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## ***Heterogeneity & Complexity of the National Geologic Resource for Sequestration***

There has been much discussion regarding the appropriate number of large scale CO<sub>2</sub> sequestration field tests. Some opined that one very large field test would be sufficient. Others have suggested 3-5 field tests. Still others have suggested 7 or more. Much of this discussion was driven by perceived funding constraints rather than science. While funding availability is indeed a constraint, decisions regarding the number and the scale of the field tests should be logically determined by or derived from the heterogeneity and complexity of the national geologic resource in terms of parameters critical to long term CO<sub>2</sub> storage and the ability to extrapolate with confidence from a limited number and type of tests to the full resource. It is up to the Administration and the Congress to balance the expected benefits of the research program against the availability of funds, given a host of other productive ways to expend tax revenues. It is the aim of organizations like the USCSC to provide the Administration, the Congress, and others with the best possible, authoritative and objective information regarding the likely benefits and consequences of incremental levels of funding, of regulatory actions, of proposed legislative bill provisions and/or related actions on the development and deployment of carbon capture and storage technology. This paper marks an initial effort to explain some of the factors that influence the scope of the required national effort to establish a viable and vigorous CO<sub>2</sub> sequestration activity. A more detailed discussion of the specific factors that impact total storage capacity, CO<sub>2</sub> injection rate, containment effectiveness, and deployment factors, by type of storage formation, is available in the attached tables: *Types of CCS Test Sites Versus Key Formation Characteristics*.

### ***Regional Variation in Key Geologic Formations & Subsurface Conditions***

The key formations which should be among the most appropriate sites for permanent storage of carbon dioxide include (1) mature oil reservoirs, (2) mature natural gas reservoirs, (3) deep un-mineable coal seams, (4) sandstone formations, (3) basalt formations, (4) oil-rich organic shale, (5) gas-rich organic shale and other gas-rich units. Mature oil fields are most promising for early applications because there

may be revenues obtained from enhanced oil recovery with CO<sub>2</sub> to offset storage costs. However, each oil field provides new challenges and additional data are needed on the long-term storage of CO<sub>2</sub> in oil fields. Modeling can assist in reducing risks, but as practiced in industry a series of demonstrations at increasing scale is always desired in order to mitigate the effects of geologic heterogeneity. Saline reservoirs, which occur in conjunction with a number of geologic formations, are extremely promising for very large-scale and reliable storage of CO<sub>2</sub>, but again saline or brine reservoirs exhibit regional and spatial variability, even across an individual basin, and this variability means that a number of research projects will be needed to predict the potential of this type of reservoir for storing CO<sub>2</sub>.

## ***Regional and Spatial Variation in Key Formation Characteristics***

### ***Regional Variation in Reservoir Quality and Capacity***

The critical characteristics for long-term storage of CO<sub>2</sub> in the cited geologic formations vary significantly both by type of formation, and also regionally. One such variable is the formation's porosity, which largely determines total CO<sub>2</sub> storage capacity and how many sites may be needed. Another is the formation's permeability which largely determines CO<sub>2</sub> injection rates and number of injection wells, and thereby the cost of injection. Another factor that could be viewed as a formation variable is the presence or absence of saline or brine reservoirs (and the characteristics of those reservoirs) in a given formation. Depth of formation is yet another variable. The deeper the injection the less likely the site is penetrated by existing wells and the less that is known of the storage potential of the formation. The deeper the injection the larger the number of secondary saline reservoirs (i.e., traps) and/or seals that are likely to be present above the primary injection site to further prevent CO<sub>2</sub> migration or leakage.

### ***Regional Variation in Flow Characteristics***

In storage time-frames of hundreds to thousands of years groundwater movement is an important characteristic which can vary rapidly. Descending groundwater flows (which are preferable) can impede upward migration of CO<sub>2</sub> versus ascending flows to shallow depths that can accelerate potential leakage. Also, the velocity of groundwater movement can help dissipate the CO<sub>2</sub> plume and facilitate dissolution in groundwater and mineral trapping. However, rapid velocities can also promote CO<sub>2</sub> escape from known traps and increased probability of leakage. These factors can be modeled, but require physical demonstration to be completely understood.

### ***Regional & Spatial Variation in CO<sub>2</sub> Trapping Characteristics***

A set of geologic characteristics that are especially important to the long term storage of CO<sub>2</sub> include (1) structural trapping mechanisms in which CO<sub>2</sub> is trapped by the structural geometry of the sedimentary layers (because CO<sub>2</sub> tends to rise buoyantly and accumulate in closed structures), (2) dissolution into the formation water, (3) capillary trapping as a residual phase in small pores, and (4) mineral trapping as the CO<sub>2</sub> chemically reacts with the mineral matter. All of the geologic characteristics vary rapidly in a local area and must be well understood.

## *Regional Variation in Primary and Secondary CO<sub>2</sub> Seals*

The long term containment of CO<sub>2</sub> is dependent on the robustness of the geologic seals and the integrity of the engineered reservoir. The length of storage suggests some CO<sub>2</sub> migration beyond the primary seals and requires consideration of the regional distribution of secondary litho logic seals, sealing faults and groundwater movement. A regional understanding of the presence or absence of cap rock and its properties, which (as its name suggests) cap or prevent the release of CO<sub>2</sub>, and the presence or absence of geologic traps and lateral barriers to CO<sub>2</sub> migration are required to keep the CO<sub>2</sub> contained.

### **Summary**

The discussion here is not a comprehensive review of all variables that need to be understood for the successful long-term storage of CO<sub>2</sub>, and does not address the variability associated with regional regulatory and permitting issues and public acceptance. This fact sheet is intended to illustrate the extensive data necessary to adequately understand the national geologic storage resource. The number of possible combinations and permutations associated with just the different formations and their regionally and spatially variable characteristics discussed above, is well over fifty. If a large-scale field test were to be pursued for each possible permutation, the resulting research program would not be economically practical. Nevertheless, there needs to be a sufficient number of field tests to permit (1) extrapolation to the full national resource with confidence and (2) understanding of the scaling issues as CO<sub>2</sub> is injected on an increasing scale. This requires a far larger number of field tests than the largest number, seven, that has been suggested by anyone to date, but they do not all have to be at the often cited “million ton per year” rate (which is an arbitrary number without a scientific basis).

The Department of Energy (DOE) has a well conceived carbon sequestration research, development, and demonstration program now under way that includes CO<sub>2</sub> sequestration field tests at different scales in different geologic formations with consideration of regional and geologic variability – the scope and pace of which is limited only by the available funding. DOE has brought together the best scientists and engineers to tackle the challenges on a regional and national level – led by the seven competitively selected Regional Partnerships. The challenge is to collect, analyze, and translate the DOE and other data into a form usable to guide the implementation of an effective regulatory structure and resolve potential liability issues and to do it in a timely manner consistent with anticipated regulatory or legislative action in this area. The Administration and the U.S. Congress also need to consider mechanisms for strengthening Government/industry partnerships in this area and the adequacy of current Federal funding available for all matters related to CO<sub>2</sub> capture and storage, especially R, D, & D funding, given the national importance of managing CO<sub>2</sub> emissions.



*The U.S. Carbon Sequestration Council ([www.uscsc.org](http://www.uscsc.org)) is a not-for-profit, 501(c)(3), organization established as an authoritative source of information to inform and to educate on all matters pertaining to carbon sequestration.*

Types of CCS Test Sites Versus Key Formation Characteristics	Mature Oil Reservoirs	Mature Natural Gas Reservoirs	Deep Unmineable Coal Seams	Deep Saline Formations
<b>Total Storage Capacity</b>	Porosity and maximum safe storage pressure (depth and seal strength) determines total CO2 storage capacity and varies considerably by type of formation, seal integrity and depth. Total volumes of oil and gas reservoirs combined are small to moderate (< 100 billion metric tons).	Porosity and maximum safe storage pressure (depth and seal strength) determines total CO2 storage capacity and varies considerably by type of formation, seal integrity and depth. Total volumes of oil and gas reservoirs combined are small to moderate (< 100 billion metric tons).	Storage capacity based on adsorption and estimated by reserve estimation for coalbed methane (CBM) using total gas in place (capacity) of individual coal seams. Capacity is influenced by the coal matrix parameters (affinity for CO2) and varies significantly among coal seams and basins. In addition, depth (pressure) and thickness are important capacity parameters. Total volumes are moderate (< 200 billion metric tons).	Storage capacity in deep saline aquifers is very complex with four trapping mechanisms acting at different rates (static, hydrodynamic, solubility & mineral trapping). Data required to evaluate Potential volumes are large (1,000 to 3,000+ billion metric tons).
<b>Injection Rate</b>	Permeability and effective thickness of a formation determines the CO2 injection rate which controls the effectiveness and cost of injection and varies considerably by type of formation as well as its depth. Ability to enhance permeability by artificial methods (e.g., fracture stimulation or horizontal drilling) is well known.	Permeability and effective thickness of a formation determines the CO2 injection rate which controls the effectiveness and cost of injection and varies considerably by type of formation as well as its depth. Ability to enhance permeability by artificial methods (e.g., fracture stimulation or horizontal drilling) is well known.	Highly dependent on fracture permeability of the coal (natural or induced). Reaction of CO2 with coal matrix can significantly reduce permeability and is dependent on gas content and coal matrix properties. Highly variable among coal seams and basins.	Permeability and effective thickness of a formation determines the CO2 injection rate which controls the effectiveness and cost of injection and varies considerably by type of formation as well as its depth. Ability to enhance permeability with fracture stimulation or horizontal drilling is unknown, but probable
<b>Containment Effectiveness</b>	Short-term containment is high as long as volume of the trap and pressure limits of the cap rock (seal) are not exceeded. Long-term containment has not been tested but there is a high probability of successful containment. Variables are numerous and depend on rock and fluid parameters, which vary by type of formation as well as its geologic location. Remediation is well-know from enhanced oil activities.	Short-term containment is high as long as volume of the trap and pressure limits of the cap rock (seal) are not exceeded. Long-term containment has not been tested but there is a high probability of successful containment. Variables are numerous and depend on rock and fluid parameters, which vary by type of formation as well as its geologic location. Remediation is known from gas field operations	Short-term and long-term containment are unknown, but due to the known adsorption trapping are highly probable to be effective. Highest risk from subsequent mining activities, but ability for prevention and remediation are very probable.	Both short-term and long-term containment are unknown and unproven and dependent on developing data equivalent to knowledge of hydrocarbon resources and smaller-scale demonstration projects. Analogy with natural gas storage suggests that short-term containment is highly probable and ability to perform remediation very possible.
<b>Deployment Factors</b>	Accepted process to recover additional oil with well-developed regulatory process in some states. Potential for offsetting or positive cost returns for additional oil production. Localized and often distant to major CO2 sources increasing transport cost.	Potential regulatory model in terms of natural gas storage. Possible small offsetting cost returns for additional gas production. Localized and often distant to major CO2 sources increasing transport cost.	Immature regulatory model based on CBM production. Definition of deep unmineable seams dependent on price and technology. Possible cost returns on ECBM production. Somewhat geographically constrained to coal basins	Very immature regulatory environment. No potential cost return. Ownership of pore volume is not defined. No known cost returns. Broad geographic distribution across major sedimentary basins. Absent in areas of the north-east and north-central US.

Types of CCS Test Sites Versus Key Formation Characteristics	Oil-Rich Organic Shale	Gas-Rich Organic Shale	Basalt Formations
<b>Total Storage Capacity</b>	Organic content and type determines total CO2 storage capacity and varies considerably by type of material and depth. Total volumes of oil-shale reservoirs are moderate to large but are localized to a few areas (e.g. western Colorado and northern Plains).	Organic content and type determines total CO2 storage capacity and varies considerably by type of material and depth. Total volumes of gas-shale reservoirs are moderate to very large and relatively widespread through the major sedimentary basins (e.g., Appalachian, Fort Worth, Michigan, Williston, Denver basins).	Storage capacity in deep basalt is very complex with multiple trapping mechanisms acting at different rates. Basalt formations have a unique chemical makeup that could potentially convert all of the injected CO2 to a solid mineral form. Data required to evaluate potential volumes are moderate and localized to the northwest US.
<b>Injection Rate</b>	Permeability and effective thickness of a formation resulting from artificial fracture stimulation determines the CO2 injection rate which controls the effectiveness and cost of injection and varies considerably by type of formation as well as its depth. Reaction of CO2 with matrix could significantly reduce permeability and is dependent on gas content and matrix properties. Ability to maintain permeability during injection of CO2 is unknown and requires further research and testing.	Permeability and effective thickness of a formation resulting from artificial fracture stimulation determines the CO2 injection rate which controls the effectiveness and cost of injection and varies considerably by type of formation as well as its depth. Reaction of CO2 with matrix could significantly reduce permeability and is dependent on gas content and matrix properties. Ability to maintain permeability during injection of CO2 is unknown and requires further research and testing.	Highly dependent on fracture and matrix permeability of the basalt. Research required on enhancing and utilizing the mineralization reactions and increasing CO2 flow within a basalt formation.
<b>Containment Effectiveness</b>	Short-term containment is excellent as long as pressure limits of the seal are not exceeded. Reservoir is its own seal. Long-term containment has not been tested but there is a high probability of successful containment since CO2 is bound (absorbed) to the shale matrix. Variables will be numerous and will depend on rock and fluid parameters, which vary by type of formation as well as its geologic location.	Short-term and long-term containment are unknown, but due to the known adsorption trapping effective containment is highly probable. Variables will be numerous and will depend on rock and fluid parameters, which vary by type of formation as well as its geologic location.	Short-term and long-term containment are unknown, but due to mineralization reactions could be highly effective. Short term static containment in traps is unknown.
<b>Deployment Factors</b>	Experimental subsurface process to recover additional oil. Enhanced oil recovery potential unknown, but potential exists offsetting or positive cost returns for additional oil production. Localized and often distant to major CO2 sources increasing transport cost. Immature regulatory model based on traditional oil production.	Moderately mature, but relatively new process (<10 years) for gas production. Enhanced gas recovery potential is unknown, but potential exists offsetting or positive cost returns for additional gas production. Somewhat immature regulatory environment.	Very immature regulatory environment. No potential cost return. Ownership of pore volume is not defined. Geographically constrained to northwest US, but may be the best opportunity in the region.