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Oil & gas reservoirs in U.S. like the producing formations at NPR-3

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INTRODUCTION

RMOTC's operations at the Teapot Dome Oil Field (NPR-3) in Wyoming provide an excellent natural laboratory in which to conduct research in Enhanced Oil Recovery (EOR) and carbon sequestration in geologic reservoirs. In addition, RMOTC provides a testing center environment ideal for testing and/or demonstrating new technologies for EOR and sequestration. Several oil-producing formations at NPR-3 have characteristics similar and analogous to nationwide CO2-EOR and sequestration target reservoirs (see Figure 1), including:

- Tensleep Sandstone
- Second Wall Creek Sandstone
- Muddy Sandstone
- Dakota Sandstone

The Shannon Sandstone is also productive at NPR-3, but it is too shallow and has too low a reservoir pressure to be a candidate for CO2-EOR, so it isn't included in this review. However, it may still be useful for sequestration research for evaluation of leakage, containment, and monitoring technologies.

The National Energy Technology Laboratory (NETL) categorizes geologic sequestration into these classes:

1. **Oil and Gas Reservoirs**
2. Unmineable Coal Seams
3. **Deep Saline Formations**
4. Basalt Formations
5. Organic Rich Shales

This summary will only address #1 and #3 for the NPR-3 site. Two other identified geologic sequestration targets, #2 coals and #4 basalts, are out of scope for this summary, as those are not present at Teapot Dome. Fractured organic-rich shales (#5), including the Niobrara Formation, are productive at NPR-3, and although these are seen as future potential sequestration targets, the sequestration science for these targets is immature and they exhibit very low permeabilities, so they are also not included.

NPR-3 does have two key deep saline formations (#3 in above list), conducive to research as sequestration targets, which are also analogous to similar saline reservoirs nationwide:

- Crow Mountain Sandstone
- Madison Limestone

These are not EOR targets at NPR-3, but they do relate to nationwide sequestration capacity numbers discussed in a later section. The screening criteria for oil and gas reservoirs used to establish suitability for CO2-EOR include reservoir depth, oil gravity, reservoir pressure, reservoir temperature, and oil composition. For the Rocky Mountain Basins in Colorado, Utah, and Wyoming, ARI (2006) positively screened 86 field and reservoir combinations as "amenable to CO2-EOR"; of these 55 were direct equiva-

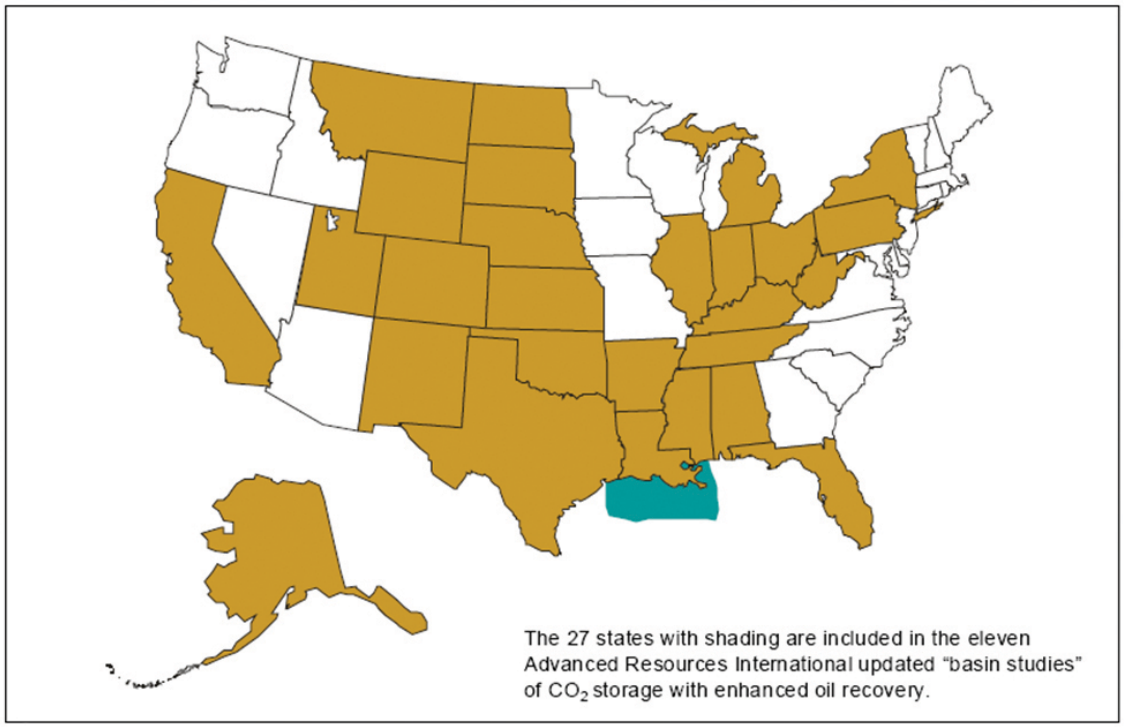

Figure 1. States with similar geology to Teapot Dome in Wyoming (NETL/ARI, 2008).

Table 1. Comparison of NPR-3 formations with other similar formations in other basins.

Formation	Primary Facies	Analogous Formations	Located in
Tensleep	Eolian	Nugget/Navajo; Rotliegendes	UT/WY Thrust Belt; UK North Sea
Wall Creek	Beaches, bars	Frio, Jackson, Woodbine, Clinton	TX, OK, OH
Muddy	Stream point-bars	Morrow, Yegua, Wilcox, "J-sand"	KS/CO/TX; TX GOM, OK, MT, CO
Dakota	Delta fronts	Wilcox, San Miguel, Puente	TX, OK, CA

lents or stratigraphic analogs of the reservoirs at NPR-3 listed above, and 7 were equivalent to the saline reservoirs at NPR-3.

An additional criteria, not included by ARI for EOR or NETL Regional Partnerships for sequestration capacity estimates, is water cut in the producing oil reservoirs. Water cut is less of an issue in CO2-EOR screening than is remaining oil saturation. Water cut can sometimes be modified with well workovers, and at NPR-3, RMOTC has attempted to limit water production in the Tensleep and in the Second Wall Creek in some wells. CO2 floods have proven to be effective even in high water cut wells.

TENSLEEP SANDSTONE

RMOTC has done the most work at NPR-3 on the Tensleep. In terms of reserves, the Tensleep and its analogs represent the largest reservoir in Wyoming. Per the University of Wyoming, Enhanced Oil Recovery Institute, 2/3 of Wyoming oil production comes from the Tensleep or equivalent reservoirs (Minnelusa, Leo, and Weber). The very large, 30-year-plus Rangely CO2 project in Colorado is in the Weber Sandstone, a Tensleep equivalent. There are also significant volumes elsewhere in Colorado and Utah. A CO2 storage capacity estimate for the Tensleep at Teapot Dome has not been generated, but UW/EORI estimates (SPE paper 122921, 2009) that 20 trillion cubic feet (TCF) of CO2 could be sequestered after CO2-EOR in Wyoming basins. If Tensleep analogs represent even a fraction of that target, the potential is enormous.

The Tensleep project would provide results of value to potential storage projects in geologic formations throughout the U.S. One of the principal benefits from a project at Teapot Dome would be the contributions to risk assessment and risk mitigation through open sharing of research and project results. Additional detail on specific geologic targets would require more investigation with geologists with broader knowledge of basins throughout the U.S., and comparisons with specific reservoirs at Teapot (Tensleep, Crow Mountain, Second Wall Creek, for example).

HOW ARE RESERVOIRS SIMILAR (NATIONWIDE)?

Most oil and gas reservoirs nationwide, by a wide margin, are in sandstones, with secondary amounts in "carbonates" (limestones and dolomites). Very rare are oil reservoirs in volcanic rocks, such as those in Nevada, which is the reason Nevada is not included in this review. All the oil reservoirs at NPR-3 are in sandstones (excluding the fractured shales as already discussed). The Madison Limestone at Teapot Dome is an example of a carbonate reservoir, and it is oil-productive elsewhere, but not at NPR-3, where it is a deep saline reservoir instead.

Sandstone reservoirs can be further classified by their environment of deposition. For example, the Tensleep is primarily an eolian sand, originating as windblown sand dunes near an ancient shoreline. A secondary lithology within the Tensleep is dolomite and dolomitic sandstone, created in near-shore lagoons where the sand dunes were re-worked by waves and tides.

The Wall Creek (Frontier) sandstones represent shoreface sands derived from beaches, bars, and barrier islands. The inter-fingered shales within the overall Frontier Formation sequence derive from adjacent mudflats behind the barrier islands, and slightly deeper offshore mud and silt. The Muddy Sandstone is a classic fluvial sequence, originating in river systems, where the good sandstones represent point-bar deposits on the inside curves of meandering streams. The Dakota

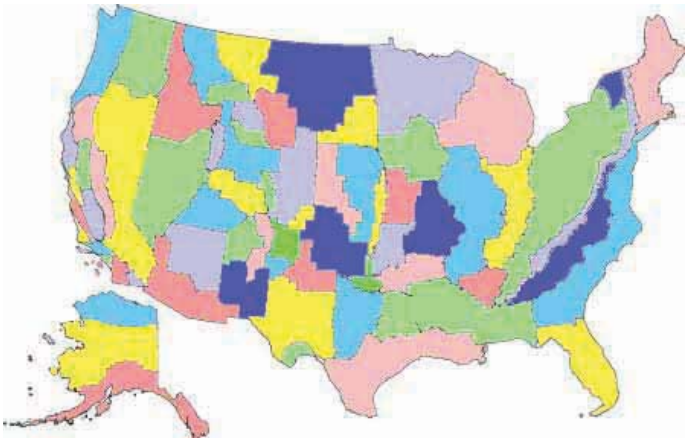

Figure 2. Basin boundaries of the U.S.

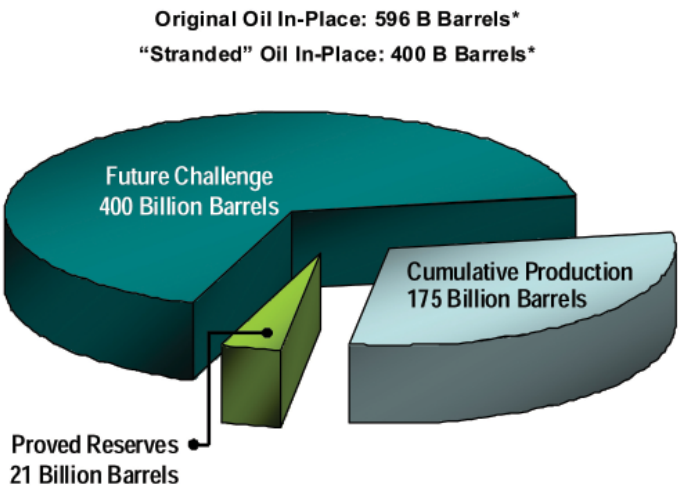

Figure 3. Large volumes of domestic oil remain "stranded" after traditional primary/secondary oil recovery. Excludes deep-water GOM. (Source: Advanced Resources International, 2008)

Sandstone has some areas of similar fluvial origin, but in other areas it exhibits delta-front sandbars originating where the river systems entered the ocean.

Producing oil and gas reservoirs in other U.S. basins nationwide are found in all of these types of sandstone facies (environments of deposition), therefore the sandstone reservoirs at Teapot Dome are directly analogous to the same types of rocks throughout all other significant producing sedimentary basins (and states) of the U.S. Table 1 compares the formations at NPR-3 with a sampling of similar formations from other basins (which are also EOR and sequestration candidates).

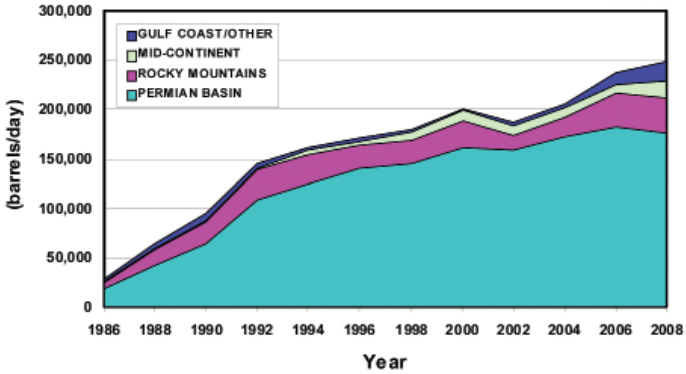

Figure 4. Growth of CO2-EOR production in the U.S. (1986-2008).

OIL POTENTIAL FROM CO2-EOR (NATIONWIDE)

A better comparison of analogs is not by state, which are political entities, but by sedimentary basin – a geologic categorization. Figure 2 shows U.S. basin outlines for comparison to the state map in Figure 1.

NETL contracted with Advanced Resources International (ARI) to do a series of 11 "basin reports" nationwide, to cover what is the total EOR target using CO2. A 2008 follow-up report compiled and updated those results, and finally, a March 2010 report for the NRDC further updated the results. The following summaries are drawn from these reports.

The total target of oil left in place in the U.S. is 400 billion barrels as shown in Figure 3.

Historical trends of CO2-EOR are shown in Figure 4 from the 2010 report.

Table 2 summarizes their findings on the future potential of what incremental oil can be recovered out of the 400 billion barrels left in the ground, based first on "technically recoverable", and secondly, on "economically recoverable" (using a $70 per barrel price), and with current technology & methods ("Best Practices"), with additional columns for "Next Generation" technology. These tabular results are listed by basin or regional group of basins, with the states covered by each region shown as well. Bottom-line, the potential resource target economically recoverable with current CO2-EOR practices, that is directly analogous to what RMOTC could do at NPR-3, is close to 50 billion barrels.

Table 2. Economically recoverable domestic oil resources from CO2-EOR*.

Region	Incremental Technically Recoverable Oil* (Billion Barrels)		Incremental Economically Recoverable Oil** (Billion Barrels)	
	"Best Practices"	"Next Generation"	"Best Practices"	"Next Generation"
California	6.3	10.0	5.5	7.8
Gulf Coast (AL, FL, MS, LA)	7.0	7.4	2.3	2.3
Mid-Continent (OK, AR, KS, NE)	10.6	17.0	5.6	8.7
Illinois/Michigan	1.2	3.2	0.5	1.7
Permian (W TX, NM)	15.9	28.0	9.4	15.0
Rockies (CO,UT,WY)	3.9	7.1	2.2	4.3
Texas, East/Central	17.6	20.0	8.4	12.1
Williston (MT, ND, SD)	2.5	5.2	0.5	0.5
Appalachia (WV, OH, KY, PA)	1.6	2.6	0.1	0.1
Louisiana Offshore	5.8	5.8	3.9	3.9
Lower 48	**72.4**	**106.3**	**38.5**	**56.5**
Alaska	12.4	12.4	9.5	9.5
TOTAL	**84.8**	**118.7**	**48.0**	**66.0**

*Incremental technically recoverable oil resources after subtracting 2.3 billion barrels already being developed with CO_2-EOR.
**Assumes an oil price of $70 per barrel (constant, real) and a CO_2 cost of $15 per metric ton ($2.38/Mcf), delivered at pressure to the field; and a 25% investment hurdle rate of return

SEQUESTRATION POTENTIAL AFTER EOR IS COMPLETE (NATIONWIDE)

Basically, the same oil and gas reservoirs targeted for EOR are excellent candidates for carbon sequestration. Therefore, the same R&D activities that could be conducted at NPR-3 related to EOR are applicable for sequestration. These reservoirs have contained hydrocarbon fluids and gases for millions of years, and so they will also be able to store and contain CO2 well into the future. NETL has compiled the total carbon sequestration capacity data for the U.S. and Canada, drawn from the Regional Carbon Sequestration Partnerships (RCSPs), and to quote,

"The RCSPs have documented the location of 138 billion metric tons (152 billion tons) of geologic CO2 storage potential in more than 10,000 oil and gas reservoirs distributed over 27 states and 3 provinces."

The state-by-state data is shown Table 3.

For Deep Saline Formations, there is greater uncertainty than for oil and gas reservoirs, due to the relative lack of characterization. Nevertheless, *"The RCSPs have documented the locations of saline formations with an estimated CO2 sequestration potential ranging from 3,300 to more than 12,000 billion metric tons (from 3,600 to more than 13,000 billion tons)."* State-by state details are in Table 4.

At Teapot Dome, however, the two candidates for deep saline reservoirs, the Madison and the Crow Mountain, are much better characterized due to their presence in an existing oil field. The Madison provides a carbonate (limestone) reservoir and the Crow Mountain is a sandstone, so NPR-3 can offer a more comprehensive test-bed for R&D-related to deep saline reservoirs than at many other sites.

The Big Sky Carbon Sequestration Partnership (BSCSP) is looking at the Nugget Sandstone for deep saline sequestration, which is stratigraphically equivalent to the Crow Mountain at NPR-3, and facies equivalent to the Tensleep, and also the Madison, a direct equivalent to NPR-3's Madison. The Plains CO2 Reduction Partnership (PCOR) is evaluating the Madison also, and the "Lower Cretaceous," which is equivalent to the Muddy and Dakota Sandstones at

Table 3. CO2 storage resource estimate for oil and gas reservoirs by state*.

State/Province	Million Metric Tons	Million Tons
Alabama	427	471
Alaska		
Alberta	9,328	10,282
Arizona	70	77
Arkansas	313	345
British Columbia		
California	7,692	8,479
Colorado	1,723	1,899
Connecticut	0	0
Delaware	0	0
District of Columbia	0	0
Florida	197	217
Georgia	0	0
Hawaii	0	0
Idaho	0	0
Illinois	338	373
Indiana	68	75
Iowa	0	0
Kansas	1,624	1,791
Kentucky	104	114
Louisiana	6,990	7,705
Maine	0	0
Manitoba	618	681
Maryland	0	0
Massachusetts	0	0
Michigan	457	504
Minnesota	0	0
Mississippi	699	771
Missouri		
Montana	1,262	1,391
Nebraska	23	26
Nevada		
New Hampshire	0	0
New Jersey	0	0
New Mexico	8,246	9,090
New York	240	264
North Carolina		
North Dakota	4,589	5,059
Ohio	3,481	3,838
Oklahoma	10,012	11,036
Ontario		
Oregon		
Pennsylvania	2,759	3,041
Rhode Island	0	0
Saskatchewan	6,245	6,884
South Carolina	0	0
South Dakota	232	255
Tennessee		
Texas	47,761	52,648
Utah	1,410	1,544
Vermont	0	0
Virginia	81	89
Washington	0	0
West Virginia	1,353	1,492
Wisconsin	0	0
Wyoming	2,100	2,315
Offshore	17,628	19,432
TOTAL	138,070	152,198

* States/Provinces with a "zero" value represent estimates of minimal oil and gas reservoir CO_2 storage resource while states/provinces with a blank represent areas that have not yet be assessed by the RCSPs.

Table 4. CO2 storage resource estimates for Deep Saline Formations*.

State/ Province	Million Metric Tons		Million Tons	
	Low Estimate	High Estimate	Low Estimate	High Estimate
Alabama	28,500	114,030	31,416	125,696
Alaska				
Alberta	75,100	75,100	82,783	82,783
Arizona	184	740	203	816
Arkansas	9,616	38,465	10,600	42,400
British Columbia	749	749	826	826
California	75,875	303,502	83,638	334,553
Colorado	34,100	123,200	37,589	135,805
Connecticut	11	46	13	51
Delaware	1	5	1	5
District of Columbia	14	57	16	63
Florida	41,837	167,348	46,118	184,469
Georgia	3,313	13,252	3,652	14,608
Hawaii				
Idaho				
Illinois	18,984	75.935	20,926	83,704
Indiana	13,200	53.000	14,550	58,422
Iowa				
Kansas	2,700	10,600	2,976	11,684
Kentucky	6,796	27,094	7,491	29,866
Louisiana	402,401	1,609,602	443,570	1,774,280
Maine				
Manitoba				
Maryland	1,309	5,260	1,443	5,798
Massachusetts	6	25	7	27
Michigan	20,194	81,030	22,260	89,320
Minnesota				
Mississippi	110,757	443,026	122,088	488,352
Missouri	149	595	164	655
Montana	265,407	988,831	292,561	1,089,998
Nebraska	13,410	13,500	14,782	14,881
Nevada				
New Hampshire				
New Jersey	49	198	54	218
New Mexico	32,186	128,744	35,479	141,916
New York	2,600	10,500	2,866	11,574
North Carolina	3,679	14,714	4,055	16,220
North Dakota	25,290	30,310	27,877	33,411
Ohio	7,117	28,663	7,845	31,595
Oklahoma	1,149	4,011	1,267	4,421
Ontario	1	3	1	3
Oregon	16,727	66,909	18,438	73,754
Pennsylvania	5,290	21,306	5,831	23,486
Rhode Island				
Saskatchewan	23,420	23,420	25,817	25,817
South Carolina	1,373	5,491	1,513	6,053
South Dakota	27,979	64,987	30,841	71,636
Tennessee	1,248	4,997	1,376	5,508
Texas	533,600	2,133,300	588,193	2,351,558
Utah	32,565	128,990	35,897	142,187
Vermont				
Virginia	137	350	151	386
Washington	90,245	360,979	99,478	397,911
West Virginia	3,343	13,463	3,685	14,840
Wisconsin				
Wyoming	196,932	763,120	217,080	841,195
Offshore	1,167,300	4,668,825	1,286,726	5,146,493
TOTAL	3,296,843	12,618,271	3,634,143	13,909,246

* States/Provinces with a "zero" value represent estimates of minimal deep saline formation CO_2 storage resource while states/provinces with a blank represent areas that have not yet be assessed by the RCSPs.

NPR-3. Lastly, the Southwest Regional Partnership (SWP) is targeting the Permian White Rim sandstone (equivalent to the Tensleep a NPR-3) and the Jurassic-Triassic Wingate sandstone (stratigraphically equivalent to the Crow Mountain at NPR-3). All three regional partnerships surrounding Wyoming are evaluating directly analogous formations as deep saline reservoirs for carbon sequestration.

WHAT COULD BE LEARNED FROM RMOTC DOING A CO2 SEQUESTRATION PROJECT?

What is learned from a project at NPR-3 depends on the zones used, project size and duration, monitoring technologies employed, and the extent and type of associated research conducted. Potential topics to be investigated include, but are not limited to:

- groundwater effects (chemical changes to groundwater)
- geomechanical effects to the reservoir and caprock
- geochemical effects to the reservoir and caprock
- monitoring for surface leakage/microseepage
- effect on faults and possible induced microseismicity
- cement/wellbore integrity monitoring
- tuning of reservoir models
- monitoring and modeling of fluid movement in fractured reservoirs
- use and effectiveness of gravity-stable injection
- saline aquifer monitoring (in our Crow Mountain Class II zone)
- integration/comparison of results from different monitoring technologies and approaches

WHY IS NPR-3 A GOOD CANDIDATE SITE?

Teapot, as a public, non-commercial site, has the flexibility to host field experiments and scientific investigations that commercial project operators may not support. More importantly, all of the resulting data can be made public. CO2-EOR and storage are currently linked, at least in industry, since there is no direct financial incentive for pure storage in the U.S. Project results and research findings from industry EOR projects are typically in the full control of the operator, and so are usually not made available to inform the public or DOE.

Teapot Dome is 100% federally owned and operated, and there is essentially unrestricted surface and subsurface access. RMOTC has in-house capability to facilitate the permitting steps required for research projects. A great deal of the necessary site characterization data is already available, unlike many other possible project sites, and benefits transfer easily to industry, regulators, and the public, via research partnerships and publications. Additional benefit is provided by incremental oil production from CO2 injection into oil-producing zones at RMOTC; those revenues would benefit the federal treasury, offsetting at least a portion of the DOE project cost.

A science-focused CO2 program at RMOTC is possible, free of the commercial constraints that typically exist with an industry site. Teapot Dome can serve as field-scale subsurface laboratory for CO2-EOR and carbon storage. There, researchers and industry can test and evaluate technologies at varying scales. Because RMOTC operations can emphasize testing and research over purely commercial production, it's possible to host projects designed specifically to complement EOR and geologic storage projects in other locations. The knowledge gained at RMOTC can inform regulatory agencies that have direct responsibilities related to CO2 injection (EPA, DEQ, DOE, etc). All of the pure storage projects in the U.S. have so far been small pilot-scale experiments and demonstrations, and none have been conducted yet in Wyoming. RMOTC can build on those results, and provide research and demonstration opportunities not easily provided on commercial EOR operations.

SOURCES

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