NATURAL BITUMEN (TAR SANDS) AND HEAVY OIL

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Contents

Summary

Tar sand (also known as oil sand and bituminous sand) is a sand deposit that is impregnated with dense, viscous material called bitumen. Tar-sand deposits are widely distributed throughout the world and the various deposits have been described as belonging to two types: (a) stratigraphic traps and (b) structural traps although gradations between the types of deposit invariably occur.

The only commercial operations for the recovery and upgrading of bitumen occur in north-east Alberta, Canada, near to the town of Ft. McMurray where bitumen from the Athabasca deposit is converted to a synthetic crude oil. Therefore most of the data available for inspection of bitumen and determination of behavior originate from studies of these Canadian deposits. The work on bitumen from other sources is fragmented and spasmodic. The exception is the bitumen from deposits in Utah, US where on-going programs have been in place at the University of Utah for more than three decades.

Methods for the recovery of bitumen from tar sand are based either on mining, combined with some further processing or operation on the tar sands *in situ*. The mining methods are applicable to shallow deposits, characterized by an overburden ratio less than 2.0, i.e., the overburden depth to thickness of tar sand deposit is less than 2.0. The

Athabasca deposit is mineable within current concepts of the economics and technology of open-pit mining. Because of the chemical and physical properties of the bitumen, non-mining (*in situ*) recovery techniques have not had the same degree of success as recovery operations. However, heavy oil, which has a varying degree of mobility in the reservoir, can be successfully recovered by use of non-mining secondary and tertiary recovery techniques.

The API (American Petroleum Institute) gravity of tar-sand bitumen varies from 5^{o} API to approximately 10^{o} API depending upon the deposit, viscosity is very high, and volatility is low. On the other hand, the API gravity of heavy oil is in the order of 10^{o} to 20^{o}. The viscosity of heavy oil is high, relative to conventional crude oil, but is substantially lower than the viscosity of bitumen. Similarly, a higher proportion of heavy oil is volatile relative to bitumen, but the constituents of both heavy oil and bitumen exhibit lower volatility than conventional crude oil.

The lack of mobility of bitumen requires a mining step followed by the hot water process that is, to date, the only successful commercial process to be applied to bitumen recovery from mined tar sand. Many process options have been tested with varying degrees of success and one of these options may even supersede the hot water process at some future date.

In addition, bitumen is relatively hydrogen-deficient when compared to heavy oil, and conventional crude oil therefore requires that there be substantial hydrogen addition during refining. Heavy oil and conventional crude oil can be commercially upgraded and refined by a variety of processes. Bitumen is currently commercially upgraded by a combination of carbon rejection (coking) and product hydrotreating. Coking, the process of choice for residua (i.e., the non-volatile portions of conventional crude oil and heavy oil), is also the process of choice for bitumen conversion. Bitumen is currently converted commercially by delayed coking and by fluid coking. In each case, the bitumen is converted to distillate oils, coke, and light gases. The coker distillate is a partially upgraded material and is a suitable feed for hydrodesulfurization to produce a low-sulfur synthetic crude oil.

1. Natural Bitumen (Tar Sands) and Heavy Oil

In addition to conventional petroleum, there are two other materials that offer some relief to the potential shortfalls in the supply of liquid fuels and other products. These (a) heavy oil, found in various reservoirs, and (b) bitumen, found in tar-sand deposits. Tar sand (also known as oil sand and bituminous sand) is a sand deposit that is impregnated with dense, viscous material that is usually immobile under reservoir conditions. Tar-sand deposits are found throughout the world, often in the same geographical areas as petroleum, including and heavy oil.

The heavy oil in various reservoirs and the bitumen in various tar-sand deposits represent a potentially large supply of energy. However, many of the reserves are available only with some difficulty and optional refinery scenarios will be necessary for conversion of these materials to liquid products, because of the substantial differences in character between conventional petroleum and heavy oil when compared to tar-sand bitumen (Table 1). However, because of the diversity of available information and the continuing attempts to delineate the various world tar-sand deposits, it is virtually impossible to present accurate numbers that reflect the extent of the reserves in terms of the barrel unit. Indeed, investigations into the extent of many of the world's deposits are continuing at such a rate that the numbers vary from 1 year to the next. Accordingly, the data quoted here must be recognized as approximate, with the potential of being quite different from one year to the next. The general lack of a cohesive definition for heavy oil and for bitumen has prevented accurate estimation of these reserves. What might be classed heavy oil or bitumen in one locale might be classed otherwise in another locale. It is apparent that bitumen is different to conventional petroleum and heavy oil.

Property	Bitumen	Cold Lake heavy oil	Lloydminster heavy oil	Conventional crude oil
Gravity, ^{o}API	8	12	14	35
Viscosity				
Centipoise @ 100^{0}F (38^{o}C)	500,000	2,000	500	10
Centipoise @ 210^{o}F (99^{o}C)	1,700			30
SUS @ 100^{0}F (38^{o}C)	35,000			
SUS @ 210^{o}F (99^{o}C)	500			
Pour point, ^{o}F	50		5	0
Elemental analysis (% by weight)				
Carbon	83	84	83	86
Hydrogen	10.6	11	12	13.5
Sulfur	4.8	4.4	3.6	0.1
Nitrogen	0.4	0.4	0.4	0.2
Oxygen	1	0.2	1	0.2
Fractional composition, (% by weight)				
Asphaltenes	19	12	12	5
Resins	32	28	17	10
Aromatics	30	35	24	25
Saturates	19	25	47	60
Metals parts per million				
Vanadium	250	190	100	10
Nickel	100	70	40	5

Carbon residue (% by weight)	14	11	10	5
Heating value (btu/lb.)	17,500	18,000	18,200	19,500

Table 1. The properties of conventional Crude Oil, Heavy Oil, and Bitumen

The definition of heavy oil has been very loosely based on the API gravity or viscosity. Such a definition of heavy oil is quite arbitrary and too general to be technologically accurate. There have been attempts to rationalize the definition based upon viscosity, API gravity, and density but they also suffer from a lack of technical accuracy. Most important, the flow properties of heavy oil are reduced relative to conventional crude oil and heavy oil is much more difficult to recover from the subsurface reservoir. These materials have a high viscosity (and low API gravity) relative to the viscosity (and API gravity) of conventional petroleum and recovery of heavy oil usually requires thermal stimulation of the reservoir.

Time period	Documented use of bitumen
3800 BC	First documented use of bitumen for caulking reed boats.
3500 BC	Bitumen used as cement for jewellery and for ornamental applications.
3000 BC	Documented use of bitumen as a construction cement by Sumerians; also believed to be used as a road material; bitumen used to seal bathing pool or water tank at Mohenjo Daro.
2500 BC	Documented use of bitumen and other petroleum liquids (oils) in the embalming process; bitumen believed to be widely used for caulking boats.
1500 BC	Documented use of bitumen for medicinal purposes and (when mixed with beer) as a sedative for the stomach; continued reference to use of bitumen liquids (oil) as illuminant in lamps.
1000 BC	Documented use of bitumen as a waterproofing agent by lake dwellers in Switzerland.
500 BC	Documented use of bitumen mixed with sulfur as an incendiary device in Greek wars; also use of bitumen liquid (oil) in warfare.
350 BC	Documented occurrence of flammable oils in wells in Persia.
300 BC	Documented use of bitumen and liquid bitumen as incendiary device (Greek fire) in warfare.
250 BC-250 AD	Documented occurrences of bitumen and oil seepage in several areas of the "Fertile Crescent" (Mesopotamia); repeated documentation of the use of liquid bitumen (oil) as an illuminant in lamps.
750 AD	First documented use in Italy of bitumen as a colour inpaintings.
950-1000 AD	Report of destructive distillation of bitumen to produce an oil; reference to oil as nafta (naphtha).

1100 AD	Documented use of bitumen for covering (lacquering) metalwork.
1200 AD	Continued use of bitumen and naphtha as an incendiary device in warfare; use of naphtha as an illuminant/incendiary material.
1500-1600 AD	Documentation of bitumen deposits in the Americas; first attempted documentation of the relationship of bitumen and naphtha (petroleum).
1600-1800 AD	Bitumen used for a variety of tasks; relationship of bitumen to coal and wood tar studied; bitumen studied; used for paving; continued documentation of the use of naphtha as an illuminant and the production of naphtha from bitumen; importance of naphtha as fuel realised.
1859 AD	Discovery of petroleum in North America; birth of modern-day petroleum science and refining.

Table 2. Use of natural bitumen in documented historical time

Bitumen (often referred to as natural asphalt) has been in use for more than 6000 years (Table 2) and it is presumed that this material was the natural material, rather than a manufactured material (asphalt). Seepage of petroleum-like materials to the surface from underground formations is well documented and it appears that the more volatile constituents would disappear with time, thereby leaving a bituminous residue.

It was such a residue that was used by the older cultures. It is also likely that the thermal decomposition of petroleum may have been known and practised, thereby giving rise to a variety of manufactured asphalt-type products. The old literature does not define which product was employed, with any degree of specificity.

Simply, bitumen is substantially non-volatile and immobile at reservoir temperatures. In fact, petroleum, and the equivalent term crude oil cover a vast assortment of materials consisting of gaseous and liquid hydrocarbon-type chemical compounds that occur in sedimentary strata throughout the world. When petroleum occurs in a reservoir that allows the crude material to be recovered by pumping operations, as a free-flowing dark-to-light-colored liquid, it is often referred to as conventional petroleum. Heavy oil and bitumen require more energy-dependent methods of recovery from the heavy oil reservoir or from the bitumen deposit.

There is very little consistent and correlated data relating to the deposits in the US and the Rest of the World. Out of necessity, the material relating to tar-sand bitumen must rely heavily on data from the Alberta tar sands. However, the properties reported herein cannot be universally applied, with any degree of certainty, to the tar sand and the bitumen occurring in other parts of the world.

Thus, because of the diversity of available information and the continuing attempts to delineate the various world tar-sand deposits, it is virtually impossible to present accurate numbers which reflect the extent of the reserves in terms of the barred unit. Indeed, investigations of the deposits are continuing at such unknown rates that the in-place reserves may vary from one year to the next. Accordingly, the data contained herein must be recognized as being approximate with the potential of being higher than quoted by the time of publication.

Other than the use of bitumen by long-dead civilizations of the world, the Cree Indians, native to the Athabasca region of north-eastern Alberta, have known about the tar-sand bitumen for well over 200 years. However, the Canadian Government took the first scientific interest in bitumen in tar-sand deposits in the latter part of the nineteenth century. This interest commenced in 1890 and in 1897 to 1898, the sands were first drilled at Pelican Rapids on the Athabasca River, approximately 80 miles (~129 km) south-west of Fort McMurray. Up to 1960, the development was mainly small commercial enterprises. Between 1957 and 1967, three extensive pilot-plant operations were conducted in the Athabasca region, each leading to a proposal for a commercial venture. Shell Canada, Ltd. tested in sift recovery of bitumen; a group headed by Cities Service Athabasca, Ltd. operated a pilot plant at Mildred Lake based on a hot-water extraction process; and Great Canadian Tar sands, Ltd. operated a pilot plant at the present commercial plant site near Mildred Lake. In addition, the Mobil Oil Company has conducted tests on in sift recovery, and Petrofina established a pilot facility across the Athabasca River from the site of the Great Canadian Tar sands (GCOS, now Suncor) plant.

The use of different terms as the petroleum industry evolved requires a brief review of the terminology applied to petroleum, heavy oil, and bitumen. For example, the definition of petroleum has been varied, unsystematic, diverse, and often archaic. Furthermore, the terminology of petroleum is a product of many years of growth. Thus the long-established use of an expression, however inadequate it may be, is altered with difficulty, and a new term, however precise, is at best adopted only slowly. Because of the need for a thorough understanding of petroleum and the associated technologies, it is essential that the definitions and the terminology of petroleum science and technology be given prime consideration. This will aid in a better understanding of petroleum, its constituents, and its various fractions. Of the many forms of terminology that have been used, not all have survived, but the more commonly used are illustrated here. Particularly troublesome, and more confusing, are those terms that are applied to the more viscous materials, for example the use of the terms bitumen and asphalt.

Petroleum is a naturally occurring mixture of hydrocarbons, generally in a liquid state, which may also include compounds of sulfur nitrogen oxygen metals (especially nickel and vanadium) and other elements. Petroleum has also been defined as: (a) any naturally occurring hydrocarbon, whether in a liquid, gaseous or solid state; (b) any naturally occurring mixture of hydrocarbons, whether in a liquid, gaseous or solid state; or (c) any naturally occurring mixture of one or more hydrocarbons, whether in a liquid, gaseous or solid state and one or more of the following, that is to say, hydrogen sulfide, helium, and carbon dioxide. The definition also includes any petroleum as defined in (a), (b) or (c), that has been returned to a natural reservoir.

When petroleum occurs in a reservoir that allows the crude material to be recovered by pumping operations as a free-flowing dark-to-light colored liquid, it is often referred to as conventional petroleum. Heavy oils are the other types of petroleum that are different from conventional petroleum, insofar as they are much more difficult to recover from

the subsurface reservoir. These materials have a much higher viscosity (and lower API gravity) than conventional petroleum, and primary recovery of these petroleum types usually requires thermal stimulation of the reservoir.
The definition of heavy oil is usually based on the API gravity or viscosity but the definition is quite arbitrary. Although there have been attempts to rationalize the definition based upon viscosity, API gravity, and density, such definitions based on physical properties are inadequate and a more precise definition should involve some reference to the recovery method. However, in a very general (but not scientifically correct) sense, the term heavy oil is often applied to petroleum that has an API gravity less than 20^{o} and usually, but not always, a sulfur content higher than 2% by weight. Furthermore, in contrast to conventional crude oil, heavy oil is darker in color and may even be black.

The term heavy oil has also been arbitrarily used to describe both the heavy oil that requires thermal stimulation of recovery from the reservoir, and the bitumen in bituminous sand (tar sand) formations, from which the heavy bituminous material is currently recovered commercially by a mining operation.

Extra heavy oil is bitumen that occurs in the near-solid state and is incapable of free flow under ambient conditions. Bitumen from tar-sand deposits is often classified as extra heavy oil. Thus, in addition to conventional petroleum and heavy crude oil, there remains an even more viscous material that offers some relief to the potential shortfalls in supply; such material is the bitumen (extra heavy oil) found in tar-sand (oil sand) deposits. It is therefore worth noting here the occurrence and potential supply of these materials. However, many of these reserves are only available with some difficulty, and optional refinery scenarios will be necessary for conversion of these materials to liquid products, because of the substantial differences in character between conventional petroleum (including heavy oil) and tar-sand bitumen.

Bitumen is a naturally-occurring material that is found in deposits where the permeability is low and passage of fluids through the deposit can only be achieved by prior application of fracturing techniques. Tar-sand bitumen is a high-boiling material with little, if any, material boiling below $350^{o}C$ ($660^{o}F$) and the boiling range may be approximately equivalent to the boiling range of an atmospheric residuum. Bitumen includes a wide variety of reddish brown to black materials of semisolid, viscous to brittle character that can exist in nature with no mineral impurity or with mineral matter contents that exceed 50% by weight. Bitumen is frequently found filling pores and crevices of sandstone, limestone, or argillaceous sediments, in which case the organic and associated mineral matrix is known as rock asphalt.

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Biographical Sketch

Dr. Speight has more than thirty years of experience in areas associated with the properties and processing of conventional and synthetic fuels. He has participated in, as well as led, significant research and development in refining heavy oil and coal, and related environmental issues. He has well over four hundred publications, reports, and presentations detailing these research activities and has taught more than forty related courses.

Dr. Speight is currently editor of the journal *Petroleum Science and Technology* (formerly Fuel Science and Technology International) and editor of the journal *Energy Sources*. He is recognized as a world leader in the areas of fuels characterization and development. Dr. Speight is also Adjunct Professor of Chemical and Fuels Engineering at the University of Utah.

Dr. Speight is the author/editor/compiler of more than twenty books and bibliographies related to fossil fuel processing and environmental issues. As a result of his work, Dr. Speight was awarded the Diploma of Honor, National Petroleum Engineering Society, For Outstanding Contributions to the Petroleum Industry in 1995 and the Gold Medal of Russian Academy of Sciences (Natural) for Outstanding Work in the Area of Petroleum Science in 1996. He has also received the Specialist Invitation Program Speakers Award from NEDO (New Energy Development Organization, Government of Japan) in 1987 and again in 1996 for his Contributions to Coal Research. Dr. Speight also received the degree of Doctor of Sciences from the Scientific Research Geological Exploration Institute (VNIGRI), St. Petersburg, Russia For Exceptional Work in Petroleum Science in 1997. In 2001, Dr. Speight was also awarded the Einstein Medal of the Russian Academy of Sciences (Natural) in recognition of Outstanding Contributions and Service in the field of Geologic Sciences.