CARBON DIOXIDE IN WYOMING

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What is carbon dioxide?

Carbon dioxide (CO_2) in its natural state is a colorless, odorless, non-explosive gas, the common product of burning carbon-containing fuels and respiration of animals. Carbon dioxide cycles through the earth by continually entering the atmosphere in a variety of ways (e.g., animal respiration, volcanic activity, natural and man-made combustion, etc.) and continually being removed by photosynthesis in plants, deposited by forming organic-rich or carbonate rocks, and by forming the calcium carbonate shells of marine animals. It exists in solid form (dry ice) at 1 atmosphere at -78.5ºC (*Figure 1*). Above this temperature, it sublimates (turns directly back into the gaseous state). At 1 atmosphere, only solid and gaseous carbon dioxide forms can exist. Liquid carbon dioxide can only exist at pressures higher than 5.2 atmospheres (*Figure 1*). At room temperature, the gas must be compressed to about 16 atmospheres to become liquid.

Where is carbon dioxide found?

Carbon dioxide is present in the atmosphere to the extent of about 0.03%; it is about 1.5 times more dense than air. Large amounts of the gas are found dissolved in

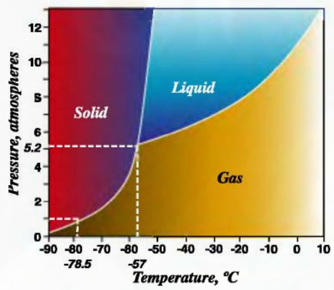

Figure 1. Phase diagram of carbon dioxide showing its triple point. Modified from Sienko and Plane, 1971.

the waters of some geysers and mineral springs. Carbon dioxide is a common component of natural gas, with a concentration between 1 and 2%. However, the high concentrations (greater than several percent, which requires removal before methane can be used commercially) and large quantities of carbon dioxide that occur in Wyoming are uncommon.

Why are there high concentrations of carbon dioxide in Wyoming?

The higher concentrations and larger quantities of carbon dioxide in some Wyoming natural gas reservoirs probably resulted from more than one of the following processes:

1) Carbon dioxide gas could have migrated from Quaternary intrusive volcanic rocks on the northern end of the Rock Springs uplift (the Leucite Hills volcanic field) into Paleozoic reservoirs in the Greater Green River Basin (Stilwell, 1989). Carbon dioxide is generally the principal carbon-based gas from fumeroles in volcanic areas (Krauskopf, 1967).

2) Thermal degradation of liquid hydrocarbons forms carbon dioxide along with methane, water, nitrogen, and hydrogen sulfide (H_2S) (Orr, 1974).

3) Anhydrite (anhydrous calcium sulfate) can provide sulfate anions that react with methane (CH_4) to form carbon dioxide and hydrogen sulfide (Hill, 1990). Anhydrite is present in most Paleozoic formations in Wyoming and could easily contact methane in gas reservoirs.

4) Sulfuric acid forms when hydrogen sulfide is oxidized. The sulfuric acid in turn reacts with carbonates to produce carbon dioxide (Hill, 1990). Paleozoic formations in Wyoming contain large amounts (or are composed entirely) of carbonate rocks and most natural gas reservoirs with high carbon dioxide concentrations contain hydrogen sulfide as well.

What are the uses for carbon dioxide?

Solid carbon dioxide sublimes (changes directly from solid to gaseous state, without going through an intermediate liquid state) at -173º F (-78.5ºC) under 1 atmosphere of pressure. This form of carbon dioxide is a convenient, clean refrigerant called dry ice. Water saturated with carbon dioxide at 3 to 4 atmospheres of pressure is called carbonated water, and is the foundation for the huge soda-water beverage industry. Carbon dioxide does not support combustion and gaseous or liquid carbon dioxide under about 60 atmospheres of pressure in cylinders is used to extinguish fires. Gaseous carbon dioxide is also used to prepare food, to purge tanks and pipelines, to manufacture aspirin, to weld, to propel aerosols, to stimulate respiration, to manufacture carbonates, and to produce an inert atmosphere.

In Wyoming, another very significant use for produced carbon dioxide is in enhanced oil recovery (EOR) projects. Some EOR projects inject liquid carbon dioxide to recover additional oil left behind in reservoirs. Typically, 50 to 60% of the original oil is left in the reservoir rocks after primary and secondary operations are completed. This remaining oil is the target for EOR operations, which include injection of carbon dioxide.

Where are the main sources of carbon dioxide in Wyoming?

Several reservoirs in large existing gas fields in Wyoming have relatively high concentrations and contain significant resources of carbon dioxide in their natural gases. In 1961, Mobil Oil Company discovered very large carbon dioxide resources in the Madison Limestone (*Figure 2*) as well as in several other Paleozoic-age formations at La Barge anticline in southwestern Wyoming (*Figure 3*). However, development of these resources by Exxon Corporation (now ExxonMobil) did not begin until the La Barge gas processing plant was completed in late 1986. The La Barge plant (*Cover photograph*) produces approximately 435 million cubic feet (MMCF) of carbon dioxide and 135 MMCF of methane per day. Only about 250 MMCF per day is saleable because of limited compression capacity. The plant also processes H_2S into sulfur from the raw gas. The plant is the largest sulfur producer in Wyoming and the largest helium producer in the U.S.

In 1985, Monsanto Oil Company discovered large carbon dioxide resources in the Madison Limestone at Madden anticline (*Figure 3*) in the northern Wind River Basin (Brown and Shannon, 1989). Burlington Resources is now developing this resource (*Figure 4*). Four wells produce natural gas from the Madison Limestone below 24,000 feet; several more wells are planned. This gas production is the deepest in the Rocky Mountain region. The Lost Cabin gas processing plant (*Figure 5*) that was built to process this gas is presently producing approximately 90 MMCF of methane along with 25 MMCF of carbon dioxide per day An expansion of the plant, scheduled for completion in 2002, will increase output of carbon dioxide to approximately 60 MMCF per day.

When is carbon dioxide used in oil fields?

Primary production occurs after a well is completed. Production from the reservoir is by natural energy (gas cap, solution gas, or water drive) that results in flowing wells, or wells on a pump with oil flowing freely by gravity to the well bore. As production proceeds, energy is lost and a natural decline occurs (*Figure 6*). Secondary production is the extraction of oil from a field beyond what can be recovered by normal methods of flowing or pumping. Water flooding and gas injection are two secondary methods. As oil left from primary production is contacted by the injected fluid, production peaks and then declines. Tertiary production from carbon dioxide once

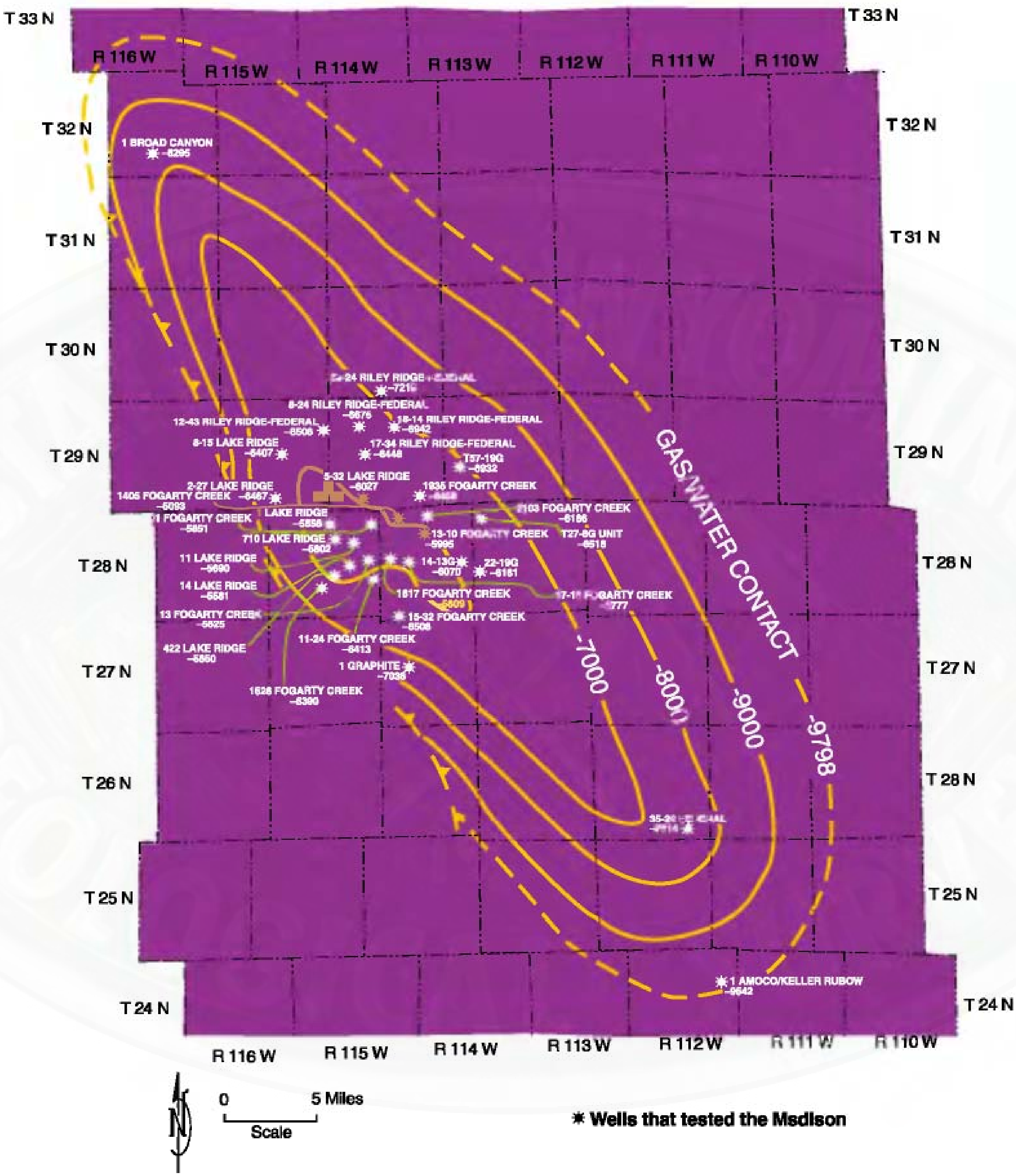

Figure 2. Structure contour map drawn on the top of the Madison Limestone at La Barge anticline (modified after Stilwell, 1989; from De Bruin, 1991).

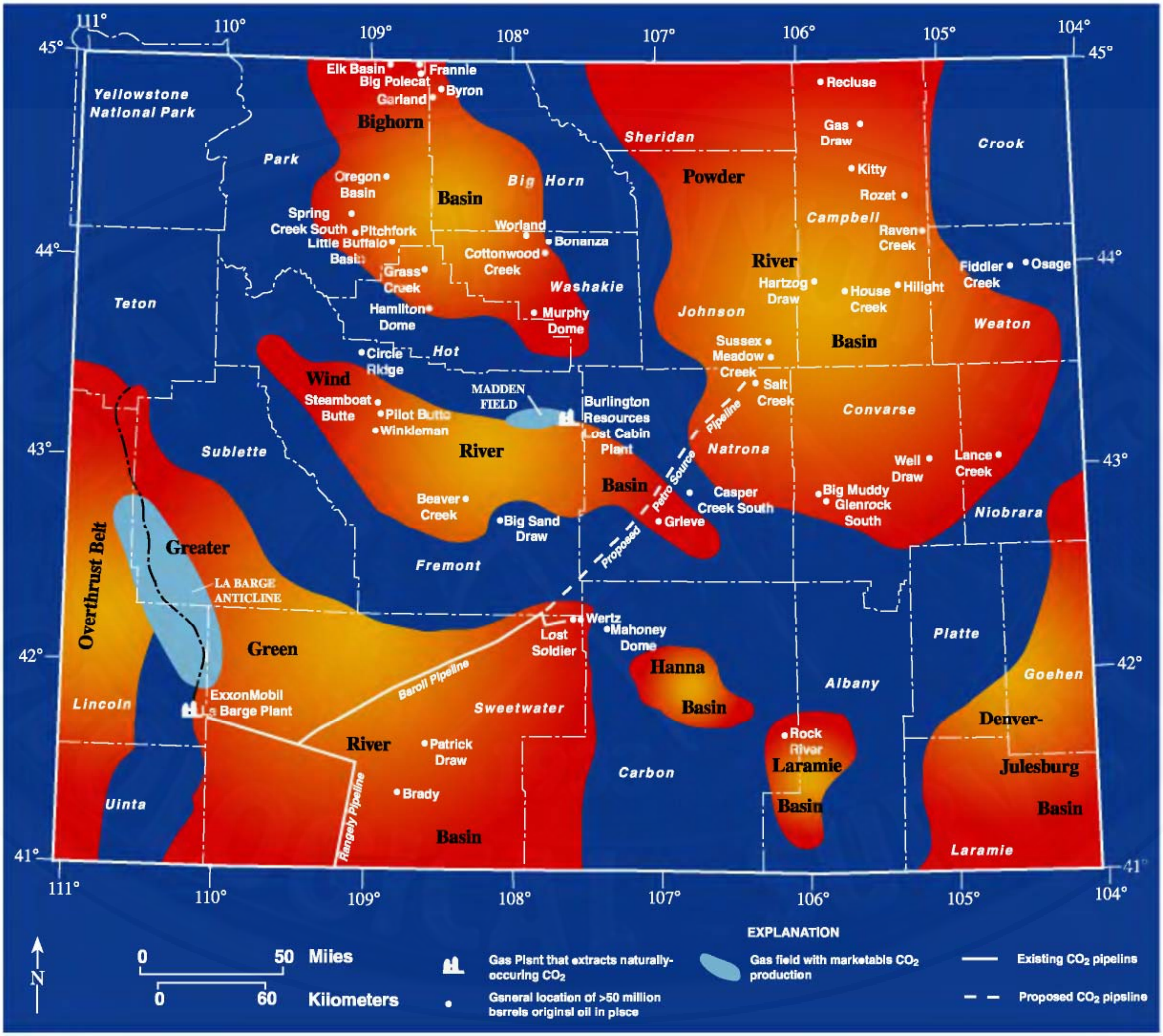

***Figure 3.** Fields and facilities in Wyoming related to carbon dioxide production, locations of current enhanced oil recovery operations that use carbon dioxide, and major oil fields that had 50 million or more barrels of original oil in place.*

again increases production and then production declines to an uneconomical limit.

How does a carbon dioxide flood recover additional oil?

There are several ways that carbon dioxide reacts within an oil reservoir to increase recovery. The most important mechanisms are: 1) Viscosity reduction of the oil; 2) volumetric increases within the reservoir; 3) blowdown recovery/solution gas drive, and 4) permeability increases in carbonate reservoirs. These mechanisms are discussed below.

Viscosity reduction

Unlike water, liquid carbon dioxide and crude oil are miscible (two fluids are miscible when they can be mixed together and they form one phase–i.e., there are no visible contacts between the two fluids and no interfacial tension). When carbon dioxide is introduced into an oil reservoir, it dissolves in the oil. This reduces the viscosity (a fluid's resistance to flow) of the crude oil from 10 to 100 times. The decreased oil viscosity makes the oil-carbon dioxide mixture more mobile, which results in increased sweep efficiency when producing the reservoir.

Volumetric Increases

Depending on the pressure, temperature, and composition of the crude oil, up to 700 cubic feet of carbon dioxide will dissolve in one barrel of crude oil, giving a 10 to 40% increase in the oil volume. The residual oil saturations left behind the displacement front (when carbon dioxide is injected into the reservoir) will be in the swollen state and consequently will occupy more reservoir volume than untreated oil. In effect, carbon dioxide rather than oil will occupy some of the original oil volume in the reservoir.

Blowdown recovery

This mechanism allows for additional oil recovery when the pressure of a reservoir is reduced after the carbon dioxide flood is terminated. As the reservoir pressure is reduced, carbon dioxide comes out of solution in gaseous form, and provides a solution gas drive which aids in the recovery of additional crude oil.

Permeability increases in carbonates

Experiments have shown that the permeability of carbonates increases when

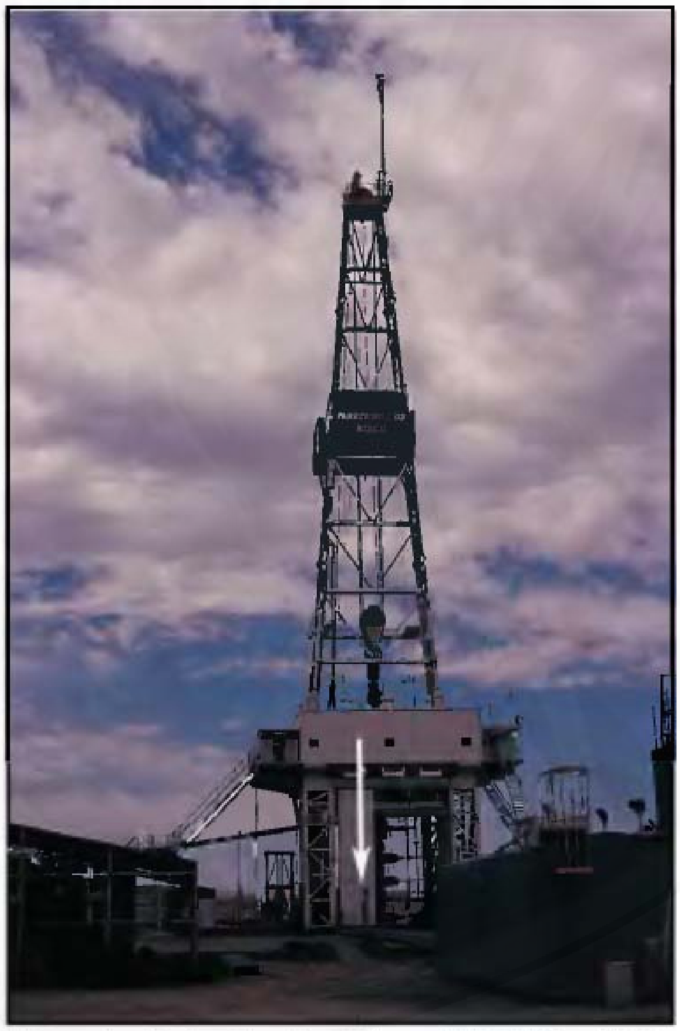

Figure 4. Parker Brothers' (now Unit Drilling's) Rig No. 201 on location at a Madden deep test. The ultra-deep rig is one of the largest land-based drilling rigs in the world, capable of drilling to depths of 30,000 feet. Arrow points to man standing at ground surface, some 50 feet below the rig floor. Photograph by Rodney H. De Bruin, summer, 1996.

carbon dioxide is introduced into the reservoir. Carbon dioxide injection ("flood") may cause a significant permeability increase in the immediate vicinity of the injection well (*Figure 7*), which may increase the efficiency of the flood. It should be noted that some crude oils might deposit asphalts when contacted by carbon dioxide. Crude oils from the field where a carbon dioxide flood is contemplated should be tested for this effect before a flood begins.

What criteria determine if a field can successfully be flooded with carbon dioxide?

Two preliminary factors determine if a carbon dioxide flood will be successful: the amount of crude oil left in the ground after waterflooding; and the ability of the carbon dioxide to contact the crude oil. Usually, good waterflood reservoirs are also good candidates for carbon dioxide floods. A good reservoir description and an understanding of a reservoir's previous production performance will help in estimating how well carbon dioxide will contact the residual oil.

High inter-well continuity, laterally and vertically uniform reservoir rock, a high frequency of vertical flow barriers, and high permeability are properties that make for carbon dioxide flood success (Exxon Company USA, 1986). Additional general screening guidelines include a reservoir depth of at least 2500 feet, an oil gravity of at least 27° API (American Petroleum Institute), an oil viscosity of less than 12 centipoise (a measure of viscosity expressed as 1/100 dyne-second per square centimeter), and a residual oil saturation after waterflood of at least 20% in those areas swept. In most cases, these guidelines can be modified if one or more of the parameters are favorable for a carbon dioxide flood, i.e., higher oil gravity or lower oil viscosity.

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Figure 5. The Lost Cabin gas processing plant (left background) and construction site for the plant expansion project (right). Photograph by Jim Eckroth, courtesy of Burlington Resources, March 2001.

How much carbon dioxide does it take to produce a barrel of oil, and how much Wyoming oil can be recovered with this process?

Generally it takes 6 to 10 thousand cubic feet (MCF) of gaseous carbon dioxide to produce one barrel of oil. The 400 MMCF per day of carbon dioxide produced at ExxonMobil's La Barge gas plant could increase Wyoming's oil production by 40,000 to 67,000 barrels per day, assuming that enough oil fields can use this process. When the expansion of the Lost Cabin plant is complete in 2002, Wyoming will have an additional 60 MMCF of carbon dioxide production, which could increase oil production by an additional 6000 to 10,000 barrels per day.

Petro Source Corporation is planning to extend a pipeline from Bairoil to the Powder River Basin (*Figure 3*) to further utilize the carbon dioxide produced at the La Barge gas plant. The company estimates that oil fields in Wyoming that are candidates for a carbon dioxide flood contained a total of over 8 billion barrels of original oil in place. Major oil fields in Wyoming that had 50 million or more barrels of original oil in place (*Figure 3*), as well as many smaller fields in the state, would also be candidates for carbon dioxide flooding.

Carbon dioxide floods typically are successful in recovering 5 to 15% of the original oil in place. Assuming 8 billion barrels of original oil in place, this translates into 400 million to 1.2 billion barrels of additional producible oil that would otherwise be left in abandoned fields. To recover 400 million barrels of oil would require 2.4 to 4.0 trillion cubic feet (TCF) of carbon dioxide. To recover 1.2 billion barrels of oil would require 7.2 to 12 TCF of carbon dioxide. For com-

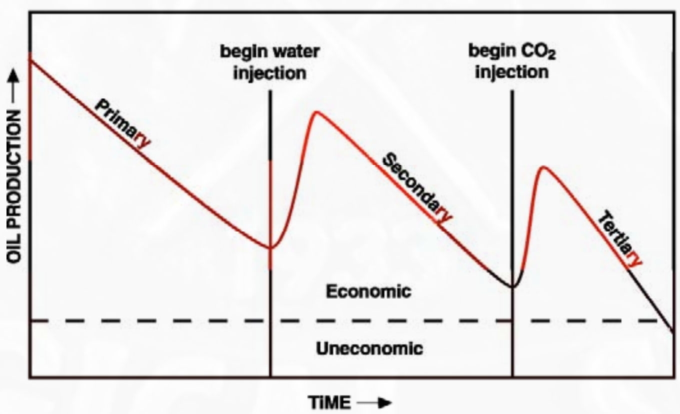

Figure 6. Production decline curves for an oil field showing production stages and effects of secondary and tertiary recovery techniques.

parison, cumulative oil production from Wyoming through the year 2000 was 6.7 billion barrels.

Does Wyoming have enough carbon dioxide to recover up to 1.2 billion barrels of additional oil?

Wyoming has abundant supplies of carbon dioxide. ExxonMobil operates one of the largest carbon dioxide-producing fields in the world at La Barge anticline (*Figure 3*). The company currently produces about 435 MMCF of carbon dioxide per day from 16 wells in the Madison Limestone at the Lake Ridge and Fogarty Creek units. The natural gas, which contains about 67% carbon dioxide, is processed at the La Barge gas plant (*Cover photograph* and *Figure 3*). De Bruin (1991) has documented Wyoming's carbon dioxide resources in several of the state's gas fields. The two most important areas in terms of reserves and current production are the La Barge anticline and the Madden Field (*Figure 3*). Through the year 2000, the two previously mentioned units on the La Barge anticline had already produced 2.0 TCF of carbon dioxide from the Madison Limestone. The Madison reservoir (*Figure 2*) underlies most of thirty townships and averages 400 feet thick. Remaining recoverable carbon dioxide, based on a 50% recovery rate is over 55 TCF. The Madison reservoir is much smaller at Madden Field and only contains 19% carbon dioxide. The reservoir only underlies about three townships and averages 145 feet thick. Remaining recoverable carbon dioxide, based on a 50% recovery rate, is slightly more than 0.5 TCF.

What are the major economic considerations for a carbon dioxide flood?

Probably the main economic consideration for a carbon dioxide flood is the price of crude oil. In general, a price of $18.00 per barrel of crude oil is required to make an economic carbon dioxide flood. A major cost in a carbon dioxide flood is the gas processing plant needed to handle produced hydrocarbon gas, high in carbon di-

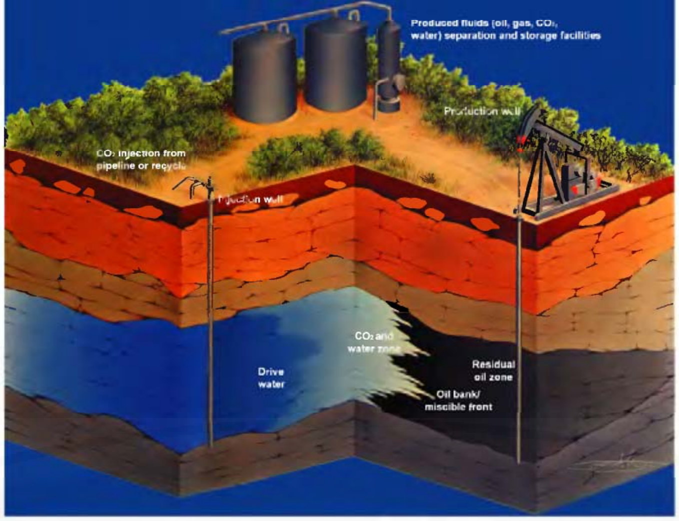

Figure 7. Schematic cross section of a typical carbon dioxide flood project and the surface facilities required. Diagram modified from Exxon Company USA (1986), used with permission.

oxide, that accompanies oil production. However, in many fields where the natural-solution gas production is low, the produced gas can usually be mixed with additional purchased carbon dioxide and reinjected without significant adverse effects (Exxon Company USA, 1986).

Other investments required for a carbon dioxide flood include a field carbon dioxide distribution system, possibly a gathering system, and wellbore work for carbon dioxide injection or production wells. Another major cost is for purchase of carbon dioxide and its associated transportation to the field. Other costs may include corrosion treating and added workovers on the wells.

The State of Wyoming presently has written an incentive for tertiary projects into its statutes. The pertinent statute reads that any tertiary project certified by the Wyoming Oil and Gas Conservation Commission by March 31, 2001 is exempt from two percentage points of the regular severance tax of 6% (severance tax is therefore 4% rather than 6%) on the produced oil. The 4% rate is in effect for five years from the date of first production. This incentive was not renewed by the 2001 Wyoming State Legislature, so new projects will be subject to the 6% tax rate.

Have carbon dioxide floods been tried in Wyoming?

The only carbon dioxide floods in Wyoming were tried at Lost Soldier and Wertz fields (*Figure 8*) at Bairoil. Oil was discov-

ered at Lost Soldier Field in 1916 by Bair Oil Company and at Wertz Field in 1920. In 1975, Amoco Production Company purchased the fields and initiated a waterflood. A plant to recycle carbon dioxide was finished in 1986 and injection of carbon dioxide originally purchased from Exxon began. Merit Energy Company purchased the property in 1999 and continues with carbon dioxide injection. Most EOR production from carbon dioxide injection at Wertz and Lost Soldier fields has been from the Tensleep Sandstone. Plans are to flood the Darwin Sandstone Member and Madison Limestone as well. Tertiary recovery from the Tensleep at the two fields so far has been 10% of the original oil in place (*Table 1*) (Don Spence, Merit Energy, personal communication, 2000). Carbon dioxide produced at La Barge is also pipelined to the Rangely Field, Colorado where it has been used with some success since the late 1980s.

Figure 8. The carbon dioxide processing plant at Bairoil recovers and recycles carbon dioxide (from La Barge) that is injected at Lost Soldier/Wertz Oil Fields. Photograph by A.J. VerPloeg, Wyoming State Geological Survey.

Table 1. Results of carbon dioxide flooding at the Lost Soldier and Wertz Fields, Wyoming. Source: Merit Energy, 2000.

Field	OOIP[1] MBO[2]	Primary & Secondary MBO	Primary & Secondary %OOIP	Tertiary Recovery MBO	Tertiary Recovery %OOIP
Lost Soldier Field	400,700	174,964	44	44,483	11
Wertz Field	208,900	95,169	46	17,245	8
Total Bairoil	609,600	270,133	44	61,728	10

[1]OOIP=original oil in place; [2]MBO=million barrels of oil.

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State of Wyoming agencies to contact about carbon dioxide:

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Cover photograph. ExxonMobil's La Barge natural gas plant. This plant processes about 435 million cubic feet (MMCF) of carbon dioxide and 135 MMCF of methane per day from gas wells on the La Barge anticline. Photograph courtesy of J.C. Knoll, ExxonMobil Production.