Future Pathways
■ Available industry and regulatory data on wellbore integrity provide a basis for identifying risks of wellbore releases and recommended mitigation procedures. ■ Sensitive measurements of casing deformation have shown promise for assessing wellbore integrity. ■ Initial adaptation of numerical models for CCS have improved predictive capabilities of hydrologic, geomechanical, and geochemical processes and impacts. ■ Laboratory and field tests of geomechanical, hydrologic, and geochemical processes in response to injected CO_2 have led to a preliminary understanding of reservoir behavior, impacts, and conformance in different storage types. ■ Initial development of geostatistical models have improved storage resource estimates in formations representing different depositional environments. ■ Field tests of microbial induced calcite precipitation (MICP) release mitigation technology, which can be delivered via low viscosity solution, has shown promise in sealing potential leakage pathways. ■ Initial approaches toward development of risk assessment strategies include the development and preliminary field testing of a quantitative CO_2 risk assessment tool that is based on a Quantitative Failure Modes and Effects Analysis (QFMEA) model, which can be customized to assess site-specific projects or integrated with other CO_2 storage assessment tools.	■ Developing improved wellbore measurements, such as wellbore deformation, and improved numerical models to assess wellbore integrity. ■ Modeling studies to support development of water management approaches that mitigate risk and increase certainty associated with long-term storage operations. ■ Developing various "simplified model" approaches to reduce computational time and improve simulation of subsurface processes. ■ Developing new methods for sealing of release pathways, such as pH-triggered polymer and polymer-cement nano-composites to improve wellbore integrity. ■ Improving fundamental understanding and modeling of CO_2 trapping mechanisms, such as capillary trapping and dissolution, in reservoirs to increase certainty associated with long-term storage operations. ■ Modeling to develop a better understanding of storage capacity in different depositional environments. ■ Validating numerical simulator results against field data to improve simulation of subsurface processes. ■ Integrating geomechanical impacts into models to assess and mitigate potential risk. ■ Developing efficient mathematical and computational models of the potential coupling between CO_2 injection and fault mechanical deformation to mitigate potential risks and increase certainty associated with long-term storage operations. ■ Developing advanced coupled numerical simulators to enable study of the impacts of geochemical reactions on hydrologic and geomechanical processes.	■ Design of new tools could help ensure wellbore integrity in complex formations, such as sub-salt, and in low strength and overpressured conditions as encountered in broad deployment projects. ■ Formulation of novel techniques for well completion could increase reservoir injectivity without compromising containment. ■ Design of advanced, coupled, geochemical, and bio-geochemical/fluid flow models for optimizing injection efficiency could reduce cost and increase storage certainty. ■ Development of new, fit-for-purpose numerical fluid flow models could reduce cost and uncertainty of simulations while increasing their accuracy; similarly, such models and methods could increase utilization of extracted water and brine (see Technology Assessment 4.C on *Carbon Dioxide Capture and Storage Value-Added Options* for further detail). ■ Creation of advanced quantitative risk assessment tools and further integration risk assessment with field operations could reduce implementation costs and increase storage security.

Additional Information

In addition to the material provided above, extensive information has been developed on carbon storage technology development, cost and performance analysis, storage security, and a host of other issues. Table 4.F.8 provides links to some of the key information available on these and other topics related to carbon storage.

Table 4.F.8 Links for Additional Information

Document Title	Link To Reference	Description
The Energy Data eXchange (EDX)	https://edx.netl.doe.gov/	The Energy Data eXchange (EDX) was developed and is maintained by NETL-ORD as an online system to support internal coordination and collaboration as well as timely tech transfer of data-driven products across NETL's research portfolios
2012 United States Carbon Utilization and Storage Atlas – Fourth Edition (Atlas IV)	http://www.netl.doe.gov/research/coal/carbon-storage/atlasiv	The primary purpose of Atlas IV is to update the carbon dioxide (CO_2) storage potential for the United States and to provide updated information on the Regional Carbon Sequestration Partnerships' (RCSPs) field activities and new information on the American Recovery and Reinvestment Act of 2009 (ARRA) funded Site Characterization projects.
Carbon Storage Technology Program Plan	http://www.netl.doe.gov/File%20Library/Research/Coal/carbon-storage/Program-Plan-Carbon-Storage.pdf	This document serves as a program plan for DOE/NETL's Carbon Storage research and development effort, which is conducted under the Clean Coal Research Program's CCS and Power Systems program area. The program plan describes the Carbon Storage R&D efforts in 2013 and beyond.
Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations - 2012 Update	http://www.netl.doe.gov/File%20Library/Research/Carbon-Storage/Project-Portfolio/BPM-MVA-2012.pdf	Best Practice Manual - This Best Practices Manual (BPM) is a technical guide to monitoring, verification, and accounting (MVA) of carbon dioxide (CO_2) stored in geologic formations.
Carbon Storage Systems and Well Management Activities - 2013 Revised Edition	http://www.netl.doe.gov/File%20Library/Research/Carbon-Storage/Project-Portfolio/BPM-Carbon-Storage-Systems-and-Well-Mgt.pdf	Best Practice Manual - The purpose of this report is to share lessons learned regarding site-specific management activities for carbon storage well systems.
Risk Analysis and Simulation for Geologic Storage of CO_2 - 2013 Revised Edition	http://www.netl.doe.gov/File%20Library/Research/Carbon-Storage/Project-Portfolio/BPM_RiskAnalysisSimulation.pdf	Best Practice Manual - The manual illustrates the concepts of risk analysis (risk assessment) and numerical simulation by describing the experience gained by the DOE Regional Carbon Sequestration Partnerships as they implemented multiple field projects.
Regional Carbon Sequestration Partnerships' Simulation & Risk Assessment Case Histories	http://www.netl.doe.gov/File%20Library/Research/Carbon-Storage/Project-Portfolio/BPM_Sim_Risk_Appdx_IV_web.pdf	Addendum to Best Practices for Risk Analyses and Simulation for Geologic Storage of CO_2
Geologic Storage Formation Classifications	http://www.netl.doe.gov/File%20Library/Research/Carbon-Storage/Project-Portfolio/BPM_GeologicStorageClassification.pdf	Best Practice Manual - This manual discusses the efforts that DOE is supporting to characterize and test small- and large-scale CO_2 injection into these different classes for reservoirs.

Table 4.F.8 Links for Additional Information, continued

Document Title	Link To Reference	Description
Site Screening, Site Selection, and Initial Characterization for Storage of CO_2 in Deep Geologic Formations - 2013 Revised Edition	http://www.netl.doe.gov/File%20 Library/Research/Carbon-Storage/ Project-Portfolio/BPM-SiteScreening. pdf	Best Practice Manual - This manual builds on the experience of the RCSP Initiative as well as the body of literature and best practice guidelines developed by the research community and private industry from around the world. It proposes a standardized framework for classifying CO_2 Storage Resources and Capacity.
Public Outreach and Education for Carbon Storage Projects - 2013 Revised Edition	http://www.netl.doe.gov/File%20 Library/Research/Carbon-Storage/Project-Portfolio/BPM_ PublicOutreach.pdf	Best Practice Manual - This manual represents a distillation of best practices for public outreach and education to support carbon dioxide storage projects; it is derived from the experiences of the seven Regional Carbon Sequestration Partnerships.
Subsurface Technology and Engineering R&D Technical Team website	http://www.energy.gov/subsurface-tech-team	Description of cross-cutting team program activities

Endnotes

1 NETL, Regional Carbon Sequestration Partnerships website, http://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/regional-partnerships.

2 NETL, Carbon Capture and Storage Database, http://www.netl.doe.gov/research/coal/carbon-storage/strategic-program-support/database

3 Carbon Sequestration Leadership Forum, CSLF, Website accessed June 2015, http://www.cslforum.org/.

4 CSLF, 2013 Carbon Sequestration Technology Roadmap, 2013, http://www.cslforum.org/publications/documents/CSLF_Technology_Roadmap_2013.pdf

5 U.S.-China Joint Presidential Statement on Climate Change, The White House, Sept. 25, 2015, https://www.whitehouse.gov/the-press-office/2015/09/25/us-china-joint-presidential-statement-climate-change

6 IEA, Technology Roadmap: Carbon Capture and Storage, 2013 http://www.iea.org/publications/freepublications/publication/technology-roadmap-carbon-capture-and-storage-2013.html

7 Lim, Xiaozhi: "How to Make the Most of Carbon Dioxide," Nature, V.526, 29 October 2015, pp.628-630.

8 NETL Website Publications Page, http://www.netl.doe.gov/research/coal/carbon-storage/publications

9 2012 United States Carbon Utilization and Storage Atlas – Fourth Edition (Atlas IV), http://www.netl.doe.gov/research/coal/carbon-storage/atlasiv

10 NETL, Regional Carbon Sequestration Partnerships website, http://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/regional-partnerships

11 2012 United States Carbon Utilization and Storage Atlas – Fourth Edition (Atlas IV), http://www.netl.doe.gov/research/coal/carbon-storage/atlasiv

12 Carbon Sequestration Leadership Forum, CSLF, Website accessed June 2015, http://www.cslforum.org/.

13 NETL Project Portfolio, http://www.netl.doe.gov/research/coal/carbon-storage/project-portfolio

Acronyms

ADM	Archer Daniels Midland
ARRA	American Recovery and Reinvestment Act of 2009
AZMI	Above zone monitoring interval pressure
BPM	Best practices manual
CBTL	Coal-biomass to liquids
CCS	Carbon capture and storage
CLC	Chemical looping combustion
CO_2	Carbon dioxide
COE	Cost of electricity
cP	Centipoise
CSLF	Carbon Sequestration Leadership Forum
EDX	The Energy Data eXchange
EOR	Enhanced oil recovery
EWR	Enhanced water recovery
H_2	Hydrogen
H_2O	Water
IGCC	Integrated gasification combined cycle
IGFC	Integrated gasification fuel cell
LIDAR	Light detection and ranging
MEA	Monoethanolamine
MGSC	Midwest Geological Sequestration Consortium
MICP	Microbial induced calcite precipitation
MRCSP	Midwest Regional Carbon Sequestration Partnership
MVA	Monitoring, verification, and accounting
NGCC	Natural gas combined cycle
NOAK	Nth of a kind
NOC	Normal operating conditions
PC	Pulverized coal
PCOR	Plains CO_2 Reduction Partnership
QFMEA	Quantitative Failure Modes and Effects Analysis model

RCSP	Regional Carbon Sequestration Partnership
RDD&D	Research, development, demonstration, and deployment
ROIP	Residual oil in place
ROZ	Residual oil zone
sCO_2	Supercritical CO_2
SECARB	Southeast Regional Carbon Sequestration Partnership
SOFC	Solid oxide fuel cell
SOTA	State of the art
SWP	Southwest Regional Partnership on Carbon Sequestration
USC	Ultra-supercritical
VSPs	Vertical seismic profiles