HEAVY-OIL RESOURCES OF THE UNITED STATES

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INTRODUCTION

Petroleum is considered to originate from marine and terrestrial organic matter (composed principally of hydrogen and carbon) buried along with sediment. The organic molecules are eventually broken by thermal stress encountered during progressive burial. The product of this heating can be liquid and(or) gas, which then moves out of the rock from which it originated and into nearby porous rock (reservoir) where further movement is curtailed by some type of trapping mechanism, such as an impenetrable rock layer. There the petroleum accumulation waits for discovery by exploratory drilling, or perhaps is subjected to additional geologic forces, such as faulting, and once again migrates closer to the surface of the Earth. Proximity to the surface increases the petroleum's susceptibility to interaction with circulating oxygenated waters and(or) bacteria, which may cause radical changes in the chemical makeup of the petroleum deposit and commonly results in heavy oil. Heavy oil makes up 9 percent of oil in the United States. California is the largest producer of heavy oil: 70 percent of California oil production is heavy oil.

Heavy oil, sometimes referred to as low-gravity oil, is defined here as oil with an API gravity of 10¡ to 20¡, inclusive. Physical and chemical properties, which differentiate it from higher gravity or light oil include viscosity, pour point, and chemical composition. They affect the producibility and the products that can be refined from it. "Heavy oil" often is applied to petroleum with a sulfur content higher than 2 percent by weight (Speight, 1991).

Heavy oil is often produced conventionally, (i.e., California); however, heavy oil is often unconventional in that the characteristics of the deposit may require special recovery methods which affect the cost of production. The recoverability of heavy oil is constrained by many factors. These characteristics include API gravity, transportation required, geological aspects, size of the deposit, depth of the deposit, technology required, and environmental impact. Biodegradation, resulting in heavy oil, ultimately has financial implications for an oil deposit because of the physical changes it imparts to the product. Bitumen in the reservoir can cause production problems by filling the reservoir porosity and preventing natural water drive from maintaining reservoir pressure. Where production of heavy oil is possible, it may be expensive or uneconomic.

When all other geologic and production conditions are equal, the reservoir size may be a more important factor for a deposit of heavy oil than it is for a deposit of lighter oil. This is because heavy oil incurs extra expenses in raising it up the well pipe and keeping it liquid during transport. The price of a barrel of heavy oil is $8.00 at this time (1994), (Toal, 1994), several dollars below that of lighter gravity oil.

ORIGIN OF HEAVY OIL

The origin of heavy oil is different from that of light or conventional oil. Conventional oil is the result of thermal cracking of organic molecules from the remains of marine algae and from some terrestrial plant material. Cracking occurs during burial and exposure to increasing temperatures encountered deeper in the Earth. Liquid hydrocarbons are believed to form within a limited temperature range informally referred to as the "oil window" (approximately 58-65¡C or 122-150¡F to 130-145¡C or 265-295¡F), which can occur within a range of burial depth depending on the local geothermal gradient. Geologists and geochemists examine organic material by optical and chemical means to determine its thermal maturity and to evaluate the remaining potential for the generation of petroleum from otherwise favorable hydrocarbon source rocks.

In most situations, increasing burial depth causes a maturation of the oil or progressive cracking of carbon chains, which results in an increase in lighter molecular weight hydrocarbons (i.e., a higher API gravity product). There are several hypotheses, though, for the origin of heavy oil. According to Tissot and Welte (1984), some characteristics of oil are derived from the source of the organic material and some from the physiochemistry of the aquatic basin of deposition, including the activity of microorganisms in the young sediment. Heavy oil sometimes begins as high(er) gravity liquids and is altered to low-gravity material. Low-gravity oil may also be the result of generation from thermally immature source rocks. Here, the product is originally immature, that is, without exposure to significant burial and cracking due to heating associated with burial. Some of the immense accumulations of heavy oil in southern California are believed to be from such a thermally immature source. Masters and others (1987) suggest that perhaps 5 percent of oil generated is immature, i.e., low gravity, while the remaining 95 percent is conventional, high-gravity petroleum that is expelled from source rocks and migrates into a trap. After entrapment, a transformation from conventional to heavy oil may take place. Alteration can be affected during migration between source rock and reservoir, such as a loss of varying degrees of API gravity due to contact with formation water.

Bacteria introduced into the petroleum reservoir by infiltration of bacteria-laden circulating or connate water can be deleterious to hydrocarbon accumulations. North (1985) believes bacteria are the principal agent of oxidation for petroleum still in the ground. Aerobic bacteria are known to survive at some shallower reservoir conditions but apparently cannot live at temperatues higher than about 80¡C (176¡F). Degradation by bacteria requires three conditions to be most effective: (1.) dissolved oxygen in the water to support the bacteria, (2.) geologic formation temperatures up to 80¡C to permit growth of the bacteria, and, (3.) an absence of H_2S, which is detrimental to these bacteria. Shallow accumulations often show evidence of oxidation, either from atmospheric oxygen penetrating to the reservoir or from oxygen dissolved in surface waters that contact the oil (Winters and Williams, 1969). Basal tar mats are layers of heavy oil or asphaltic tar at or just below the water/oil contacts of producing fields and are often taken as direct evidence for bacterial or water attack. Bacterial and water-caused degradation of petroleum can commence, theoretically, at any stage of maturation of the oil. Waples (1985), lists a number of hydrocarbon compounds and their preferential order of removal during biodegradation. The end product(s) of alteration are partially dependent on the initial composition of the petroleum. Waples (1985) notes that heavily degraded oils often are difficult or impossible to produce.

Precipitation of asphalt from a high-gravity oil may result from the movement of reservoir gas through the petroleum accumulation. Degradation occurs when the gas removes low-molecular-weight hydrocarbon molecules, thus creating a higher molecular weight product.

PHYSICAL AND CHEMICAL COMPOSITION OF HEAVY OIL

The difference between heavy, low-gravity oil and light, high-gravity oil is largely a matter of chemistry; low-gravity oil is comprised of molecules with more than 15 carbon atoms ($>C_{15}$; 15 is the number of carbon atoms), whereas high-gravity oil is comprised of lighter weight organic molecules ($<C_{15}$).

Heavy and light oil differ in viscosity and density. By definition (Speight, 1991) heavy oil has a viscosity between 100 and 10,000 centipoises or a density in the range of 934-1000 kg/m^3 at 15.6¡C (60¡F). Viscosity slows movement through a formation. Density is influenced by chemical composition and is used to give rough estimations of the nature of petroleum and petroleum products. Heavier, more complex molecules require more complex refining to produce gasoline, diesel, and heating oil.

Low-gravity oils contain heavy molecular components, such as asphaltenes and aromatics, and NSO (nitrogen, sulfur, and oxygen) compounds, primarily due to the selective removal of lighter compounds such as straight-chain compounds, such as *n*-alkanes and isoprenoids, early in the degradation process.

GEOLOGY

Geological conditions for recoverability of heavy oil are comparable to those for lighter conventional oil and include: depth, presence of faults, hydrologic continuity of the reservoir rocks, clay content, trap configuration, size of the reservoir, and whether the reservoir is a single layer or lens or a set of stacked bodies.

The geologic setting for much of the production of heavy oil is within fault zones, usually at the up-dip limits of strata within a hydrocarbon province. One such setting is in south-central Arkansas. This area marks the up-dip limit of the Smackover Formation, a known hydrocarbon source rock for a wide area of the Gulf Coast of the United States. In addition to the stratigraphic setting, there is also an extensive east-west fault system that extends down through much of the producing formations. A second example occurs in Pennsylvanian age rocks around the western edge of the Powder River Basin in northeastern Wyoming. Here down-warping and faulting along the basin margin has created a situation very similar to the first example in Arkansas. The faults have provided a conduit for the invasion of meteoric waters into hydrocarbon accumulations. One such occurrence is along a mountain range front where the Kate Spring field in Nevada occurs. Meteoric water recharge is along the fault at the front of the range. In all the above situations most of the production is from relatively shallow depths, usually less than 4,000 ft.

The majority of all heavy oil fields occur at depths of less than 5,000 ft, although deposits are exploited at depths as deep as 10,000 ft (IOCC, 1984; Meyer and Duford, 1988). The Smackover Formation in the Toxey field, Alabama, produces from depths greater than 10,000 ft. The implications of a depth correlation are two/fold: (1.) the depth to production will directly impact the methods and techniques of extraction of the resource, (2.) there may be an additional correlation to the degree of alteration by the mere proximity of the petroleum to oxidizing agents (such as water in aquifers and normal recharge along faults)-- these agents are more readily available closer to the Earth's surface.

ENHANCED RECOVERY

Special techniques are required in order to produce commercial quantities of heavy oil. High viscosity necessitates assistance to move the oil out of the producing formation and into the borehole. Enhanced oil recovery (EOR) is a diverse technology that helps to accomplish this.

Moritis (1990) lists a number of EOR methods (including thermal, chemical, and gas methods) that are used when both methods (utilizing natural reservoir pressure) and secondary methods (usually water-washing) fail to move oil out of the producing formation. A third iteration of recovery is called tertiary recovery and includes (1.) thermal methods (combustion, steam soak, steam drive, and hot-water drive), (2.) a gas method (covering hydrocarbon, miscible/immiscible, CO2 miscible/immiscible, nitrogen and flue gas), (3.) and chemical methods such as micellar/polymer, alkaline, polymer, and foam. Microbial applications represent another category. The details of each method are discussed in Moritis' text. Also, solvents are sometimes used to reduce viscosity.

The most common procedures for extracting low-gravity oil involve heating of the reservoir rock by hot water or steam. Production from increasing depths means that more heat will be lost in the borehole, ultimately requiring higher temperatures. They state that 3,000 ft may be the limit for production by conventional steam-drive and combustion methods because too much heat is lost in the borehole and the reservoir. Estimated energy expenditures to produce the oil range up to one third of that available from the recovered product. Thermal methods account for about 78 percent of EOR production in the United States (Negus-deWys, and others 1991).

API gravity of heavy oil for this report is defined to be 10¡ to 20¡, inclusive. Petroleum in the range of 10¡-15¡ gravity is more difficult to move from the reservoir to the borehole than 15¡-20¡ oil. Lower viscosity is one reason for this, another may be the degree of degradation. Lower gravity oil rapidly approaches the consistency of solid bitumen, and its producibility becomes about nil. There are few methods for enhanced oil recovery operations for oil below 15¡ gravity, and they become less effective with heavier, more viscous oils. The Athabasca tar sands of Alberta, Canada, and the

Orinoco deposits of Venezuela are two examples of this type of extra heavy material. Mining may be the only cost-effective method of removing it.

ENVIRONMENTAL ISSUES:

Environmental constraints may be as significant in production of low-gravity oil as physical or geological conditions.

A list of the more serious concerns includes:

- Damage by steaming and extraction equipment in environmentally sensitive areas.
- Availability of water for thermal processes, especially in arid regions where the water supply is limited.
- Contamination of subsurface water supplies by solvents and foams used to reduce viscosity.
- Air pollution from high-sulfur heavy oil used for steaming.

Oil and Gas Journal (May 2, 1994, anonymous author) addresses environmental concerns facing California, which has stringent laws relating to all aspects of air and water quality; this article addresses the effect of these laws on industry. New laws will certainly be enacted by more and more States as the pollution situation warrants. Environmental issues will undoubtedly be major for production of both low- and high-gravity oil petroleum products and will extend from drilling and extraction to refining.

RESOURCES

PRODUCTION AND RESERVES

Major sources of data on location, production, and individual reservoirs are: Crysdale and Schenk (1990) and Interstate Oil Compact Commission (IOCC) (1984). Crysdale and Schenk (1990) provide a comprehensive list of production and reservoir information for all States except Alaska; occurrences of heavy oil are plotted on a general-purpose map. IOCC (1984) is less comprehensive, and even though the production numbers are outdated, tabulated reservoirs and field data by state, along with a variety of geologic and engineering aspects, make the publication useful. Neither publication offers discussion of economics or ultimate recoverability.

Individual States' production statistics are often incomplete or accuracy is compromised because of production commingled with high-gravity oil.

Published information sources relating to the volume and recoverability of resources are numerous, but so are the interpretations of the terminology used to describe them, such as undiscovered, in-place, indicated, measured, and economic resources. It follows that the statistics for these terms will vary according to the user. Without being able to directly measure the volume of petroleum in the reservoir, it becomes necessary to use other methods- statistics, analogs and rational assumptions- to make educated guesses about the size and recoverability of an oil deposit. Dolton and others (1993), Masters and others (1992), and Meyer and Duford (1988) present explanations of the assessment process and terminology.

Perhaps the single most important point in understanding assessment figures is that they do not merely represent reservoir volumetrics. To assume that is to reduce geology and petroleum reservoirs to unrealistically simplistic terms. The simple volumetrics assumption almost always yields the largest and least accurate estimates of all methodologies. In short, the assessment process places a premium on production and geological data, and related information: it is information intensive. Different agencies use different methodologies for assessments nd interpret definitions, such as identified, inferred, ultimate recoverable, etc. differently. For this reason, the numbers for heavy-oil resources will be variable. Heavy oil is not routinely evaluated by State agencies or even producers. When reporting the statistics by State, it can be seen that some include oil of 20¡ API gravity and some (most notably California) only go to 19.9¡ API gravity.

The resources of heavy oil in the United States are substantial. Meyer and Duford (1988) state that U.S. production of heavy oil in 1985 was 423.3 MMBO, (1.16 MMBOPD), with cumulative production and initial reserves of 30,510.4 million barrels. Almost 11,000 million barrels alone are contained within 10 giant fields. The United States produced about 7.4 MMBOPD of conventional and heavy oil in 1990; low-gravity oil comprised about 9 percent of this total (about .67 MMBOPD). The numbers for U.S. 1993 production were about 6.842 MMBOPD of all liquids; a comparable percentage (9 percent) of low-gravity production is assumed- about .616 MMBOPD.

Masters and others (1992, p. 52), estimate that 9 percent (18.08 BBO) of the U.S. cumulative production and identified reserves of conventional crude oil are made up of <20¡ gravity oil. This figure includes extra heavy oil (10¡ gravity) and bitumen.

RESERVES

Several fields were selected for consideration of recoverability versus their ultimate resources. The data are primarily presented to demonstrate the variability between producing formations and geographic regions. Table 1.

No single number can be given for the total reserves of heavy oil of the United States, but upper and lower limits can be assigned. Using numbers from Meyer and Duford (1988) for cumulative production plus identified reserves (30,510.4 MMB) and the lowest recovery factor (9.8 percent) from table 2 would yield 2,990 million barrels; using the highest recovery factor (49 percent) yields 14,950 million barrels of heavy oil available in the United States. Using the same factors, the numbers from Masters and others (1992) gives 1,764 million barrels of original reserves of identified reserves and 8,820 million barrels of undiscovered resources.

PRODUCTION FOR SELECTED STATES

Seventeen States report heavy oil production, but not all report reserves. Annual production of the producing States is shown in table 2. California ranks first, with Texas second, followed by Wyoming, Arkansas, Louisiana, and Alabama.

In 1992, California produced over 234 MMB of heavy oil. The Department of Energy (DOE) (in Conservation Committee of California Oil and Gas Producers 1992, p. C-5), for the review of California 1992 oil and gas production, not broken down in terms of API gravity, estimates an indicated future recovery of 6,819 MMBO and reserve and ultimate production capability of 29,957 MMBO. Of this, more than over 61 percent was produced from three fields; the Midway Sunset (60 MMBO), Kern River (44 MMBO), and Belridge South (39 MMBO). In 1993, 67.3 percent of California's petroleum production was heavy oil; the immense Midway Sunset and Kern River fields alone reported more than 106 MMBO. The California Department of Conservation (1992) lists estimated recoverable (proved) oil reserves at 3.5 BBO from onshore fields and 856 MMBO from offshore fields for a total of 4.3 BBO. This number is for all oil- heavy oil is not distinguished. The State is projecting a production volume of .325 BB in 1997 if official State policy and prices remain stable.

In 1991, Texas was the second largest producer of low-gravity oil with 8.81 MMBO .

CONCLUSIONS

Heavy or low gravity oil is either directly generated from source rock, or it is the product of the alteration of higher gravity oil by an agent such as bacteria or oxygenated water.

The majority of heavy-oil deposits currently being exploited are within 5,000 ft of the surface, although there are numerous deposits at depths to 10,000 ft under production. The depth to production is important because the very low viscosity of heavy oil requires special considerations in extracting it. Enhanced recovery techniques for heavy oil include several types of heating or steaming and the use of solvents. These techniques often incur environmental concerns relating to water and air pollution.

Heavy-oil production makes up about nine percent of the total production of oil in the United States. In California 70 percent of annual production is low gravity oil. Using estimates for original reserves and best and worst recovery percentages, the upper and lower limits for resources of less than 20¡ oil in the United States are: 14,950 MMBO and 2,990 MMBO, respectively.

Production of heavy oil ultimately will be controlled by technology and by environmental concerns, which will exert considerable influence on development of more efficient technologies.

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Table 1. Known oil, original oil in place, and percent recovery in selected fields.

State	Field Unit	Producing (MBO)	Known Oil[1] (MBO)	OOIPFLD[2] recovery[3]	Percent
Ala.	Toxey	Smackover	1,790	6,550	27.3
Ark.	Falcon	Nacatoch	3,530	36,000	9.8
Calif.	Midway-Sunset	Pliocene	2,650,000	6,190,000	42.8
Miss.	Heidelberg	Eutaw	205,000	12,000	40
Miss.	Baxterville	L Tuscaloosa	262,000	58,500	39.8
Tex.	Thompson area	L Miocene	505,000	1,030,000	49

[1]Cumulative production plus identified reserves.

[2]Original oil in place for the field.

[3]Oil known divided by OOIPFLD (Oil known/OOIPFLD).

Table 2. Annual and cumulative production of low gravity oil by State. Complete annual statistics for Alaska, Illinois, Michigan and Nebraska were not available. Volumes are in thousands of barrels (MB). [NA, not available].

State	**1990**	**1991**	**1992**	**Cumulative**
Alabama	339[1]	268[2]	NA	23,921[2]
Arkansas	324[2]	NA	NA	42,268[2]
California	238,853[1]	241,832[1]	(19,310*)	23,500,000**
Colorado	37[1]	36[1]	33[1]	NA
Kansas	355[3]	246[1]	292[3]	13,875[1]
Louisiana	NA	2,479[1]	NA	156,700[1]
Mississippi	2,399[3]	3,376[1]	1,905[3]	317,075[1]
Montana	158[1]	191[1]	236[2]	14,025
New Mexico	256[1]	257[1]	238[1]	8,693[1]
Oklahoma	NA	13[1]	NA	771[1]
Texas	9,026[3]	8,812[2]	7,853[3]	1,167,152[2]
Utah	NA	388[1]	NA	22,871[1]
Wyoming	4,842[3]	4,330[3]	4,077[3]	NA

*--Production for Jan. '93 would equate to 231,720 MB annual
** Total cumulative production for petroleum--light and heavy oil
1--From Wells (1992)
2--Data from State publication
3--Data from DOE. API gravity includes 19.9¡ oil and does not include 20¡ oil; all other sources include 20¡ gravity.