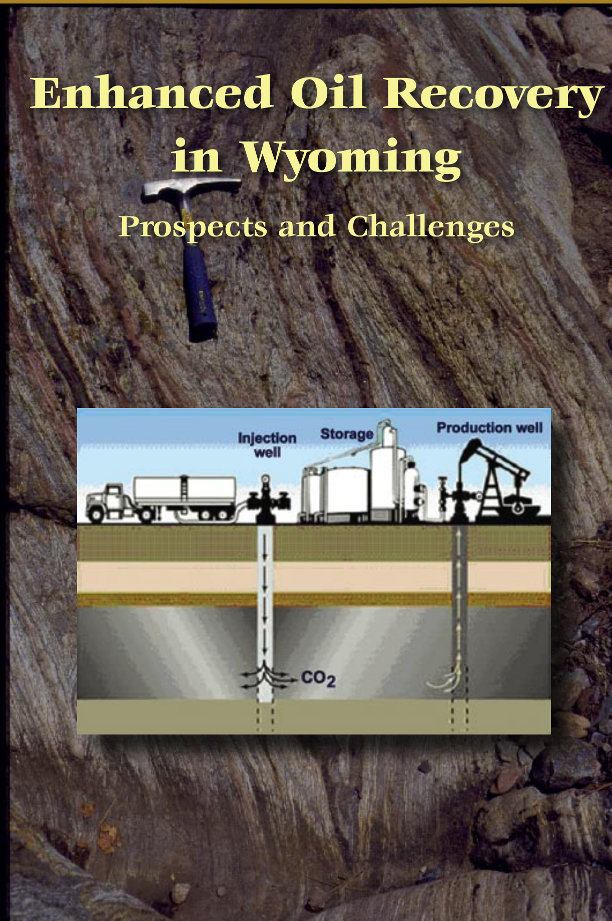

Prepared for

Governor Dave Freudenthal

Prepared by

Dag Nummedal, Brian Towler, Charles Mason, and Myron Allen

UNIVERSITY OF WYOMING

June 15, 2003

This report was edited and designed by Claudette Cohen, Editor
University of Wyoming Department of Geology and Geophysics

Enhanced Oil Recovery in Wyoming

Prospects and Challenges

Prepared for

Governor Dave Freudenthal

Prepared by

Dr. Dag Nummedal, Director, Institute for Energy Research
Dr. Brian Towler, Associate Professor, Department of Chemical and Petroleum Engineering
Dr. Charles Mason, Professor, Department of Economics and Finance
Dr. Myron Allen, Associate Vice President, Academic Affairs

University of Wyoming

June 15, 2003

Executive Summary

Most of Wyoming's oil fields have been in production for many decades, and in most cases their production is now in decline. However, the vast majority of the oil originally in place is still underground, and much of this resource is unrecoverable by traditional production methods. Enhanced oil recovery (EOR) is a class of techniques for overcoming the physical, chemical, and geologic factors that inhibit production of this oil. This report briefly examines the prospects and challenges for EOR in Wyoming.

Petroleum production remains an important part of the state's economy: in 2000, oil and gas production accounted for over 45 percent of the total property taxes levied in Wyoming and over 70 percent of all the severance taxes paid by minerals. Petroleum production also accounted for significant royalty income to the state, and it is directly responsible for nearly 22,000 jobs.

Nevertheless, Wyoming's annual oil production has declined for over a quarter century. Accompanying this decline is the fact that small, independent oil companies have increased their share of the state's oil production. As a consequence of these two trends, two striking features of current oil and gas production in Wyoming are the relatively low average productivity of the oil wells and the diffuse ownership of the fields.

The significance of EOR lies in the promise it holds for increasing the expected production from existing oil fields. While several EOR methods have the potential to benefit Wyoming's oil production significantly, the one that appears to have greatest potential statewide is carbon dioxide (CO_2) injection. At sufficiently high pressures, CO_2 is miscible with oil, and, once dissolved, it has two effects. First, it causes the oil to swell, lowering the oil's viscosity and making it flow more easily toward production wells. Second, under miscible conditions it reduces the interfacial forces that cause oil to stick to the reservoir rock, in much the same way that dry cleaning fluids reduce the interfacial forces that cause oil to stick to textiles. Injection of CO_2 also increases the permeability in carbonate reservoirs by dissolving part of the rock matrix.

There are at least three reasons why CO_2-based EOR is of special interest in Wyoming. First, a large number of Wyoming's oil fields are technically suitable for CO_2 miscible flooding. For example, Amoco initiated the Lost Soldier and Wertz CO_2 miscible floods, near Bairoil, in the late 1980s, and these projects are still operational. While these multi-well floods are technically and economically successful, experiments with another form of CO_2-based EOR —single-well huff-n-puff injection—have been less successful. A recent analysis conducted by the Wyoming Geological Survey estimates that successful CO_2-based EOR could increase the state's ultimate oil production by 0.4–1.2 billion barrels.

Second, Wyoming is particularly well positioned to take advantage of emerging market forces in the sequestration of atmospheric greenhouse gases, of which CO_2 is an example. Wyoming has significant sources of CO_2, including the Greater Big Piney–LaBarge Area in southwestern Wyoming, the Madden field on the northern flank of the Wind River basin, and several coal-fired power plants, whose flue gas is mostly CO_2 and nitrogen. Increasingly economical separation techniques may make it feasible to use CO_2 from power plants as an EOR injection fluid. In addition, there are potential economic incentives—in the forms of emission-reduction credits and carbon-capture credits—for reducing atmospheric CO_2 emissions. The utility of CO_2 in EOR, together with the potential economic incentives associated with CO_2 sequestration, suggest that CO_2 injection can play a more important role in the future of Wyoming's oil fields than it has to date.

Third, Wyoming is on the verge of having the transportation infrastructure needed to capitalize on these two effects. A CO_2 pipeline network exists in Wyoming. It originates at Shute Creek in the Greater Big Piney–LaBarge Area and extends south to Colorado's Rangely field

and east to the Lost Soldier and Wertz fields. Moreover, the pipeline network lies close to large CO_2-emitting power plants. A pipeline extension to the edge of the Powder River Basin, now in the final design stage at Anadarko, will create significant new EOR opportunities in Wyoming and possibly spur planning for further pipeline extensions.

There are several important challenges that Wyoming must overcome if EOR is to reach its full potential in the state's reservoirs. These are enumerated below.

1. **Initial costs and long payoff horizons.** CO_2 injection may not yield significant new oil production until 18 to 24 months after fluid injection starts, and the full benefits may not appear for another three to five years after that. The ultimate payoff is uncertain because crude oil prices are subject to large, unpredictable variations. There are additional risks associated with the future economics of CO_2 sequestration.
2. **Access to technology.** The design and operation of CO_2-based EOR projects require access to expertise, software, and laboratories that few independents can afford on their own.
3. **Cost, transportation tariffs, and access to CO_2.** These barriers may diminish in importance as current plans for pipeline extensions progress, but for many operators this set of issues will remain a barrier for at least several years to come.
4. **Effects of the size and multiplicity of Wyoming's producing firms.** There are several additional effects associated with the predominance of small independents in Wyoming, including issues associated with unitization.

Because of these challenges and the difficulty of re-opening depleted fields after they are closed, Wyoming's window of opportunity for EOR will not last forever. Therefore, the state must initiate timely measures if it is to overcome the most significant challenges to CO_2-based EOR. The following steps are worth considering.

Step 1: Screen Wyoming reservoirs for suitability for CO_2-based EOR.

Step 2: Assess the economics of CO_2 supply.

Step 3. Quantify the value of CO_2 sequestration and the associated risks.

Step 4: Initiate technology transfer to Wyoming independents.

Step 5: Develop a demonstration project.

The report describes these steps in brief, but each deserves more careful planning.

1. Introduction

In 1978, a few years after the Arab oil embargo, the Congress commissioned the Office of Technology Assessment (OTA) to assess the state of the art in US oilfield production. The OTA concluded that about 300 billion barrels of known oil in the United States remained unproduced because it was not economically attainable by conventional methods. The report evaluated a range of enhanced oil recovery (EOR) techniques and their potential for recovering a significant fraction of this oil. EOR is a class of techniques that overcome the physical, chemical, and geologic factors that inhibit the flow of oil from its host rock to production wells. Since the 1960s, there have been many EOR projects in many producing regions. After the release of the OTA report, however, EOR experienced its most significant growth in California and the Permian Basin of west Texas.

Now, 25 years later, there is again a strong national interest in energy security. Another major US onshore province now stands poised to become a major contributor to EOR-based production: the central Rocky Mountains. Wyoming's extensive sedimentary basins and oil fields lie at the heart of this province. Wyoming is an old oil-producing region. Most of the state's oil fields have been in production for many decades, and in most cases their production is now in decline. Thus, the majority of the oil originally in place in Wyoming's reservoirs is still underground, stuck to the reservoir rock or bypassed by the production techniques applied to date. This remaining oil constitutes a significant yet underutilized resource in a state that relies heavily on underground resources for its economic health.

This report outlines a vision of how Wyoming can advance the efficient extraction of known domestic oil resources in existing fields. At the same time, the state can benefit economically by helping to solve a worldwide environmental problem, namely the emission of greenhouse gases. The link between the two problems is direct. Carbon dioxide (CO_2) is the most important greenhouse gas; Wyoming produces it in abundance; it is a remarkably effective injection fluid for EOR; and emerging economics favor CO_2 injection not only as an EOR technique but also as a method of sequestering the gas.

Intelligent decisions about EOR in Wyoming hinge on detailed knowledge in several arenas:

- The nature and history of Wyoming's reservoirs
- The range of EOR technologies available
- The promising potential of CO_2 injection
- Wyoming's strategic position for CO_2 injection and sequestration.
- The economic, technological, and scientific challenges that have deterred widespread application of EOR in Wyoming to date.

A preliminary report of this scope cannot cover all of these arenas in depth. Nevertheless, the report briefly reviews each of these topics, as an invitation to further inquiry and as a prompt for discussion of EOR as an issue for the state's policy makers. The report concludes by sketching a vision for the future of carbon dioxide-based EOR in Wyoming, again as a prompt for discussion on the part of technology leaders and policy makers.

The issues associated with EOR in Wyoming being so varied, and the possibilities being so vast, we hope that the report stimulates both discussion and actions that will enhance Wyoming's economic and environmental future, by increasing oil production from wells that have already been drilled.

2. A Profile of Oil Production in Wyoming

History of Oil Production in the State

The presence of oil in the Wyoming region has been known for centuries. Native Americans used the Great Tar Spring, 10 miles southeast of Lander, to provide liniment for their horses. Pioneers traveling across the country used oil from the spring as axle grease for their wagons. The first oil well in the state, the discovery well for the Dallas field along the Little Popo Agie River, was drilled in 1884. The largest oil field in Wyoming, Salt Creek, was discovered in 1889. However, it was not until the early twentieth century that oil production in Wyoming became truly profitable. Between 1910 and 1915 numerous oil fields began production in Hot Springs County, including Warm Springs, Grass Creek, Gebo Dome, Golden Eagle and Hamilton Dome. By 1916, Hot Springs County alone was producing over 1.5 million barrels of oil annually. The Garland, Oregon Basin, and Elk Basin fields in the Bighorn Basin were also discovered between 1906 and 1915. These three large fields have produced over 1.1 billion barrels of oil since their discovery.

Throughout the twentieth century, Wyoming remained one of the major hydrocarbon-producing states in the US. Oil and gas production remains an important part of the state's economy: during 2001, a total of 3,151 wells were drilled and completed in the state. Of that number, 89—about three percent—found oil; 2,971—about 94%—found gas (mostly coalbed methane); and 91—about three percent—were dry holes. New oil and gas reservoirs are getting harder to find in Wyoming; only 47 wildcat wells (wells in unproven areas) were drilled in 2001. In recent years, about 30 percent of all wildcat wells in Wyoming have hit oil or gas.

Drilling for oil has declined in Wyoming since the early 1980s. The all-time record year for drilling-rig activity in Wyoming occurred in 1981, toward the end of a period of high oil prices. That year, there was an average of 192 drilling units working monthly. In 1995, a year of relatively low oil prices, the average was 23, the lowest since World War II. The 2001 monthly average rig count was 55.

In recent years, the production of natural gas from coalbeds has become an important factor in the state's economy. In addition to the rigs listed above, there were 75 rigs drilling for coalbed methane in Wyoming in 2001. Although this report focuses mainly on oil production, it also touches on the enhanced production of coalbed natural gas, another subject undergoing active investigation and testing.

Current Oil Production in Wyoming

Nationally, Wyoming ranked sixth among the states in crude oil production and fourth in natural

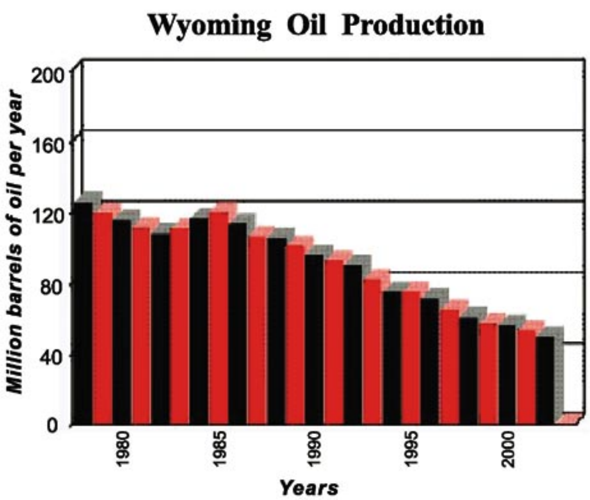

Figure 1. Annual oil production in Wyoming, 1978-2002 (from the Wyoming Oil and Gas Conservation Commission).

gas production during 2002. That year, production of Wyoming crude oil totaled 54,725,528 barrels, down 4.8 percent from 2001. Production of Wyoming natural gas in 2002 totaled 1,746,444,089 thousand standard cubic feet (Mcf), up 7.5 percent from 2001[1].

The trend toward lower annual oil production and higher annual gas production is now over a quarter century long. The year 2002 saw Wyoming's highest level of natural gas production, reflecting an upward trend that has been sustained since 1975. The same year marked the lowest level of crude-oil production since 1954, a downward trend dating from 1970. The attached plot illustrates this trend. The increased production from 1983 through 1985 reflects unusually high oil prices, which spurred short-term increases in drilling and production. Since that exceptional price spike, Wyoming's crude-oil output has declined at a rate of about 3.4 million barrels per year.

Two striking features of current oil and gas production in Wyoming are the relative absence of market concentration and the relatively low average productivity of the oil wells. According to data from the Wyoming Oil and Gas Conservation Commission[2], in 2001 there were 496 firms that actively extracted oil, with 33,740 wells between them. The largest firm had 2,838 wells, and only seven firms had more than 1000 oil wells in operation. There were 289 firms producing natural gas from 23,941 active wells, with an average annual production per well of 67,073 Mcf. The four largest oil-producing firms accounted for 22 percent of the active wells; the eight largest firms had 35 percent of the active wells. These data point to an industry characterized by diffuse ownership.[3]

Wyoming's oilfields are small by international standards, and the operators tend to be even smaller by comparison. The data for 2001 are illustrative. Within the state, 811 fields produced oil from 21,756 wells. The average field had been in play for 35 years, had 27 wells, and produced 71,220 barrels in 2001. The average field had produced 8,258,587 barrels during its lifetime, with an average production of 4,106 barrels per well. The largest field had 1,113 wells; only six fields had more than 400 wells. Table 1 shows two size distributions of wells in 2001, the leftmost column showing the cumulative distribution of operators by number of wells and the rightmost column showing the cumulative distribution of oil fields by number of wells. These data confirm the

Table 1. Cumulative size distributions of producing oil wells in Wyoming in 2001, arrayed by operators and by fields.

Operators		Producing fields	
Number of wells	Percentile	Number of wells	Cumulative frequency
1	18%	1	17%
2	30%	2	29%
3	35%	3	37%
4	40%	4	44%
5	45%	5	50%
6	47%	6	54%
7	50%	7	60%
12	60%	12	70%
23	70%	23	80%
44	80%	44	90%
144	90%		

[1]One barrel of oil is 42 US gallons. One standard cubic foot of natural gas is the mass that occupies one cubic foot at 60° F and atmospheric pressure.

[2]http://wogcc.state.wy.us/cfdocs/2001stats.htm

assessment that most of Wyoming's oil wells are in the hands of relatively small operators working in relatively small fields.

Refining And Transportation

Wyoming's first refinery was constructed in Casper in 1895. In 2002, there were five active refineries in the state with a capacity to refine 140,670 barrels of oil per day (BOPD):

- Sinclair Refining Co. (Sinclair, 62,000 BOPD)
- Frontier Refining Inc. (Cheyenne, 38,670 BOPD)
- Little America Refining Co. (Evansville, 24,500 BOPD)
- Wyoming Refining Co. (Newcastle, 12,500 BOPD)
- Silver Eagle Refining (Evanston, 3,000 BOPD)

These five plants—down from 14 in 1981—refine most of the crude oil produced in Wyoming, although some is refined in Billings, Montana, and Denver, Colorado.

The first crude-oil pipeline was constructed in 1911. Today, 42 companies operate about 13,500 miles of pipelines in Wyoming carrying crude oil, natural gas, or petroleum products. Petroleum pipelines pass through most of the state's 23 counties.

Proved Reserves

One indicator of the future of Wyoming's oil and gas production is the amount of proved reserves. This term refers to the volume known to exist and be economically recoverable, using existing technologies at the current price. Proved reserves are typically only a small fraction—15 percent to 30 percent—of the known oil originally in place (OOIP). At the beginning of 2002, Wyoming ranked seventh among states in the nation in proved reserves of crude oil. It ranked second in proved reserves of natural gas. Reserves of natural gas were at their highest levels in Wyoming's history in 2002, at 18.40 trillion cubic feet (Tcf). In contrast, Wyoming's crude-oil reserves were at their highest in 1960. Crude-oil reserves have been decreasing steadily since then; in 2002 they stood at 489 million barrels.

In principle, the potential for future oil recovery in Wyoming is much higher than the proved reserves indicate. The technologies used in most of Wyoming's oil fields leave most of the OOIP stuck to the underground reservoir rock. The use of EOR has the potential to add more than a billion barrels of oil to the proved reserves (De Bruin, 2001). As subsequent sections of this report explore, these technologies are sufficiently well understood and their economics are sufficiently promising to be of importance to Wyoming's future.

Oil and gas production are crucial to Wyoming's economy. The impacts on the public treasury are direct, through property taxes, severance taxes, and royalties. The appendix to this report contains data summarizing these impacts. Wyoming's petroleum industry employs nearly 22,000 wage earners, with an annual payroll of over $850 million. Employment in oil and gas peaked in Wyoming in 1981, with more than 32,000 individuals working in the industry.

3. Opportunities for EOR: Overview The Significance of EOR

The significance of EOR lies in the promise it holds for increasing the expected production from existing oil fields. Increases in reserves in existing fields are subtler than the resource growth associated with successful exploration. Nevertheless, in mature petroleum provinces, such as the onshore US in general and Wyoming in particular, growth of reserves in existing oil fields typically contributes more to the industry's continued viability than the discovery of new fields. In other words, in thoroughly explored provinces, better technology, more accurate reservoir characterization, and more effective production from known fields typically add new reserves faster than exploration for new fields.

Although Wyoming's natural gas industry is an important exception, in which exploration currently dominates new additions to reserves, the largest known oil resource in Wyoming is the vast quantity of oil left unproduced by primary recovery mechanisms. EOR is a class of technologies for producing a significant fraction of this resource.

These claims deserve closer scrutiny. Because reserves provide an imprecise measure of future production, subject to soft assumptions about technology and commodity price, it is useful to apply a more robust measure of production, the estimated ultimate recovery (EUR). The EUR is the sum of known production to date and the remaining proved reserves.

Studies of oil fields in both onshore US and Russia have demonstrated that EUR tends to increase over time. The most rapid reserve growth occurs during the first 10 years of the life of an oil field, the phase during which reservoir delineation and rapid devel-

[3] The Herfindahl index, widely used to determine the degree to which market power is concentrated within a few firms, equaled 234 in 2001. By comparison, the cutoff value for this index at which the Department of Justice considers an industry to be highly concentrated is 1800.

opment occur. However, 80 years later, on average, the EUR is more than twice what it was thought to be at the completion of that initial growth phase. Figure 2 shows this effect graphically.

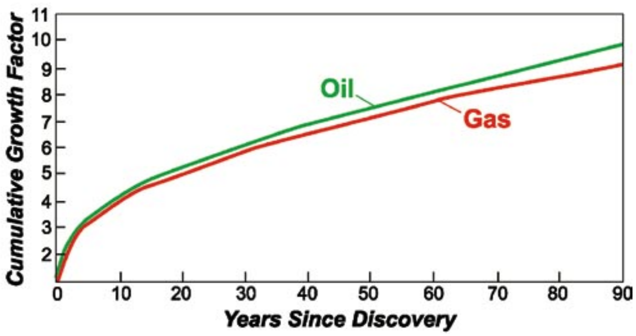

Figure 2. EUR growth of oil and gas fields in the US (from Attanasi et al., 1999; Verma, 2000).

This growth in EUR seems anomalous at first, because oil fields are not recharged with new oil on this time scale. The explanation lies in several technological and economic factors, foremost among which are two: the use of EOR and improved drilling and completion technologies. The former is a class of methods used to overcome the forces that hold oil to the reservoir rock, through mechanisms discussed below. The latter provides well-bore access to thin and often low-permeability reservoir zones, enables the discovery of new oil-bearing strata in existing fields, and facilitates the use of ever-improving methods to image and characterize the reservoirs and therefore understand their hydrocarbon flow patterns. Both technologies have the potential to increase oil reserves dramatically. As discussed in this report, Wyoming is especially well situated to take advantage of EOR.

EOR Methods

The EOR technologies most applicable to Wyoming's oil reservoirs are:

- Steamflooding
- Waterflooding and spontaneous imbibition
- Polymer-enhanced waterflooding
- Surfactant flooding
- CO_2 injection, including miscible and immiscible flooding and huff-n-puff

Several of these technologies have been field tested at Teapot Dome (National Petroleum Reserve Number 3), in the Powder River Basin north of Casper. The equipment and facilities necessary to support various EOR methods are available for field tests there.

Each of these methods involves the injection of fluids (water, steam, polymer solutions, surfactants, or CO_2) into the reservoir. One effect of fluid injection is to increase the pressure gradient between injection wells and production wells, thus increasing the tendency of the reservoir fluids to flow toward production wells. However, in many EOR technologies the injected fluids have additional chemical or physical effects that help mobilize the oil and sweep it towards the production wells.

Steamflooding. The idea behind steamflooding is to mobilize the oil using heat. This method is especially applicable to heavy (high-specific-gravity or low API gravity) oils, some of which are so viscous that it is impossible to get them to flow by pumping alone. Injecting steam into the reservoir under pressure has two effects: the heat thins the oil, lowering its viscosity, and the increased pressure helps push the oil toward production wells, as illustrated in Figure 3. Steamflooding is widely applicable in many California fields containing heavy crude oil, but it has seen little application in Wyoming, in part because much of the state's crude oil is light and in part because of problems associated with expansive clays in the pore spaces of many Wyoming oil fields.

Waterflooding and Spontaneous Imbibition. In waterflooding the injected fluid is water. This technology is so common that many people do not classify it as EOR, referring to it as secondary recovery. The method is widely applicable in Wyoming,

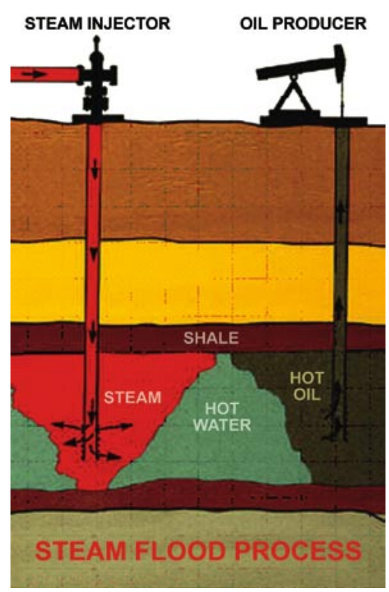

Figure 3. Schematic diagram of steamflooding, from the California Conservation Commission.

depending on the availability of water. Waterflooding typically yields an extra 10 percent to 25 percent of the OOIP. Many Wyoming reservoirs that are good candidates for waterflooding still have not been waterflooded. Recent research at the University of Wyoming, under the direction of Professor Norman Morrow, has shown that low-salinity water typically works best as the injection fluid, except where the producing formation contains water-sensitive clays. In these cases, fresh water can cause the clays to swell and plug the pores in the rock through which oil and water flow. In such reservoirs, water containing potassium chloride stabilizes the clays and is more effective for waterflooding.

Some accumulations of oil reside in low-permeability, fractured reservoirs. In these reservoirs, brine injection rapidly displaces oil from the fractures, but a substantially greater volume of oil remains in the rock matrix. The spontaneous imbibition of brine into the rock matrix expels some of the remaining oil into the fracture system, where it can flow more readily toward production wells. Scientists in the University of Wyoming's Department of Chemical and Petroleum Engineering recently initiated research into the fundamentals of this process as an EOR method.

Polymer-Enhanced Waterflooding. In many reservoirs, the oil is much more viscous than the injected water. Also, in many reservoirs the reservoir rock has streaks in which the permeability to water is quite high. In these cases, the mobility ratio between the injected fluid and the resident oil is adverse, and the water tends to finger through the oil or channel down the high-permeability zones, bypassing much of the oil. A common EOR technology is to inject specially formulated slugs of viscous polymer-water solutions ahead of the water, to stabilize the displacement. In many fields, this technology greatly improves the sweep efficiency of the flood and hence the timing and amount of the overall oil recovery. Polymer-enhanced waterflooding has been applied successfully in Wyoming, especially in the Minnelusa formation in the Powder River Basin (Towler and Griffith, 1999; Vargo et al., 1999).

Surfactant Flooding. It is possible to enhance oil recovery by adding surfactants to the injected water. These chemicals have molecular structures that allow them to attach to both water and oil, like a detergent. As a consequence, the surfactant-water mixture washes oil off of the rock, and the zone swept by the injected fluid contains less residual oil. Among the types of surfactants used are laboratory-designed surfactants, such as petroleum sulfonates, and surfactants generated in situ using alkaline chemicals or microbes. It is common to inject polymer solution behind the surfactant-water mixture, to help stabilize the flood and improve the sweep efficiency. Because of the difficult design issues and expensive chemicals involved, surfactant flooding has found more limited use than other methods in EOR projects. In recent years it has been widely applied in the remediation of contaminated groundwater aquifers.

CO_2 Injection. CO_2 is a remarkably effective injection fluid. Various forms of CO_2 flooding, including CO_2 miscible flooding and CO_2 huff-n-puff, have been in use in the US since the 1970s. At sufficiently high pressures, CO_2 is miscible with oil, and, once dissolved, it has two effects. First, it causes the oil to swell, thereby lowering the oil's viscosity significantly and making it flow more easily in response to pressure gradients. Second, under miscible conditions it reduces the interfacial (capillary) forces that cause oil to stick to the reservoir rock, in much the same way that dry cleaning fluids reduce the interfacial forces that cause oil to stick to textiles. An additional effect occurs in carbonate reservoirs, where injected CO_2 mixes with water to form an acid solution that dissolves some of the rock, thereby enhancing the permeability and possibly changing the rock fabric in other ways.

In CO_2 miscible flooding, CO_2 is injected continuously into the reservoir, to displace the oil from the rock and sweep it toward production wells. Figure 4 illustrates this method. Most of the injected CO_2 stays in the reservoir, although some may break through at production wells. Even after CO_2 breakthrough, oil production can continue for some time, and the produced CO_2 can be separated, recovered and reinjected. Depending on the efficiency of the sweep pattern, the stability of the displacement, and the operator's ability to control the adverse effects

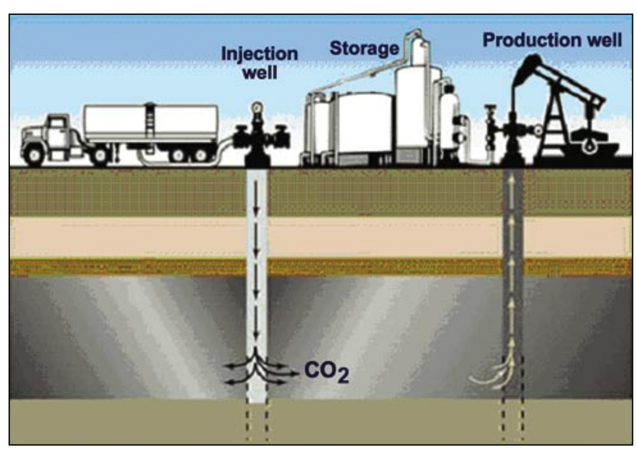

Figure 4. Schematic diagram of CO_2 miscible flooding.

of geologic heterogeneity in the rock formation, CO_2 miscible flooding can recover an additional five to 20 percent of the OOIP. As discussed further below, CO_2 miscible flooding is already working in the Lost Soldier and Wertz fields in south-central Wyoming.

An alternative approach is the huff-n-puff method. In this technique, the operator injects CO_2 into a well for several days or weeks, then converts the same well to production. Both oil and CO_2 are produced from the near-wellbore zone of the reservoir. Between 1989 and 1992 there were six field tests of the huff-n-puff method in Wyoming. The companies involved were Wold Oil Properties, Amoco Production Co., Marathon Oil Co., Timberline Production Co., and G.G. Nicolaysen. The Enhanced Oil Recovery Institute at the University of Wyoming, now part of the Institute for Energy Research, coordinated the tests. While none of these tests was economically successful, they yielded some insight into the relative utility of the huff-n-puff method and CO_2 miscible flooding (Smith and Surdam, 1992; Olenick et al., 1993).

In particular, some of the same reservoir characteristics that make for successful CO_2 miscible floods, such as high reservoir continuity, work against the single-well huff-n-puff method. In the huff-n-puff method, it is important to confine the CO_2 to a region near the wellbore during the "huff," or injection phase. The resulting high concentration of CO_2 reduces the oil viscosity in the near-well region, enhancing back-production during the "puff" phase. Few of the tested reservoirs have patterns of geologic heterogeneity that fit this confinement model. Sandstone reservoirs often have high lateral continuity, and many reservoir formations are intensely fractured. Both of these characteristics promote the flow of CO_2 away from the injection well, working against the huff-n-puff method but in favor of CO_2 miscible flooding. In addition, old oil fields often have close well spacing. In these cases, nearby producing wells establish local pressure gradients that further draw CO_2 away from the injection wellbore. While the huff-n-puff method may be applicable in certain specialized cases, CO_2 miscible flooding offers a more promising technology for many of Wyoming's large, older oil fields.

While all of these EOR methods have the potential to benefit Wyoming's oil production significantly, the one that appears to have the most potential statewide—and the one for which infrastructure improvements are most needed—is CO_2 injection. Section 4 of this report examines this technology at some length.

Concomitant Technologies

CO_2-based EOR projects can exploit a wide variety of other proven technologies for enhancing oil production in existing fields. Among the most prominent examples are water-alternate-gas (WAG) injection strategies, which incorporate slugs of injected water to reduce the effects of adverse mobility ratios between CO_2 and oil; targeted infill drilling, which can access zones of old fields where there remain large saturations of oil; and horizontal drilling, which can help overcome adverse fluid density ratios and allow the injected fluids to contact more of the oil-bearing rock as they sweep resident fluids toward production wells. These technologies are most effective when linked with the use of state-of-the-art reservoir imaging methods and numerical modeling of the fluid flow between injection and production wells.

4. A Closer Look at CO_2-Based EOR

There are at least three reasons why CO_2-based EOR is of special interest in Wyoming: (1) a large number of Wyoming's oil fields are technically suitable for CO_2 miscible flooding (McDaniel, 1991; De Bruin, 2001); (2) Wyoming is particularly well positioned to take advantage of emerging market forces in the sequestration of atmospheric greenhouse gases; and (3) Wyoming is on the verge of having the transportation infrastructure needed to capitalize on the first two factors. In particular, as discussed later in this section, existing and planned CO_2 pipelines in Wyoming make it increasingly likely that CO_2-based EOR will play a significant role in the state's future.

Technical Suitability of Wyoming's Reservoirs for CO_2-Based EOR

The use of CO_2 injection for enhanced oil recovery in Wyoming is already a proven technology. Amoco initiated the Lost Soldier and Wertz CO_2 miscible floods in the late 1980s, and these projects are still in operation under the ownership of Dallas-based Merit Energy. The production spikes in Figure 5 show that the incremental oil production has been substantial. The estimated ultimate EOR from the Tensleep reservoir at Lost Soldier alone is 24 million barrels of oil, or 9.9 percent of the estimated OOIP (EPRI, 1999). The total EOR at Wertz is a bit less, but the incremental production as a percentage of OOIP is about the same. Across

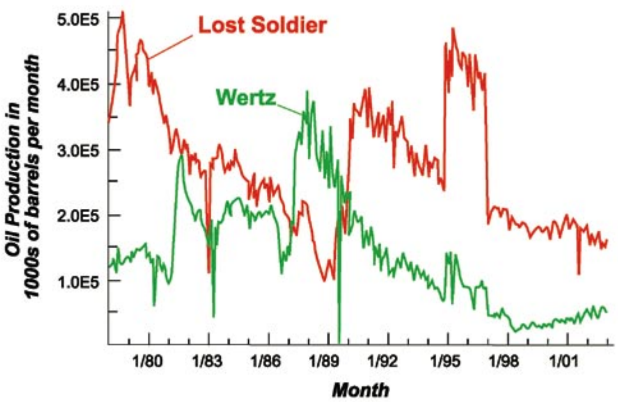

Figure 5. Incremental production from CO_2 miscible flooding in the Lost Soldier and Wertz fields (thousands of barrels).

the state line in Colorado's Rangely field, ChevronTexaco has conducted CO_2-based EOR since the mid-1980s; this project has recovered an additional 10.5 percent of the estimated OOIP, and the project is still in operation. Even if these incremental recovery estimates prove to be typical for CO_2 miscible flooding in Rocky Mountains fields, they are arguably conservative. Kinder-Morgan, which operates an extensive CO_2 pipeline network in the Permian basin of West Texas, has found that incremental recoveries in that province range from 10 percent to 15 percent of OOIP[4].

The Lost Soldier, Wertz, and Rangely fields are by no means special cases. Many Wyoming oil fields meet the basic technical criteria for CO_2 flooding. The optimal characteristics include high lateral continuity of the reservoir's producing zones, high permeability, and internal barriers, such as shale layers, that inhibit vertical flow. In addition, reservoirs should contain light oil and lie at depths greater than about 2500 feet, depending on oil gravity, to sustain pressures high enough to allow the CO_2 to be miscible with the oil. Reservoirs that have responded well to waterflooding are also generally considered to be good candidates for CO_2 flooding.

De Bruin (2001) identified many Wyoming fields as good candidates for EOR. Summary data for these fields appear in Table 2. As this table reveals, the fields have several common traits. They generally have very large amounts of OOIP. They also tend to be old and to have much larger cumulative production than the typical Wyoming field. In 2001, the average candidate field had been in production for 64 years and had produced 112,671,352 barrels, with 130 active wells. The average annual production for these fields is also much larger than that of the typical Wyoming field (1,768,384 barrels per year as compared to 235,960 barrels per year). In short, the candidate fields tend to be large, old, prolific oil fields. These EOR candidate fields are also in decline. In 2001, their average production was 643,484 barrels—roughly 36 percent of their annual production averaged over the life of the fields.

De Bruin's 2001 analysis concludes that EOR can increase the state's cumulative oil production by 0.4 to 1.2 billion barrels. This increase would require injection of somewhere between 2.4 and 12 Tcf of CO_2.

EOR and CO_2 Sequestration: A New Economic Driver

The economics of CO_2-based EOR in Wyoming may soon enjoy a fortuitous boost, owing to a concern that appears to be only peripherally related to petroleum reservoir engineering. The sequestration of greenhouse gases, of which CO_2 is the dominant example, has emerged as a significant societal issue worldwide. This fact is rapidly leading to a market for the capacity to sequester CO_2 from the atmosphere.

More specifically, global agreements such as the Kyoto Protocol, together with parallel efforts in the US, such as President Bush's Global Climate Change Initiative, have triggered interest in technological, economic, and legislative measures for reducing atmospheric CO_2 emissions. Among these measures is the Chicago Climate Exchange[5], a system for trading carbon credits. Such market-based approaches allow CO_2-emitting companies to purchase offsets, which are essentially rights to continue emitting, bought by paying other firms to reduce their emissions. Through mechanisms of this type, resources will flow toward the most cost-effective sequestration projects. Because CO_2 injection sequesters CO_2 and enhances oil recovery, firms that apply this EOR technology stand to benefit from carbon-credit trading. Section 7 of this report lists recent events that indicate the near-term prospects for such a market.

Wyoming has large CO_2 reserves, including the Greater Big Piney–LaBarge Area in southwestern Wyoming, one of the world's largest natural sources of CO_2, and the Madden field on the north flank of the Wind River basin. In addition several coal-fired power plants in the southwestern, eastern, and northeastern parts of the state emit significant amounts of atmospheric CO_2. While some may view these CO_2 sources as liabilities, it is possible to turn them into assets. The utility of CO_2 in EOR, together with the potential economic incentives associated

[4]http://www.kne.com/business/co2/tech.cfm
[5]http://www.chicagoclimatex.com/

Table 2. Summary data for EOR candidate fields in Wyoming (from the Wyoming Oil and Gas Conservation Commission)[6].

Field	Unit Operator	Percent Owned by Operator	Year Discovered	Active Wells	Cumulative Production (bbl)	2001 Production (bbl)
A. Fields close to the LaBarge - Bairoil CO_2 pipeline						
Brady	Anadarko	100	1973	35	68,101,299	511,849
Patrick's Draw	Anadarko	50	1959	39	7,490,281	89,114
Wertz	Merit	96	1921	51	113,669,412	472,029
Lost Soldier	Merit	97	1916	98	246,669,827	2,128,365
Mahoney Dome	Wold Oil	98	1919	11	6,724,578	30,859
B. Fields close to the proposed Bairoil–Salt Creek extension						
Grieve	Wold Oil	89	1954	9	34,240,908	21,072
Casper Creek South	Quicksilver Res.	100	1919	55	16,856,169	137,884
Salt Creek	Anadarko	98	1889	963	680,106,829	2,128,518
Meadow Creek	Westport	98	1949	16	35,515,524	37,959
Sussex	Westport	98	1948	45	91,806,178	146,524
C. Powder River Basin fields distant from existing or proposed CO_2 pipelines						
Hartzog Draw	Exxon Mobil	100	1976	146	104,498,324	1,948,730
House Creek	Devon	74	1968	152	32,038,932	1,315,809
Hilight	RIM	65	1969	181	78,848,576	126,487
Raven Creek	Citation	100	1956	14	46,415,097	122,543
Rozet	Osborn	69	1959	18	53,396,363	166,519
Kitty	Devon/Kennedy	35	1965	149	21,824,758	82,911
Gas Draw	Skull Creek	90	1968	11	27,889,668	27,483
Recluse	Oilfield Sal. & Ser.	28	1967	18	22,888,953	72,306
Fiddler Creek	Underwood	76	1948	45	16,980,829	30,667
Osage	SOIS_Osage	45	1919	268	31,357,472	77,444
Big Muddy	Vortex	44	1916		53,744,313	15,110
Glenrock South	Continental	80	1950		75,240,721	66,288
Well Draw	Matrix	56	1973		31,947,154	242,346
Lance Creek	JP Oil	57	1918		120,076,297	63,421
D. Bighorn Basin fields						
Murphy Dome	Nance	63	1949	30	39,619,520	138,648
Cottonwood Cr.	Continental	98	1953	228	63,868,916	546,564
Bonanza	Equity	90	1950	15	41,994,456	43,069
Worland	Devon	98	1946	42	19,110,391	57,594
Hamilton Dome	Merit	99	1918	246	255,695,802	1,590,677
Grass Creek	Marathon	99	1914	236	205,784,474	1,126,236
Little Buffalo Basin	Citation	99	1914	126	133,479,638	711,212
Pitchfork	Marathon	100	1930	71	49,619,704	836,372
Spring Creek	Marathon	100	1929	50	21,713,972	546,112
Oregon Basin	Marathon	100	1912	573	455,993,661	3,160,048
Garland	Marathon	92	1906	269	188,197,726	1,518,774
Byron	Marathon	93	1918	73	129,606,414	600,466
Big Polecat	Cline	65	1916	3	6,668,062	13,672
Frannie	Merit	96	1928	39	117,495,619	221,469
Elk Basin	Anadarko	96	1915	223	477,328,998	1,735,941
E. Wind River Basin fields						
Steamboat Butte	Marathon	99	1943		94,067,009	1,020,010
Pilot Butte	Family Tree	67	1916		15,157,858	54,208
Winkelman	Camwest	100	1917	105	92,549,628	322,748
Beaver Creek	Devon	100	1938		58,270,067	220,123

[6]http://wogcc.state.wy.us/cfdocs/2001stats.htm

Table 2 (continued). Summary data for EOR candidate fields in Wyoming.

Field	Unit Operator	Percent Owned by Operator	Year Discovered	Active Wells	Cumulative Production (bbl)	2001 Production (bbl)
F. Other areas						
Big Sand Draw	Wold Oil	60	1918		57,756,407	60,887
Rock River	Rock River	74	1918		39,782,872	57,791
Circle Ridge	Marathon	99	1923		35,723,959	598,452

with CO_2 sequestration; suggest that CO_2 injection offers tremendous opportunities for the future of Wyoming's oil fields. In particular, CO_2 miscible flooding has the potential both to increase the profitability of production from Wyoming's mature oil fields and to attract emission-offset revenues by sequestering CO_2 underground.

An interesting question arises when the source of CO_2 is power-plant flue gas. This gas consists of about 15 percent to 20 percent CO_2, the rest being primarily nitrogen. Sequestering flue gas itself therefore requires roughly five times as much underground storage volume as separating the CO_2 before injection and venting the nitrogen to the atmosphere. However, there are costs associated with flue-gas separation. These costs depend on the choice between conventional separation technologies, based on amine units, and the newer membrane technology. Understanding the trade-off between separation costs and the cost of storage volume requires further economic analysis, but preliminary data suggest that it may be more cost-effective to separate the gases and use the CO_2 for EOR. This approach has the dual economic benefit of sequestering CO_2 while recovering additional oil.

Other opportunities for economically beneficial CO_2 sequestration exist in Wyoming. Although these opportunities lie outside the realm of EOR, they merit at least brief mention in this report. It is possible to inject CO_2 into coalbed methane fields to enhance the recovery of natural gas. CO_2 preferentially adsorbs onto the coal, displacing the methane into fractures (called cleats) in the solid matrix and allowing it to flow toward production wells. Once adsorbed, CO_2 remains sequestered on the coal as long as the pressure remains sufficiently high. The presence of giant coalbed methane fields in the Powder River Basin makes it worthwhile to investigate possibilities for sequestering CO_2 in the coal beds while enhancing the gas recovery there.

5. Wyoming's Strategic Position

Wyoming is in a unique position to couple the environmental benefits of CO_2 sequestration with the increased energy production possible through EOR. Total statewide underground reserves of CO_2 are about 150 Tcf. In addition, Wyoming's coal-fired power plants emit about 1.7 Tcf of CO_2 per year. And, as discussed in earlier sections, the state has numerous oil fields in the Powder River, Wind River, and Bighorn Basins where CO_2-based EOR is technically feasible.

Combining EOR with CO_2 sequestration is no longer just a hypothetical possibility. The state already produces great quantities of indigenous CO_2 from the Greater Big Piney - LaBarge Area. Although most of this CO_2 is being vented to the atmosphere, in the near future some of the vented CO_2 will be sequestered in EOR projects. Anadarko has announced plans to utilize CO_2 from the Greater Big Piney - LaBarge Area .for CO_2 miscible flooding in the Salt Creek field. Anadarko has also announced plans to flood the Almond Formation, in the Patrick Draw field east of Rock Springs.

The economics of CO_2 miscible flooding are more favorable than is commonly recognized. As discussed earlier, in mature onshore provinces the growth of proved reserves in existing fields adds more oil volume than do new discoveries. In highly advanced economies like those in the US and Europe, the costs of finding and developing new oil fields currently exceed $6 per barrel. In that environment, CO_2 flooding of existing oil fields is cost-competitive in the aggregate, as Figure 6 illustrates.

Wyoming's New CO_2 Pipeline Network and Its Expected Growth

The single largest challenge to the development of a thriving CO_2-based EOR industry in Wyoming is access to CO_2 at an affordable price. Wyoming has a CO_2 pipeline network, as illustrated in Figure 7. It originates at Exxon-Mobil's gas plant at Shute Creek, which processes gas from the Greater Big

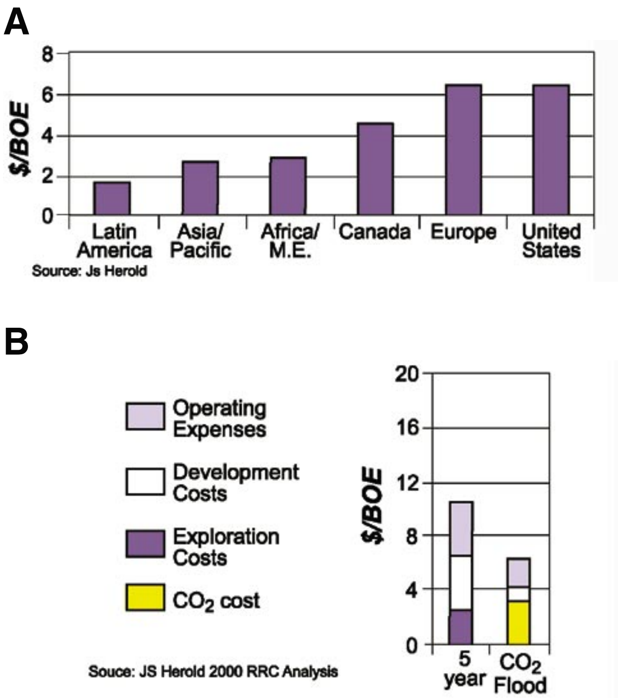

Figure 6. Comparison of worldwide finding and development cost with the cost of CO_2 miscible flooding. (A) Average finding and development cost from 1995 to 1999, in different regions. (B) Average finding, development, and production cost in the US from 1995 to 1999 ($10/barrel, left column), compared to cost per barrel of reserves developed for CO_2 flooding ($6/barrel, right column). From Bradley (2001).

Piney–LaBarge Area. From Shute Creek, pipelines extend south to the Rangely field in Colorado, which has been under CO_2 miscible flooding since the late 1980s, and east to Baroil, where it supplies the Lost Soldier and Wertz fields.

In the near future, this pipeline network will become more extensive. As reported in the April 7, 2003, edition of the Casper Star-Tribune,

> Early this year, Anadarko entered Salt Creek with its purchase of Howell Corp. for $265 million, including $65 million of Howell's debt. Anadarko's plan is to use Wyoming-produced CO_2 to flood the 100 year old Salt Creek Field, gradually increasing production from the current level of 5,500 barrels per day to nearly 30,000 barrels per day four years from now. Production could continue 10 to 20 years beyond that point to sweep a total additional 150 million barrels of oil from Salt Creek, according to company literature. Over the same period, Anadarko would have sequestered 30 million tons of CO_2—a greenhouse gas—that otherwise would be vented to the atmosphere. Anadarko expects to construct the 125-mile CO_2 pipeline during the second half of this year. [...]
>
> In addition to its plans at Salt Creek, Anadarko also purchased marketing rights of CO_2 produced at ExxonMobil's LaBarge gas plant. The idea is to woo other oil producers in the Powder River Basin into tapping into the Salt Creek CO_2 line to revive more oilfields in the basin.

These developments will dramatically affect access to CO_2 for EOR in Wyoming. The pipeline capacity from LaBarge will be 90 billion standard cubic feet (Bcf) of CO_2 per year, which is nearly half of the field's current annual CO_2 production. Half of this volume—about 125 MMcf per day or 45 Bcf per year—is earmarked for EOR in the Salt Creek field. The remaining half will go to other fields in the Powder River Basin, which incidentally is the locus of Wyoming's large coalbed methane reservoirs.

The new pipeline eventually may extend beyond the Powder River Basin. Relatively short spurs from Salt Creek northwest could carry CO_2 into the Bighorn Basin, which may have the largest remaining oil reserves of any basin in Wyoming. An extension of the pipeline westward to the Wind River basin is also an option. Also, CO_2 for Wind River and Bighorn basin projects could come from the Madden field or from the large Colstrip power plant, on the northwest shoulder of the Powder River Basin in Montana.

To link these observations to the list of candidate fields for CO_2 miscible flooding, Table 2 groups the fields by geographic distribution. The fields listed in category A are close to the existing pipeline from the Greater Big Piney - La Barge Area to Baroil. These fields have relatively easy access to CO_2, since they need only install a short spur pipeline to tap into an existing source. The fields listed in category B lie close to the Anadarko's proposed pipeline extension to the Salt Creek field. These fields are likely to have ready access to CO_2 in the near future. The fields in categories C, D, and E lie in important current oil-producing basins (Powder River, Bighorn, and Wind River, respectively), which are too far from any currently planned CO_2 pipelines to have ready access in the near term. While these fields are potential candidates for EOR on technical grounds, realizing their promise will require a significant expansion of the current CO_2 delivery system.

Fortuitously, pipeline networks developed to transport natural CO_2 also have the potential to facilitate the use of anthropogenic CO_2, which

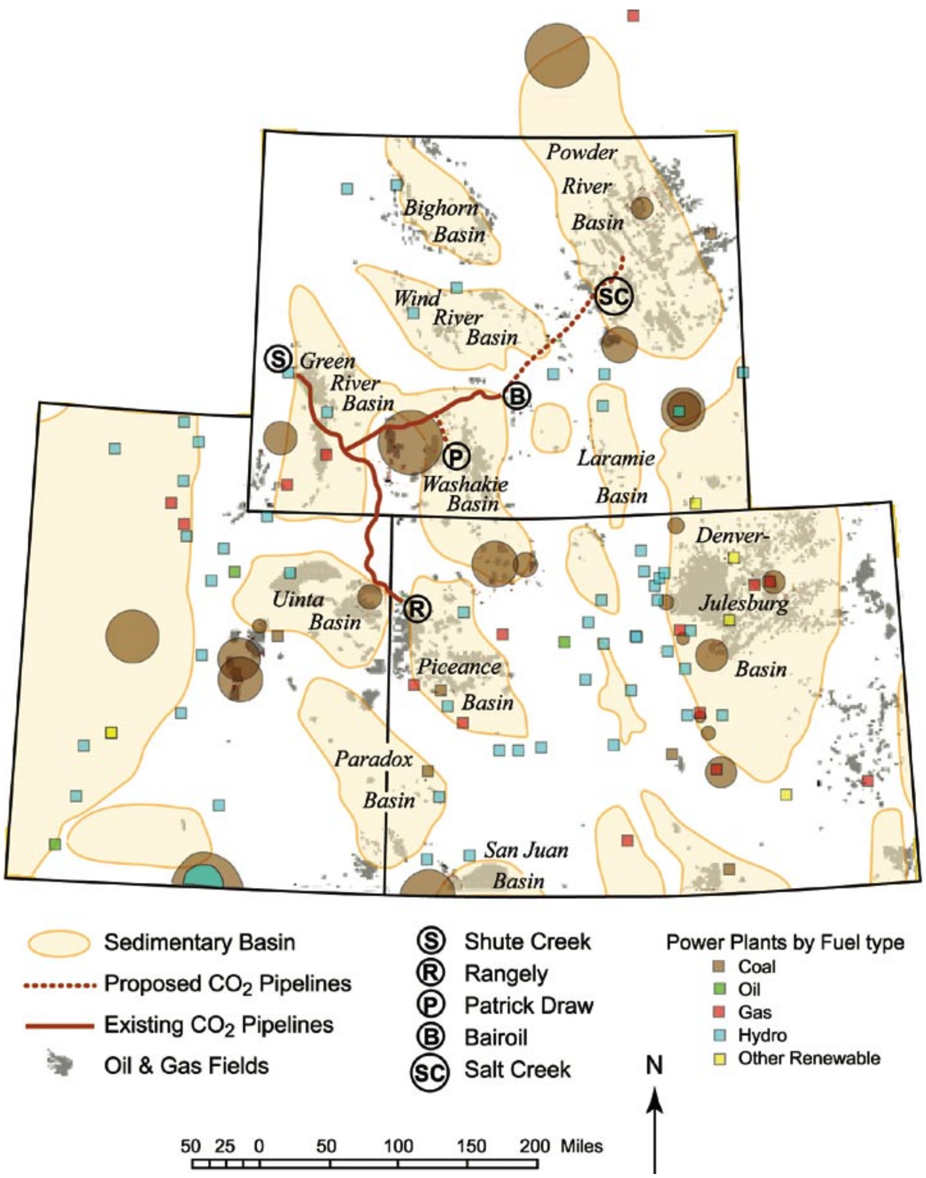

Figure 7. The location of existing and planned CO_2 pipelines in the central Rocky Mountain province and their proximity to major CO_2-producing power plants ("bubble" sizes indicate CO_2 production rates), sedimentary basins, and oil and gas fields.

the region's coal-burning power plants produce in abundance. Figure 7 shows the proximity of several major coal-fired power plants to existing or planned CO_2 pipelines. This geography has distinctive implications for the emerging economics of CO_2 sequestration. Compared with much of the rest of the power-generating US, Wyoming has a competitive advantage: with the addition of short spurs, pipelines constructed to transport natural CO_2 to supply EOR projects can transport anthropogenic CO_2 for the same purpose. This advantage is likely to grow stronger given the current international emphasis on research and development in flue-gas separation.

It is reasonable to hope that these recent developments in the CO_2 pipeline network herald a new era in CO_2-based EOR in Wyoming—an era that capitalizes on opportunities to sequester a significant greenhouse gas and, at the same time, maximize the exploitation of existing oil fields. It is also reasonable to hope that these opportunities are already stimulating new analyses and business plans by many of the oil companies currently active in Wyoming.

Other Examples of CO_2-Based EOR Initiatives in Wyoming

Anadarko's Salt Creek initiative is only the most visible current example of the changing prospects for CO_2-based EOR in Wyoming. In addition, there are several other projects in various stages of planning. For example, Burlington Resources operates the state's second largest CO_2-producing natural gas plant at Lost Cabin, near the Madden field in the northeastern Wind River Basin. Following a facilities upgrade in 2002, Burlington produces 60 MMcf of CO_2 per day. However, at present there is no network of pipelines to distribute this CO_2. In response to the growing value of CO_2 as a resource, together with the emerging economics of sequestration, Burlington has begun appraising the use of the CO_2 for EOR in other reservoirs in their own fields, and they are exploring the option of building a local pipeline network to serve adjacent fields on the Casper Arch.

Also, the University of Wyoming has initiated a joint project, together with the US Department of Energy and Anadarko, to assess the feasibility of using National Petroleum Reserve No. 3 (NPR-3) at Teapot Dome as a test site for CO_2 sequestration. The CO_2 for this project would come via a pipeline spur from the Salt Creek field into the northwestern corner of NPR-3. Salt Creek and NPR-3 are similar fields, being part of the same geologic structure and producing from many of the same reservoir formations. The incremental oil production from this project is likely to be relatively small. The primary motivation for injecting CO_2 at NPR-3 is to investigate the engineering practices needed to optimize the efficiency of CO_2 sequestration in this representative class of oil fields in Wyoming.

6. The Challenges

Wyoming must overcome several important challenges if EOR is to reach its full potential in the state's petroleum industry. These include the initial capital costs, which are large for the long payoff horizons involved; access to technology; cost of and access to CO_2, and effects associated with the size and number of Wyoming's oil-producing firms.

In evaluating these challenges and risks, it is useful to bear in mind how EOR compares with petroleum exploration. Conventional exploration carries significant risks, related to whether there actually is a reservoir and whether it contains hydrocarbons in sufficient quantity to allow profitable production. The risks associated with EOR are somewhat different, because the location of the hydrocarbon resource is known. The two major sources of uncertainty are: first, the reliability of the reservoir characterization and fluid-flow modeling required to design the project; and second, the future commodity prices of the injected and produced fluids. It is often possible to control the first category of risk, albeit at significant cost. The risks in the second category—market-related risks—are harder to control or predict.

Identifying the Risks: Interviews with Wyoming Producers

To gain insight into the oil industry's views on barriers to CO_2-based EOR in Wyoming, we interviewed people at several firms that have oil-producing operations, including ongoing EOR, in the state:

- Burlington Resources, operator of the Madden field
- Merit Energy, which operates the Wertz and Lost Soldier fields
- ChevronTexaco, operator of the Rangely oil field
- Wold Oil Company
- Barlow and Haun, Inc.
- Rocky Mountain Oilfield Testing Center, operator of Teapot Dome
- Anadarko Corporation, operator of the Salt Creek field.

All agree that the impediments to widespread use of EOR among independents include financial, technological, and structural barriers. The barriers are somewhat different for companies of diverse size, yet a common set of issues was clearly evident in all the interviews. We list these as challenges faced by the State of Wyoming on the road to a thriving enhanced oil recovery industry. The challenges are:

1. Project start-up costs and long payoff horizons
2. Access to technology
3. Cost of and access to CO_2
4. Effects of the size and multiplicity of Wyoming's producing firms.

Challenge 1: Project Start-up Costs and Long Payoff Horizons

A typical EOR project requires large investments. Much of the money is needed early in the project, to characterize the reservoir, design the fluid injection, and develop the physical infrastructure needed to transport, inject, and produce the fluids. For CO_2 miscible flooding, these costs can be significant: reservoir characterization requires drilling, well logging, core testing, instrumentation, fluid assessment, and expertise. Project design and reservoir analysis require expertise, computer models, and facilities. Physical infrastructure requires special attention to the corrosion and produced-fluid processing systems associated with CO_2 handling. Also, there are costs associated with separation of the CO_2 and methane from the produced gas stream and the recycling of CO_2 back into the reservoir.

Gauging these costs a priori is difficult because they depend on the scale of the project. Table 3 gives an analysis of costs associated with a small project, the Central Kansas CO_2 Enhanced Oil Recovery Project[7]. These costs—$5.4 million—compare with estimates of $200 million for new wells, facilities, a CO_2 pipeline extension, gas treatment, and engineering for the first four years of Anadarko's much larger project in the Salt Creek field.

Even in the best of scenarios, the up-front expenditures and access to technical expertise are large investments that have long payoff times. A CO_2 miscible flood may not yield significant new oil production until 18 to 24 months after fluid injection starts, and the full benefits of CO_2 injection may not appear for another three to five years after that. Because most of the benefits from the project occur well in the future, EOR projects rarely pay off within five years. This long payoff horizon is a deterrent to many small firms, which have limited access to the capital required and whose acceptable payoff horizons are often no longer than two or three years.

Compounding the long payoff horizon is the strong dependence of the ultimate payoff on the future stream of crude oil prices. The volatility of these prices makes EOR a high-risk investment. This risk stands as another deterrent to small firms. Policy changes can have some effect on these risks, but their efficacy requires careful scrutiny. For example, a policy change that reduces the payoff horizon from five years to four years is not likely to induce many small oil-producing firms to invest in EOR.

In addition to risks associated with the future price of oil, there are risks associated with future policies. For example, investments predicated on anticipated policies intended to encourage CO_2 sequestration may become less attractive after an unanticipated future policy change or after the entry of unexpected sellers of carbon credits. At present, small producers have few tools with which to manage risks of this type.

Challenge 2: Access to Technology

Designing an EOR project and conducting the reservoir analysis needed to operate one successfully requires expertise, computational models, and laboratory facilities. Small producers face special problems in this regard, because they do not have ready access to the expertise needed for reservoir characterization and project design. Unitization is not an effective way to overcome this difficulty. The missing link is an effective mechanism for technology transfer. Such a mechanism would provide consortia of small producers with access to the expertise needed to pursue EOR effectively, without having to hire a permanent staff of scientists and engineers and equip the computational and laboratory facilities needed for reliable reservoir analysis.

Table 3. Summary of costs for the Central Kansas CO_2 EOR Project

Category	Cost	Remark
Capital costs	$1.1 million	1 injection well, 5 production wells, 5 containment injectors
Operations	$0.8 million	6 years
CO_2	$2.0 million	Purchase, transportation, recycling
Research, technology transfer	$1.5 million	
Total	**$5.4 million**	

[7]http://www.kgs.ukans.edu/CO2/Presentation/XX991112_BYRNES_Update_on_KS_CO2/

Challenge 3: Cost of and Access to CO_2

The third challenge hinges on three factors: the price of CO_2 at its source, the availability of effective infrastructure for transporting it from the source to the target field, and the cost of transporting it.

The price of CO_2 depends not only on the production costs but also on the structure of the market. At present, there appears to be only one economically viable source of CO_2, namely ExxonMobil's Shute Creek plant in the Greater Big Piney–LaBarge Area. As discussed earlier, a CO_2 pipeline from this source is in place, and there are plans to extend it. There is therefore a reasonable prospect for better access to CO_2 in some fields in the foreseeable future.

Less certain are the prospects for a competitive CO_2 market in Wyoming. Among the other firms that could potentially compete in selling CO_2 is Burlington Resources, which owns the Lost Cabin plant at the Madden field. In addition to natural sources, coal-fired power plants that emit CO_2 may soon have economic incentives to sell it, as an alternative to venting it in the flue gas. But before these power plants can become useful sources of CO_2, a variety of technical problems must be solved. The most significant of these are the collection, separation, and transport of CO_2. As mentioned earlier, improvements in the processes used to collect and separate CO_2 from flue gas are likely to alleviate the first two problems.

To solve the transport problem will require both the construction of pipelines and the ability of oil producers to access CO_2 through them at an acceptable price. Pipeline tariffs   the prices that pipeline owners charge for transportation   are an important determinant in the delivered price of CO_2. In the absence of regulatory oversight, these tariffs depend on successful bilateral agreements between pipeline owners and potential users. When it is difficult for negotiations to yield a reasonable price, regulatory agencies, such as the Wyoming Oil and Gas Conservation Commission at the state level and the Federal Energy Regulatory Commission (FERC) at the federal level, can help mediate the tariff-setting process. Mediation of this type can be important when there are many small users.

Regulatory agencies typically follow one of two broad approaches, both aimed at obtaining a specified rate of return on the pipeline owner's investment. The approaches differ in the rate bases used to calculate the return. In the first approach, often used by FERC, the rate base is the cost of constructing the pipeline, multiplied by a weighted average of the cost of debt (bonds) and equity (stocks). In this approach the interest expense associated with the debt financing is recovered in the overall rate of return. The second approach regards the interest expense from issuing bonds as part of the operating cost. In this approach the overall return is then the allowed rate of return multiplied by the portion of the rate base that was financed with equity.

A difficulty with the first approach is that it invites the pipeline owner to finance construction costs with a large amount of debt (often as high as 90 percent); the money actually put at risk is the residual, which is the part financed with equity. The allowed tariffs then generate an effective rate of return that can be much larger than that envisioned by the regulatory agency. Tariffs set in this way can be larger than what is needed to make the pipeline economically viable and too large to attract users. In the case of a pipeline transporting CO_2 to an oil field, these extra tariff charges can impede the use of EOR. In a decision-making environment in which oil producers are skeptical about investing in EOR, pipeline tariff structures can have significant implications.

Challenge 4: Effects of the Size and Multiplicity of Wyoming's Producing Firms

In addition to the challenges mentioned so far, there are other consequences of the size and multiplicity of Wyoming's oil-producing firms. One such consequence is the difficulty of organizing field-wide or reservoir-wide production strategies. When many small firms produce from the same oil field, there is a natural tension balancing competition and cooperation among the interest owners. Oil fields defy the usual assignment of property rights. While one can own the surface land, one cannot own the oil in a reservoir that lies beneath until the resource has been produced. Courts have defined this oil as migratory. If one owner pumps faster, causing oil to migrate from under another owner's surface property, the only recourse for the other owner is to pump at a faster rate. This competition leads to less efficient depletion, ultimately limiting the amount of oil that can be extracted before pumping becomes uneconomical.

Unitizing the fields can often resolve this problem. Under unitization, one firm is designated as the operator, and all firms share in the proceeds from extraction according to predetermined criteria. For example, the distribution of revenues may be according to the percentage of the OOIP that lies under the land that each firm owns.

Unitization has historically been successful in the large oil fields of Texas and Oklahoma. It is important in EOR, because of the large amounts of money that must be invested up front and the fact that all firms tapping into a CO_2-flooded reservoir stand to benefit, whether or not they help pay for the project. To make investments in EOR worthwhile in an industry characterized by so many small producers, it is essential to form cooperative structures.

Designating the oil field operator may be difficult. In many instances, the operator is a large firm. For example, Chevron operated the SACROC field in Texas for many years. Likewise, Shell has operated the Wasson field near Denver City, Texas. Some of Wyoming's candidate fields for EOR are wholly owned by one firm; for example, Merit Energy owns and operates the Lost Soldier and Wertz fields. In other cases, one firm owns such a large share that it can force unitization (and presumably name itself as operator). In some fields, however, ownership is so broadly distributed among so many firms that voluntary unitization is difficult. The Wyoming Oil and Gas Conservation Commission can require operators to unitize. Hartzog Draw, with more than 113 working-interest and royalty owners, is an example of a field subjected to mandatory unitization.

7. A Vision for CO_2-Based EOR in Wyoming

Wyoming is at an important crossroads, where several factors combine to make EOR an important opportunity for the state's future. Among these factors, the following four are critical:

1. The state has many reservoirs that are in decline but that still harbor significant volumes of OOIP. The nominal value of this resource is enormous.
2. Although most of this resource may be impossible to produce using traditional technologies, many of the reservoirs are amenable to EOR, which can facilitate the production of a significant fraction of the remaining oil. One of the most promising EOR technologies for the reservoirs in question is CO_2 miscible flooding.
3. Wyoming has tremendous natural reserves of CO_2 in the southwestern portion of the state. Another large natural source of CO_2 exists in central Wyoming. And Wyoming has several coal-fired power plants that emit large quantities of CO_2 in their flue gas. To date, limitations in the transportation infrastructure and the economics of separating CO_2 from flue gas have inhibited the broader use of these resources for EOR projects.
4. Emerging restrictions on CO_2 emissions and the associated economics of CO_2 sequestration are likely to alter the economics of CO_2 miscible flooding in the next few years. The changes are likely to make CO_2-based EOR a more attractive investment for oil-producing firms, provided they have access to the gas and to the expertise needed to implement EOR projects.

To take advantage of this constellation of factors, Wyoming must initiate measures to overcome the most significant challenges to CO_2-based EOR. Timing is a factor: depleted oil fields are difficult to re-open after they have been closed. The following steps are worth considering in the near term.

Step 1: Screen Wyoming Reservoirs for Suitability for CO_2-Based EOR

The first step is to conduct a review of Wyoming's major oil fields, to identify the most important candidates for CO_2-based EOR. The first level of screening must be for technical feasibility: do the available reservoir characterizations and estimates of remaining oil in place justify more detailed consideration of CO_2 miscible flooding? At issue are the feasibility of high injection rates and high pressures (typically requiring a producing zone deeper than 2000 feet), the presence of light oil (typically having API gravity 25 or greater), and the possibility of good fluid control underground (as indicated, for example, by small water-injection losses during secondary recovery).

The state already has a head start on this step. The Wyoming Geological Survey has appraised the potential of Wyoming's oil reservoirs for future CO_2 miscible flooding (De Bruin, 2001). Industrial experience with EOR, in the Permian Basin of West Texas since the early 1970s and in the Rocky Mountains since the late 1980s, has yielded a suite of well-understood reservoir and fluid criteria that can help predict the likelihood of success of CO_2 miscible floods in specific fields. De Bruin's study carefully applied these criteria to Wyoming's oil fields, concluding that CO_2 flooding will make it possible to produce 400 million to 1.2 billion barrels of additional oil that, without EOR, will remain in the ground.

Similar assessments should be made of incremental enhanced gas production and enhanced coalbed methane production. In addition, it will be worthwhile to assess the potential for hydrocarbon extraction from oil shales using CO_2. Even though the potential for traditional EOR is huge, the aggregate potential for CO_2 injection to enhance the recovery of gas from these three other sources may be even greater.

Any further screening should take economics into account. For example, would the recovery of an additional 10 percent of the OOIP over a 10-year project life justify the financing of a pipeline spur, the cost of injected fluid and injection equipment, and the design expertise required?

Step 2: Assess the Economics of CO_2 Supply

The second step is to assess the cost-effectiveness of transporting CO_2 from the existing sources to the wide range of EOR targets in Wyoming. As Figure 7 illustrates, several large CO_2-emitting power plants are very close to existing CO_2 pipelines. For example, the Jim Bridger plant, which produces 18.5 million tons of CO_2 per year, is about 12 miles from the existing CO_2 pipeline that connects the Shute Creek gas plant to Baroil.

A significant ingredient in the economics of CO_2 supply is the prospect for improved methods to separate CO_2 from power-plant flue gas. Increased efficiencies in amine scrubber technologies and membrane separation techniques, together with the developing economics of CO_2 sequestration, could help make flue-gas CO_2 economically competitive with natural CO_2. The state has an interest in collaborating with major utilities in the region such as PacifiCorp, Basin Electric, Black Hills Power, Platte River Power and Xcel Energy to encourage accelerated research and development in separation technologies.

Another important determinant in the economics of CO_2 supply is the structure of CO_2 pipeline tariffs. As argued in Section 6, careful analysis of the regulatory issues associated with these tariffs must be part of any coherent vision for CO_2-based EOR in Wyoming.

Step 3. Quantify the Value of CO_2 Sequestration and the Associated Risks

The future economic incentives for EOR in Wyoming may no longer be limited to the incremental oil and gas production. Increasingly, another dominant economic driver will be the credits that accrue to companies and states that effectively capture CO_2 and sequester it. Evidence for this assessment includes several recent events:

- Senators McCain and Lieberman introduced Senate Bill S139 on January 9, 2003. This bill establishes mandatory emissions-reduction credits for atmospheric CO_2
- The US Department of Energy's annual budget appropriations for CO_2 sequestration have increased steadily, and DOE has made significant commitments to research and development in CO_2 sequestration.
- President Bush has made a formal commitment, under the Global Climate Change Initiative, to reduce greenhouse gas emissions intensity—quantity emitted divided by gross domestic product—by 18 percent by 2010.
- On February 27, 2003, the White House and DOE formally announced a $1 billion commitment to build FutureGen, the world's first true zero-emissions power plant. The facility will use coal-gasification techniques to produce hydrogen for fuel cells, with the resulting CO_2 to be sequestered or used in EOR.

Wyoming's many large and nearly depleted gas fields (some in the southwest Wyoming thrust belt, some in the north half of the state) provide excellent sites for CO_2 sequestration, as do the many older oil and gas fields with residual production everywhere else. It is also possible to imagine a central role for Wyoming in the FutureGen project, an initiative that will require a substantial commitment and influx of technically skilled personnel. To respond effectively to the emerging market forces associated with greenhouse gases as well as to the changing economics of EOR and new opportunities to use the state's substantial coal resources, Wyoming's decision makers will need access to a rigorous economic analysis of CO_2 sequestration.

Finally, the analysis should examine coherent strategies by which independent producers can manage the risks associated with future CO_2 sequestration policies and markets. These strategies may involve policy measures, financial instruments, or a combination of these two approaches.

Step 4: Initiate Technology Transfer to Wyoming Independents

Among the factors inhibiting further application of EOR in Wyoming are the size and distribution of Wyoming's oil producers. Many of these firms have little access to the expertise needed to plan, design, and implement EOR projects. There are several steps that Wyoming can take to address this challenge. In the near term, scientists and engineers at the

University of Wyoming, under the auspices of the Institute for Energy Research, the Enhanced Oil Recovery Institute, and the Department of Chemical and Petroleum Engineering, might organize and deliver a short course on CO_2 flooding for Wyoming's oil-producing professionals. State support for such a project could signal the commitment of Wyoming's elected officials to the future of EOR.

For the longer term, it is possible to envision more ambitious efforts. One example is the establishment of an EOR technology transfer program, possibly involving experts from the University of Wyoming, the Rocky Mountain Oilfield Testing Center (RMOTC), and other agencies, such as the Petroleum Technology Transfer Council (PTTC). The mission of such a center would be to provide a channel for consulting services and the dissemination of state-of-the-art research results to aid in the implementation of EOR projects in Wyoming. Programs of this type require sustainable funding to attract and retain qualified scientists and engineers. They also provide advanced training and employment opportunities for students and graduates in a wide variety of technical disciplines.

Step 5: Develop a Demonstration Project

Such a project would involve a CO_2 miscible flood in a small oil field, probably in the Powder River Basin. The purpose of the project would be to marshal a thorough technical analysis—including advanced reservoir characterization, computer modeling, and engineering design—to support a technically successful flood. To advance the state of knowledge applicable to Powder River Basin oil fields more generally, it may be appropriate to make intensive investments in design and analysis, even if these expenditures reduce the chances for strict economic profitability. Such a demonstration project might involve a consortium of participants, including the state government, DOE, one or more independent producers, and experts from UW and RMOTC. It should be possible to capitalize on the findings from Anadarko's experience in the Salt Creek Field and from the DOE sequestration project at Teapot Dome, described in Section 6.

The main purpose of the project would be to assess the technical and economic feasibility of CO_2-based EOR in a class of Wyoming reservoirs for which these feasibilities have yet to be determined, based on the screening developed in step 1. A secondary purpose would be to provide a model for the facilities, equipment configurations, and operating practices required to run an EOR project in one of Wyoming's most important oil-producing basins.

Demonstration projects are not a new concept in EOR. A relevant example of such a project is the Central Kansas CO_2 Enhanced Oil Recovery Project, in the Hall-Gurney Field in Russell County, Kansas[8]. This project involves a consortium that includes the Kansas Geological Survey, Shell CO_2 Company, DOE, the Tertiary Oil Recovery Project at University of Kansas, Murfin Drilling Company and MV Energy LLC, and the Kansas Department of Commerce. The $5.4-million costs for this project are split between DOE, Shell CO_2 Company, and the State of Kansas.

The presence of a well-designed CO_2 flood, in one of Wyoming's historically prominent oil fields, would have the potential to spur independent producers to pursue EOR projects. It would stimulate a sustained commitment to EOR-related research and technology transfer. And it would signal the state's interest in turning a pressing global issue —the sequestration of greenhouse gases—into an opportunity for the efficient production of one of the region's most important natural resources.

Acknowledgments

The authors greatly appreciate the initiative of University of Wyoming President Philip Dubois, who suggested the idea of a "white paper" on the issues covered in this report, and Governor Dave Freudenthal, who charged the university with producing the study. The Honorable Jim Barlow and Ambassador Tom Stroock asked the critical and insightful questions that set this study in motion. We have learned a great deal, and we hope that in a small way we have helped contribute to a better future for our state.

We want to express sincere thanks to colleagues who reviewed early versions of the manuscript and contributed useful data and suggestions. These include Philip Dubois, UW Vice President Richard Miller, Rodney De Bruin (Wyoming Geological Survey), Lance Cook (State Geologist), Randi Martinsen (UW), Peigui Yin (UW), Jason Shogren (UW), and Norman Morrow (UW). We also want to acknowledge several people for their helpful responses to telephone and personal interviews: Peter Wold (Wold Oil), Mark Doelger (Barlow and Haun), Frank Lim (Anadarko), Don Spence (Merit Energy), Hutch Jobe (Burlington Resources), Jaqueline Pirkle and Dave Howell (Exxon Mobil), and Jim Barnum (Chevron Texaco).

[8]http://www.kgs.ukans.edu/CO_2/

References to Published Literature

Attanasi, E.D., Mast, R.F., and D.H. Root, 1999, Oil and gas field growth projections – wishful thinking or reality: Oil and Gas Journal, 97:14, 79-81.

Bradley, R.T., 2001, CO_2 breathes new life into old fields: The American Oil and Gas Reporter, March 2001.

De Bruin, R.H., 2001, Carbon dioxide in Wyoming, Information Pamphlet 8, Wyoming Geological Survey, Laramie, WY, 11 pp.

Electric Power Research Institute (EPRI), 1999, Enhanced Oil Recovery Scoping Study, Palo Alto, CA: TR-113836.

McDaniel, J. K. 1991, The feasibility of tertiary oil recovery by carbon dioxide injection in the Powder River Basin in Wyoming: M.Sc. Thesis, Department of Petroleum Engineering, University of Wyoming, 258 pp.

Office of Technology Assessment, Congress of the United States, 1978, Enhanced Oil Recovery Potential in the United States: NTIS Order # PB-276594; 12 volumes.

Olenick, S.O., F.A. Schroeder, H.K. Haines, and T.G. Monger-McClure, 1993, Cyclic CO_2 injection for heavy-oil recovery in Halfmoon field: laboratory evaluation and pilot performance; in Wyoming Geological Association Guidebook, 50th Anniversary Field Conference, B. Stroock and S. Andrew, eds., p. 271-280.

Smith, L.K., and R.C. Surdam, 1992, Cyclic CO_2 enhanced oil recovery in Wyoming Cretaceous fields; in Wyoming Geological Association Guidebook, 43rd Field Conference, C.E. Mullen (ed.) 1992, p. 145-166.

Towler, B.F., and Griffith, B., 1999, Comparison of 20 Minnelusa waterfloods in the Powder River Basin, presented at the Society of Petroleum Engineers Rocky Mountain Regional Meeting, Gillette, WY, 15-18 May 1999. Available from the Society of Petroleum Engineers, Richardson, TX.

Vargo, J., et al., 1999, Alkaline-Surfactant-Polymer Flooding of the Cambridge Minnelusa Field, presented at the Society of Petroleum Engineers Rocky Mountain Regional Meeting, Gillette, WY, 15-18 May 1999. Available from the Society of Petroleum Engineers, Richardson, TX.

Verma, M.K., 2000, The significance of field growth and the role of enhanced oil recovery; USGS Fact Sheet FS-115-00, 4 pp

About the Authors

Dr. **Dag Nummedal** is Professor of Geology and Geophysics and Director of the Institute for Energy Research at the University of Wyoming. His expertise is in stratigraphy and petroleum geology. He recently completed a term as President of the Society for Sedimentary Geology and served as the Distinguished Speaker for the American Association of Petroleum Geologists. IER's mission is to conduct interdisciplinary research in geoscience and related fields, to improve exploration success and production efficiencies in the upstream oil and gas industry. The institute is also home to UW's Enhanced Oil Recovery Institute. For more information about research in IER, the Enhanced Oil Recovery Institute, and the Department of Geology and Geophysics, see http://www.ieronline.org.

Dr. **Brian Towler** is Associate Professor of Chemical and Petroleum Engineering at the University of Wyoming. His research interests include reservoir engineering and simulation, enhanced oil recovery, natural gas processing, wax deposition, and fluid phase behavior. His textbook, Fundamental Principles of Reservoir Engineering, was recently published as Number 8 in the Society of Petroleum Engineers textbook series. For more information about research in the Department of Chemical and Petroleum Engineering, see http://wwweng.uwyo.edu/chemical/.

Dr. **Charles Mason** is Professor of Economics and Finance at the University of Wyoming. His research interests include environmental and resource economics, the economics of decision-making under uncertainty, common property resources, applied game theory, and collusion. For the last five years he has served as co-editor at the Journal of Environmental Economics and Management. For more information about research in the Department of Economics and Finance, see http://business.uwyo.edu/econfin/.

Dr. **Myron Allen** is Associate Vice President for Academic Affairs and Professor of Mathematics at the University of Wyoming. His scientific expertise is in underground flow modeling, numerical analysis, and mathematical fluid mechanics. He is author of several books and monographs, including *Numerical Analysis for Applied Science*. For more information about research in the Department of Mathematics, see http://math.uwyo.edu/.

Appendix: Fiscal Impacts of Oil Production in Wyoming

This appendix summarizes data quantifying the impacts of oil production on Wyoming's economy. Many of the impacts have direct implications for the state's treasury, through property taxes, severance taxes, and royalties. In addition, petroleum production is a significant source of jobs for Wyoming's citizens.

Property Taxes

As Table A-1 indicates, oil and gas production accounted for over 45 percent of the total property taxes levied in Wyoming and more than 76 percent of the property taxes levied on all minerals. Table A-2 shows that, for many of Wyoming's counties, the oil and gas industry accounts for a substantial share of the total property assessed for taxation.

For fiscal year 2001, production and equipment in the oil and gas industry constituted nearly 51 percent of the state's total taxable valuation. Minerals are the only kind of property in Wyoming valued and taxed at 100 percent of actual value. Property taxes across the state averaged 6.70 percent on oil and 6.48 percent on natural gas.

Table A-1. Property taxes levied in Wyoming in 2000, from the Petroleum Association of Wyoming.

Crude oil	$ 96,414,790
Natural gas	217,948,285
Total, oil and gas	$314,363,075
Coal	$ 80,628,703
Trona	14,331,600
All others	4,011,268
Total, all minerals (including oil and gas)	$413,334,646
Total, all state property	$695,534,661

Table A-2. The oil and gas industry's percentage share of property assessed for taxation, by county, in fiscal year 2001.

Albany	4.43	Natrona	52.00
Big Horn	52.64	Niobrara	33.20
Campbell	37.93	Park	57.11
Carbon	77.94	Platte	4.77
Converse	43.87	Sheridan	5.83
Crook	54.30	Sublette	91.53
Fremont	71.32	Sweetwater	52.86
Goshen	4.13	Teton	0.17
Hot Springs	79.16	Uinta	87.78
Johnson	46.73	Washakie	50.62
Laramie	5.03	Weston	51.32
Lincoln	71.10		

Severance Taxes

Minerals, including oil and gas, are also the only kind of property subject to a second direct tax: the severance tax. In 2000, crude oil and natural gas production yielded over $253 million in severance taxes. As Table A-3 shows, this amount was about 71 percent of all the severance taxes paid by minerals produced in 2000.

Currently, a six-percent severance tax applies to crude oil and natural gas production. For stripper wells—those producing 10 BOPD or less—the severance tax rate is four percent. To encourage EOR, the 2003 Wyoming Legislature reactivated a reduction in severance tax, from six percent to four percent, on the first five years of incremental production resulting from EOR operations.

Severance tax revenues contribute to a variety of funds that are important to the economic life of the state, including the General Fund, the Permanent Mineral Trust Fund, schools, cities, towns, highways, counties, and water development.

Table A-3. Severance taxes levied in Wyoming in 2000, from the Petroleum Association of Wyoming.

Crude oil	$ 77,555,142
Natural gas	175,541,408
Total, oil and gas	$253,096,550
Coal	$ 92,766,944
Trona	8,248,759
All other minerals	937,676
Total, all minerals (including oil and gas)	$355,049,929

Royalties

In addition to property and severance taxes, Wyoming collects a royalty for petroleum produced on state-owned lands, along with certain fees and rentals. The state also receives one-half of the royalties paid to the federal government for leasing, production and fees on federal lands. Typically, the royalty rate on state leases is 16 2/3 percent. On federal lands, the rate is 12 ½ percent.

Table A-4 shows the overall amounts that oil and gas production contributed to state and local governments in fiscal year 2001. In the aggregate, these contributions were equivalent to a direct payment of nearly $1,600 for every person living in Wyoming.

Table A-4. Overall contributions of oil and gas taxes to state and local treasuries in Wyoming, fiscal year 2001 (millions), from the Petroleum Association of Wyoming[9].

Property Taxes	$169.1
Severance Taxes	253.1
Federal Royalties	258.6
State Royalties	59.5
Sales and Use Taxes	24.5
Conservation Mill Levy	3.3
Total for the state	$768.1

[9]http://www.pawyo.org/oilgas_facts.html