[PS]Development of Quick-Look Maps for CO_2-EOR Opportunities in the Appalachian and Michigan Basins*

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Abstract

The Midwest Regional Carbon Sequestration Partnership (MRCSP) is currently in the final phases of comprehensive characterization of carbon capture utilization and storage (CCUS) opportunities throughout the ten-state region. Spanning from the offshore Atlantic Coastal Plain through the Appalachian and Michigan basins, this region hosts a diverse assemblage of reservoir types and provides multiple CCUS targets. A key component of this research is the evaluation of opportunities for enhanced oil recovery (EOR) in legacy oil fields via carbon dioxide (CO_2) floods. In support of this task, the West Virginia Geological and Economic Survey has developed a set of "quick-look" maps that illustrate state-specific opportunities for CO_2-EOR. These maps contain a variety of field-specific data, including CO_2 storage capacity, residual oil in place, and oil gravity.

Several data types, most notably reservoir permeability and oil gravity, are significantly under-represented in the dataset. Oil gravity is particularly useful as it is used to calculate minimum miscibility pressure. In this case, methods were developed to help predict values for oil fields in the Appalachian Basin where applicable.

For each of seven MRCSP partner states (NY, PA, WV, KY, OH, IN, MI), a map was developed illustrating the location and reservoir characteristics of key legacy fields, as well as their proximity to major CO_2 point sources. This work is designed to be used by any researcher or stakeholder interested in investigating viable CCUS opportunities within the MRCSP region.

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KEYWORDS: EOR, CO_2, Appalachian Basin, Michigan Basin, CCUS, MRCSP

ABSTRACT

The Midwest Regional Carbon Sequestration Partnership (MRCSP) is currently in the final phases of comprehensive characterization of carbon capture utilization and storage (CCUS) opportunities throughout the ten-state region. Spanning from the offshore Atlantic Coastal Plain through the Appalachian and Michigan basins, this region hosts a diverse assemblage of reservoir types and provides multiple CCUS targets. A key component of this research is the evaluation of opportunities for enhanced oil recovery (EOR) in legacy oil fields via carbon dioxide (CO_2) floods. In support of this task, the West Virginia Geological and Economic Survey (WVGES) has developed a set of "quick-look" maps that illustrate state-specific opportunities for CO_2-EOR. These maps contain a variety of field-specific data, including CO_2 storage capacity, residual oil in place, and oil gravity.

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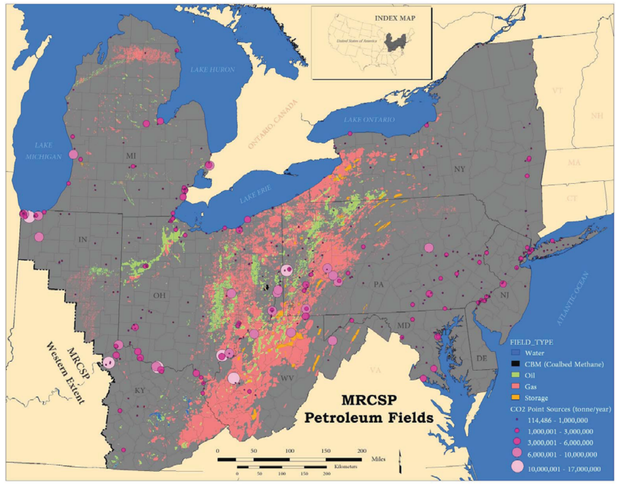
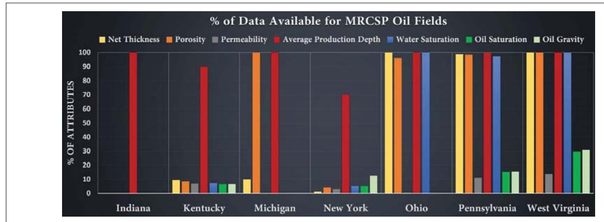
For each of seven MRCSP partner states (NY, PA, WV, KY, OH, IN, MI), a map was developed illustrating the location and reservoir characteristics of key legacy fields, as well as their proximity to major CO_2 point sources. This work is designed to be used by any researcher or stakeholder interested in investigating viable CCUS opportunities within the MRCSP region.

MRCSP is supported by U.S. Department of Energy-National Energy Technology Laboratory Agreement No. DE-FC26-0NT42589.



Updated geospatial distribution of petroleum fields for MRCSP Phase III, Budget Period 4, in relation to power plants within the region. WVGES is responsible for evaluating regional support for implementation of carbon capture utilization and storage (CCUS). Proximity to point sources is a major factor when assessing reservoirs and their ability to utilize and store CO_2 (modified MRCSP, 2009) (NATCARB, 2014).



Previous MRCSP phases have focused on storage in deep saline aquifers and reservoir data such as thickness, porosity, depth, and water saturation were collected (MRCSP, 2005). Permeability, although limited in availability, has been added, as well as oil gravity and oil saturation, due to the new focus on EOR in the current phase.

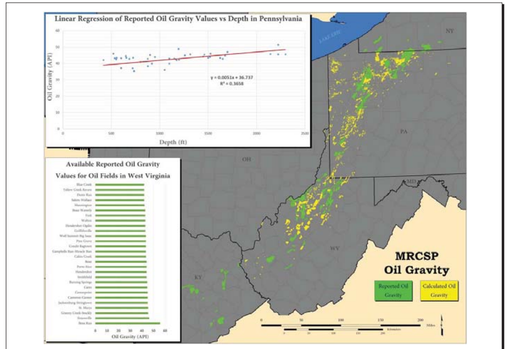
Storage Capacity = A*h*ϕ*(1-Sw)*ρ*Ef/2200

where A = field area (ft^2), h = field thickness (ft), ϕ = field porosity, Sw = connate water saturation, ρ = CO2 density (lb/ft^3), 2200 = conversion factor, Ef = storage efficiency factor

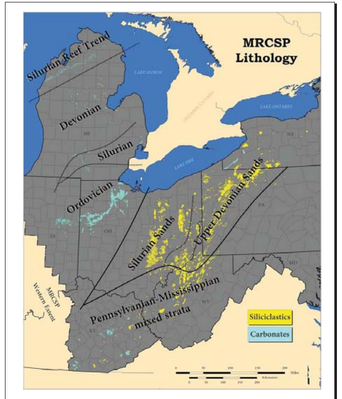
Equation used to calculate storage capacity, in tonnes, for all petroleum fields within the MRCSP region.

		EOR Efficiency Factor		
Region	States	Min	Mode	Max
Appalachian Basin	OH, E. KY, PA, WV, NY	0.177	0.294	0.539
Michigan/Illinois Basin	MI, IN, W. KY	0.372	0.557	0.680

Two different ranges of efficiency factors (Ef) are used because the study area includes both the Appalachian and Michigan basins. The "Min", "Mode", and "Max" factors refer to the fraction of oil that can be produced at different stages of the recovery process (Kuuskraa *et al*, 2011).

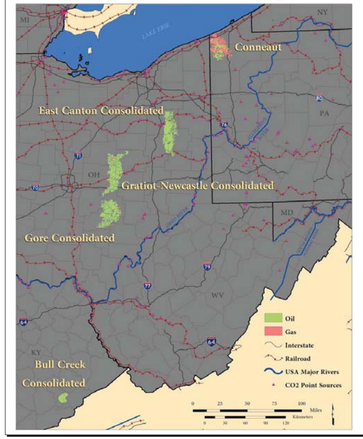


Only Appalachian Basin states reported oil gravities in select oil fields. Oil gravity is important because it is used to calculate Minimum Miscibility Pressure (MMP), one method for determining if a field is suitable for miscible EOR. In absence of reported values, WVGES determined that enough WV and PA oil gravity information was documented to predict missing oil gravities as a function of depth for wells in those states (Carter *et al*, 2015) (Whieldon and Eckard, 1962).



The dominant lithologies of active and legacy oil fields within the two separate basins are distinctly different. Carbonates dominate the Michigan Basin, whereas siliciclastics are confined to the Appalachian Basin.

Top 5 Oil Fields with Highest Storage Capacities



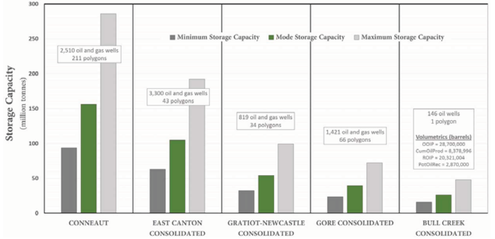
The five oil fields in the MRCSP region with the highest capacities to store CO_2 are found along the western edge of the Appalachian Basin and, according to average depths, appear to be capable of miscible CO_2 floods. However, high storage capacity estimates may be due to the large aggregate size of these consolidated fields, which consist of multiple smaller pools and/or reservoirs.

All are active oil and gas fields, but only one (Bull Creek Consolidated) has historical records on oil production (CumOilPro) and estimates of Original Oil in Place (OOIP), enabling calculation of Remaining Oil in Place (ROIP) and Potential Oil Recovery (PotOilRec).

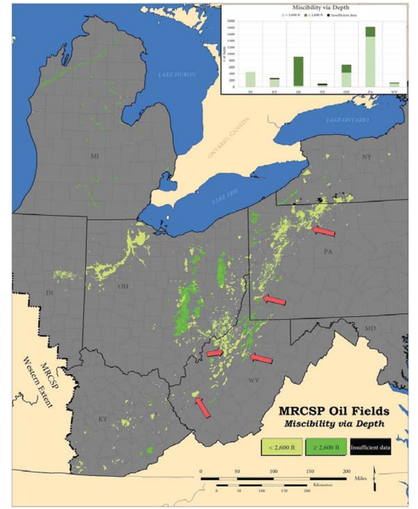
Remaining Oil in Place (ROIP) = OOIP - CumOilPro.
Potential Oil Recovery (PotOilRec) = 10% of OOIP (miscible) (MRCSP, 2009).

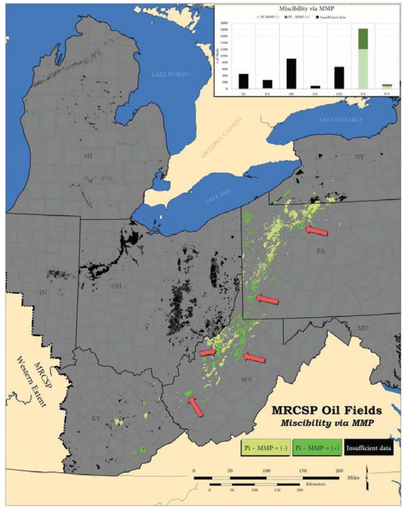
Production in Bull Creek Consolidated is primarily from the Mississippian Newman Limestone. The Conneaut field in north-western Pennsylvania produces from multiple formations and lithologies, ranging in age from Cambrian through Devonian; however, sandstones of the Cambrian Gatesburg and Silurian Medina are the dominant reservoirs. In eastern Ohio, East Canton, Gratiot-Newcastle, and Gore Consolidated fields exclusively target the Silurian Clinton Sandstone.

*** Total storage capacities in the graph to the right reflect those of oil AND gas pools/reservoirs within fields.**



FIELD NAME	Average Production Depth (ft)	Average Reported Initial Pressure (psi)	Average Reported Bottom Hole Temperature (°F)	Total Reservoir Area (sq ft)	Average Calculated Oil Gravity (decimal)	Average Net Thickness (ft)	Average Porosity (decimal)	Average Water Saturation (decimal)	Average Density of CO_2 at depth (lbs./ft^3)
CONNEAUT	4,372	991	93.65	8,971,260,095	0.63	61	0.09	0.37	41.01
EAST CANTON CONSOLIDATED	3,300	1,500	100.00	7,156,962,202	0.71	43	0.08	0.25	44.80
GRATIOT NEWCASTLE CONSOLIDATED	3,010	1,000	90.00	7,045,442,883	0.70	16	0.10	0.30	46.43
GORE CONSOLIDATED	3,150	1,200	90.00	6,390,756,798	0.69	15	0.10	0.31	45.92
BULL CREEK CONSOLIDATED	3,850	460	86.00	1,448,880,820	0.85	24	0.14	0.15	47.24

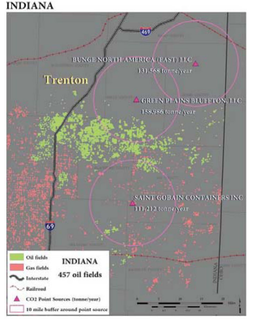




Oil recovery using CO_2 injection has been proven to be more beneficial in miscible fields than in those considered to be immiscible. Potential for miscibility can be determined using depth (***miscibility via depth***), or MMP (***miscibility via MMP***). MMP requires temperature and oil gravity data which can be more difficult to obtain than depth; therefore, *miscibility via depth* is acceptable for regional assessments, but *miscibility via MMP* should be determined for more detailed evaluations. MRCSP has traditionally defined miscible fields as being deeper than 2,600 ft. Although more data are required for the calculation, determining MMP can allow for a more detailed representation of miscible potential in an oil field. MMP values greater than the calculated hydrostatic pressure (Pi) are considered to be immiscible [**Pi – MMP = (-)**] (Takacs *et al*, 2010). The difference between the two methods is most noticeable in WV and PA, where oil gravities for 80% of the oil fields were predicted (**red arrows**).

WVGES
West Virginia Geological and Economic Survey

INDIANA

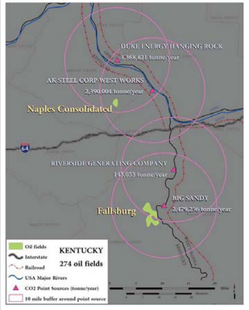


All oil fields in Indiana, which are located in the eastern part of the state, are named "Trenton", after the Ordovician Trenton Limestone. Due to insufficient data, depth is the most effective way to determine miscibility, and an accurate storage capacity cannot be determined for any of the oil fields.

Averages

* depth = 980 ft
^ temperature at depth = 70° F
^ P_i = 426 psi
(* reported ^ calculated)

KENTUCKY

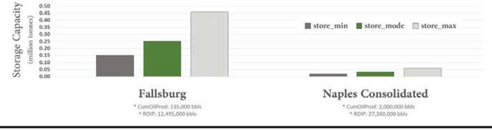


KENTUCKY

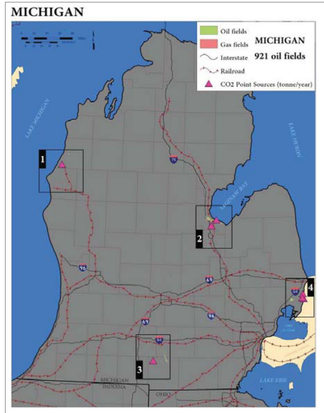
Oil fields in Kentucky within 10 miles of a power plant were selected initially. Natural miscibility does not appear to be an option with those proximal locations; however, it's possible that Fallsburg may be pressurized to attain miscibility without compromising the integrity of the overlying strata. Naples Consolidated was included because it, in addition to Fallsburg, reports production data. Both fields target the Devonian Berea Sandstone and the high oil saturations and porosities make these possibly economic reservoirs with a PotOilRec of 1,675,600 barrels.

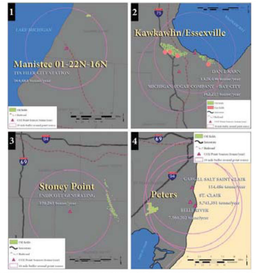
Averages

* depth = 1,375 ft
^ temperature at depth = 72° F
^ P_i = 440 psi
* oil saturation = 43.5%
* porosity = 13.0%
^ MMP = 868 psi
^ water saturation = 46.5%
* thickness = 22.5 ft
* oil gravity = 38.5 API
^ density of CO_2 at depth = 43.4 lbs/ft^3
* permeability = 2mD
(* reported ^ calculated)



MICHIGAN

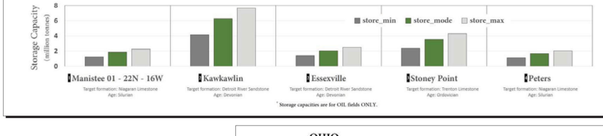




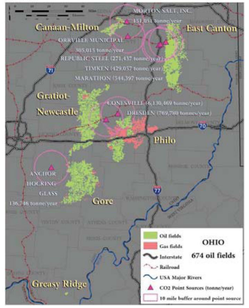
Ranking of the oil fields in Michigan begins by selecting those within 10 miles of a CO_2 point source, or power plant. Due to insufficient data, depth is the most effective way to determine miscibility; therefore, any fields less than 2,600 ft deep were eliminated. Of the remaining fields, these five have the highest storage capacities.

Averages (* reported ^ calculated)

* depth = 3,380 ft
^ temperature at depth = 99° F
^ P_i = 1,464 psi
^ oil saturation = 60%
* porosity = 9.7%
^ water saturation = 29%
* thickness = 122 ft
^ density of CO_2 at depth = 43.4 lbs/ft^3



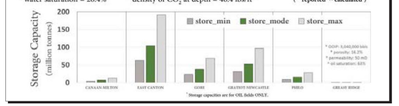
OHIO

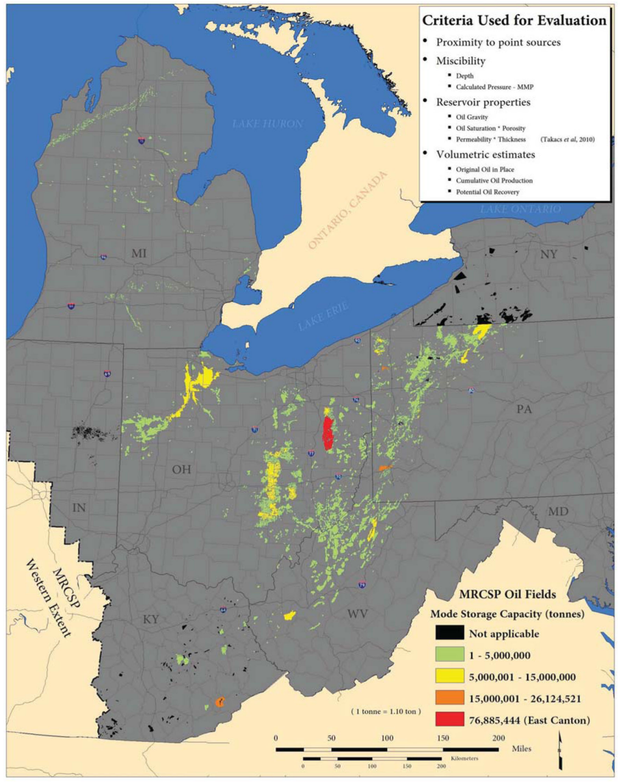


A lack of data makes it possible to only determine miscibility via depth in Ohio's oil fields. First, oil fields were selected based on their proximity to point sources. Next, fields shallower than 2,600 ft were eliminated and the top five with the highest storage capacities were selected. The Greasy Ridge field to the south, although considered to be immiscible, is displaced because it is the only field in Ohio with volumetric data. All displayed fields target the Silurian Clinton Sandstone, except for Greasy Ridge which produces from the highly porous, and permeable, Pennsylvanian Pottsville Sandstone.

Averages (excluding Greasy Ridge)

* depth = 4,294 ft
^ temperature at depth = 94° F
^ P_i = 1,240 psi
^ oil saturation = 71.6%
* porosity = 8.6%
^ thickness = 21.2 ft
* water saturation = 28.4%
^ density of CO_2 at depth = 46.4 lbs/ft^3
(* reported ^ calculated)





There are approximately 1,300 individual oil fields reported in the MRCSP region which are represented by 4,391 polygons of varying area and their associated data. Several criteria are being used to evaluate these oil fields in terms of their ability to enhance recovery of oil via CO_2 floods. The "mode" storage capacity is an estimate of the individual polygons' ability to store CO_2. Of the three estimates used in this study, it is expected to be the most likely outcome when compared to the "minimum" and "maximum", which are conservative and generous, respectively (Kuuskraa *et al*, 2011). Approximately 20% of the rows of data do not have attributes which allow for the calculation of storage capacity (mapped in black). The bulk of the remaining 80% contain estimates for storage of up to 26,124,520 tonnes of CO_2. The exception is East Canton oil field in Ohio, which dwarfs all other polygons in the region with an estimated mode storage capacity of 76,885,444 tonnes (in red).

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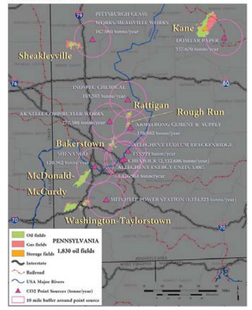
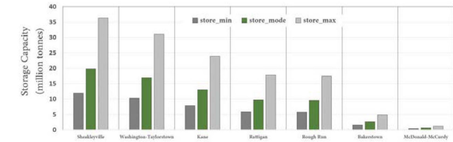
PENNSYLVANIA



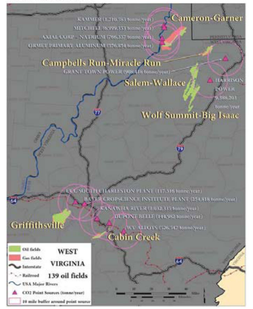
Prediction of oil gravities in Pennsylvania's oil fields make it possible to prepare a more accurate assessment of the potential for miscibility. In this example, analysis of the fields' proximity to point sources was followed by the elimination of fields that were deemed immiscible. Finally, the fields with the highest storage capacities were selected for display. McDonald-McCurdy, also considered miscible, was selected because of its inclusion of production data and high storage potential. Miscibility via depth considers all of these fields (except Sheakleyville) to be immiscible; however, when MMP is compared to the hydrostatic pressure at depth, all of these fields are considered to be miscible. All fields displayed produce from Devonian sandstones except for Sheakleyville which targets the Silurian Medina Group.

Averages

* depth = 2,565 ft
^ temperature at depth = 82.6° F
^ P_i = 1,110 psi
^ oil saturation = 62.7%
* porosity = 11.9%
^ water saturation = 37.3%
* thickness = 219.5 ft
^ MMP = 850.8 psi
^ density of CO_2 at depth = 32.0 lbs/ft^3
* oil gravity = 49.6 API
(* reported ^ calculated)



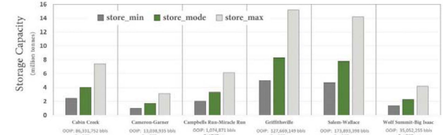
WEST VIRGINIA



As in Pennsylvania, prediction of oil gravities in West Virginia's oil fields allow for more precise miscibility evaluations. Following a selection of oil fields within 10 miles of CO_2 point sources, fields considered miscible via MMP were sorted according to storage capacity. The top six oil fields with the highest storage capacities were selected for display and all target Devonian sandstones. Griffithsville and Cabin Creek are located in a highly industrialized area where nearly four years worth of CO_2 emissions from power plants within 10 miles of both fields could potentially be sequestered.

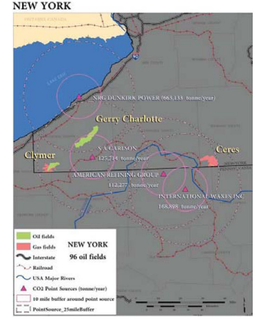
Averages

* depth = 2,751 ft
^ temperature at depth = 84° F
^ P_i = 1,191 psi
* oil saturation = 72.8%
* porosity = 12.9%
^ water saturation = 27.3%
* thickness = 12.2 ft
^ density of CO_2 at depth = 43.6 lbs/ft^3
^ MMP = 974.9 psi
* oil gravity = 43.4 API
(* reported ^ calculated)



MRCSP
MIDWEST REGIONAL CARBON SEQUESTRATION PARTNERSHIP

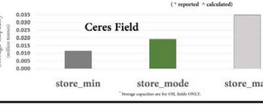
NEW YORK



Available reported oil gravity data allowed for calculation of MMP for several of the oil fields in New York. Both capable of miscible completions, Gerry Charlotte is within 10 miles of a power plant, while Clymer is inside of 25 miles. Ceres was selected for display because it is the only petroleum field in the State containing production and storage parameters. Also, it's possible that it may obtain miscibility if pressurized.

Averages

* depth = 2,362 ft
* temperature at depth = 80° F
* P_i = 723 psi
^ oil saturation = 41.3%
* water saturation = 46.3%
^ MMP = 963.2 psi
^ density of CO_2 at depth = 34.8 lbs/ft^3
* oil gravity = 40.7 API
(* reported ^ calculated)



CONCLUSION

Utilization of CO_2 floods for enhanced oil recovery (EOR) is a developing technology in the Appalachian and Michigan basins. While it may still be too early to predict its contribution to America's future energy balance, many opportunities for implementation exist within the region. A comprehensive assemblage and evaluation of petroleum data by the MRCSP Geo-Teams will enable stakeholders from diverse backgrounds to evaluate of these opportunities on a regional, and/or field-specific, basis.

The latest phase of MRCSP research added several new attributes to an already-comprehensive database in order to identify and rank the best opportunities for CO_2 EOR throughout the 10-state region. Detailed reservoir parameters are necessary to perform a comprehensive evaluation of any given EOR target, and a ranking of opportunities depends on both availability of data and relative consideration or weight assigned to the various attributes. For example, a ranking based upon identifying fields with high storage capacities yields vastly different results than a ranking that focuses on reservoirs capable of miscible completion, or those in closest proximity to sources of CO_2.

A renewed focus on CO_2-EOR also helped to identify information severely lacking in the MRCSP region, such as permeability and oil gravity. Where possible, steps have been taken to increase data density and enable improved reservoir characterization. This is most notable in the Appalachian Basin states of Pennsylvania and West Virginia, where calculated oil gravities replaced hundreds of null values. As a result of these combined efforts, MRCSP continues to build a platform for future energy development throughout the ten-state region.

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