Clean Air Task Force
Availability of Geologic Carbon Storage
Updated 6-22-15.
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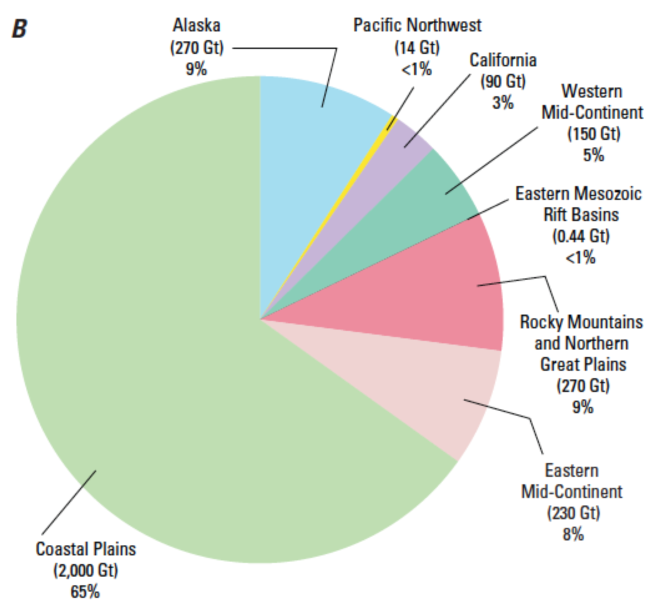
I. Storage Capacity

Introduction. In its 2013 National Assessment of Geologic Carbon Dioxide Storage Resources, the U.S. Geological Survey assessed the technically accessible geologic carbon storage resources in 36 sedimentary basins in the onshore and beneath state waters of the United States. [1] The assessment only inventoried deep geologic formations below 3,000 feet with adequate porosity and permeability to accept industrial volumes of CO_2. The assessment estimates that there are approximately 3,000 Gt of technical subsurface storage capacity. This represents 1500 times the 2014 annual rate of 2 Gt of electricity generation-related CO_2 emissions in the U.S. Added to the onshore total are 500 to 7,500 Gt of CO_2 could be sequestered in U.S. offshore formations on the outer continental shelf.[2] Therefore total technical storage capacity could sequester thousands of years of emissions at the current rate of 2 Gt per year.[3]

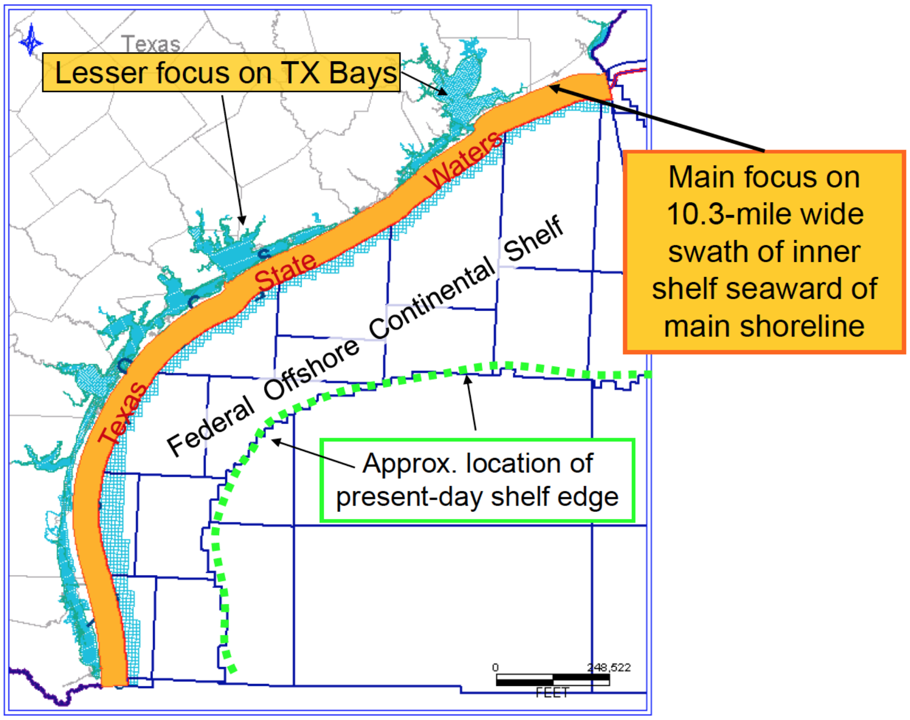
The analysis reveals storage potential in nearly all regions of the U.S.[4] Capacity and transportation and injection infrastructure currently available in enhanced oil recovery ("EOR") fields in the parts of the Rocky Mountains, Midwest, Southeast and parts of California provide a model for expansion. Where formations that have capacity for CO_2 don't exist, research shows that the expansion and build-out of today's 4,000-mile CO_2 pipeline network is feasible and would reach much of the rest of the U.S. An example of such infrastructure build-out is the natural gas pipeline network, which expanded throughout the nation within decades. Distribution models for offshore areas are under investigation.



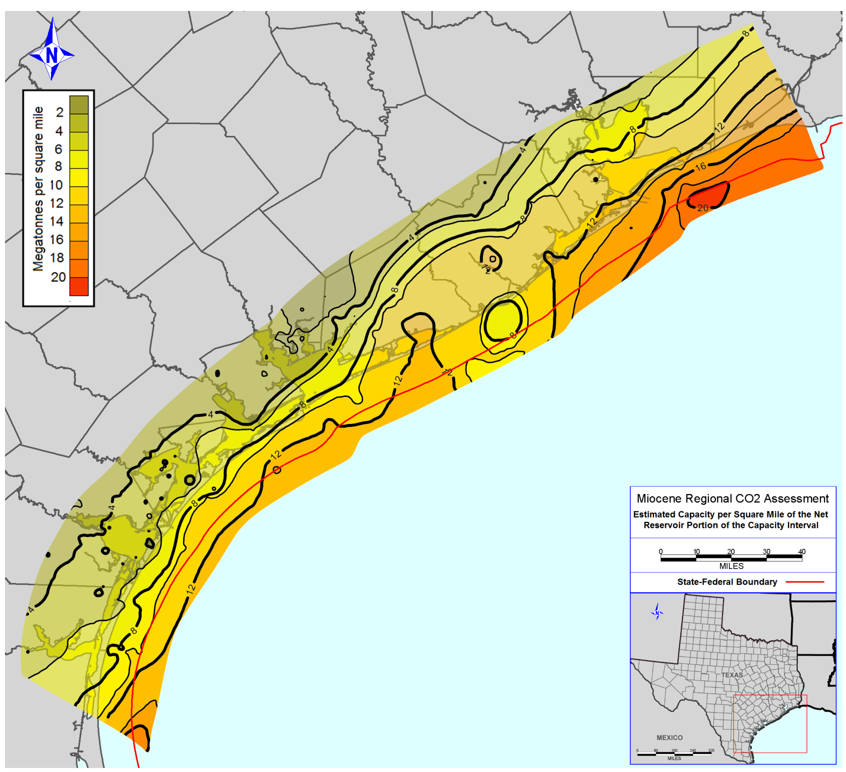
Importantly, U.S.-China CCUS partnerships are in active development in the area of geologic storage, and receiving attention at the highest levels of the U.S. government. In November 2014, Presidents Obama and Xi signed a historic agreement to curb greenhouse gases. As a part of that agreement, CCS was specifically called out as a high priority focal area for low-carbon energy cooperation through the advancement of that technology here and in China through the efforts of the U.S. – China Climate Change Working Group (CCWG). [5] CATF is helping facilitate one such CCWG U.S.–China counter-facing CCS project, an MOU between the University of Texas at Austin Gulf Coast Carbon Center and Guangdong CCS Center in an effort to investigate, and eventually test, the feasibility of offshore geologic carbon storage in the Gulf of Mexico and the South China Sea. On June 22 2015, the U.S. State Department will host a signing ceremony for this MOU in Washington D.C.

Texas / Gulf Coast: A Hub for U.S. CO_2 . Over the past 4 decades, Texas and its Permian Basin and Gulf Coast regions have become a CO_2 hub, connecting natural and captured CO_2 sources with pipelines with CO_2 EOR projects. An important recent addition to the hub is the captured CO_2 supply from Air Products in Port Arthur that is being transported via the Denbury Resources Green Pipeline to supply CO_2 to downstream Texas EOR projects, including the Denbury Hastings EOR-storage project in Houston.

Opportunities for further CO_2 capture, EOR utilization, and storage are widespread in the region. A completed four-year study (2010-2014) by the Gulf Coast Carbon Center (GCCC) at the University of Texas at Austin characterized the geology and estimated the CO_2 storage capacity for sites within 10 miles of shore in the Gulf of Mexico (see map below). This "Mega-Transect Project" has identified the Gulf of Mexico as a storage resource of national significance.[6] [7] [8] Using the NETL methodology for calculation of CO_2 storage capacity in saline aquifers, the project determined that 172 Gt (over 8 decades of storage at the 2 Gt annual amount of CO_2 from U.S. fossil-fueled electricity production in 2014) could be stored in offshore Texas Miocene formations over the study area.[9]



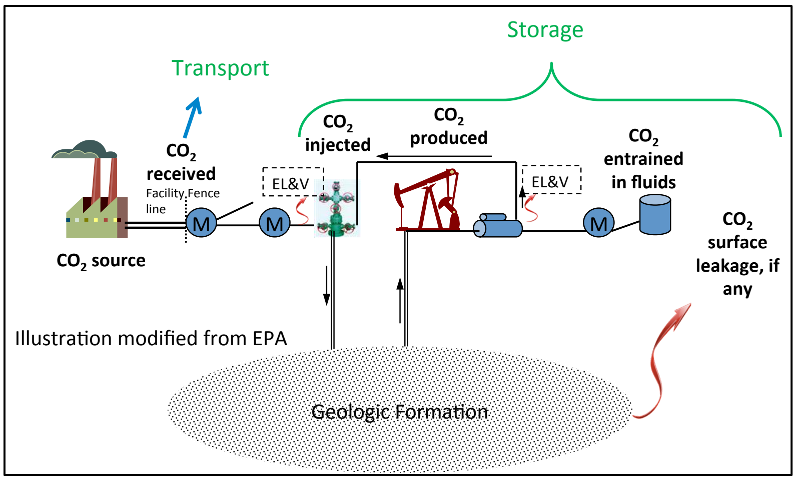
*Above: University of Texas BEG Gulf Coast Mega-Transect Study location map***.** *Below: University of Texas BEG Mega-Transect map of estimated capacity per square mile.*



II. CO2 Capacity in Depleted Oil Fields

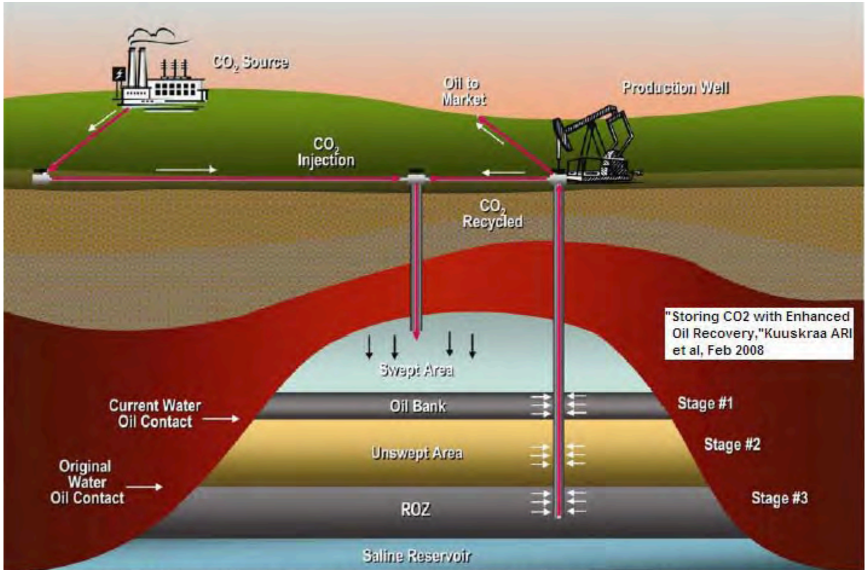
CO$_2$ Enhanced Oil Recovery. EOR presents both economic and technical opportunities to jump start geologic storage by using existing transportation, injection and recycle infrastructure and by taking advantage of current and future demand for purchased CO_2. "Next-generation" EOR will, in fact, require advanced monitoring and CO_2 surveillance methods resulting in a nexus with MRV-related CO_2 plume tracking.

As of April 2014 there were 136 U.S. CO_2 EOR projects with approximately 7,100 CO_2 injection wells and 10,500 producing wells. According to the National Petroleum Council, approximately 3 billion cubic feet per day of CO_2 (57 Mt/yr) of newly purchased CO_2 (dominantly from natural subsurface geologic accumulations) are presently injected for tertiary EOR producing 300,000 barrels of oil per day (about 110 million barrels per year). [10] The EOR market is currently under-supplied with respect to CO_2.



The graphic above (EPA) illustrates how CO_2 received at a project site is recycled, reinjected and subsequently accounted for in EPA's greenhouse gas accounting scheme (Subpart RR). During the progressive injection, production, recapture and reinjection of CO_2 virtually all of the CO_2 is stored in geologic formations since CO_2 *is rarely vented due to the high cost of* CO_2.[11]

Residual Oil Zones (ROZ): Residual oil zones (ROZs) are naturally water-flooded formations below the oil water contact in oilfields (see illustration below). U.S. DOE NETL is actively providing research support for ROZ economic development (production).[12] ROZs were formed when natural subsurface artesian water flushed out the primary oil accumulation over geologic time leaving only residual (stubborn) oil behind. That residual oil can be volumetrically substantial-- in some cases as large as the primary resource (e.g. Hess Seminole Field, TX) -- but it can only be produced using tertiary EOR methods since water flooding will not be effective. Because oil is soluble in CO_2 at pressure, ROZs represent another technological and economic frontier for CO_2-EOR oil production while at the same time promising capacities for large volumes of CO_2 to be stored. Significant ROZs have been discovered and are being produced in with West Texas Permian Basin and in the Bighorn Basin of Wyoming and are being investigated elsewhere. The Kinder Morgan "Tall Cotton" project is injecting CO_2 into a "greenfield" ROZ, which has no overlying main pay zone.[13] The significance is that there may be an even larger capacity for CO_2 than currently estimated by the U.S. Geological Survey.



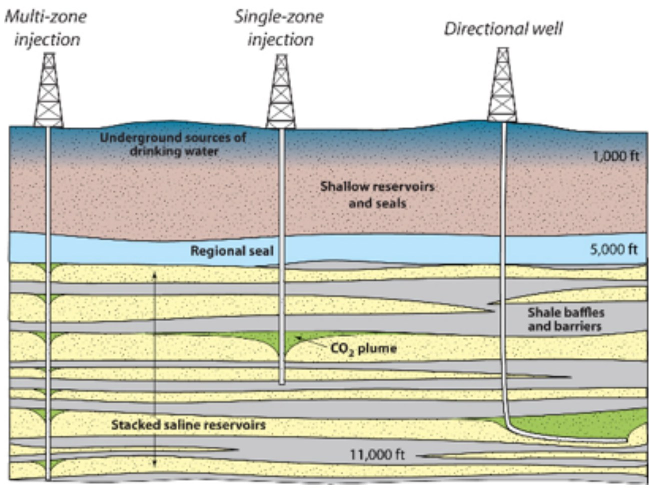
(ARI)

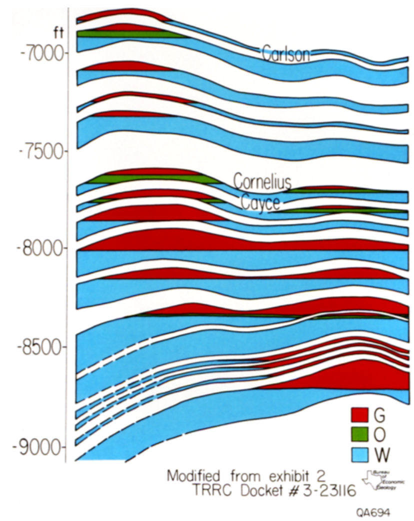
<u>CO_2 Demand:</u> Advanced Resources Inc. (ARI) has estimated that next generation EOR combined with currently limited estimates of ROZ production could produce a demand for an approximate additional 33 Gt of CO_2 .[14] [15] [16] [17] This suggests ROZs could alone accept/store on the order of a dozen years of U.S. electricity generation system CO_2 (at the 2014 rate of 2 Gt/year).

III. Stacked Storage.

<u>What is Stacked Storage?</u> Thick sedimentary sequences commonly are characterized by repeating layers of interbedded sand and shale. Stacked storage takes advantage of these repeating sequences in the geologic section to build storage capacity vertically (See illustrations below). Utilizing multiple layers for storage is advantageous because instead of creating a large plume, CO_2 volumes can be managed --along with formation pressures-- by spreading out the CO_2 vertically in the geologic section.

<u>Commercial Advantages of Stacked Storage:</u> stacked storage, when used in combination with EOR, would allow for commercial volumes of CO_2 to be stored by the same existing surface facilities that are being used to produce tertiary oil by EOR. EOR combined with stacked storage therefore takes advantage of existing pipeline transportation and injection infrastructure and could allow EOR operators to transition from oil production once the field is depleted, to storage with incidental EOR. As a result, is a potential for large commercial volumes to be stored not only in oilfields but in the formations associated with oilfields at reduced capital cost.





Illustrations above-- Left: Illustration of stacked saline storage (J Pashin). Right: Illustration of layered oil, gas and saline formations (and intervening caprock in white) at the SECARB Frio project, TX that could be accessed in stacked storage (Courtesy S. Hovorka, Gulf Coast Carbon Center).

IV. Updates on North American Commercial CO2 Storage Projects

1. DOE Regional Carbon Sequestration Partnership Updates

SECARB/Southern Co. Plant Barry-Citronelle Integrated capture-transportation and storage test. AL With injections completed in 2015, this was of the first successful fully integrated carbon capture and storage projects in the world. CO_2 was captured at Plant Barry with Mitsubishi Heavy Industries amine technology and transported 12 miles by pipeline to Denbury Resources' Citronelle oilfield where it was injected as part of ongoing EOR activity. The plant began capturing CO_2 in the 4th quarter of 2011 at a rate of up to 650 of naturally occurring CO_2 per day, amounting to a target of approximately 50,000 tons per year.[18] Alabama Power constructed a pipeline from Plant Barry to Denbury's nearby Citronelle oilfield with successful injection of the captured CO_2 into a saline unit in the Paluxy Formation beginning in 2012.

SECARB Cranfield, MS Project: The Cranfield Mississippi oilfield geologic carbon storage project began injection operations in 2008 and was completed in 2015 with an injected total of 11 Mt CO_2 into the Tuscaloosa Formation (including recycled CO_2), 5Mt of that is permanently stored (Figures courtesy Susan Hovorka, TX BEG 6-15-15). The SECARB/ Gulf Coast Carbon Center project is the site of numerous monitoring efforts and experiments that have substantially improved scientists' understanding of what is needed to ensure secure permanent geologic storage of CO_2.

Big Sky Partnership. Kevin Dome, MT.[19] [20] Injection of 1 Mt of CO_2 into a northern Montana saline aquifer is planned to begin in 2015 and continue through 2018 to demonstrate the viability of Kevin Dome as a secure target for regional CO_2 emissions. Kevin Dome is a geologic structure with naturally occurring CO_2 that has been trapped for 50 million years, and that promises the ability to hold commercial volumes of captured CO_2. In the test, CO_2 will be produced from the dome, then transported 6 miles to an injection site into the Duperow

Formation at the edge of the dome. The injections will be accompanied by monitoring demonstration and research projects.

MGSC Partnership lllinois Basin Decatur Project: A successful 7,000 foot deep CO_2 injection test was completed in 2014 Decatur IL, including a comprehensive subsurface and surface monitoring program.[21] It is a cooperative project of the Archer Daniels Midland (ADM), The Midwest Geological Sequestration Consortium (MGSC) and Schlumberger, with $4.4 million of DOE support.[22] During the 3-year injection program, 1,000 tons CO_2 per day were successfully injected, reaching a milestone of 1 million tons stored in the Mount Simon Formation.[23] The $CO_2$was captured at ADM's ethanol plant. CO_2 is being injected into the Cambrian Mt. Simon Formation.

A new ADM project from the same source but in a different field has been permitted under UIC Class VI. The total injection is expected to be 1 million tons per year.

PCOR Regional Partnership. Bell Creek, WY**:** Beginning Spring 2013, 1 million tons of CO_2, sourced from the Lost Cabin natural gas separation plant, are being injected for EOR ad stored.[24] Cost-effective monitoring protocols are the focus of this study.

MRCSP Partnership Northern Lower Michigan project: 1 Mt of CO_2 captured at an Antrim Shale (gas) Formation natural gas separation facility is being injected over a 4 year period into several small oil fields in a carbonate formation for the purposes of EOR and storage and accompanying monitoring development.[25] [26]

2. Other North American Projects

Dakota Gasification/Weyburn, Saskatchewan, Canada: Weyburn-Midale oil field is an EOR project located in Saskatchewan Canada that is the receptor site for captured CO_2 from the Beulah Dakota gasification site in the U.S. as well as the Boundary Dam project described below.[27] Over the life of the field, approximately 44 million tons of CO_2 will be injected at Weyburn, with approximately 17 million tons permanently stored to date. The IEAGHG, in conjunction with Canada's non-profit Petroleum Technology Research Centre (PTRC), has implemented a monitoring demonstration and research program to investigate the most effective methods for ensuring CO_2 injected for EOR is securely stored. In 2011 it was alleged that CO_2 from the project was leaking at the surface at Kerr Farm. Subsequent independent, peer-reviewed analysis by the University of Texas belies this allegation, instead confirming that the methane in the soils at the farm was of biologic and not geologic origin.[28]

Boundary Dam, Saskatchewan Canada: Post-combustion capture was installed and is operational at unit 3 at The SaskPower Boundary Dam Power Station, resulting in a net power output of 110MW, capturing 90% of the CO_2, an approximately 1 million tons per year.[29] [30] Operation of the plant began in the Fall of 2014.[31] CO_2 capture from Boundary Dam is being injected at the Weyburn EOR project and the Sasketchewan Aquistore facility. Boundary Dam, Weyburn, Aquistore the largest commercial and fully integrated CO2 capture and storage facility in the world. The IEAGHG's Aquistore, a collaborative industry and government program, initiated injection operations in May 2015 and is being operated by Canada's non-profit Petroleum Technology Research Centre (PTRC).[32] Aquistore is located in a 3-kilometer deep 100 meter thick Cambro-Ordovician age saline sandstone reservoir located in the

Williston Basin in Saskatchewan, Canada.[33] Captured CO_2 is being sent via pipeline from the SaskPower Boundary Dam project which is two kilometers away.

Monitoring Tools are Commercially Available.

Over the past several years, ongoing and concluded studies have advanced research and refinements in monitoring, reporting and verification (MRV) tools which will allow robust but cost effective methods for CO_2 plume tracking and MRV surveillance in industrial scale projects.[34] Most of these monitoring technologies are now available commercially, augmented by high-value R&D led by the national laboratories such as Lawrence Berkeley National Laboratory. In the past year, field operations and data collection for three important projects, among others, (Gulf Coast Carbon Center Cranfield MS project, Illinois Basin Decatur Project, Plant Barry/Citronelle) have come to a close following a decade of successful storage-related projects during which time many existing CO_2 EOR tools were tested and adapted to geologic storage. In recognition of this success, the U.S. DOE has extended its regional sequestration partnership work for 3 additional years to 2019 to facilitate technology transfer.

Current EOR-storage projects with MRV now under development such as Hilcorp's West Ranch Field Texas (capture by Petra Nova), Denbury Hastings Field Texas (capture by Air Products) and the second phase of the Illinois Basin Decatur project (capture by ADM) can and will likely take advantage of these now readily available monitoring and verification tools and techniques.

The following are highlights of several (but not all) significant MRV testing projects that exemplify successful MRV development and deployment in different parts of the U.S. with different challenges.

SECARB Cranfield Project. Project complete in 2015. Some of the highest volumes of CO2 injected to date (11 Mt total CO_2 injected including recycle) for the purposes of MRV method development. A SECARB supported project with numerous cooperators, but including Texas Bureau of Economic Geology (BEG). Extensive testing of in-injection zone and above-injection zone monitoring and crosswell CO2 tracking methods.[35]

SECARB Citronelle Field Project: Cooperative field MRV research with industrial participation of the CCP, EPRI, LBNL and ARI. The project, completed in 2015, tested Modular Borehole Monitoring (MBM) which was supported by the industry Carbon Capture Project (CCP) and designed and tested by LBNL for deep borehole sensing combined with in-zone and above-zone monitoring and shallow well groundwater surveillance.[36] The following capabilities were tested and demonstrated: leak detection/well integrity, fluid sampling, and tools for detecting injection reservoir pressure and temperature as leakage indicators.

MGSC Illinois Basin Decatur Project (IBDP). First injection program was completed in 2014 with just under 1 Mt injected. Well closure under UIC class VI In its first phase, Schlumberger successfully worked with IBDP to test a an exhaustive array of monitoring tools, including seismic surveys, groundwater monitoring, InSar (proven in the In Salah field, Algeria), downhole measurements and sampling using Schlumberger's Westbay tool.[37] Successful microseismic use for plume tracking. A second phase by ADM site will result in a larger scale injection, has an EPA approved permit under the UIC Class VI. Industrial MRV techniques will be utilized.

Bell Creek. A cooperative project of PCOR, EERC and Denbury Resources monitoring research in an EOR environment is ongoing at the Bell Creek field in Montana, including soil gas profiles with baseline sampling between 2011 and 2013, 3-d seismic, vertical seismic profiling, deep well monitoring, micro-seismic studies, and employing fiber optic technology to assess interval temperatures and pressures that could be indicative of leakage and by assessing EOR data such as injection rates and production metrics.[38]

Dover 33 MRCSP Core Energy project. Monitoring of CO_2 behavior is ongoing at Core Energy's EOR fields in Michigan.[39] Tools tested include microseismic, geochemical sampling, gravity, pulsed neutron capture and other available methods for CO_2 plume detection.

References.

[1] See USGS at: http://pubs.usgs.gov/ds/774/

[2] DOE, *The National Carbon Storage Atlas* (2012) (Available at http://www.netl.doe.gov/technologies/carbon_seq/refshelf/NACSA2012.pdf). Attached as Exh.III-71.

[3] See US DOE at: http://energy.gov/fe/articles/third-carbon-sequestration-atlas-estimates-5700-years-co2

[4] New England could, access storage in the Midwest by pipeline, or in the offshore outer continental shelf (OCS) along Georges Bank as was suggested by an abandoned CCS project that would have stored its CO2 in the Mississauga Formation 70 miles off of the coast of New Jersey.

[5] See: https://www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change%20

[6] Meckel, et al., *Offshore CCS in the Northern Gulf of Mexico and South Atlantic*, Poster, Regional Carbon Sequestration Partnership Meeting Pittsburgh (September 2011), attached as Exh. III-89.

[7]http://www.netl.doe.gov/publications/proceedings/11/carbon_storage/tuesday/11_1115_Meckel_DOE_Review_mtg_offshore_compress.pdf

[8] http://www.aapg.org/explorer/2010/09sep/co2storage0910.cfm

[9] See: Wallace, Meckel, Carr, Trevino, and Yang, 2014, Regional CO2 sequestration capacity assessment for the coastal and offshore Texas Miocene interval, Greenhouse Gas Science and Technology, 4:53-65. At: http://onlinelibrary.wiley.com/doi/10.1002/ghg.1380/abstract

[10] Kuuskraa, V., Wallace, M. (2014). CO2-EOR set for growth as new CO2 supplies emerge. Oil and Gas Journal, April 7, 2014.

[11] Field life carbon balance data from the Kinder Morgan SACROC project suggest that if total storage is offset by emissions associated with the operations, then a net 93% is stored. See: http://www.co2conference.net/wp-content/uploads/2013/05/Fox-KM-Presentation-SACROC.pdf

[12] See: http://www.netl.doe.gov/research/oil-and-gas/project-summaries/enhanced-oil-recovery

[13] See: http://news.kindermorgan.com/press-release/2010-present/kinder-morgan-increases-quarterly-dividend-045-share-10

[14] Vello Kuuskraa, Advanced Resources International, Inc. (2012). Using the Economic value of CO2-EOR to accelerate the deployment of CO2 capture, utilization and storage. (CCUS, EPRI Cost Workshop, Palo Alto, CA, April 25-26, 2012.

[15] Meckel, et al., *Offshore CCS in the Northern Gulf of Mexico and South Atlantic*, Poster, Regional Carbon Sequestration Partnership Meeting Pittsburgh (September 2011), attached as Exh. III-89.

[16]http://www.netl.doe.gov/publications/proceedings/11/carbon_storage/tuesday/11_1115_Meckel_DOE_Review_mtg_offshore_compress.pdf

[17] http://www.aapg.org/explorer/2010/09sep/co2storage0910.cfm

[18] Koperna, et al., *The SECARB anthropogenic test: the first U.S. integrated CO2 capture, transportation and storage test* (2011) (Available at: http://www.adv-res.com/pdf/Pitt_Coal_Conference_Paper_FINAL.pdf). Attached as Exh. III-42.

[19] See: http://sequestration.mit.edu/tools/projects/kevin_dome.html

[20] See: http://www.bigskyco2.org/research/geologic/kevinstorage

[21] See IBDP project at: http://sequestration.org/mgscprojects/deepsalinestorage.html

[22] *See* http://sequestration.mit.edu/tools/projects/decatur.html. Attached as Exh. III-102.

[23] See: http://summitcountyvoice.com/2015/01/25/climate-carbon-capture-test-reaches-milestone/

[24] See PCOR project site: http://www.undeerc.org/pcor/co2sequestrationprojects/default.aspx

[25] See: http://216.109.210.162/MichiganBasin_development.aspx

[26] See: http://216.109.210.162/userdata/Presentations/MRCSP%20Poster_GHGTnov%202012.pdf
[27] See: http://www.ieaghg.org/docs/general_publications/weyburn.pdf . Attached as Exh. III-45.
[28] Romanak, *Analysis of Gas Chemistry at the Kerr Site*, IPAC Publication (2012). Attached as Exh. III-46.
[29] Global CCS Institute, *The Global Status of CCS: 2011*, pp. 25, 102 (2011). Attached as Exh. III-66.
[30] http://www.saskpower.com/sustainable_growth/assets/clean_coal_information_sheet.pdf. Attached as Exh. III-65.
[31] See: http://saskpowerccs.com/newsandmedia/latest-news/worlds-first-full-scale-clean-coal-plant-opens-in-canada/
[32] http://aquistore.ca/news/item/?n=32 .
[33] See: http://www.ptrc.ca/aquistore_overview.php. Attached as Exh. III-49.
[34] See: http://www.netl.doe.gov/File%20Library/Events/2014/carbon_storage/1--International-Monitoring-Updates-IEAGHG.pdf
[35] See: http://www.netl.doe.gov/File%20Library/Events/2014/carbon_storage/4--Cranfield-Field-Project-SECARB.pdf
[36] See: http://www.netl.doe.gov/File%20Library/Events/2014/carbon_storage/5--Plant-Berry-Citronelle-Field-Project.pdf
[37] See: http://www.netl.doe.gov/File%20Library/Events/2014/carbon_storage/5--Illinois-Basin_Decatur-Project-MGSC.pdf
[38] See: http://www.netl.doe.gov/File%20Library/Events/2014/carbon_storage/4--Bell-Creek-Field-Project-PCOR.pdf
[39] See: http://www.netl.doe.gov/File%20Library/Events/2014/carbon_storage/6--Michigan-Basin-Field-Project-MRCSP.pdf