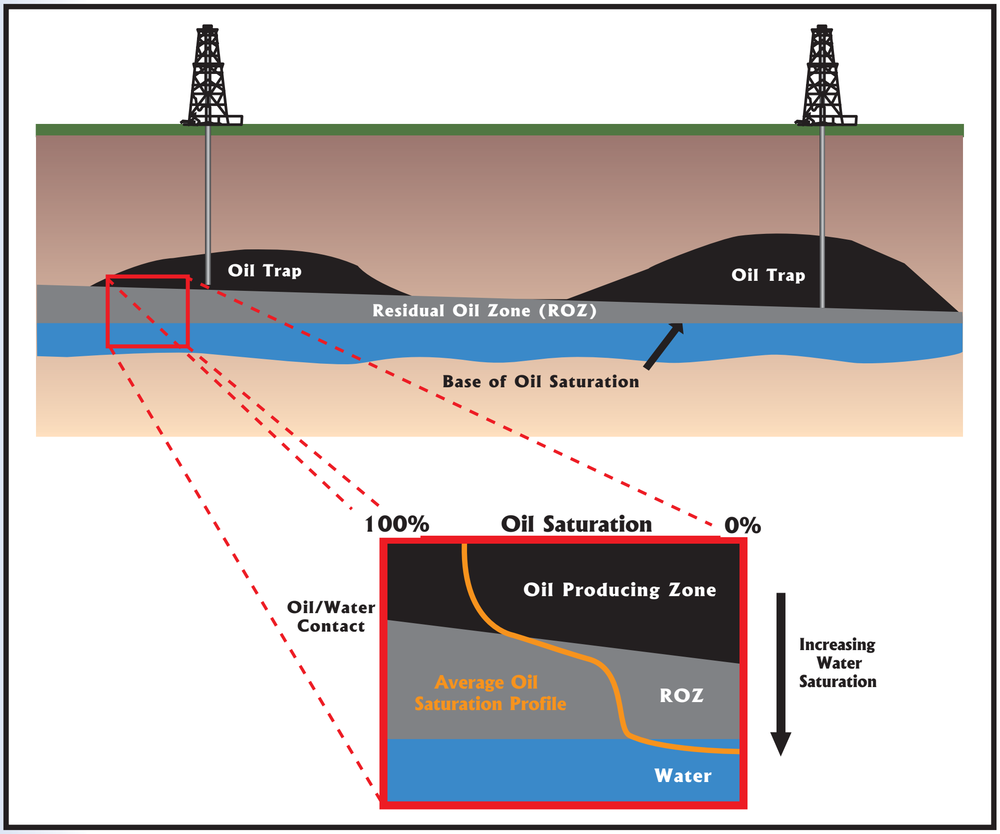
Technical Oil Recovery Potential from Residual Oil Zones: Big Horn Basin



Prepared for
U.S. Department of Energy
Office of Fossil Energy - Office of Oil and Natural Gas

Prepared by
Advanced Resources International

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I. INTRODUCTION

Residual oil zones (ROZ), the portion of an oil reservoir below its traditional producing oil-water contacts, can hold large volumes of previously undocumented and undeveloped domestic oil resources. The first comprehensive report on this topic, "Stranded Oil in the Residual Oil Zone," examined the origin, nature and presence of ROZ resources.[1] The second report "Assessing Technical and Economic Recovery of Resources in Residual Oil Zones" provided a reservoir simulation-based study of applying CO_2-EOR to establish the feasibility of recovering oil from residual oil zones in five major oil reservoirs[2]. The third report and the first in a series of three, "Technical Oil Recovery Potential from Residual Oil Zones: Permian Basin", provided an in-depth documentation of the in-place and recoverable ROZ potential in the Permian Basin. The fourth report and the second in a series of three, "Technical Oil Recovery Potential from Residual Oil Zones: Williston Basin", provided an in-depth documentation of the in-place and recoverable ROZ potential in the Williston Basin. This report, "Technical Oil Recovery Potential from Residual Oil Zones: Big Horn Basin", is the third of this three part series and explores the in-place and recoverable ROZ potential for the Big Horn Basin.

A. Overview of ROZ Recovery Potential. Because of their low to moderate oil saturation settings, ROZ resources are not economic when using primary or secondary oil recovery. As such, the traditionally domestic oil wells have traditionally been completed at or above the oil-water contact (the first observance of water) and thus consistently above the residual oil zone. Outside of a small group of forward-looking operators, little is still known about the ability to successfully identify and produce the ROZ resource. However, in the current economic climate, with depleting domestic oil reserves and operators' desires to extend reservoir life, ROZ resources offer an important new source of domestic oil production. Because of this, there is growing interest in further understanding the resource size and recoverable oil potential

[1] Melzer, S., (2005) "Stranded Oil in the Residual Zone." U.S. Department of Energy Report.
[2] "Assessing Technical And Economic Recovery Of Oil Resources In Residual Oil Zones", Advanced Resources International, September 2005, U.S. Department of Energy Report.

in the relatively thick (100 to 300 feet) residual oil zones located beneath the main pay zones of oil reservoirs.

Carbon dioxide (CO_2) enhanced oil recovery (EOR) has emerged as a viable technique for recovering residual oil left behind ("stranded") after waterflooding, mainly in light oil reservoirs below 3,000 feet in depth. Yet, the oil saturation in the transition (TZ) and residual oil zones (ROZ) of a reservoir is often similar to the oil saturations left after waterflooding. As such, with progress in CO_2 flooding technology and availability of affordable supplies of CO_2, the oil resource in the ROZ could readily become a feasibility target.

Further confirmation of this new oil resource potential is provided by the various residual oil zone CO_2-EOR pilot tests currently underway in Texas. Two of these pilot tests are operated by OxyPermian in the Denver and Bennett Ranch Units of the giant Wasson oil field. The Denver Unit pilot was the first to target transition and residual oil zones. A third ROZ pilot test, operated by Amerada Hess, is in the Seminole San Andres Unit. This is a 500 acre pilot TZ/ROZ flood underway since 1996. The response from this field pilot test has been most promising, providing an estimated cumulative recovery of 3 million barrels of oil to date, at an oil rate of 1,400 Bbls/day.[3] An expanding CO_2-EOR project targeting the ROZ is also underway in the Salt Creek field (by ExxonMobil) involving 36 wells and incremental production of 2,000 bbls/day.[4]

The information on the operation and performance of these ROZ field pilot projects has been most valuable in calibrating the reservoir simulation-based oil recovery assessments of the TZ/ROZ resource examined by this study.

B. Outline for Report. This report assesses the size of the in-place technically recoverable oil resource from the transition and residual oil zones of the Big Horn Basin. It first provides a very brief introduction to the oil plays and the major fields

[3] "2004 Worldwide EOR Survey," Oil & Gas Journal, April 12, 2004, pp. 53-65.
[4] Wilkinson, J.R., Genetti, D.B., and Henning, G.T., " Lessons Learned fro Mature Carbonates for Application to Middle East Fields", SPE 88770, presented at the SPE 11th Abu Dhabi International Petroleum Exhibition and Conference, October 10-13, 2004.

with tilted oil-water contacts (OWCs) and TZ/ROZ resources in the Big Horn Basin. Then, it examines, using a reservoir simulation calibrated streamtube model, the technical feasibility of recovering this previously by-passed TZ/ROZ resource using CO_2-EOR.

C. Definition of Terms. The term ***residual oil zone* (ROZ),** as used in this study, also includes the more commonly known ***transition zone* (TZ).** Although often used interchangeably, the two terms describe different portions of an oil reservoir. All oil reservoirs have a transition zone, an interval tens of feet below the traditionally-defined producing oil-water contact (OWC) where the oil saturation falls rapidly. The thickness of this interval is controlled by capillary forces and the nature of the rock's "wetting phase", with lower permeability oil-wet rocks providing thicker TZs and water-wet rocks providing thinner ones.

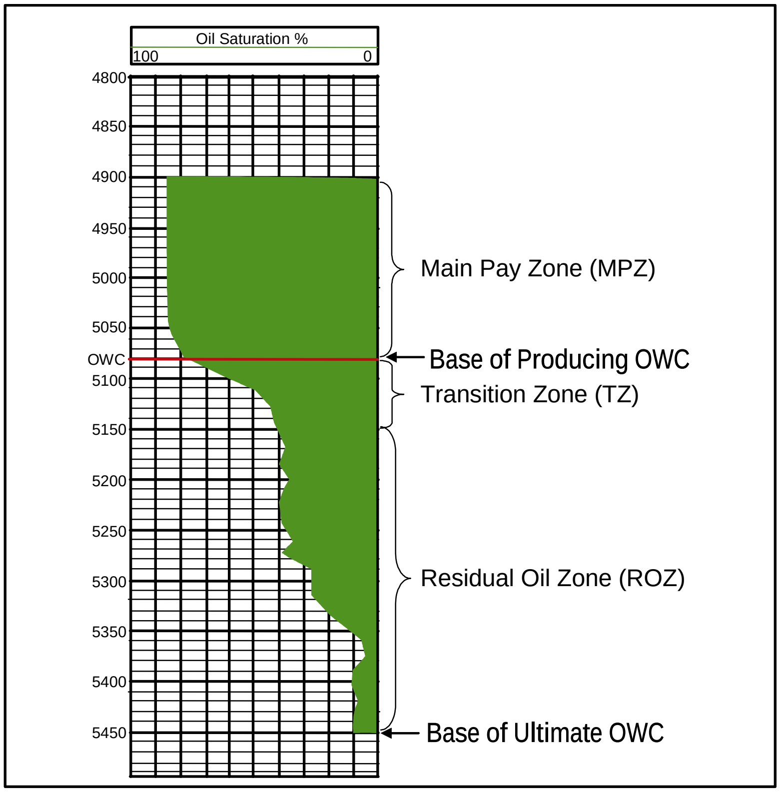
While all oil reservoirs have a transition zone, not all have a residual oil zone, as specific hydrological or geological conditions need to have occurred to create a ROZ, as further discussed below. The great bulk of the ROZ will be at a residual oil saturation (similar to that after a conventional waterflood), tapering to near zero oil saturation at the base. A typical reservoir oil saturation profile is shown in **Figure 1**.

The transition zone (TZ) is the upper portion of the reservoir interval just below the traditional OWC and produces both water and oil. The residual oil zone (ROZ) is generally the middle and lower portions of the reservoir interval below the traditional OWC and upon initial completion produces primarily water.

The reason that both terms - - residual oil zone (ROZ) and transition zone (TZ) - - are used in this report is to bring special attention to the abnormally thick ROZs that can exist for reasons beyond normal capillary effects. For example, if the original oil trap possessed a thick oil column in its geologic past and the lower portion of this oil column was tilted and/or invaded by water, this lower reservoir interval would have an oil saturation much like that of the residual oil saturation in the swept zone of a water flood.

In certain geologic settings, oil reservoirs can have an anomalously thick ROZ and thus could contribute considerable additional CO_2-EOR reserves.

Figure 1. Oil Saturation Profile in the TZ/ROZ: Adapted from a Wasson Denver Unit Well



D. Origin of Residual Oil Zones. A number of possible actions may create a ROZ after the initial accumulation of oil in a reservoir. Specifically, the original oil accumulation may subsequently be affected by natural forces such as regional basin uplift, seal breach, or a change in the hydrodynamics of the underlying regional aquifer, leading to the development of an ROZ. Additional discussion of the origins and nature of ROZs is provided into previously prepared reports.[5,6]

E. Evidence for ROZs in the Big Horn Basin. Much like the work done by Brown to detail the effects of hydrodynamic flow upon the oil-water contact in the

[5] Melzer, S., (2006) "Stranded Oil in the Residual Zone." U.S. Department of Energy Report.
[6] "Assessing Technical And Economic Recovery Of Oil Resources In Residual Oil Zones", Advanced Resources International, February 2006, U.S. Department of Energy Report.

northern and central shelf carbonates of the Permian Basin[7], Bredehoeft, et. al., developed an excellent treatise of *The Hydrodynamics of the Big Horn Basin: A Study of the Effects of Faults*[8]. The authors studied the role that faults play in the hydrogeology of oil fields in the Big Horn Basin. Based on previous studies, the authors concluded that along the eastern margin of the Big Horn Basin oil accumulations in the Tensleep Formation, originally in stratigraphic traps, mirror the structural dip in their location as a result of hydrodynamic flow.

Prevalence of the Tensleep Formation (**Figure 2**) throughout the Big Horn Basin and the enclosure of the basin by mountains suggest that tilted OWC's are most likely to be found in fields located around the edges of the basin. Based on the available geologic information and documented OWC tilts, a number of major oil reservoirs with ROZs were established in the Big Horn Basin oil plays.

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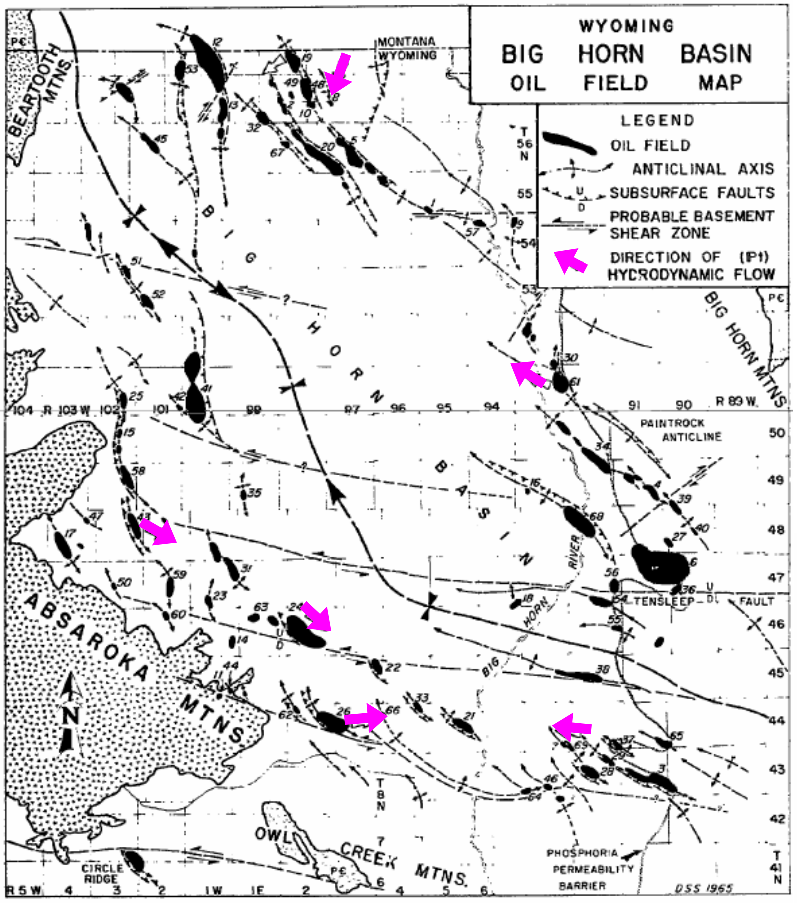
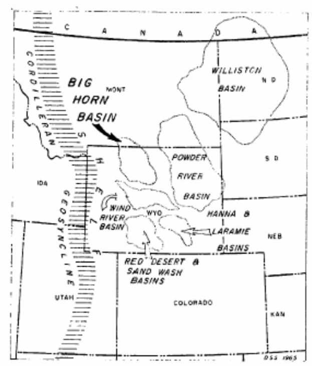
[7] Brown, A., (2001), "Effects of Hydrodynamics on Cenozoic Oil Migration, Wasson Field Area, Northwestern Shelf of the Permian Basin," West Texas Geological Society Fall Symposium, Pub 01-110 (Viveiros, J.J. & Ingram, S.M. eds), Oct 2001, pp 133-142.

[8] Bredehoeft, J.D., Belitz, K. and Sharp-Hansen, S., (1992), The Hydrodynamics of the Big Horn Basin: A Study of the Role of Faults, AAPG Bulletin, v. 76, no. 4, pp. 530-546.

Figure 2. Location of Oil Fields, Structure and Direction of Hydrodynamic Flow, Big Horn Basin, Wyoming



2	Big Polecat
5	Byron
12	Elk Basin
13	Elk Basin, South
19	Frannie
20	Garland
21	Gebo
24	Grass Creek
26	Hamilton Dome
31	Little Buffalo Basin
37	Murphy Dome
41	Oregon Basin



Adapted from Stone, D.S., (1967), “Theory of Paleozoic Oil and Gas Accumulation in Bighorn Basin, Wyoming,” AAPG Bulletin, V. 51, pp. 2056-2114.

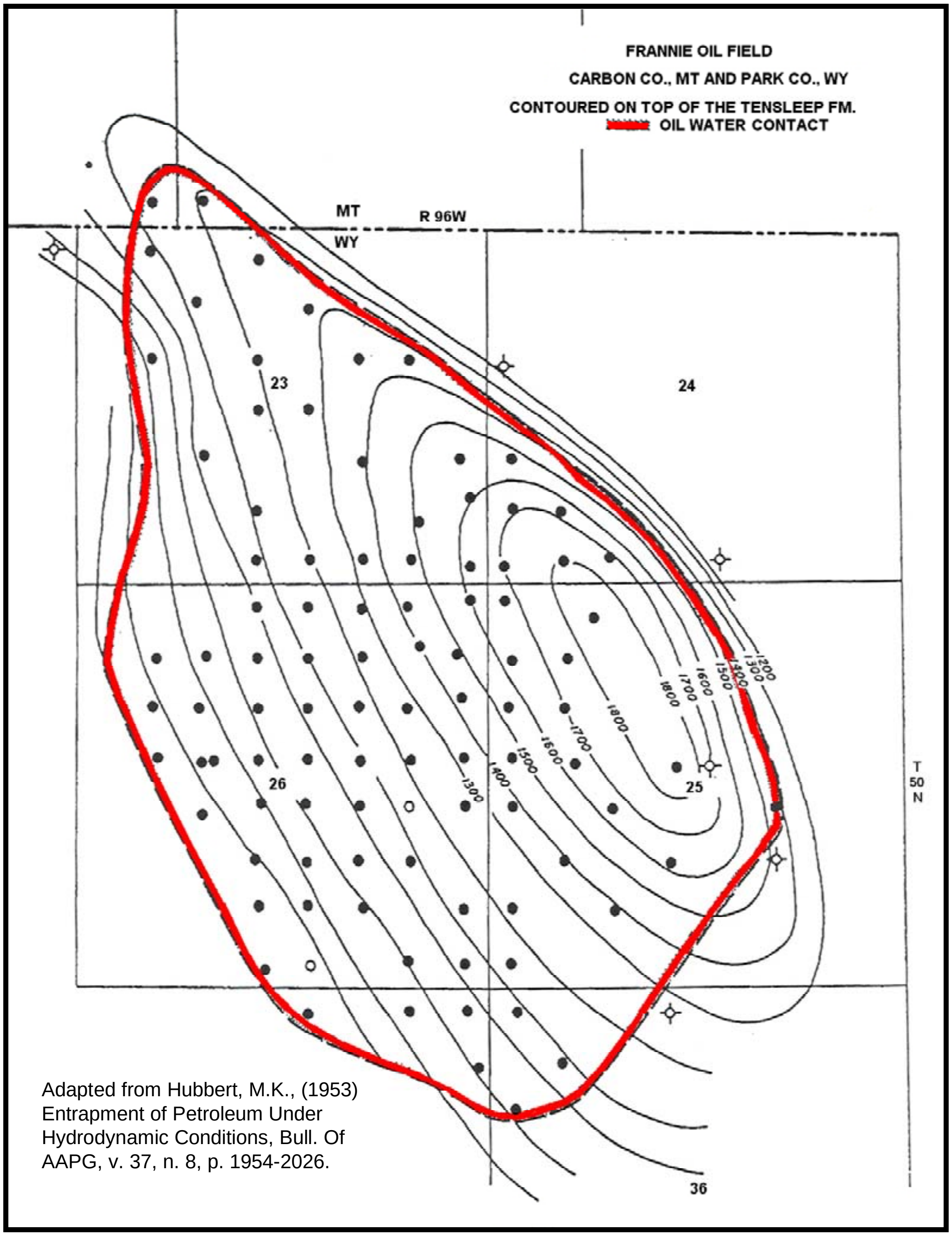
II. IDENTIFYING AND EVALUATING OIL FIELDS WITH ROZ RESOURCES

A. Big Horn Basin (Tensleep Reservoir). The Big Horn Basin is an intermontane basin located in north-central Wyoming and south-central Montana, encompassing an area of 13,200 square miles.[9] To date, the basin has produced 2.4 Bbbls of crude oil and has roughly 0.2 Bbbls of reserves. The source rock of the majority of the oil in the basin is the Permian-age Phosphoria formation, an organic-rich mudstone. Most of the field traps in the basin are classic anticlinal or domal structures where oil has migrated into the permeable Tensleep formation, a Pennsylvanian-age sandstone. Soon after production in the basin began, in the early 20th century, it was discovered that some fields, such as the Frannie field, did not have classic oil reservoir geometries with horizontal oil-water contacts (OWC's), but instead had steeply dipping oil-water OWC's.

At first glance, the Frannie field (Tensleep reservoir), discovered in 1928, has a typical anticline trap reservoir geometry. However, during development of the field, producers found that wells could be successfully completed further down dip to the west of the crest than on the east, **Figure 3**. It was determined that the OWC in the field was dipping towards the southwest at 600 feet per mile, suggesting that a strong hydrodynamic flow through the Tensleep formation from the northeast was flushing the oil downdip.[10] This Hydrodynamic flow is thought to originate from the Tensleep formation outcrop in the Big Horn mountain range, 10 miles to the east. To date, the field has produced 118 MMbbls of oil.

[9] Fox, J.E., and Dolton, G.L. (1995) USGS National Oil and Gas Assessment, Bighorn Basin Province (034)
[10] Hubbert, M.K. (1953) Entrapment of Petroleum under Hydrodynamic Conditions, Bull. Of AAPG, v. 37, no. 8, p. 1054-2026.

Figure 3. The Frannie Field, Big Horn Basin, Wyoming



After the discovery of the tilted OWC in the Frannie field, a USGS mapping project was conducted (in 1956) on the basin's Tensleep sandstone to determine the extent of the hydrodynamic flow in the Big Horn Basin and its effect on the OWC's of the basin's oil fields.[11] The study demonstrated that tilted OWC's were common in the basin's fields, identifying at least 11 fields with OWC tilts, generally dipping towards the basin center or following structural crests suggesting that the source of the tilts was hydrodynamic flow originating from the Tensleep Formation outcrops in the surrounding mountain ranges.

Figure 4 shows a generalized potentiometric contour map of the Tensleep Formation in the Big Horn Basin. A potentiometric contour map represents locations of equal hydraulic head within a reservoir. Because groundwater flows from areas with high hydraulic head to those with low hydraulic head (generally perpendicular to the contour lines) such maps can illustrate hydrologic flow within a reservoir. In the case of the Big Horn Basin, hydrologic flow moves from the outer edges of the basin towards the center. The field OWC dips shown in the USGS map indeed show this trend, with OWC's dipping basin-ward in many fields, with steeper dips occurring generally where the potentiometric gradients are steeper such as the north and south basin flanks. The OWC dip directions shown in the USGS map also show several examples where the dip direction does not follow the general hydrodynamic flow pattern, suggesting that secondary controls on flow are present.

The above described USGS map was the primary source of data for OWC dips used in this study. Additional data were gathered from a review paper on the hydrodynamic effects on oil accumulations by Hubbert (1967),[12] and the Wyoming Geological Association's Big Horn Basin oil field map series (1989).[13] It should be noted that although dipping OWC's in the basin are common, there are notable exceptions, such as the Garland field with an OOIP of over 350 MMbbls on the northern edge of the basin. In fields where a dip is present, the dip magnitude varies by as much as an order of magnitude. For example, in the Byron field the OWC dip less than 40 feet per mile compared to the Frannie field, located only 25 miles to the north, with a dip of 600 feet per mile.

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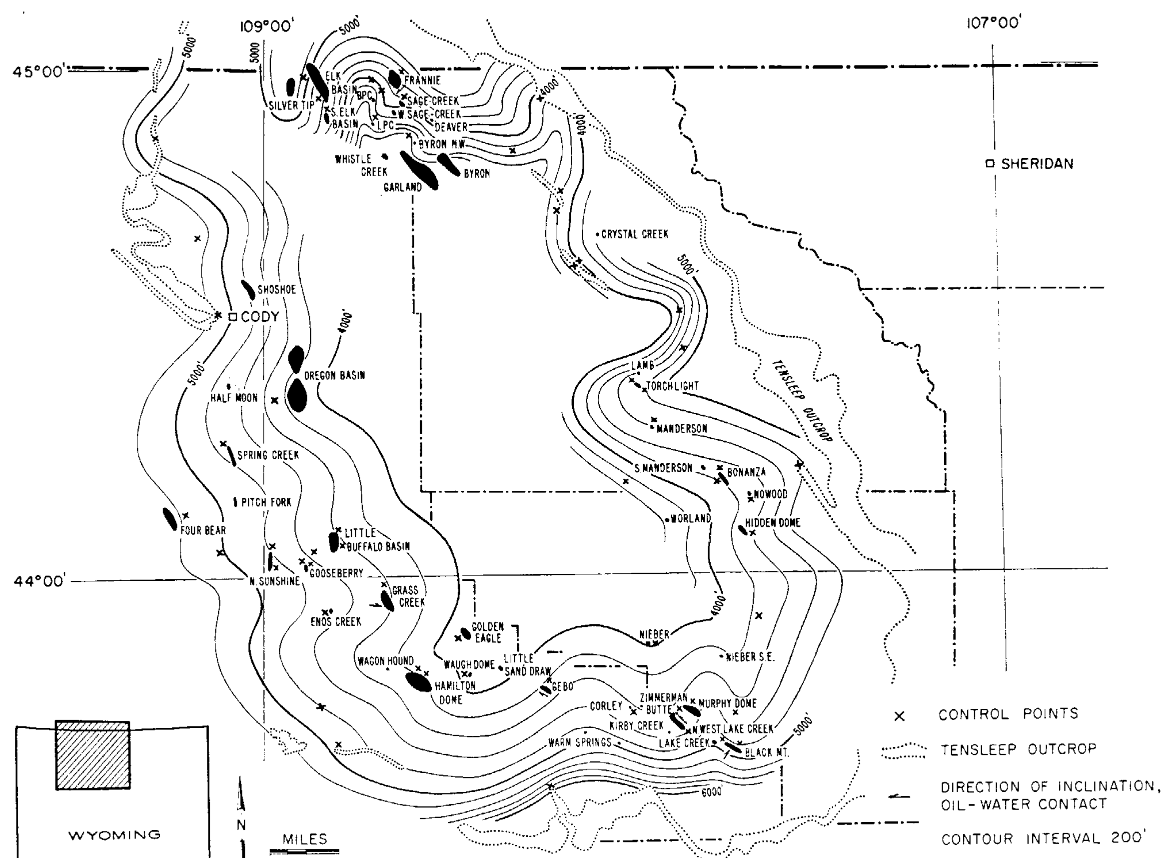
[11] Zapp, A.D., (1956) "Structural Contour Map of the Tensleep Sandstone in the Big Horn Basin, Wyoming and Montana" USGS Map OM-182

[12] Hubbert, M.K. (1967) "Application of Hydrodynamics to Oil Exploration" 7th World Petroleum Congress Proceedings, V1B, p. 59-75.

[13] Wyoming Geological Association Guidebook, Bighorn Basin Oil Fields. 1989.

Based on these studies, 13 large Big Horn Basin oil fields with Tensleep reservoirs were determined to have tilted OWC's and potential residual oil zones (ROZ's). Eight of these fields screened for miscible CO_2-EOR and five fields screened for immiscible CO_2-EOR due to their relatively heavy oil gravities (<23°). The ROZ's within these 13 fields are the target for the CO_2-EOR simulations described in Chapter IV. **Table 1** shows the cumulative Tensleep production in these fields and **Figure 5** shows their location within the basin.

Figure 4. Potentiometric Surface, Tensleep Formation, Big Horn Basin, Wyoming and Montana



Adapted from Todd, T.W., (1963), "Post-Depositional History of Tensleep Sandstone (Pennsylvanian), Big Horn Basin, Wyoming," AAPG Bulletin, V. 47, No. 4, pp. 599-616.

Figure 5. Location Map of Major Tensleep Reservoirs: Big Horn Basin

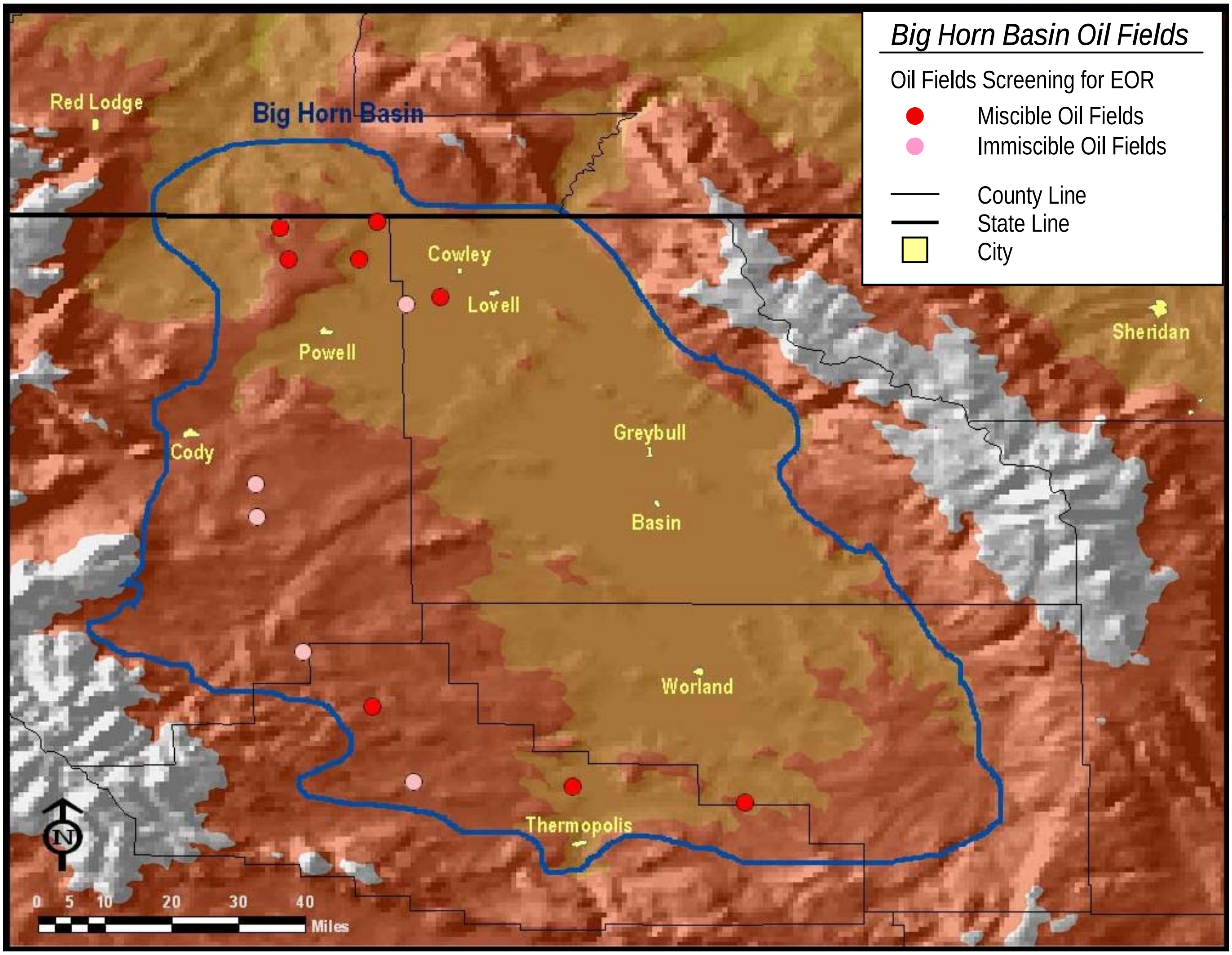


Table 1. Large Big Horn Basin (Tensleep) Oil Reservoirs with Potential for ROZ Resources

Field (Reservoir)	State	County	Cum. Tensleep Oil Production (MMBbls) (1-1-05)
Miscible CO_2-EOR Fields			
1. Big Polecat (Tensleep)	WY	Park	6.2
2. Byron (Embar/Tensleep)	WY	Big Horn	119.1
3. Elk Basin (Embar/Tensleep)	WY/MT	Park/Carbon	345.4
4. Elk Basin South (Embar/Tensleep)	WY	Park	20.3
5. Frannie (Phosphoria/Tensleep)	WY	Park	133.4
6. Gebo (Tensleep)	WY	Big Horn	10.9
7. Grass Creek (Tensleep)	WY	Park	41.1
8. Murphy Dome (Tensleep)	WY	Washakie	37.4
Immiscible CO_2-EOR Fields			
1. Garland (Tensleep)	WY	Big Horn	101.9
2. Hamilton Dome (Tensleep)	WY	Hot Springs	239.4
3. Little Buffalo Basin (Tensleep)	WY	Park	114.9
4. Oregon Basin North (Tensleep)	WY	Park	98.3
5. Oregon Basin South (Tensleep)	WY	Park	130.4

III. ESTIMATING TECHNICALLY RECOVERABLE ROZ RESOURCES

This chapter discusses the comparison and calibration of the *CO2-PROPHET* steamtube model with a full-scale, industry standard compositional reservoir simulator. As shown in the following materials, *CO2-PROPHET* provides an excellent match of oil recovery, for both the MPZ and the TZ/ROZ for four sample major Permian Basin oil fields. As such, there is confidence in using the *CO2-PROPHET* model to estimate oil recovery from the TZ/ROZ for the larger number of Big Horn Basin oil fields assessed by this study.

A. *Background on CO2-PROPHET.* The *CO2-PROPHET* model was developed by the Texaco Exploration and Production Technology Department (EPTD) as part of the DOE Class I cost-share program.[22]

In its simplest form, this model generates streamlines for fluid flow between injection and production wells, and then uses finite difference methods to determine oil displacement and recovery calculations along the established streamlines. Data input requirements are less demanding and computational times are much shorter for using *CO2-PROPHET* than for using full-scale reservoir simulation. Moreover, input requirements for *CO2-PROPHET* can generally be obtained or calculated using engineering formulations. Key input parameters impacting oil recovery in *CO2-PROPHET* include:

1. Residual oil saturation,
2. Dykstra-Parsons coefficient,
3. Oil and water viscosity,
4. Reservoir pressure and temperature, and
5. Minimum miscibility pressure.

B. Comparison and Calibration of *CO2-PROPHET* with a Full-Scale Reservoir Simulator. The *CO2-PROPHET* model was compared and calibrated by Advanced Resources with an industry-standard compositional reservoir simulator. The

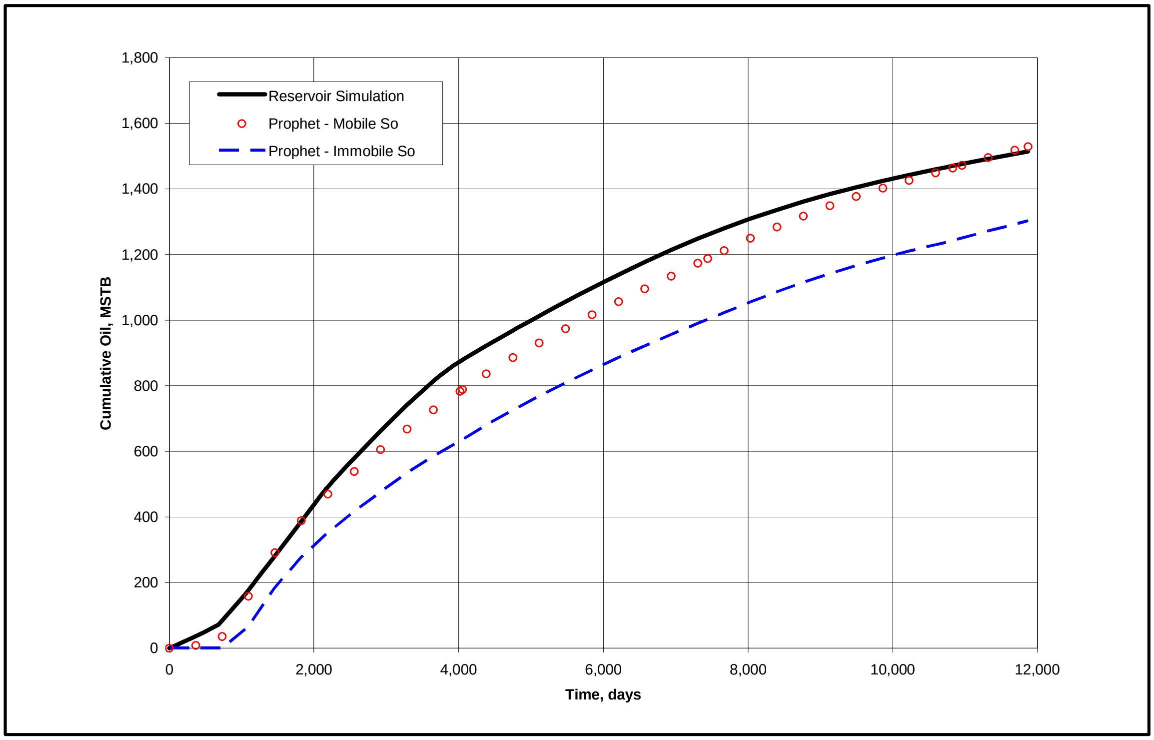
[22] "Post Waterflood CO_2 Flood in a Light Oil, Fluvial Dominated Deltaic Reservoir" (DOE Contract No. DE-FC22-93BC14960).

primary reason for the comparison was to determine whether *CO2-PROPHET* could effectively model oil recovery from the TZ/ROZ. A second reason was to better understand how the absence of a gravity override function in *CO2-PROPHET* might influence the calculation of oil recovery in these low oil saturation zones.

As a first step, the Wasson Denver Unit (San Andres) reservoir data set was used as the input file for modeling a simultaneous MPZ and TZ/ROZ CO_2 flood using a full-scale simulator. An analogous data set was placed into *CO2-PROPHET* to replicate the MPZ and TZ/ROZ simultaneous flood. First, for simplicity, all oil saturations in the input database for the *CO2-PROPHET* model were set at residual oil. Under this simplified condition, *CO2-PROPHET* had lower oil recoveries than the full-scale simulator.

A closer review of the two input data sets enabled us to understand the reasons for the divergence. No mobile oil saturations were initially included in the input file for *CO2-PROPHET*; however, the input data file for the full-scale reservoir simulator had higher (and mobile) oil saturation in the TZ interval. Using simple weight-averaging, a small mobile oil saturation (~3%) was added to the reservoir intervals in the *CO2-PROPHET* input file to account for the mobile oil in the TZ. An excellent match for projected Wasson cumulative oil recovery was obtained between *CO2-PROPHET* and the full-scale simulator, after making this adjustment. This two step comparison and match is shown on **Figure 6**.

Figure 6. Analysis of Simultaneous MPZ and TZ/ROZ Oil Recovery: Simulation Comparison Results, Wasson Denver Unit



Similar *CO2-PROPHET* and full-scale simulator comparisons were completed for three additional oil fields - - Seminole (San Andres Unit), Wasson (Bennett Ranch Unit), and Vacuum (San Andres/Grayburg) (**Figures 7, 8** and **9**) - - again showing an excellent match between the two models when the oil saturation modification (discussed above) was included in the *CO2-PROPHET* input data set.

Figure 7. Analysis of Simultaneous MPZ and TZ/ROZ Oil Recovery: Simulation Comparison Results, Seminole San Andres Unit

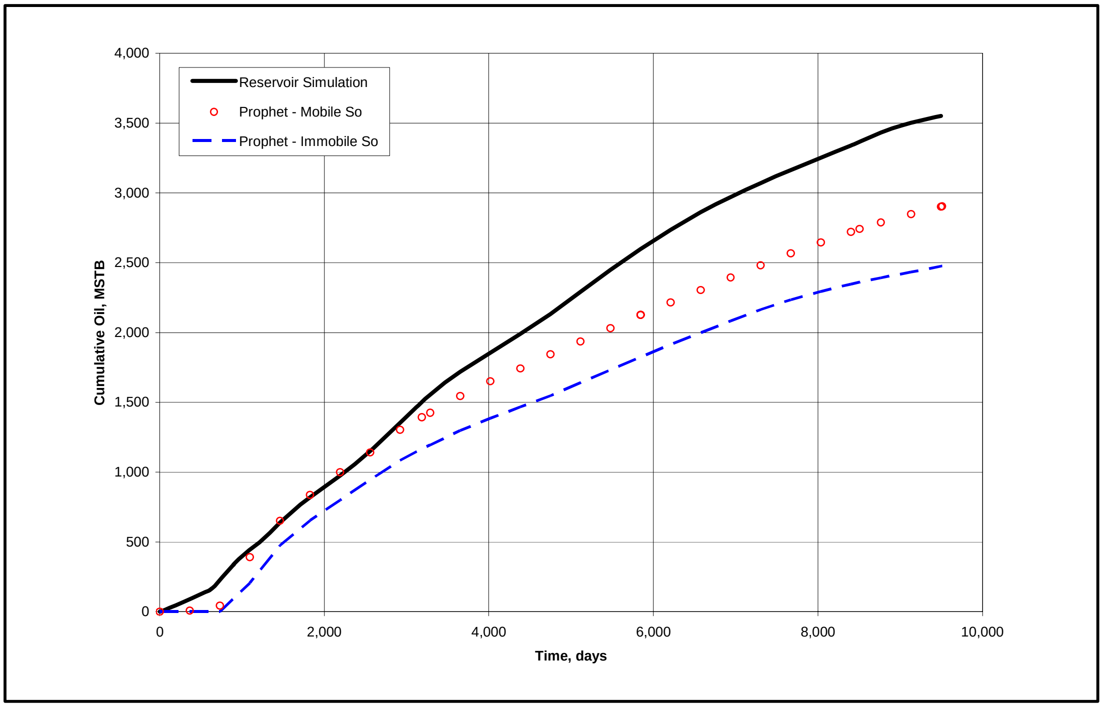


Figure 8. Analysis of Simultaneous MPZ and TZ/ROZ Oil Recovery: Simulation Comparison Results, Wasson Bennett Ranch Unit

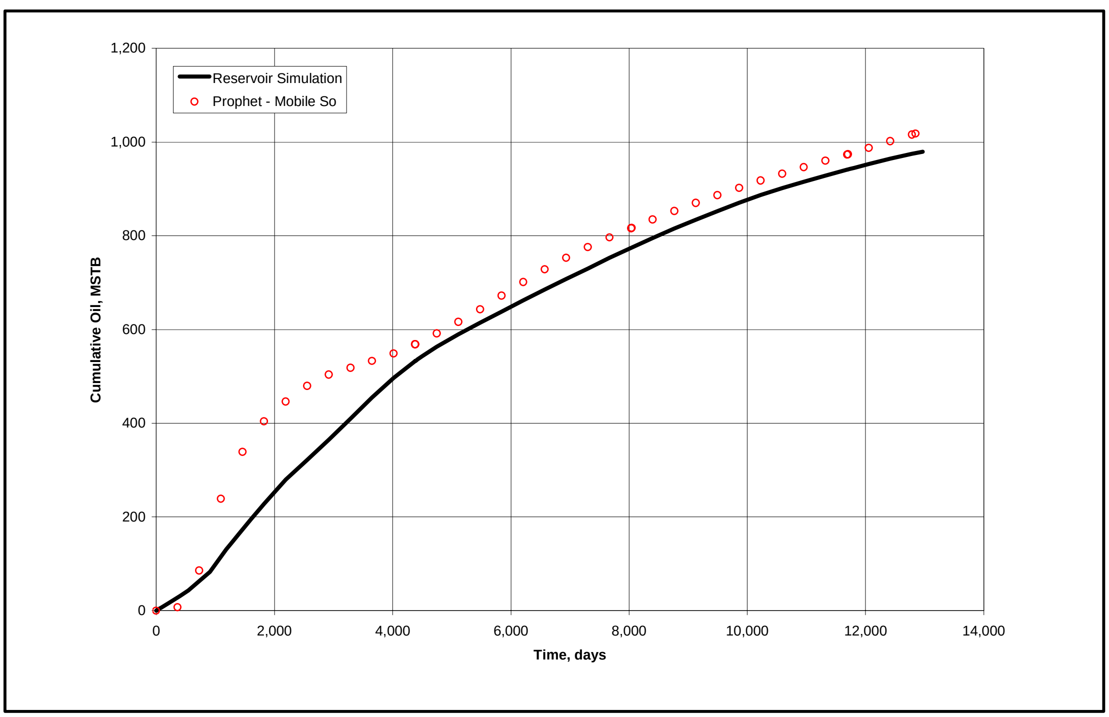


Figure 9. Analysis of Simultaneous MPZ and TZ/ROZ Oil Recovery: Simulation Comparison Results, Vacuum (San Andres/Grayburg)

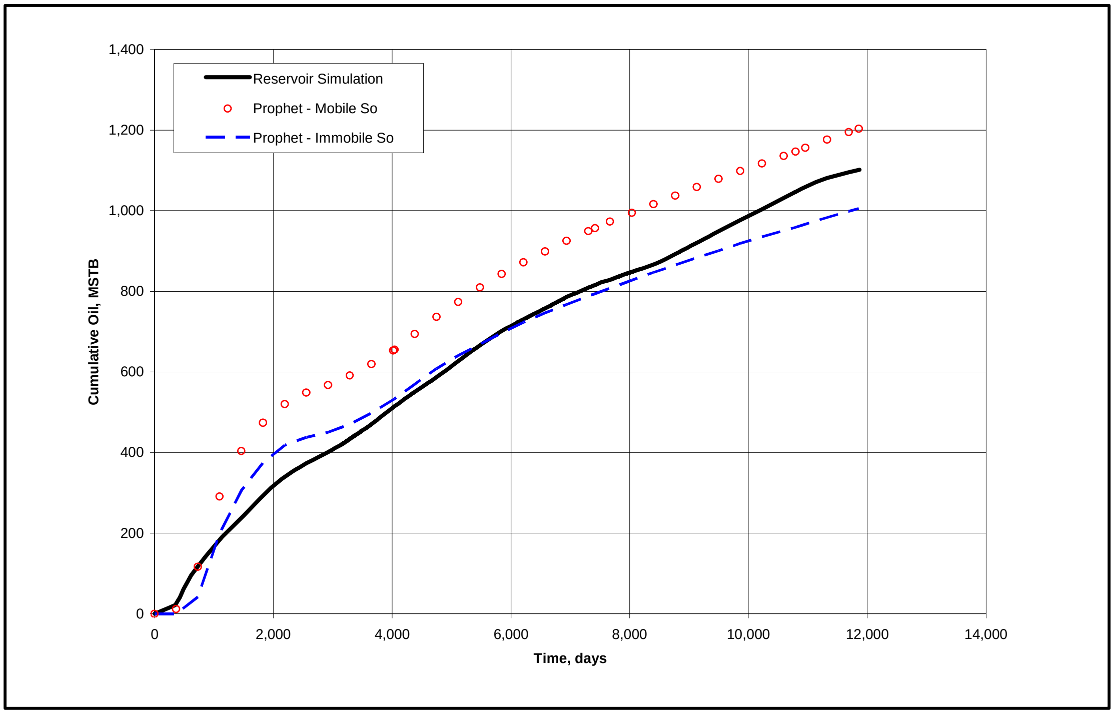


Table 2 provides the model comparisons, with the ultimate oil recovery from these four oil fields scaled to field level. While oil recovery calculations for individual fields vary somewhat, overall the two models provide an excellent match of the aggregate oil production from the four sample oil fields.

Table 2. Comparison of Compositional Model Simulation and *CO2-PROPHET* Model Simulation.

Field/Unit	Compositional Model Simulation: Field Level Oil Recovery (MMbbls)	*CO2-PROPHET* Model Simulation: Field Level Oil Recovery (MMbbls)	% Difference Between Models
Seminole (San Andres Unit)	696	569	(18%)
Wasson (Denver Unit)	1,054	1,064	1%
Wasson (Bennett Ranch Unit)	172	179	4%
Vacuum (Grayburg/San Andres)	529	577	9%
Total	2,451	2,389	(2%)

C. Evaluating ROZ Development Strategies. Our analytic work shows that two "best practices" would enable the TZ/ROZ resource to be efficiently developed, namely: 1) selectively completing only the upper portion of the ROZ; and 2) simultaneously CO_2 flooding the MPZ and TZ/ROZ.

1. Selective Zone Completion in the ROZ. Two ROZ completion options were explored: (1) completing only the upper 60% of the ROZ; and (2) completing the full ROZ interval. The two ROZ completion practices were then further examined under variable oil saturation profiles and alternative vertical permeability situations.

- **Methodology**. Reservoir simulation was used to model the injection of one HCPV of CO_2 into the ROZ (only) zone. The Wasson Denver Unit's San Andres reservoir ROZ interval was used as the input data set. Two oil saturation profiles were used: (1) a uniform saturation through the ROZ (uniform); and, (2) a variable, high to low, oil saturation through the ROZ (gradational). Finally, the vertical permeability was varied in the gradational oil saturation case.

- **Results. Table 3** shows the results for the two completion schemes (partial and full) and for each of the three sensitivity cases (uniform ROZ oil saturation, gradational ROZ oil saturation and gradational ROZ oil saturation with large vertical perm). These results are representative of a single forty acre CO_2-EOR pattern.

Table 3. Results from Two ROZ Completion Schemes (Partial and Full)

Project	Cumulative Oil Production (Mbbls)	Cumulative Gross CO_2 Injection (Bcf)	Gross CO_2/Oil Ratio (Mcf/Bbls)	Cumulative Water Production (Mbbls)	Producing Water-Oil Ratio (Bbls/Bbls)
1. Uniform Oil Saturation					
Partial ROZ Completion	273	6	22.0	2,439	8.9
Full ROZ Completion	280	10	35.7	3,965	14.1
2. Gradational Oil Saturation					
Partial ROZ Completion	421	6	14.3	2,239	5.3
Full ROZ Completion	427	10	23.4	3,747	8.8
3. Gradational Oil Saturation/High Vertical Perm					
Partial ROZ Completion	373	6	16.1	2,886	7.7
Full ROZ Completion	441	10	22.7	4,296	9.7

The partial ROZ completion case outperforms the full ROZ completion case (in terms of CO_2-oil and water-oil ratios) and produces nearly as much oil. These results suggest that, in general, a partial ROZ completion should be considered. However, the full interaction of permeability and aquifer strength (not explored here) in combination with the oil saturation profile should be reviewed prior to making a final ROZ completion decision.

2. Simultaneous MPZ and TZ/ROZ CO_2 Flooding. Significant efficiencies may also be gained by simultaneously CO_2 flooding the MPZ and the TZ/ROZ. Even where a MPZ CO_2 flood is already underway, the TZ/ROZ flood can be added. In fact, many of the Seminole San Andres Unit, the Wasson Denver Unit and the Wasson Bennett Ranch Unit patterns are now being developed using joint MPZ and TZ/ROZ CO_2 floods, after initially CO_2 flooding only the MPZ.

- **Methodology**. Reservoir simulation was used to gain further understanding of simultaneously versus separately flooding the MPZ and TZ/ROZ zones. A 40 acre field pattern was modeled using an industry-standard compositional simulator. The input data drew on information from the Wasson Denver Unit's San Andres reservoir. The stacked pay included a 141 foot main pay zone, a 50 foot transition zone and a 150 foot residual oil zone. A weak Carter-Tracy aquifer was applied to the bottom of the reservoir to model water influx from the aquifer. Permeability was allowed to vary based on the Dykstra-Parsons coefficient, with an average permeability of 5 md.

  Development of the reservoir started with a 2 HCPV water flush into the main pay zone (simulating primary and secondary recovery), to reach residual oil saturation. Following the initial MPZ waterflood, 1 HCPV of CO_2 was injected using a coarsely tapered one to one WAG scheme, which consisted of larger CO_2 slugs in the first 0.6 HCPV and smaller CO_2 slugs in the remaining 0.4 HCPV of CO_2. Initially, this CO_2 flooding process was performed separately—first, in the main pay zone, and then followed by the transitional and residual oil zones. Next, both the main pay zone and the TZ/ROZ were CO_2 flooded simultaneously.

- **Results**. **Figure 10** shows the comparison of results for a forty acre pattern. The simultaneous MPZ and TZ/ROZ CO_2 flood has a 25% higher oil recovery than the separate zone CO_2 flooding scheme. Further, oil production is accelerated, which should provide a superior economic return. Water production over the life of the each CO_2 flooding option is similar, **Table 4**.

A closer look at the reasons for the higher oil recovery efficiency from simultaneous CO_2 flooding of the MPZ and TZ/ROZ shows that the simultaneous CO_2 flood has a more uniform distribution of pressure between the two zones, which limits out of zone CO_2 flow and losses. In the separate CO_2 flooding case, each of the two flooding stages is plagued by out of zone flow (particularly upward flow by the injected CO_2), reducing the overall oil recovery and CO_2 utilization efficiency.

Figure 10. Comparison of Simultaneous and Separate MPZ-ROZ CO_2 Flooding, Sample Oil Reservoir

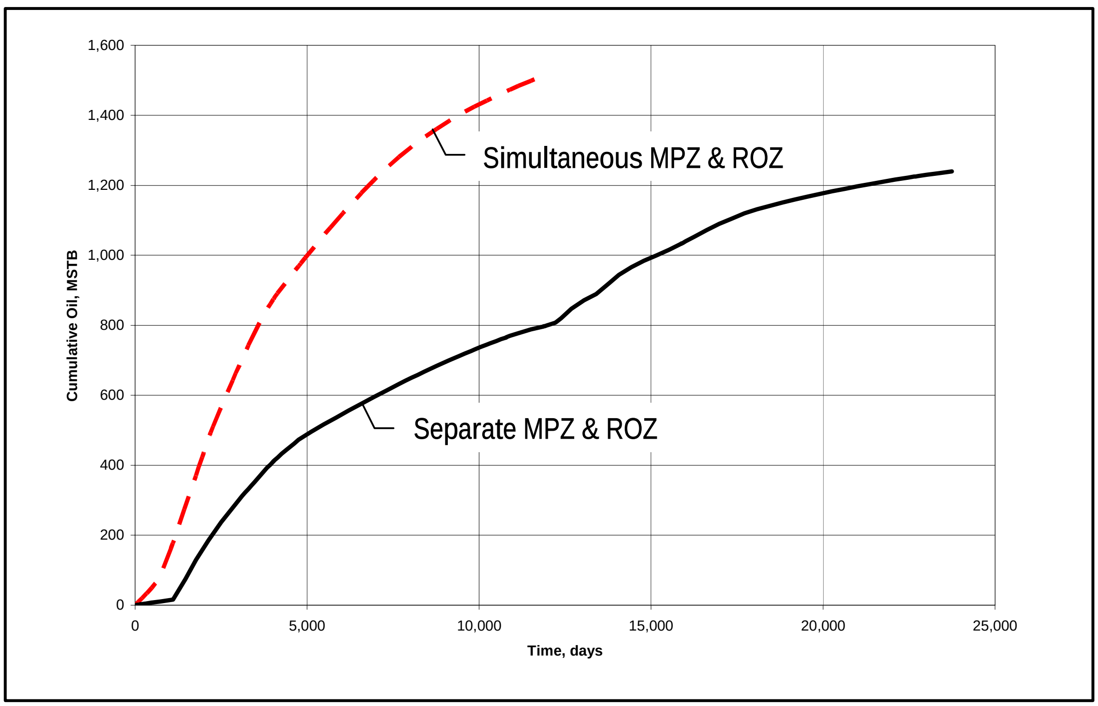


Table 4. Comparison of Separate vs. Simultaneous MPZ and TZ/ROZ CO_2-EOR Flooding: Sample Oil Reservoir

CO_2-EOR Strategy	Duration (Years)	Cumulative CO_2 Injection (Bcf)	Cumulative Oil (MMbbls)	Cumulative Water (MMbbls)
Separate MPZ and TZ/ROZ	65.0	18.8	1.2	7.6
Simultaneous MPZ and TZ/ROZ	32.5	18.8	1.5	7.6

IV. RESULTS

A. MPZ AND TZ/ROZ OIL IN PLACE. In Section II, we identified 13 fields in the two Big Horn Basin oil plays that have potential for significant TZ/ROZ resources. Five of these fields, are heavy oil fields which will require immiscible CO_2-EOR methods. The TZ/ROZ OIP in these 13 fields is estimated at 4.4 billion barrels, which is nearly equivalent to the OOIP of the MPZ, **Table 5**.

Table 5. Estimates of MPZ OOIP and TZ/ROZ OIP in Two Big Horn Basin Oil Plays

Play	MPZ OOIP (BBbls)	TZ/ROZ OIP (BBbls)	No. of Fields
1. CO_2-miscible fields	2.1	2.0	8
2. CO_2-immiscible fields	2.4	2.4	5
Total	4.5	4.4	13

B. Technically Recoverable Resources from the MPZ and ROZ. Based on reservoir modeling of applying CO_2-EOR to the TZ/ROZ resources, we estimate that 1.1 billion barrels is technically recoverable from the 4.4 billion barrels of TZ/ROZ oil in-place in these Two Big Horn Basin oil plays, **Table 6**.

Table 6. Technical Oil Recovery Totals, Two Big Horn Basin Oil Plays

Play	Total CO_2-EOR (BBbls)	MPZ CO_2-EOR (BBbls)	TZ/ROZ CO_2-EOR (BBbls)
1. CO_2-miscible fields	1.3	0.3	1.0
2. CO_2-immiscible fields	0.3	0.2	0.1
Total	1.6	0.5	1.1

To date, no CO_2-EOR projects of the TZ/ROZ have been undertaken in these study fields. As such, no information regarding the potential performance of such a flooding scheme is available to validate the results of this work. Nevertheless, the estimates of TZ/ROZ OIP for these 13 fields may make an attractive recovery target and data collected in ongoing Powder River basin MPZ CO_2-EOR floods such as Sussex, Salt Creek, and Hartzog Draw fields may add further insight into the potential flood performance of these TZ/ROZ targets.