Impact of Enhanced Oil Recovery and Unconventional Reservoirs on Oil Supply

ER291: Transportation Energy, Spring 2007

The goal of this project was to assess the impact of enhanced oil recovery and unconventional reservoirs on oil supply. Historical oil production data sequences for enhanced oil recovery by various methods and production from unconventional reservoirs demonstrate a trend toward increasing carbon dioxide injection in the United States and rapid growth of steam injection and oil mining in Canada. If cost-effective, these technologies could significantly enhance the future of global oil supply if used as widely outside the United States as they are currently used within it.

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Introduction

Enhanced oil recovery (EOR) refers to oil production techniques during the tertiary stage of recovery utilizing 'enhanced' technologies such as carbon dioxide flooding or horizontal drilling subsequent to primary or secondary production.

> **Primary Recovery** – oil and gas recovery where natural pressure of the reservoir acts as the driving force for collection.
>
> **Secondary Recovery** – flooding of water and natural (methane) gas improve recovery factors subsequent decreases in the reservoir's natural pressure
>
> **Tertiary Recovery** – enhanced techniques such as horizontal drilling or injection of thermal, chemical, or carbon dioxide gas to ensure pressure, as well as optimum levels of rock and fluid properties.

Implementation of EOR projects can vastly improve recovery factors of struggling reservoirs – for a price. In comparison to conventional production, there are minimal exploration costs and fewer uncertainties. Nonetheless, these projects require large capital investments paired with higher operating costs for long periods of time. Given this and the variability of global crude oil prices, "companies tend to use long-term price forecasts to justify initiating [EOR projects.]" (EOR OGJ 2006).

New investments may be inhibited by increasing cost of natural (methane) gas, tightened supplies of CO2, and the fact that contracts for carbon dioxide in EOR projects explicitly link quantity to the price of crude. Implementation of carbon capture and sequestration technologies may open up new supplies of carbon dioxide from electricity-generation facilities. Given such uncertainty, there is a high option value present in deferring planned EOR projects until these long-run crude price forecasts and environmental regulations meet the constraints of firm's internal financial policies. This may be a lurking force pulling down EOR production figures below what "might be expected" (id.) from sources such as the Oil and Gas Journal's EOR Survey that "tend to reflect the industry's economic perceptions from several years ago" (id.)

Definitions

Thermal enhanced oil recovery involves application of heat, usually in the form of steam, to reduce oil viscosity and increase recovery factors. There are two kinds of steam injection; cyclic steam and steamflood. Cyclic steam injection, called huff and puff or CSS in Canada, involves injecting steam into a well for several days, then producing oil from the same well. The only part of the reservoir that is filled with a steam phase is the immediate area of the wellbore. Steamflood, called ICV in Venezuela, involves dedicated injection and production wells. Steam flows from injector to producer, filling the reservoir. A special form of steamflood called steam-assisted gravity drainage (SAGD) is used extensively in Canada. SAGD uses a horizontal steam injector in the middle of the oil sand and a horizontal producer near the base of it. This method requires a hundred-foot sand with no vertical permeability barriers. This requirement rules out SAGD in almost all heavy oil reservoirs in California and Venezuela.

For steam injection to be viable, porosity should be at least 25% because the whole reservoir must be heated. Depths from 500 to 1500 feet are best because too shallow does not allow enough reservoir pressure and too deep results in problems with corrosion and heat loss. Steam injection works best when there is a large drop in oil viscosity with increasing temperature so heavy crudes are better, especially if they are high in wax content as in Indonesia.

In-situ **combustion** is a form of thermal EOR that is broken out separately. This involves injecting air to combust some of the oil in place. The steam, heat and carbon dioxide generated increase the oil recovery. Combustion fronts are notoriously difficult to control and this method is of only minor importance in spite of decades of research.

Miscible hydrocarbon injection is mostly used in Canada, the north slope of Alaska, and the Furrial-Musipan trend in the Venezuelan state of Monagas. This involves injection of a hydrocarbon solvent, usually propane or wet gas, to reduce the viscosity of the oil and increase recovery. Increases in the price of propane have discouraged this approach and production is declining. If the gas is not miscible, gas injection is simply pressure maintenance and is outside the scope of this study.

Miscible carbon dioxide injection takes advantage of the fact that liquid carbon dioxide is the cheapest nonpolar solvent available. It will dissolve in light oil, thereby increasing its volume and decreasing its viscosity. Carbon dioxide liquefies at 67 atmospheres at 25˚ C, so carbon dioxide injection projects tend to be at least 2,000 feet deep where it will be a miscible liquid at reservoir conditions. Miscibility is greater for light oil, so most carbon dioxide injection projects produce oil that is 30˚ API or lighter. Most carbon dioxide projects are in Texas and have been limited by carbon dioxide availability. Concerns about atmospheric carbon dioxide levels have increased interest in this technology. There is only one natural carbon dioxide field east of the Mississippi, so there could be a market in the Gulf Coast, the Illinois Basin and other areas for carbon dioxide from Midwestern industrial sources.

Immiscible carbon dioxide and nitrogen injection involve injection of gas that does not dissolve in the oil. This increases reservoir pressure and increases recovery by means of gravity drainage in zones where gas has become the dominant phase. Nitrogen injection and immiscible carbon dioxide injection are listed in the EOR survey of the Oil and Gas Journal, but in fact are pressure maintenance similar to natural gas or water injection, which are not listed. The world's largest nitrogen injection project, Mexico's Cantarrell Field, is listed without production figures in the Oil and Gas Journal survey, we presume this is because Pemex did not respond to the survey. As these methods represent an incomplete list of pressure maintenance methods, they were excluded from this study.

Polymer and **microbial** enhanced oil recovery are similar in that both involve creating an obstacle to water flow by means of a waterflood in order to forcing water into previously bypassed zones. In polymer floods, a polymer is injected into the high-flow zone where it forms a gel. In microbial enhanced oil recovery, culture and nutrients are injected and the microbes secrete viscous material that blocks the high-flow zone. Several projects of both kinds are currently producing about 15,000 barrels per day in China, but all US polymer projects have been abandoned. The alternative to these approaches is to isolate high-flow zones by selectively blocking perforations. These techniques are a subset of waterflooding and were excluded from this study.

Unconventional reservoirs are oil shales and similar rocks that have been buried deeply enough for earth heat to generate oil and gas. For a long time they were considered too costly, but improvements in drilling and fracturing technology have increased US natural gas supply to the point that onshore US lower-48 gas production increased 4% in 2006 relative to 2005. Unconventional oil reservoirs present an even greater technical challenge, but they contain enormous volumes of hydrocarbons in place.

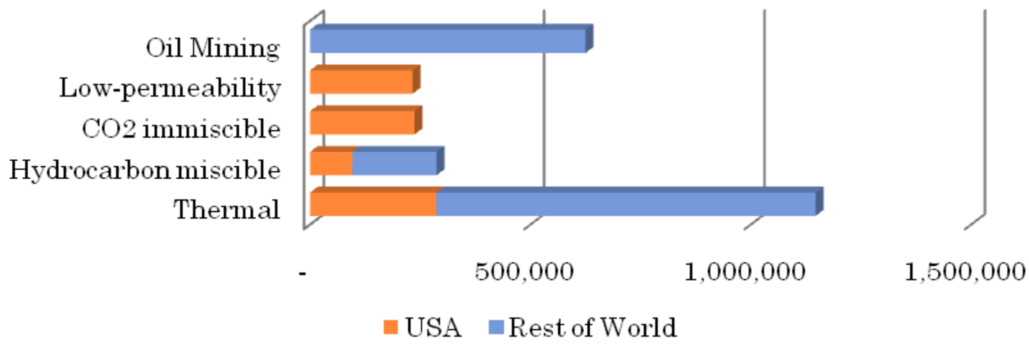
Although it is very difficult to assign reserves to unconventional light oil reservoirs, the volume of oil in place is thought to be very large. The United States Geological Survey estimates that the Bakken Shale in North Dakota and Montana contains 416 billion barrels of oil in place. The low recovery factor provides incentives for future technological improvements.

Table 1 World Enhanced Oil Recovery

2006 Barrels per Day	USA	Rest of World	Global
Thermal	286,668	860,629	1,147,297
Hydrocarbon miscible	95,800	191,514	287,314
CO2 immiscible	237,013		237,013
Low-permeability	232,860		232,860
Oil Mining		625,000	625,000
Total	**852,341**	**1,677,143**	**2,529,484**

Data sources: Oil and Gas Journal, Alberta Energy and Utilities Board

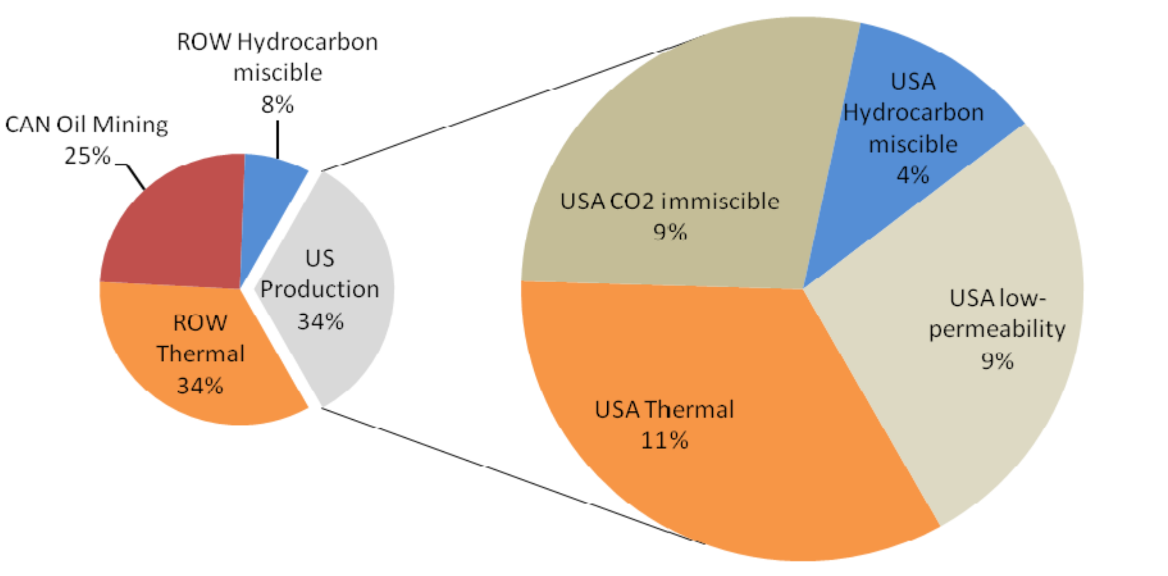
Figure 1 **2006 World Enhanced and Unconventional Oil Production**



Data Sources: Oil and Gas Journal, Alberta Energy and Utilities Board

Looking at the US (right pie graph) in Figure 2 below, the picture is quite different with no oil mining and a major role played by carbon dioxide injection and unconventional reservoirs. These last two categories are still less important than steam injection, but will probably exceed it in the next few years as major California steamflood projects decline. Miscible hydrocarbon injection shown in the figure is entirely in Alaska and two deep-water Gulf of Mexico fields.

Figure 2 **Distribution of US Production Methods** (right) of **Global Enhanced and Unconventional Oil Production** (left)



Data Source: Oil and Gas Journal

Data Sources and Consistency

Our cornerstone source for this study is biennial EOR survey in the Oil and Gas Journal. This survey has the advantage of covering the world and including a range of technologies, but participation is voluntary, so the survey underreports EOR activity. The survey also does not include mine production of heavy oil in Alberta, which is available from the annual report of the Alberta Energy and Utilities Board. Production from Venezuela's heavy oil belt is not included in the Oil and Gas Journal survey except for a small steam pilot project because the commercial production does not involve any EOR technology. Another problem with the Oil and Gas Journal survey's Venezuela data is that it shows the same production increment (199,578 barrels per day) from thermal EOR in 2000, 2002, 2004 and 2006. This cannot be true, and we predict it is likely that these projects are declining.

Compiling data from difference sources for this study was complicated in that our sources incorporate varying degrees of data aggregation. For example, the Alberta Energy and Utilities Board disaggregates oil sands production between mine production and in-situ production, but does not separate steam-enhanced production such as is reported in the Oil and Gas Journal.

Data for unconventional reservoirs is based upon the US Energy Information Administration and state regulatory agencies. Unconventional reservoirs are not usually singled out as a separate category, but continuous accumulations in the US are usually listed as single fields, such as Wattenberg or Spraberry. The data from the Energy Information Administration does not agree with the state data. We found it intriguing that, in all cases, the federal production figures are higher.

EOR Trends

Thermal enhanced oil recovery is an important technology for developing the huge heavy oil resources of Canada and Venezuela. Most of the thermal enhanced oil recovery projects listed in the oil and gas journal survey are located in five areas; California, Alberta, Sumatra, China or western Venezuela.

Table 2

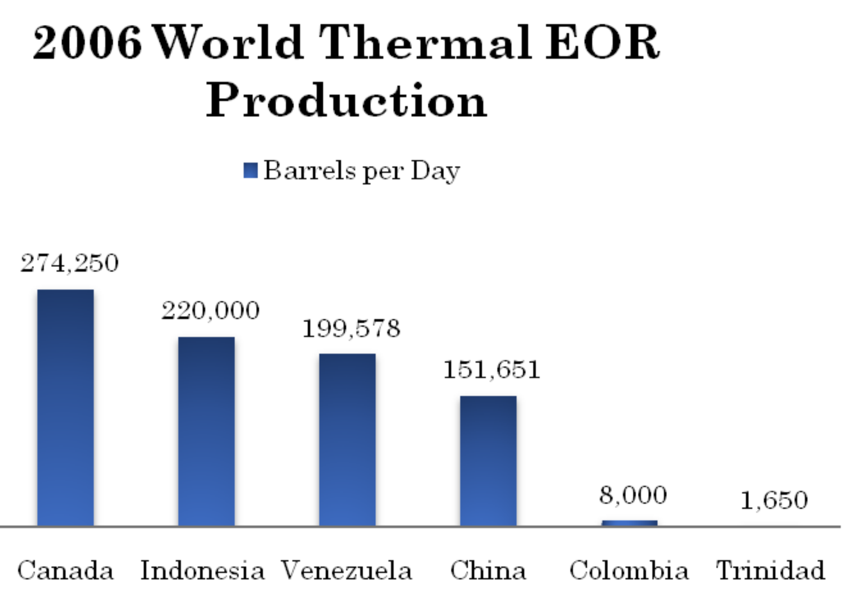
Termal EOR	Barrels per Day
US	286,668
Canada	274,250
Indonesia	220,000
Venezuela	199,578
China	151,651
Colombia	8,000
Trinidad	1,650

Incremental production from thermal EOR in the **United States** showed a declining trend due to the depletion of major California fields since 1985. The Oil and Gas Journal survey shows a decline of 34.7% from 1998 to 2006. Data from the California Division of Oil and Gas show the same trend, declining 29.9% from 1998 to 2005. Total US incremental production from steam injection was 286,668 barrels per day in 2006 according to the Oil and Gas Journal.

Most of the growth in steam-enhanced oil production in recent years has come from **Canada**. The largest part of this growth has been SAGD and cyclic steam projects in the oil sands. Incremental production from steam injection in Canada was 274,250 barrels per day in 2006 according to the Oil and Gas Journal.

Indonesia's thermal enhanced oil recovery comes from only one project, but it is the world's largest. The Duri Field in central Sumatra is an ideal candidate for steamflood; it is shallow and it contains high-wax crude that is almost solid at reservoir conditions. A modest elevation in reservoir temperature causes a dramatic reduction in the viscosity of the waxy crude. Incremental production from steam injection at Duri was estimated at 220,000 barrels per day in 2006.

Figure 3



Data Source: Oil and Gas Journal

Thermal enhanced oil recovery in **Venezuela** is concentrated along the eastern shore of Lake Maracaibo in Zulia state. According to the Oil and Gas Journal, Zulia accounted for 89% of Venezuelan thermal EOR in 2006. The heavy oil belt in Eastern Venezuela includes the 400 barrels per day of steam-enhanced production at Cerro Negro that is reported in the Oil and Gas Journal survey. The incremental production from steam in Venezuela is the same (199,578 barrels per day) in all of the Oil and Gas Journal surveys from 2000 through 2006. This cannot be the case, so looking for production trends is meaningless. All steam injection in Venezuela is cyclic and huge steamflood potential in the Lake Maracaibo area remains untapped.

China uses steam injection in several fields in Liaohe (eastern China) and Xinjiang (western China). Incremental production from steam injection in China was 151,851 barrels per day in 2006 according to the Oil and Gas Journal.

Miscible carbon dioxide injection shows rapid growth in the US. Between 1998 and 2006, incremental production from carbon dioxide grew 31.7% to 237,000 barrels per day according to the Oil and Gas Journal surveys. This technique is almost unique to the US, where it is used on a large scale in the Permian Basin of Texas and New Mexico, the Bighorn Basin of Wyoming, and the Rangely Field of Colorado. Denbury Resources uses carbon dioxide injection in the Mississippi Salt Basin because they own the only carbon dioxide field in the area. Carbon dioxide availability is greatest in the Rocky Mountains, where it occurs naturally, and the Permian Basin, where it is separated from natural gas. Carbon dioxide from the Great Plains Coal Gasification project is injected into the light oil field at Weyburn in Saskatchewan.

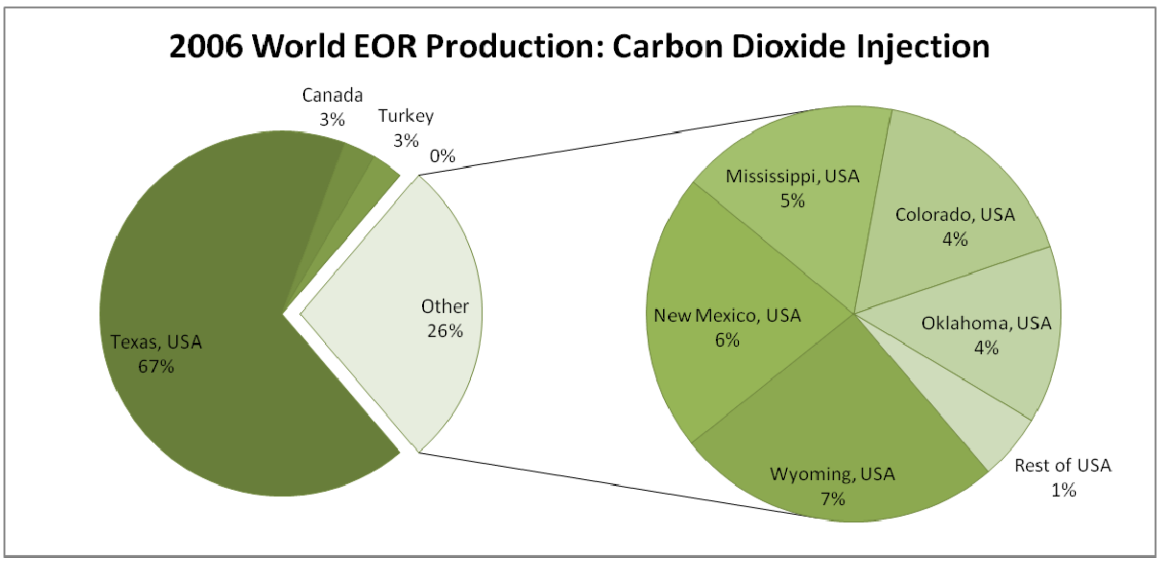
The potential for carbon dioxide injection in the Middle East and North Africa is very large. Carbon dioxide fields are present in Iran, but have not been developed for enhanced oil recovery yet. The potential for carbon dioxide injection worldwide is so large that petroleum engineers are puzzled to read climate science journal articles mentioning other methods of sequestering carbon dioxide emissions when there is plenty of demand in the oil sector.

Table 3: Carbon dioxide EOR

CO2 Injection	Barrels per Day
Texas, USA	167,956
Canada	7,200
Turkey	7,000
Wyoming, USA	17,640
New Mexico, USA	14,950
Mississippi, USA	11,745
Colorado, USA	11,600
Oklahoma, USA	9,548
Rest of USA	3,574

Data Source: Oil and Gas Journal

Figure 4



Miscible hydrocarbon injection is mostly used in Canada and Alaska. Also, deep oil fields in the El Furrial, Carito and Musipan areas of eastern Venezuela. Alaska and Venezuela have stranded gas of little value, and firms have found it worthwhile to inject the fields as means to saves them for possible future use. Increases in the price of natural gas and propane in Canada have discouraged this approach and production is declining.

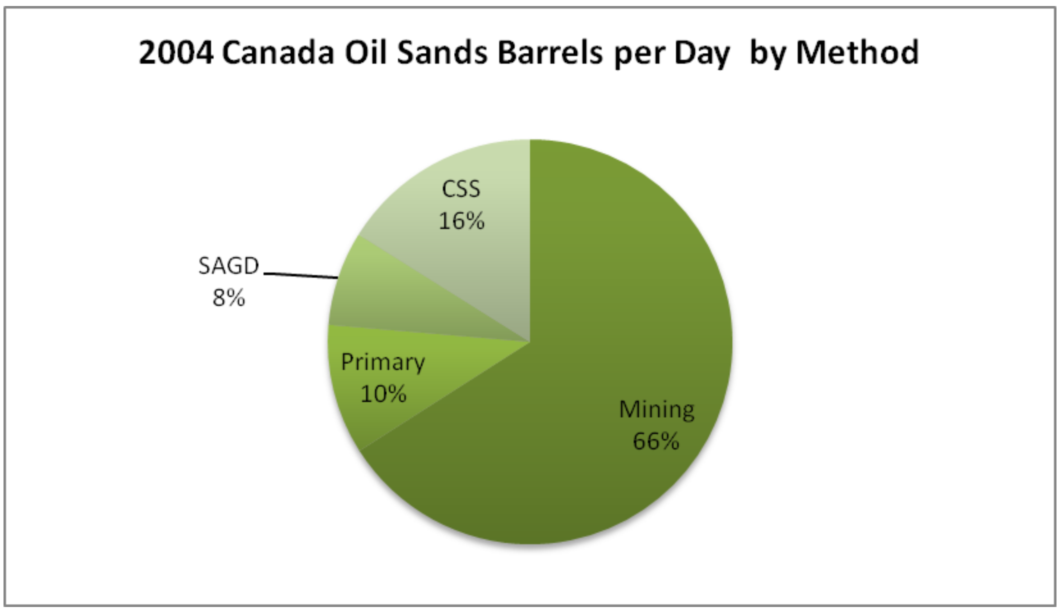
Oil Mining in Alberta was one of the most important technologies, accounting for 625,000 barrels per day in 2005. This was a decline from 709,000 barrels per day in 2004, but there has been a trend of steadily increasing production and several large mines are at the planning and development stage. Oil mining has been tried on a pilot scale in California at McKittrick and oil sands have been mined for asphalt in many areas, but mining as an oil production method is unique to Alberta at present. **Figure 5** below shows the dominance of mining in Canada's oil sands production. This dominance will have to change with time; of the 174 billion barrels of oil estimated to be recoverable by the Alberta Energy and Utilities Board, 25 billion are mineable and the rest must be recovered by in-situ methods, mostly SAGD and cyclic steam.

Table 4: Alberta Oil Sands Production by Location and Method

Location	Method	Barrels per Day
Athabasca	Mining	704777
Athabasca	Primary	39165
Athabasca	SAGD	71833
Cold Lake	CSS	171967
Cold Lake	Primary	64773
Cold Lake	SAGD	794
Peace River	Primary	7087
Peace River	SAGD	8080

Data Source: Alberta Department of Energy

Figure 5



Information source: Alberta Department of Energy

No discussion of oil mining is complete without addressing **oil shale**. Oil shale contains up to 20% organic matter by weight in individual specimens, but average organic matter content is about 5% by weight. The normal cutoff for oil mining projects in Alberta is 10% heavy oil by weight. No oil shale in the world makes the cut. Besides the lower oil yield per ton of rock, oil shale must be heated to crack the large kerogen molecules into oil. Oil shale occurs in oilshort countries such as Israel, Jordan and Thailand, but it has not been a commercial success in spite of many pilot projects.

Primary production of heavy oil is an alternative approach for holders of extra-heavy oil reserves, but it is not an enhanced recovery method. In 2005, Canada produced 111,000 barrels of bitumen per day from the oil sands by primary production and Venezuela produced 622,000 barrels per day from the Faja del Orinoco by primary production. The steam-enhanced production in the Faja del Orinoco is limited to one project of 400 barrels per day. The reasons for using primary production are low capital cost and low operating cost. Numerous small operators in Alberta use primary production because SAGD or mines are out of their price range. Petroleos de Venezuela (2005) reports that operating costs in the Faja del Orinoco averaged $0.95 per barrel, down from $1.50 in 2000 and comparable to onshore light oil production. PDVSA attributes the decline in operating cost to increased per-well productivity from combining multilateral horizontal wells with progressing-cavity pumps.

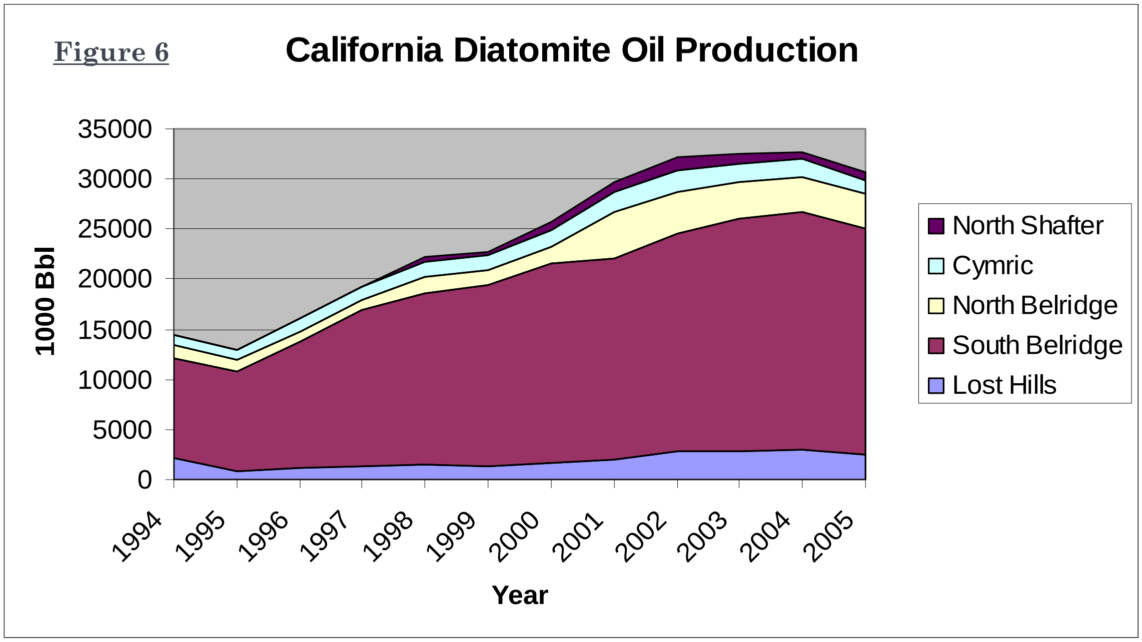
The direct operating costs in the Alberta oil sands are an order of magnitude higher than in Venezuela. Since the Alberta and Venezuela heavy oil accumulations are the largest hydrocarbon deposits in the world and are of comparable size, the economic significance of the Venezuelan heavy oil becomes clear. Because primary production is relatively simple, the rate at which Venezuelan heavy oil can be brought on stream is limited by the rate of growth of upgrading capacity, not production capacity.

Unconventional Oil Reservoir Trends

Production of oil from continuous accumulations is predominantly a US technology. This will change with time because many continuous oil accumulations exist outside of the US. Lopatin et al (2003) describe unconventional production from the Bazhenov Shale, which is the source of nearly all of the oil and gas in the West Siberian Basin. This is the world's second most important oil-producing basin and the world's most important gas-producing basin, so it is potentially an important development. Production data were gathered for five major US unconventional reservoirs; the Monterey Diatomite, the Spraberry, the Bakken Shale, the Codell/Niobrara and the Austin Chalk.

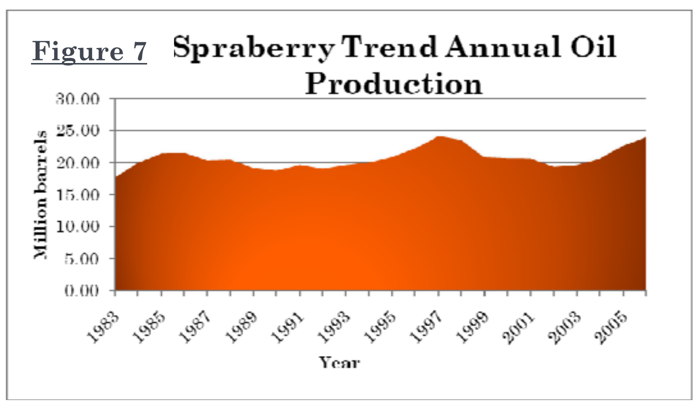
The **Monterey Diatomite** in California was the most important unconventional oil reservoir in the United States in terms of 2005 production, accounting for 30.6 million barrels. This study only includes production from the five largest fields; South Belridge, North Belridge, Lost Hills, Cymric and North Shafter. Only the diatomite production is included. Naturally fractured diatomaceous shales such as produce onshore at Orcutt or offshore at Hondo are not included because they require no specialized technology for their production, rendering them conventional. Diatomite oil production from the five fields showed strong growth from 1995 to 2004, but declined in 2005. The critical technologies for producing from the diatomite are artificial fracturing and water or steam injection. Diatomite is characterized by high porosity but low permeability.

The diatomite oil is light, typically around 30° API, so increased diatomite oil production from 1995 to 2004 is reason that the proportion of light oil in California's production increased during that time. Preliminary 2006 production data suggest a continued decline in those fields, but do the data is too aggregated for a more thorough review.



Data source: California Division of Oil, Gas, & Geothermal Resources

In 2005, The **Spraberry Trend** in West Texas was the second most important unconventional oil reservoir in the United States. In 2006 it produced 23.93 million barrels, almost regaining its 1997 production peak of 24.08 million barrels. The Spraberry Trend ranked number 11 of US fields in oil production and number 26 in gas production in 2005. As shown in Figure 7 below, the Spraberry Trend has produced oil at high rates since before 1983. Although it requires artificial fracturing, the Spraberry does not require horizontal drilling, so high production rates were achieved earlier.



Data source: Texas Railroad Commission

Unlike many unconventional reservoirs, the Spraberry Trend is not self-sourced. It is a sandstone that has low permeability due to cementation. Roadifer (1986) estimates the original oil in place in the Spraberry Trend as 8.89 billion barrels.

The **Bakken Shale** in Elm Coulee Field, Montana, has rapidly become the third most important unconventional oil reservoir in the United States. In 2005, The Elm Coulee Field ranked number 18 on US oil production charts. We estimate that this rapid growth slowed or stopped in 2006 due to inadequate pipeline capacity forced operators to accept lower wellhead prices for 40° API Dakota sweet crude than what California operators get for 13° Kern River heavy oil.

The Bakken Shale was recognized as a major oil source rock years ago. The critical technology that made Elm Coulee a commercial success was fracturing of horizontal wells. Because a typical well has 4,000 to 8,000 feet of hole in the Bakken, it must be fractured in multiple stages. It is typical for the fracture job to cost as much or more than drilling the well.

The Bakken play is growing in North Dakota and Saskatchewan and it is not yet clear what the extent of the productive area will be. The production in Saskatchewan is interesting because the Bakken is not thermally mature there, yet it is still oil-saturated. Several published estimates of oil in place in the Bakken exceed 200 billion barrels. The North Dakota Geological Survey puts that much in North Dakota alone and the USGS gives a most likely value of 416 billion barrels in North Dakota and Montana. How much of this can be recovered remains to be seen, but the Bakken Shale is one of the most exciting developments in US oil supply.

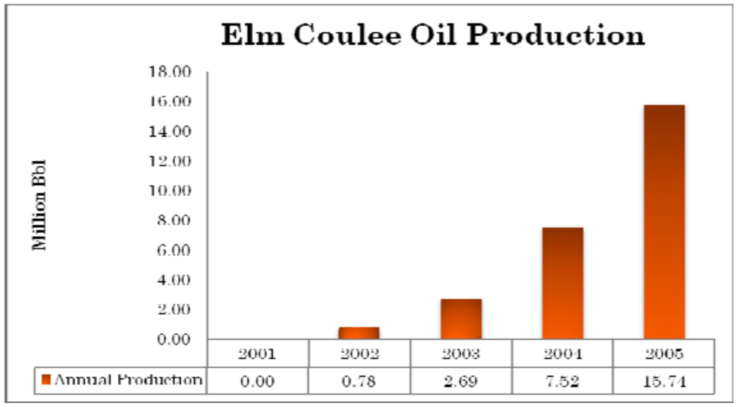


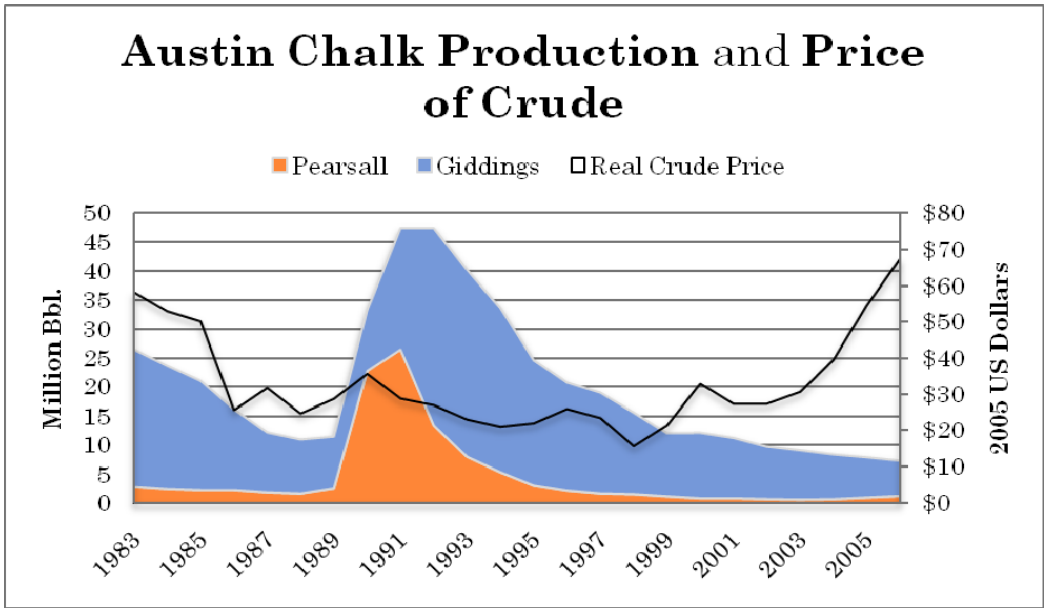
Figure 8

Data source: Montana Department of Natural Resources and Conservation

Colorado's **Wattenberg** Field produced 10.36 million barrels in 2006, mostly from the Codell and Niobrara formations. It is located in the center of the Denver Basin and has no structural closure. Oil production from Wattenberg was almost double the level of 1999 and fifteen times the level of 1983. This is a good example of the difficulty in assessing unconventional reservoirs; larger oil companies would have bought in to Wattenberg years ago if they had any idea how big it was. The Wattenberg Field ranked number 26 in the US in oil production and number 9 in gas production in 2005.

Oil production from the **Austin Chalk** has declined dramatically from 40.04 million barrels in 1993 to 7.20 million barrels in 2006, according to data from the Texas Railroad Commission. Giddings, the largest Austin Chalk accumulation, ranked number 35 in the US in oil production and number 18 in gas production in 2005. The Austin Chalk is believed to be the source of mot of the oil in the Texas Gulf Coast as well as the giant East Texas Field.

The production history of the Austin Chalk illustrates the impact of technological change, where the dramatic increase in production from 1989 to 1993 was a result of the introduction of horizontal drilling. Before that, drilling in the Austin Chalk was risky because vertical wells often failed to intersect natural fractures and wouldn't produce oil.



Data source: Texas Railroad Commission

Importance of Unconventional Gas Reservoirs

Figure 9

It is not a stretch to contribute production from unconventional reservoirs as the American innovation that rescued the domestic US gas supply from depletion. Thus far, unconventional gas reservoirs show greater successful than unconventional oil reservoirs. Table 5 below shows the eight most important unconventional gas fields and their 2005 production rank among all US gas fields. Note that 8 of the top 11 gas fields are unconventional. This is important for three reasons; it provides hope that unconventional oil may also become more important, natural gas can also be used as a transportation fuel, and natural gas liquids make excellent transportation fuels.

According to the EIA, two unconventional gas fields ranked among the top 100 US liquids producing fields, Pinedale (#69, 3.5 million Bbl) and Jonah (#84, 2.6 million Bbl). Both are located in Sublette County, Wyoming. Unconventional reservoirs are often difficult to identify, which is why it took until 2002 to discover what is now the second largest gas field in the United States even though it underlies much of the city of Fort Worth, Texas.

Table 5: Major US Unconventional Gas Fields

Rank	Name	State	Discovery	2005 Production (Bcf.)
1	San Juan Basin	NM, CO	1927	1397
2	Newark East	TX	2002	496.5
4	Pinedale	WY	1955	457.3
5	PRB Coalbed	WY	1992	336.1
6	Jonah	WY	1977	273.1
7	Carthage	TX	1981	214.1
9	Wattenberg	CO	1970	179.1
11	Antrim	MI	1965	164.9

Data source: Energy Information Administration

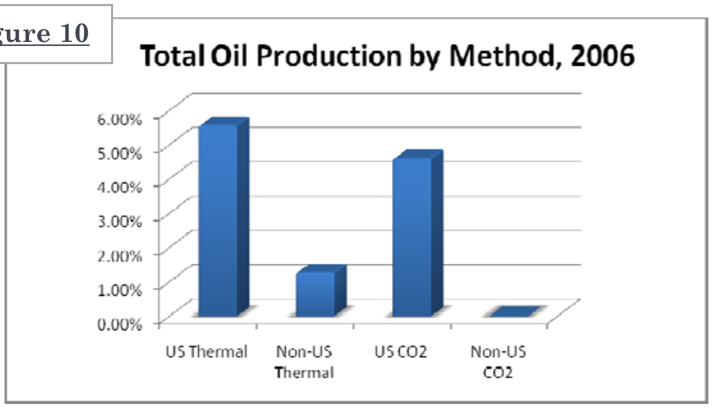
CONCLUSIONS

Enhanced oil recovery and unconventional reservoirs only account for a small part of world oil production now. The methods described in this study produce a combined 2.5 million barrels per day worldwide. Although total oil production from these sources is increasing, trends within these broad categories range from rapid increase to rapid decline. Truly impressive growth is seen from carbon dioxide injection, as well as the Elm Coulee and Wattenberg unconventional oil reservoirs. The largest declines were in steam enhanced recovery in the US and in the Austin Chalk unconventional reservoir.

Looking at the production histories suggests that new increments of US oil production occur immediately after enabling technological developments, even in periods of low oil prices. An example of this is the Austin Chalk, which was not generally economical until the widespread use of horizontal drilling in the late eighties. Its production rapidly increased to the 1993 peak and then declined.

On a more optimistic note, the almost complete absence of oil production from carbon dioxide injection or from unconventional reservoirs outside the US indicates that these technologies have a bright future as they expand to the rest of the world. Carbon dioxide injection may still be at an early stage of development in the US, as many fields have passed basic screening criteria and are waiting for carbon dioxide supplies. Additionally, many oil producing countries have contract terms that do not encourage costly approaches such as carbon dioxide injection or horizontal drilling in low-permeability. reservoirs.

Figure 10



To show the potential of expanding these technologies outside the United States, one can compare the technologies' share of total US oil production to their share of total world oil production, as in Figure 10 above. Using 2006 oil production numbers from the Oil and Gas Journal, the US produced 5.143 million barrels per day in 2006. The rest of the world produced 67.43 million barrels per day. Thermal EOR contributed 5.6% of US oil production, but only 1.3% of the rest of the world. Carbon dioxide EOR production contributed 4.6% of US oil production, but only 0.01% of the rest of the world. Low permeability reservoirs accounted for 4.5% of US oil production in 2005. Increasing the rest of the world to the same proportions as the US would add 2.9 million barrels per day of thermal EOR production, 3.1 million barrels per day of carbon dioxide EOR production and 3.1 million barrels of production per day from low permeability reservoirs. In aggregate, these three methods could equal Saudi Arabia's conventional oil production.

This projection, however, is too conservative because the thermal EOR potential in Alberta alone is at least 2.9 million barrels per day. Additionally, much of carbon dioxide potential has yet to be developed in the US. The limits to carbon dioxide EOR and unconventional reservoirs are still being explored in the US lower-48. Although unconventional reservoirs outside the US are poorly documented, a well-known example is Mexico's Chicontepec Trend. Roadifer (1986) estimates the oil in place at Chicontepec to be 100 billion barrels. This is much larger than Spraberry's -- the unconventional reservoir examined in this study that most resembles Mexico's Chicontepec.

Table 6 below lists the world's largest known hydrocarbon accumulations in order of original oil in place. This shows the importance of heavy oil and tar sands, especially when one considers that steamfloods often recover as much as 70% of the oil in place, more than most light oil fields. Dr. Roadifer was the chief geologist of the Mobil Oil Corporation, and was sure to have had an impressive data collection. Even so, the below list most likely undercounts unconventional reservoirs given that his estimations were made in 1986.

Table 6: World's Largest Hydrocarbon Accumulations by Oil in Place

Name	Type	Country	OOIP (Billion Bbl)
Orinoco	X-Heavy Oil	Venezuela	1,200
Athabasca	Tar Sand	Canada	869
Cold Lake	Tar Sand	Canada	271
Ghawar	Oil Field	Saudi Arabia	190
Burgan	Oil Field	Kuwait	190
Bolivar Coast	Oil Field	Venezuela	160
Melekess	Tar Sand	Russia	123
Wabasca	Tar Sand	Canada	119
Chicontepec	Unconventional	Mexico	100
Peace River	Tar Sand	Canada	92

Data source: Roadifer (1986)

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