OTC Paper Number OTC-21987-PP

Carbon Capture and Sequestration: The U.S. Department of Energy's R&D Efforts to Characterize Opportunities for Deep Geologic Storage of Carbon Dioxide in Offshore Resources

J.T. Litynski[1] and B.M. Brown[1] National Energy Technology Laboratory, and D.M. Vikara[2] and R.D. Srivastava[2], KeyLogic Systems

1 National Energy Technology Laboratory, United States Department of Energy, Pittsburgh, PA 15236, USA.

2 KeyLogic Systems, National Energy Technology Laboratory, United States Department of Energy, Pittsburgh, PA 15236, USA.

This paper was prepared for presentation at the Offshore Technology Conference held in Houston, Texas, USA, 2–5 May 2011.

Abstract

The United States Department of Energy (DOE) is the lead federal agency for the research, development, demonstration, and deployment (RDD&D) of carbon sequestration technologies. This effort is being implemented through several activities, including applied research and development (R&D), demonstration projects, and technical support to loan guarantee and tax incentives programs. The sequestration program started in 1997 and has grown significantly. In Fiscal Year 2010, $145 million in federal funding was received to support carbon capture and storage (CCS) related R&D. The Sequestration Program also received $80 million in funding from the 2009 American Recovery and Reinvestment Act (ARRA) to support the development of resources for geologic storage of CO_2. The goal of the program is to develop a suite of technologies that can support the implementation of commercial CCS projects by 2020.

Part of the program funding is being used to assess the potential for storing CO_2 in offshore geologic formations. This paper presents an overview of projects awarded to assess the potential for geologic storage in state and federal waters in the Gulf of Mexico (GOM), the Atlantic and Pacific Oceans, and in Texas and California state territorial waters, as well as research efforts DOE is supporting world-wide. These efforts are aimed at capacity assessments; monitoring and modeling of sub-seabed storage projects; characterization of projects that are drilling wells and conducting seismic surveys; and assessment of regulatory gaps relative to storing CO_2 in offshore formations. The results are expected to provide a summary of basin-scale suitability and will identify and prioritize potential offshore CO_2 geological storage opportunities.

Introduction

Fossil fuels are projected to be the primary source of energy for the United States and most developed and developing countries over the next several decades, and their consumption is expected to increase. Atmospheric levels of carbon dioxide (CO_2) have risen significantly from preindustrial levels of 280 parts per million (ppm) to present levels of around 384 ppm (Tans, 2008). Evidence suggests that the observed rise in atmospheric CO_2 levels is the result of expanded use of fossil fuels for energy. The concentration of CO_2 in the atmosphere is expected to rise due to the anticipated increase in fossil fuel usage unless major advances in energy management and production are made (Socolow et al., 2004; Greenblatt and Sarmiento, 2004). Carbon capture and storage (CCS) is an emerging strategy for preventing the emission of anthropogenic CO_2 into the atmosphere. The long-term storage of anthropogenic CO_2 is a promising technology for slowing, and ultimately reversing, the build-up of greenhouse gas (GHG) emissions in the atmosphere (NETL, 2009).

The United States Department of Energy (DOE) is the lead federal agency for the research, development, demonstration, and deployment (RDD&D) of carbon sequestration technologies. The Carbon Sequestration Program being implemented by the DOE's Office of Fossil Energy and managed by the National Energy Technology Laboratory (NETL) is helping to develop technologies to capture, separate, and store CO_2 in order to reduce greenhouse gas emissions without adversely affecting energy use or hindering economic growth. NETL's primary carbon sequestration research and development objectives are (1) to lower the cost and energy penalty associated with CO_2 capture from large point sources and (2) to improve understanding of factors affecting CO_2 storage permanence, capacity, and safety in geologic formations and terrestrial ecosystems (Rodosta et al., 2010). This effort is being implemented through several activities, including applied R&D, demonstration projects, and technical support to loan guarantee and tax incentives programs. NETL's sequestration program started in 1997 and has grown significantly. In Fiscal Year 2010, $145 million in federal funding was received to support the Carbon Sequestration Program within the DOE's Office of Fossil Energy. The Sequestration Program also received $80 million in funding from the 2009 American Recovery and Reinvestment Act (ARRA) to support the development of resources for geologic storage. The goal of the program is to develop a suite of technologies that can support the implementation of commercial CCS projects by 2020.

Part of this funding is being used to assess the potential for storing CO_2 in offshore geologic formations. Offshore geologic storage involves capturing CO_2 from a stationary emissions source (such as a coal-fired power plant or other industrial facility), transporting the highly compressed CO_2 offshore via a sub-sea pipeline or ocean tanker, and injecting it into a geologic formation deep beneath the seabed where it will remain safely stored (isolated from the ocean water) for hundreds to thousands of years. Offshore CO_2 sources can also utilize CCS technology, often while avoiding extensive CO_2 transportation costs. For instance, natural gas separation rigs located offshore can geologically store CO_2 that has been separated as part of the natural gas extraction process. This type of process has been successfully demonstrated since 1996 at Statoil's Sleipner field, located approximately 240 km off the cost of Norway in the North Sea. At Sleipner, 1 million metric tons per year of CO_2 is separated from produced natural gas and stored in a deep saline formation (Utsira Formation) over 1 km beneath the sea bed (Schrag, 2009).

Advantages of Offshore Geologic Storage of CO_2

Most investigations of CO_2 storage in North America focus on onshore geologic formations, particularly deep saline formations, unmineable coal seams, and oil and gas reservoirs. Offshore geologic sequestration offers additional CO_2 storage opportunities and may prove to be easier, safer, and less expensive than storing CO_2 in geologic formations on land, particularly during the early days of commercialization (Schrag, 2009). Suitable offshore storage reservoirs require the same features as for onshore geologic storage, including sufficient porosity, permeability, and thickness in the injection zone and a suitable confining layer (caprock). These characteristics are critical to the success of any geologic CO_2 storage site, as they dictate the rate at which CO_2 can be injected (permeability), the total storage capacity at the site (porosity, thickness, and formation areal extent), and the security of the formation for preventing the upward migration of CO_2 to other formations or the atmosphere (confining caprock) (WRI, 2008). Offshore CCS is a promising technology due to several key advantages:

- Offshore storage provides additional CO_2 storage potential in the United States to supplement existing onshore capacity estimates.
- The formation fluid in offshore sediments is typically similar to sea water in terms of chemistry and salinity with 30,000 to 40,000 ppm total dissolved solids (TDS). The U.S. Environmental Protection Agency (EPA) mandates onshore geologic sequestration be restricted to formations with high salinity fluid (>10,000 ppm total dissolved solids) (Rodosta et al., 2010). Based on EPA's regulations for the discharge of produced water from oil platforms into the ocean, offshore CCS operators have the advantage of direct plume and pressure management of the formation through direct release of marine pore fluids to surrounding waters without treatment (Schrag, 2009).
- Locating sequestration sites away from heavily populated, onshore areas avoids the perception of storing waste material beneath a populated area. This also reduces the difficulty of establishing surface and mineral rights at candidate storage sites. With the exception of Texas, lands more than three miles offshore are owned solely by the federal government (Schrag. 2009).
- Offshore storage reduces the risk to underground sources of drinking water (protected groundwater).
- Establishing transport pipeline corridors or using existing infrastructure should be feasible based on already existing infrastructure for natural gas and oil.
- Offshore CCS provides storage sites in the vicinity of heavily populated areas along U.S. coastlines (like the Northeast and California).
- The overall economics of offshore CCS may be more favorable compared to onshore CCS, despite higher capital costs (for drilling rigs, well manifolds, etc.) typically associated with working in an offshore environment. This will be especially true if offshore storage projects prove relatively easy to permit, finance, and operate (Schrag, 2009).

DOE Supported Offshore Storage Research and Development Efforts

This paper presents an overview of NETL-supported projects awarded to assess the potential for geologic storage in state and federal waters in the Gulf of Mexico (GOM), the Atlantic and Pacific Oceans, and in Texas and California state territorial waters. These efforts are aimed at capacity assessments; monitoring and modeling of sub-seabed storage projects; characterization of projects that are drilling wells and conducting seismic surveys; and assessment of regulatory gaps relative to storing CO_2 in offshore formations. The results will provide a summary of the basin-scale suitability for CO_2 storage and will identify and prioritize potential offshore CO_2 geologic storage opportunities.

NETL's Carbon Sequestration program is providing financial support to and management oversight of the following Core R&D (NETL, 2010a), Regional Carbon Sequestration Partnership (RCSP) (Rodosta, et al., 2010), and American Recovery and Reinvestment Act (ARRA) (NETL, 2010b) efforts to assess storage in sub-seabed geologic formations:

- Several of DOE's Regional Carbon Sequestration Partnerships are assessing the potential for CO_2 storage in geologic formations in the Gulf of Mexico and the Atlantic and Pacific Oceans.
- The Scripps Institute for Oceanography developed and is testing micro-gravity monitoring technology to determine the fate of CO_2 injected offshore at Sleipner in the North Sea.
- Lawrence Livermore National Laboratory is conducting geomechanical modeling to assess the potential for propagation of existing and/or new fractures in the reservoir and caprock.
- The Southeast Regional Carbon Sequestration Partnership (SECARB) is working with the Interstate Oil and Gas Compact Commission (IOGCC), the Bureau of Ocean Energy Management and Enforcement (BOEMRE), and several states to identify the currently applicable regulatory structure and gaps for CO_2 storage in geologic formations under offshore waters of the United States.
- NETL is supporting two projects to characterize promising geologic formations for CO_2 storage as part of the ARRA Site Geologic Characterization effort. Terralog Technologies, Inc. is characterizing Pliocene and Miocene formations in the Wilmington Graben, offshore of Los Angeles, for large-scale geologic storage of CO_2. The University of Texas is investigating Texas' offshore subsurface Miocene formations in the Gulf of Mexico as candidate geologic storage formations.

RCSP Efforts in Assessing Offshore Geologic Storage Potential

Three of DOE's RCSPs, the Midwest Geological Sequestration Consortium (MRCSP), West Coast Regional Carbon Sequestration Partnership (WESTCARB), and SECARB are assessing CO_2 storage potential in offshore geologic formations, particularly off the eastern coast of the United States and in the Gulf of Mexico and the Atlantic and Pacific oceans.

SECARB continues to characterize the region's geologic storage options, both onshore and offshore, and to identify barriers and opportunities for the wide-scale construction of pipelines in the Southeastern United States to transport CO_2 for geologic storage, EOR, and other commercial uses. Much of the CO_2 storage resource in the SECARB region lies in a thick wedge of sandstones in several sub-basins along the Gulf Coast. Sandstones of the Cretaceous Tuscaloosa Formation and the Paluxy Formation host the current SECARB field tests. Overlying Tertiary formations extend offshore, and a recent reassessment of these units has quantified additional storage potential (Figure 1).

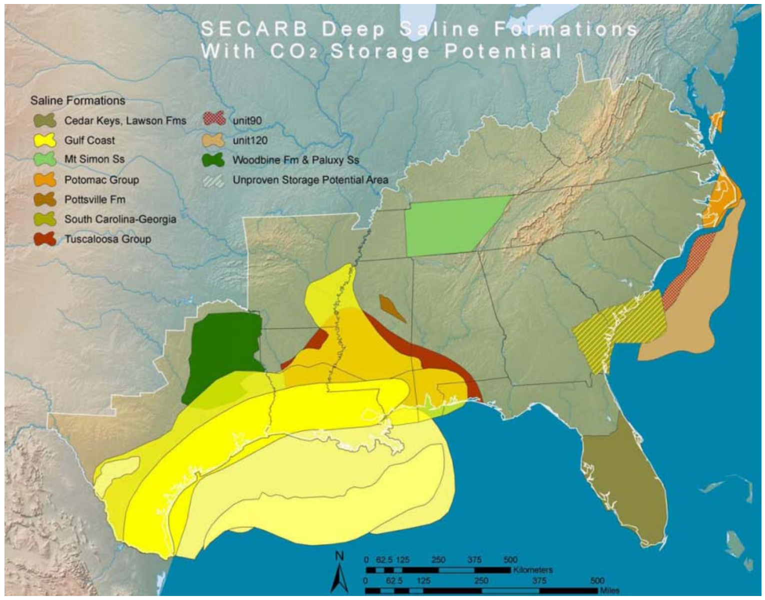

Figure 1: Deep saline formations in the Southeast Regional Carbon Sequestration Partnership (SECARB) Region. Several formations have offshore storage potential, including the Offshore Atlantic Units 90 and 120, the multiple Gulf Coast Basins, the South Carolina–Georgia Basins, and the Potomac Group (NETL, 2010b).

Other Cretaceous formations that provide significant storage potential include sandstones in Texas and those extending from South Carolina to Georgia, the sub-seabed in the Atlantic Ocean offshore of the Carolinas and Virginia, as well as carbonates and sandstones in Florida. Recent reassessments of all offshore saline and oil and gas storage formations estimate a minimum of 502,750 million metric tons of CO_2 storage potential (NETL, 2010b).

The MRCSP is assessing technical potential, economic viability, and public acceptance of carbon storage within the states of Indiana, Kentucky, Maryland, Michigan, New Jersey, New York, Ohio, Pennsylvania, and West Virginia. The region has a diverse range of CO_2 sources and many opportunities for geologic and terrestrial storage. Potential locations for geologic storage in the MRCSP region extend from the deep rock formations in the broad sedimentary basins and arches in the western portion of the region to the offshore continental shelf adjacent to New Jersey, Delaware, and Maryland in the east (Figure 2). Offshore areas along the east coast and Great Lakes also contain significant storage resource not included in MRCSP's regional capacity assessment (NETL, 2010b) (Figure 2). In the eastern States, sedimentary deposits in the coastal plain along the continental shelf are being considered for potential CO_2 storage. MRCSP began preliminary characterization of potential reservoirs and confining units in the New Jersey continental shelf by utilized existing well logs from the outer continental shelf and continental slope, acquired well paleontology data, as well as newly scanned multi-chanel seismic (MCS) data from older seismic profiles in the offshore region conducted by Exxon, the United States Geological Survey (USGS) and Germany's Federal Institute for Geosciences and Natural Resources (BGR). This seismic data, in particular, was used to develop tracings of the seafloor, the top Cenomanian sands, and the bottom Cenomanian sands to add to the overall charactereization of candidate offshore formations off the coast of New Jersey. Well data has indicated that the Cenomanian sands contain high values of porosity and permeability (30% and 1,200 md, respectively). MRCSP is utilizing these existing data to construct 3-D geologic models to obtain first eatimates of CO_2 storage potential within the New Jersey continental shelf.

The WESTCARB partnership has characterized onshore and offshore geologic storage options in the west coast region of the United States and Canada. The geology of the WESTCARB region is varied, ranging from the shield volcanoes of Hawaii to tectonic plate margins along the western U.S. and Canadian coastlines, to interior regions featuring mountains and large and small sedimentary basins. California is a possible candidate for CO_2 storage in offshore basins, although the lack of available data has limited the assessment of CO_2 storage potential to areas where oil and gas exploration has occurred. Offshore oil and gas accumulations in California have been found in the Santa Maria, Ventura, and Los Angeles Basins. Specifically, for the offshore formations around California, the estimated CO_2 storage resource for the known developed and undeveloped offshore oil and gas fields within conventional sandstone reservoirs of the Los Angeles and Ventura Basins is approximately 240 million metric tons (NETL, 2010b). Other storage formations off the coasts of Oregon, Washington, and Alaska have been screened and assessed. Screened saline formations, both offshore and onshore, in the WESTCARB region have storage potential, but volumes have not been estimated due to insufficient data and the formations require further evaluation.

In Alaska, critical constrainining data for developing volumetric CO_2 storage capacity estimates are typically sparse or lacking in many of the vast sedimentary basins both on and offshore. Data such as depth, salinity, presence and capacities of seals and traps, porosity, permeability and geochemistry, are all needed to make reasonable quantitative volumetric estimates. The lack of constraining data in most basins makes obtaining reasonable volumetric estimates of storage potential problematic and challenging. Regions in Alaska with extensive data include the Colville Basin on the North Slope, and the Cook Inlet Basin in south central Alaska, both which have producing oil and gas fields, large coal deposits, and have significant seismic and well data coverage.

Preliminary screening for CO_2 storage potential in Alaska saline basins and coal seams did not account for the uniqueness of the Alaskan environmental conditions and economy, despite following established DOE capacity estimation methodology. Initial studies (Stevens and Moodhe, 2009) indicated large areas with potential for sequestration in both northern Alaska and offshore saline aquifers [16,700 Gigatons (Gt)] and onshore coal seams [120 Gt]. Incorporating factors for sedimentary basins such as known and expected water salinity, tectonic environment, offshore environments and distance from infrastructure (particularly the economic and logistical challenges related to the long distances between remote interior basins and CO_2 sources, roads or pipelines), as well as rank, permafrost presence, and adsorption data for coal, will significantly constrain these resource estimates. When these volumes are further constrained with additional geological and logistical variables, estimates are expected to decrese by an order of magnitude for offshore saline formations and by two orders of magnitude for coal seam storage estimates (on and offshore formations) (CEC, 2010). In summary, with the exception of the Cook Inlet Basin and North Slope region, offshore basisns in Alaska are contstrained, located in extremely difficult working environments, and are far from both CO_2 sources and infrastructure.

While revised estimates show the saline and coal sequestration potential is much lower than initial estimates, WESTCARB researchers are focusing on refining capacity estimates for the Cook Inlet Basin and North Slope of Alaska, where proximity to industrial CO_2 sources and extensive infrastructure, as well as ample characterization data from oil and gas exploration, make CO_2 storage more feasible. The oil and gas fields on the North Slope of Alaska are of prime interest because of the large potential for CO_2-EOR, as well as their proximity to some of largest sources of stationary CO_2 emissions in Alaska. The hydrocarbon reservoirs of the Cook Inlet also offer potential for CO_2 storage and EOR given their proximity to industrial CO_2 sources. Fortunately, since CO_2 from oil and gas operations produces 75% of Alaska stationary sources, source and sink locations are essentially co-located (Figure 2) (NETL, 2010b).

The Scripps Institute for Oceanography Project

Researchers funded by DOE are partnering with European scientists to track injected CO_2 in the world's first and longest running carbon storage operation located at the Sleipner gas field in the North Sea. The researchers—from the Scripps Institution of Oceanography at the University of California–San Diego, and the Lamont-Doherty Earth Observatory (LDEO) in New York—are conducting surveys on the seafloor to monitor injected CO_2 in the one kilometer deep reservoir (NETL, 2009).

Since 1996, about one million metric tons of CO_2 per year have been injected into the Sleipner reservoir for a total of more than 10 million metric tons. Carbon dioxide, produced along with natural gas, is separated on the production platform and, to prevent it from venting to the atmosphere, is compressed and injected into a sandstone formation above the gas-bearing zone at a depth of about 1 km below the seabed. An 80-meter-thick shale caprock holds the CO_2 securely in place.

The gravitational monitoring technology used at Sleipner is based on measuring the change in density of the sandstone formation as injected CO_2 displaces higher density water in the pores. This density change affects the strength of the Earth's gravitational field. Gravity surveys performed at different times provide snapshots of the CO_2 plume's migration deep below the seafloor. In the years 2002, 2005, and 2009 precision seafloor gravity measurements were made at 30 seafloor stations above the Sleipner CO_2 plume. These surveys performed by Scripps validated the gravity technique as an effective monitoring tool. Specifically, data were analyzed that accounted for multiple sources for the changes in gravity to obtain an estimate of in situ CO_2 density.

The injected CO_2 (approximately 5.88 million metric tons) over this time period displaced denser formation water, resulting in a negative gravity change above the plume. In addition, hydrocarbon gas production and subsequent water influx into the deeper, nearby gas reservoir caused an increase in gravity of higher amplitude and longer wavelength. Observing vertical changes in the seafloor between surveys to millimeter precision enables quantification of CO_2 movement caused by sediment scouring. Some of the elevations have experienced more than a 10 centimeter vertical movement over the 7 year duration of the experiment, and erosional topography can be seen in a >10 meter broad area around some of the elevation markers. Results suggest that CO_2 density is also sensitive to impurities that make up 1-2% of the injected material at Sleipner. As a result, CO_2 density estimates were reduced to slightly below expected levels (Alnes et al., 2010).

The dissolution of CO_2 into the brine increases its density by about 1%, resulting in the CO_2-saturated brine sinking to the bottom of the formation. This is an important process that ensures long-term, leak-proof storage of CO_2. The gravity survey is important in this situation because it is used in estimating the rate of CO_2 dissolution into formation water. Since the undisturbed formation temperature and the injection temperature are fairly well known, the gravity change from 2002–2009 at Sleipner can be used to constrain the rate of dissolution of CO_2 into the formation water. Dissolved CO_2 is not detected by seismic analysis; therefore, utilizing gravimetric data could be valuable for monitoring this process, which is important for long-term predictions of the CO_2 storage, particularly in offshore CCS applications where in situ monitoring can be a challenge. By combining the CO_2 density estimate from gravity measurements with the estimate based on the temperature measurements, the rate of dissolution of CO_2 into brine was found to be less than 1.8% per year for the Sleipner site (Alnes et al., 2010).

Future gravity monitoring surveys at Sleipner will continue to improve on this result as the volume of injected CO_2 increases. Lessons learned from monitoring the Sleipner CO_2 storage reservoir can be applied elsewhere in the world.

Lawrence Livermore National Laboratory Geomechanical Modeling

LLNL is conducting research aimed at understanding the role of injection-induced mechanical deformation and directed sea-floor monitoring at the Snøhvit Project in the Barents Sea, operated by StatoilHydro. The Snøhvit project is the first petroleum production plant to be located in the Barents Sea. At the associated onshore liquefied natural gas plant, CO_2 is separated from the production stream to make the product suitable for compression and export. Separated CO_2 is then sequestered below Snøhvit at rates up to 700,000 metric tons of CO_2 per year.

Large-scale commercial CO_2 sequestration projects like the one at Snøhvit face several new technical challenges in development and operations, including pressure build-up caused by large-volume CO_2 injection and associated stress issues. Examples of these stresses include dilation or closure of faults and fractures (and development of leakage pathways), slip and dislocations along faults or fractures, change in the connectivity within the injection reservoir, and microseismic or teleseismic events. Another issue is the operational challenge of monitoring the sea-floor. CO_2 detection methods for CO_2 fluxes typically used at the surface will not work in the deep sea environment, nor can they be deployed easily and economically, creating challenges for the appropriate stewardship and environmental security of large projects. LLNL is studying two components relevant to storage effectiveness and operational success: (1) the geomechanical effects of injection on rock deformation and fault leakage hazards and (2) guidance on developing a monitoring program focused on possible migration of CO_2 and brines to the seafloor.

Utilizing shared data and information from StatoilHydro and other sources (e.g., public domain), LLNL is developing a static geomodel of the Snøhvit injection site. This includes the development of fracture network models that are representative of (1) the known structural geometry of major faults and fractures in and above the reservoir and (2) conceptual models of caprock structure. These fracture models allow LLNL to calculate fluid-pressure driven deformations of the fractured rock mass at different scales. Coupling the fracture models with a discrete-fracture-network flow code (FracHMC) that accommodates stress-induced changes in transmissivity (Detwiler and Rajaram, 2006) will provide estimates of changes in effective permeability caused by altered transmissivities of individual fractures within the fracture networks. The geomechanical modeling effort will aid in forecasting of fault failure, caprock deformation and fracturing, and injection-induced seismicity.

Additionally, LLNL is developing seafloor geochemical and geophysical monitoring approaches. , LLNL, with shared data and information from Statoil-Hydro and other sources and based on the results of all the modeling studies, will design prototypes for monitoring array systems. The seafloor monitoring study will focus on the consequences of reactive transport through fractured media, geochemical and geophysical evolution of the system, and simulation of accumulation and dispersion on the seafloor for consideration of deployment of monitors. Results will provide operational information for Snøhvit and inform the development of operational protocols for commercial CCS deployment in a marine setting. Developing the seafloor geochemical and geophysical monitoring approaches includes (1) performing a seafloor site hazard assessment (including identifying potential flow paths through the caprock and identifying areas of current pock-marking, deep wells, or other potential fast paths), (2) forward geophysical, geochemical transport, and plume simulation, and (3) design and prototype testing of a seafloor monitoring array. The overall results from this LLNL study will enhance the predictive capability of field performance models, provide a new basis for interpretation of geo-physical and operational data at Snøhvit, and provide support for the creation of appropriate regulations and monitoring schemes for subsea geological storage of CO_2.

DOE Collaboration with IOGCC and BOEMRE on Offshore CCS Regulations

Regulatory authority over many aspects of CCS continues to be examined by numerous agencies, many of which are involved with regulating CO_2 transport and geologic storage. DOE is actively coordinating with the states and other federal agencies on CCS-related rule making activities. Relative to offshore CCS, DOE has sponsored SECARB to team with the Interstate Oil and Gas Compact Commission (IOGCC), the Bureau of Ocean Energy Management and Enforcement (BOEMRE)—formerly the Minerals Management Service—and several states to identify the currently applicable regulatory structure and gaps for CO_2 storage in geologic formations under offshore waters of the United States. This effort includes identifying requirements for potential offshore sequestration, identification of stakeholder challenges, re-use of existing wells for CO_2 injection, conducting CO_2 capacity assessment for delineated federal and state waters, and inventorying existing wells and pipelines in both federal and state waters. At the conclusion of the study, the IOGCC and SECARB anticipate conducting public outreach and education efforts on study results and distributing findings to regional and national stakeholders.

DOE Supported ARRA Offshore Geologic Site Characterization Projects

NETL has selected 10 projects to characterize promising geologic formations for CO_2 storage. The majority of the project funding is being provided by the American Recovery and Reinvestment Act of 2009. The 10 projects will provide greater insight into the potential for geologic formations across the United States to safely and permanently store CO_2 and develop a national assessment of CO_2 storage capacity in deep geologic formations. Two projects are specifically evaluating CO_2 storage potential in offshore geologic formations (NETL, 2010a) (Figure 2).

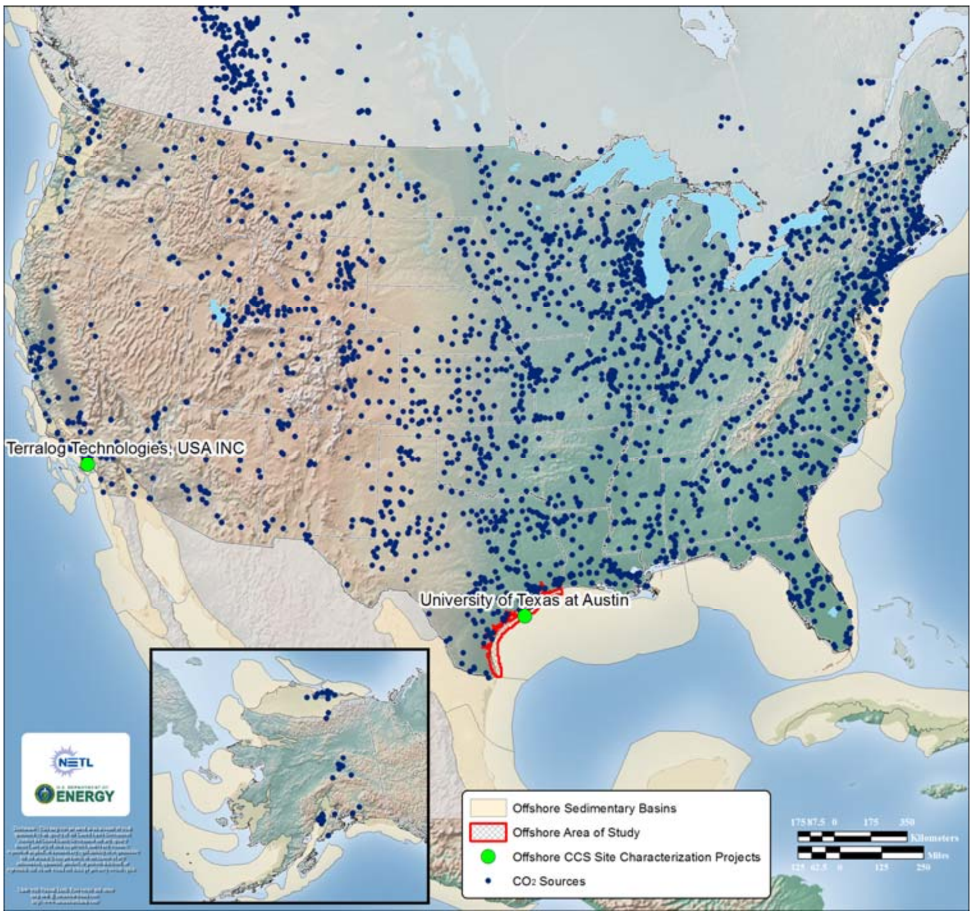

Figure 2: Location of offshore ARRA Site Characterization Projects, CO_2 source locations, and offshore sedimentary basin locations

Terralog Technolgies, USA Inc.

Terralog Technologies, Inc. is implemeting a comprehensive research program to better characterize Pliocene and Miocene sediments in the Wilmington Graben (Graben) within the Los Angeles Basin for high volume CO_2 storage. These sediments are expected to span more than 1.5 km of vertical interval and are expected to possess significant CO_2 storage potential. The Los Angeles Basin presents a unique and special combination of high need and significant opportunity for large scale CO_2 storage. The Pliocene and Miocene sediments in the Los Angeles Basin (massive interbedded sand and shale sequences) are known to provide excellent and secure traps for oil and gas. Given the population density in the Los Angeles Basin, it can be challenging to site a geologic storage project onshore due to complex land ownership issues and proximity to human receptors. The Graben is located directly offshore in the Los Angeles and Long Beach Harbor area making it easily accessible, yet is geologically isolated from the nearby Wilmington oilfield and onshore area, reducing communication risks and public risk.

This site characterization project effort is being conducted in two phases; the first of which is devoted to completing a detailed review and interpretation of existing geologic data from nearby oil and gas exploration in the region, including well log evaluation and interpretation of existing 2-D and 3-D seismic data. This first phase is focused on identifying, characterizing, and quantifying likely targets and seals within Pliocene and Miocene sediments. The second phase consists of filling gaps in geologic data through acquisition of new 2-D seismic lines; drilling, coring, and injection testing (using two evaluation wells) into the Graben; developing 3-D CO_2 migration simulation models, and conducting a risk assessment. Terralog has started integrating existing data from the first phase with newly acquired data from the second phase to develop predictive models and assess storage capacity within the Graben.

Terralog has recently acquired 175 km of new 2-D seismic lines and completed drilling of the first characterization well into the Pliocene Repetto Formation. Rock properties have been obtained of the Pliocene Pico and Repetto Formations and used to supplement existing data to develop preliminary 3-D geologic structure maps. Both the existing and newly acquired site data have been integrated into a 3-D CO_2 migration model (TOUGH2) and a geomechanical model (FLAC3D). These models allow for additional quantification and analysis of storage targets and seals and simulation of long-term CO_2 injectivity, migration, and storage. Preliminarly CO_2 storage estimates in the Graben exceed 100 million metric tons.

Terralog is continuing work on targeting the Miocene Puente Formation by drilling, coring, and testing a second well in the eastern Graben area. The integrated 3-D CO_2 migration and geomechanical models will be refined with lithologic properties as new well data are acquired and 2-D seismic acquisition continues. In addition, a comprehensive risk assessment (including geologic uncertainty, potential well leakage paths, and natural and induced seismicity) is being developed and documented. Terralog Technologies, Inc. is also conducting an analysis of the industrial CO_2 sources (cement plants, biofuel production, fertilizer production, etc.) within the Los Angeles region and an engineering study of existing and new pipeline systems to transport CO_2 from local sources to sequestration sites.

This effort provides greater insight into the potential for offshore geologic formations of the United States to safely and permanently store CO_2 and refines the national assessment of offshore CO_2 storage capacity in deep geologic formations.

University of Texas at Austin – Gulf of Mexico Miocene CO_2 Site

The University of Texas at Austin (UT–Austin) will identify one or more CO_2 injection sites within Texas' offshore state lands that are suitable for the safe and permanent storage of 30 million metric tons of CO_2 from future large-scale commercial CCS operations (NETL, 2010c). Unlike the rest of the U.S., Texas state lands extend 10.3 miles offshore instead of the usual three miles, yielding a prospective area of approximately 6,400 square miles. UT–Austin has partnered with the General Land Office (GLO) of Texas, the owner of these offshore lands. This single-owner situation avoids typically troublesome issues such as liability, pore space ownership, and risk to underground sources of drinking water (protected groundwater). UT–Austin will use existing data from hydrocarbon exploration activity to identify candidate CO_2 storage opportunities and refine capacity calculations for optimal Miocene age rock formations within the region (Figure 3). The approach for identifying these injection sites is to use both new and historic data to evaluate the candidate geologic formations.

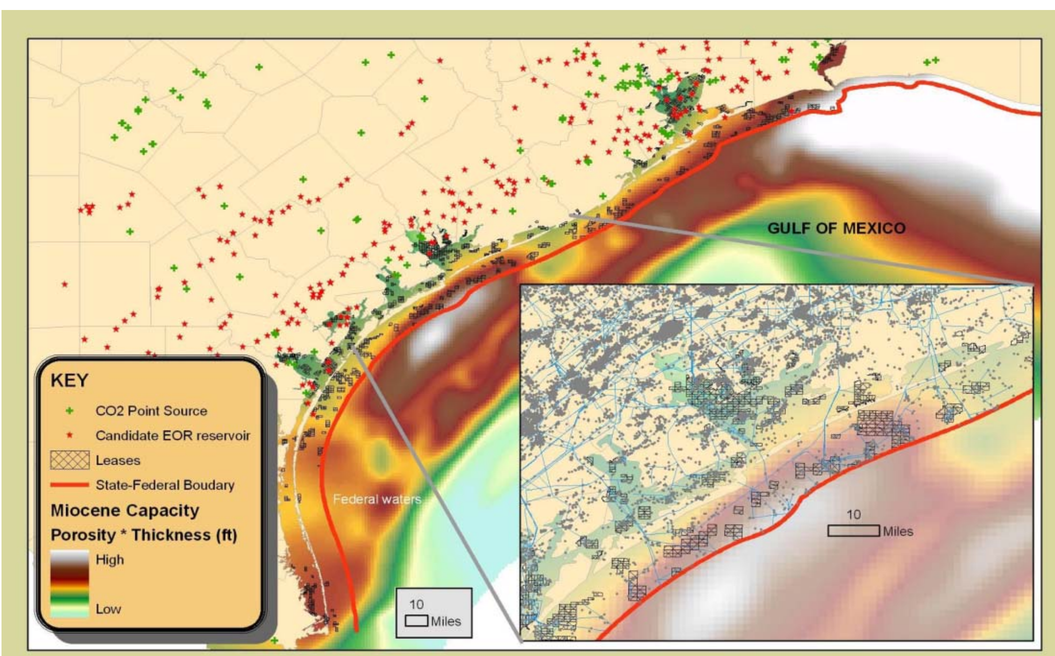

Figure 3: CO_2 Storage Capacity in Saline Formations in the Gulf Coast Region. Storage capacity is indicted in a "high to low" scale as indicated by color contours. Capacity is calculated as Miocene formation porosity multiplied by thickness as

indicated in the figure legend. The location of CO_2 point sources, candidate enhanced oil recovery (EOR) reservoirs, and state/federal boundaries is also indicated.

The project is being implemented in two phases: an initial site characterization effort followed by uncertainty reduction and additional data collection. The site characterization phase involves obtaining an initial assessment of capacity, injectivity, containment potential (stratigraphic and through mineralization), seal integrity, and identification of any leakage pathways based on historical or newly acquired site-specific data. There is a vast amount of existing geologic data pertaining to the Texas Gulf Coast, including well logs, cores, seismic surveys, as well as production and test data from major oil and gas exploration. The second phase of the project will reduce any uncertainty about the CCS potential (capacity, injectivity, containment, and identification of leakage pathways) in the Gulf Coast region through additional data collection (including core measurements from existing cores), brine/chemical reaction simulations and modeling, and collection of a shallow marine seismic survey. Efforts from these two phases will assist in selecting and ranking one to four specific candidate reservoirs based on their ability to contain 30 million metric tons of CO_2.

Additional work being conducted includes the generation of a three-tiered risk analysis and mitigation plan in support of near-term commercial development efforts. The first tier of the review includes a compilation of available technical literature on risks of offshore sequestration, as well as a detailed risk assessment simulation study. The second tier utilizes CO_2-PENS, a coupled process-systems model, to integrate field/laboratory observations with numerical models and abstractions to predict long-term performance of a geologic CO_2 sequestration site. The model accounts for CO_2 migration in the primary reservoir and beyond through potential leakage pathways such as wellbores and faults. The third tier involves the collection and assessment of potential risks and various concerns of regional CCS stakeholders.

This effort will provide greater insight into the potential for geologic formations across the United States to safely and permanently store CO_2, including the refinement of a national assessment of CO_2 storage capacity in deep geologic formations. Specifically, UT–Austin's ability to develop and utilize offshore geological storage capacity could contribute significantly to the management of CO_2 emissions

Other Significant Offshore Geologic Opportunities

The significant potential for geologic storage of CO_2 in offshore formations is indicated by the interest of other international governments as well. For example, the Victoria State Government in Australia is studying this potential. A qualitative comparison among the various basins indicates that the offshore Gippland Basin has the best overall potential for CO_2 geologic storage. This basin has an extensive sedimentary fill with numerous reservoir and seal horizons. Third in ranking is the offshore Otway Basin. The overall conclusion is that the State of Victoria and its adjacent waters show considerable potential for CCS projects (Gibson-Poole, 2007).

Conclusion

It is predicted that, unless remedial actions are initiated, the buildup of GHGs in the atmosphere will continue. A promising approach for controlling CO_2 emissions is CCS. One option for CCS is injection into land-based geologic formations, but an option with significant advantages is injection into offshore geologic formations. Offshore sites add signifincatly to potential storage capacity, should allow discharge of untreated produced water directly into the ocean, avoid populated areas, avoid issues pertaining to underground sources of drinking water, and will likely enjoy lower costs, especially in areas where existing infrastructure is in place. The United States Department of Energy is the lead federal agency for the research, development, demonstration, and deployment of carbon sequestration technologies. The DOE has a robust program to evaluate the potential of CCS projects involving offshore injection of CO_2 into geologic formations. This effort will provide increased insight into the potential for safe and permanent storage of CO_2 in geologic formations off the coast of the United States and will refine the national assessment of CO_2 storage capacity in deep geologic formations offshore.

References

Alnes, H., Eiken, O., Nooner, S., Sasagawa, G., Stenvold, T., and Zumberge, M. 2010. Results from Sleipner gravity monitoring: updated density and temperature distribution of the CO_2 plume. *Energy Procedia.* Proceedings of the 10th International Conference on Greenhouse Gas Control Technologies (GHGT-10), September 19–23, 2010. Amsterdam, The Netherlands.

California Energy Comissions (CEC). 2010. Alaska Geologic Carbon Sequestration Potential Estimate: Screening Saline Basisns and Refining Coal Estimates. Prepaired by the Alaska Department of Natural Resources – Division of Oil and Gas.

Detwiler, R., and Rajaram, H. 2007. Predicting dissolution patterns in variable aperature fractures: Evaluation of an enhanced depth-averaged computational model. *Water Resources Research*. 43, W04403, doi:10.1029/2006WR005147, 4 April 2007.

Gibson-Poole, C.M., Edwards, S., Langford, R.P., and Vakarelov, B. 2007. Review of Geologic Storage Opportunities for Carbon Capture and Storage (CCS) in Victoria—Summary Report.

Greenblatt, J.B., and Sarmiento, J.L. 2004. Variability and climate feedback mechanisms in ocean uptake of CO_2. In: The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World. Field, C.B., and Raupach, M.R., Eds. Island Press, Washington, DC.

National Energy Technology Laboratory (NETL), 2009. DOE Study Monitors Carbon Dioxide Storage in Norway's Offshore Sleipner Gas Field. News Release.

National Energy Technology Laboratory (NETL), 2010a. Carbon Sequestration Project Portfolio; http://www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2010/index.html.

National Energy Technology Laboratory (NETL), 2010b. Carbon Sequestration Atlas of the United States and Canada – Version 3. U.S. Department of Energy Report: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasIII/index.html

National Energy Technology Laboratory (NETL), 2010c. Gulf of Mexico Miocene CO_2 Site Characterization Mega Transect. Project Facts.

Rodosta, T., Litynski, J., Plasynski, S., Spangler, L., Finley, R., Steadman, E., Ball, D., Hill, G., McPherson, B., Burton, E., and Vikara, D. 2010. U.S. Department of Energy's Regional Carbon Sequestration Partnership Initiative: Update on Validation and Development Phases. *Energy Procedia*. Proceedings of the 10th International Conference on Greenhouse Gas Control Technologies (GHGT-10), September 19–23, 2010. Amsterdam, The Netherlands.

Schrag, D. 2009. Storage of Carbon Dioxide in Offshore Sediments. *Science* **325**, 1658, DOE: 10.1126/science.1175770

Socolow, R., Hotinski, R., Greenblatt, J. B., Pacala, P. 2004. Solving the climate problem –Technologies available to curb CO_2 emissions. Environment 46 (10): 8-19.

Stevens, S., and Moodhe, K. 2009. Alaska Geologic CO_2 Storage: Scoping Evaluation of Deep Coal Seams and Saline Aquifer Storage Potential. Ddraft final report by Advanced Resources International, Inc., prepared for West Coast Regional Carbon Sequestration Partnership (WESTCARB), March 23, 2009, 97 p.

Tans, P. 2008. Trends in Atmospheric Carbon Dioxide – Mauna Loa. National Oceanic and Atmospheric Administration, US Department of Commerce. Accessed May, 2008. http://www.esrl.noaa.gov/gmd/ccgg/trends/

World Resources Institute (WRI). 2008. CCS Guidelines: Guidelines for Carbon Dioxide Capture, Transport, and Storage. Washington, DC: WRI.