Chapter 8

PETROLEUM

For the foreseeable future, oil will remain a critical fuel for the United States and all other industrialized nations. [In order to make the U.S. economy less dependent on oil,] the National Energy Strategy proposes initiatives to (1) reduce the economic consequences of disruptions in world oil markets, and (2) increase domestic oil and petroleum product supplies.

(*National Energy Strategy, Executive Summary*, 1991/1992)

The growing level of U.S. oil consumption raises potential economic and national security concerns. In addition to emphasizing efficient use of oil products and enhancing fuel flexibility, national energy policy must address declining domestic production levels with minimum interference with market forces. The Administration's policy is to improve the economics of domestic oil production by reducing costs, in order to lessen the impact on this industry of low and volatile prices.

(*Sustainable Energy Strategy*, 1995)

Petroleum (or crude oil) is a complex, naturally occurring liquid mixture containing mostly hydrocarbons, but containing also some compounds of oxygen, nitrogen and sulfur. It is often referred to as the "black gold." The Rockefellers, the Rothschilds, the Gettys, the Hammers and the royal families of the Persian Gulf area would certainly agree. A view at Fortune magazine's list of billionaires confirms it: the Sultan of the oil-rich Brunei, on the island of Borneo, has been at the very top for quite some time. Saudi Arabia's King Fahd is up there as well.

After World War II, the huge oil reserves in the Middle East became available, at a very low cost, and they rapidly revolutionized the way we live. Indeed, the twentieth century – with all the dramatic changes that it has brought to society – is probably best characterized as the century of oil. A fascinating account of the "epic quest for oil, money and power" is given by Daniel Yergin, in his Pulitzer prize-winning book *The Prize* (see Further Reading, p. 461).

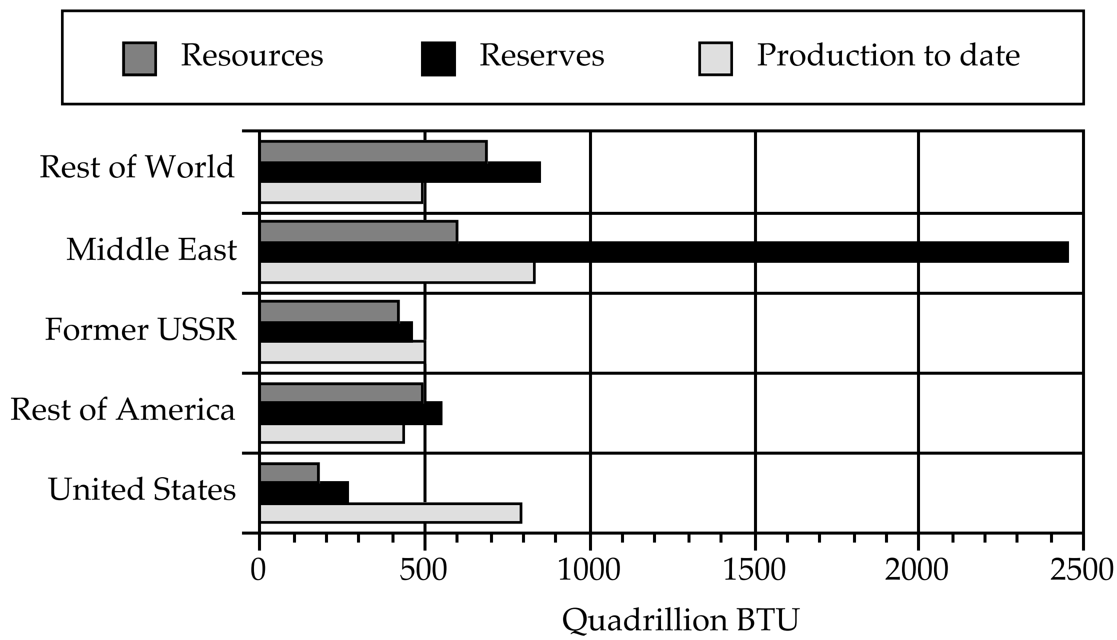


FIGURE 8-1. World distribution of petroleum resources and reserves.
[Source: W. Fulkerson et al., *Scientific American*, September 1990, p. 129.]

Most of the world's petroleum is to be found in the Middle East, as shown in Figure 8-1 and in more detail in Figure 8-2. Figure 8-1 also illustrates the fact that the world reserves and resources of crude oil are orders of magnitude smaller than those of coal. In particular, it is seen that the U.S. reserves are just an order of magnitude larger than the annual oil consumption (see Figure 8-3). Obviously, United States imports a large portion of the petroleum that it consumes. This increasing trend is likely to continue. The economic, political and policy implications of this state of affairs are discussed in Chapter 21.

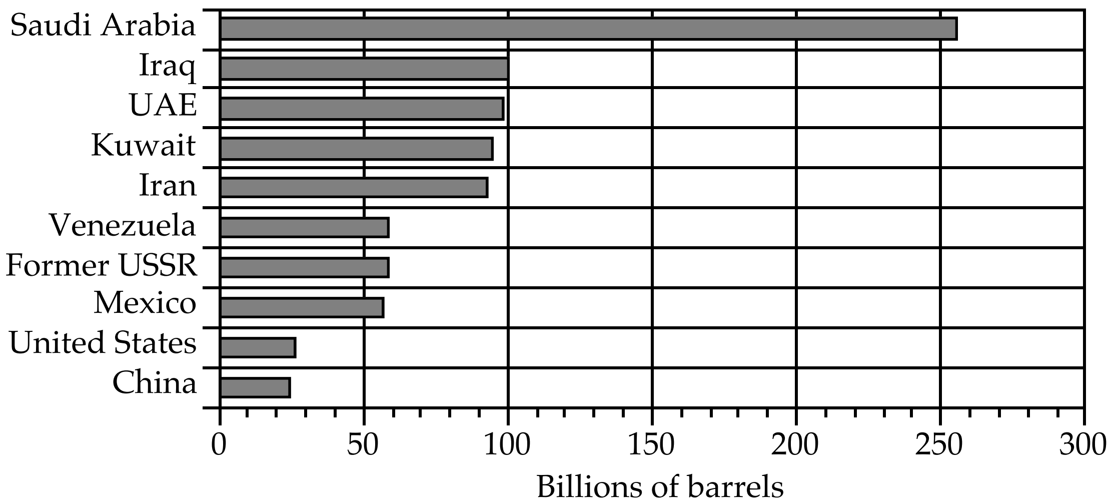


FIGURE 8-2. Distribution of major petroleum reserves in the world.
[Source: *The New York Times*, September 2, 1990.]

Petroleum Formation

Petroleum forms by the breaking down of large molecules of fats, oils and waxes that contributed to the formation of kerogen (see Chapter 6). This process began millions of years ago, when small marine organisms abounded in the seas. As marine life died, it settled at the sea bottom and became buried in layers of clay, silt and sand. The gradual decay by the effect of heat and pressure resulted in the formation of hundreds of compounds.

Because petroleum is a fluid, it is able to migrate through the earth as it forms. To form large, economically recoverable amounts of oil underground, two things are needed: an oil pool and an oil trap. An *oil pool,* which is the underground reservoir of oil, may literally be a pool or it could be droplets of oil collected in a highly porous rock such as sandstone. An *oil trap* is a non-porous rock formation that holds the oil pool in place. Obviously, in order to stay in the ground, the fluids – oil and associated gas – must be trapped, so that they cannot flow to the surface of the earth. The hydrocarbons accumulate in *reservoir rock*, the porous sandstone or limestone. The reservoir rock must have a covering of an impervious rock that will not allow the passage of the hydrocarbon fluids to the surface.

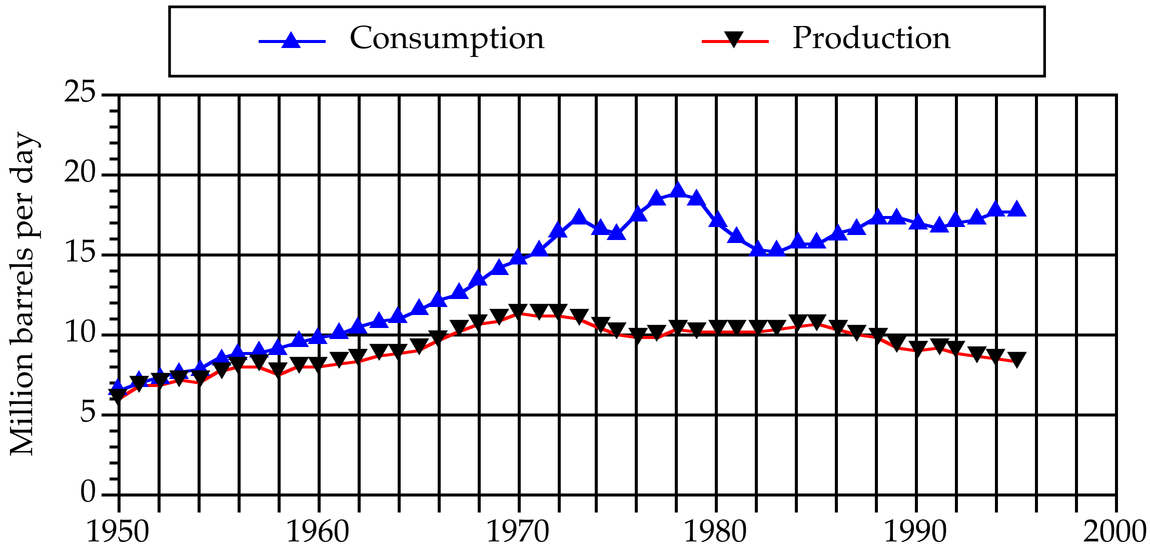


FIGURE 8-3. U.S. petroleum production and consumption in the last 45 years. [Source: Energy Information Administration.]

The impervious rock covering the reservoir rocks is called a *cap rock*. As shown in Figure 8-4, oil traps consist of hydrocarbon fluids held in porous rock covered by a cap rock.

A hot, wet climate fosters the growth of large amounts of organisms. If this growth takes place in a shallow sea, the eventual drying out of the environment and evaporation of the sea water leaves behind large deposits of salt. Salt makes an excellent cap rock for a reservoir. If these conditions are enhanced by a gentle geological folding of the subsurface rocks, the rock folding can produce very large reservoirs, with the impervious salt deposits acting as a cap. These are precisely the conditions that prevailed in the Middle East, giving rise to the enormous deposits of oil found in that region of the world.

Properties of Petroleum

The elemental composition of petroleum is much less variable than that of coal: 83-87% carbon, 11-16% hydrogen, 0-4% oxygen plus nitrogen, and 0-4% sulfur. Note that most crude oils contain substantially more hydrogen than coals. Only a brief discussion is needed here regarding the distribution of these elements among the thousands of compounds found in petroleum.

Most of the compounds in petroleum contain from five to about twenty carbon atoms. Many of them consist of straight chains of carbon atoms (surrounded by hydrogen atoms), as illustrated below:

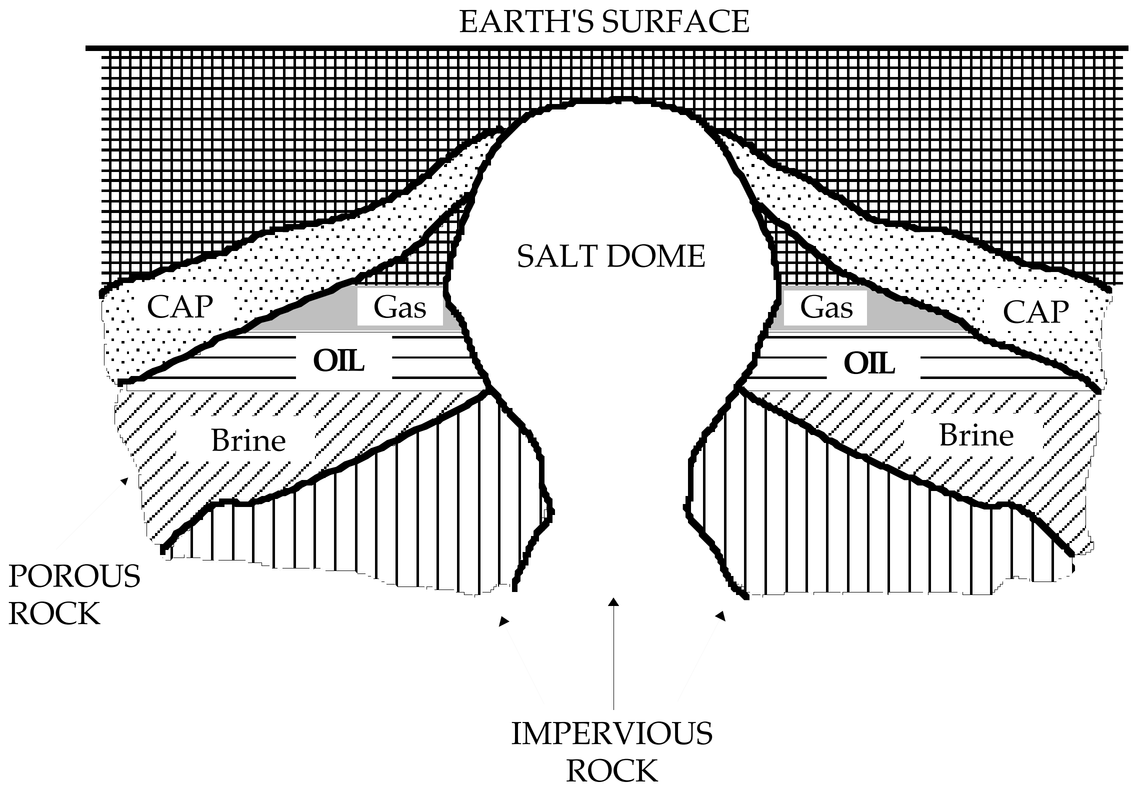


FIGURE 8-4. Representative geologic structure of an oil trap: a salt dome.

–C–C–C–C–C–   –C–C–C–C–C–C–C–C–   –C–C–C–C–C–C–C–C–C–C–C–C–C–

Compounds having branched chains and rings of carbon atoms are also present. Here are some examples:

Compounds of the types shown above with chains of carbon atoms, either branched or straight, are called *paraffins*. All paraffins have the molecular formula C_nH_{2n+2}. For example, n = 8 for a compound called octane.

The physical state of the paraffins depends on the number of carbon atoms in the molecule. Paraffins with less than five carbon atoms are gases at ordinary temperatures. Paraffins with five to fifteen carbon atoms are free-flowing liquids. Paraffins with more than fifteen carbon atoms range from very thick, viscous liquids to waxy solids. As the number of carbon atoms increases, so too does the number of possible molecular structures resulting from their combination. For example, the paraffin with five carbon atoms (called pentane) can exist as one linear chain and two branched chains:

As the number of carbon atoms increases beyond five, the number of different molecular structures with the same number of carbon atoms increases drastically (exponentially).

We shall see later, in our discussion of the quality of gasoline, that the branched-chain paraffins are very important in providing good automobile engine performance. The reader will be relieved to know, however, that it will be necessary to learn the structure of only one or two of the most important branched paraffins, not the million or so possible structures.

Another class of molecules found in petroleum are the aromatic compounds. They have a ring structure and are typically derivatives of a compound called benzene, C_6H_6. They do indeed have a characteristic aroma, but they typically have a negative environmental impact. The ones that have a low molecular weight are volatile; for example, they easily evaporate from gasoline at filling stations. Many among them are carcinogenic.

Crude oils can be classified in a number of ways. Consider first a crude oil that is in the very early stages of being produced from kerogen. The long-chain compounds in the kerogen will not have broken apart to a great extent, because the oil or kerogen has not yet been buried very deeply (so it has not been exposed to high temperatures in the earth), nor has it been buried for a very long time. The carbon atom chains in this oil are likely to be very long. These long chains give the crude oil two properties: (a) They make it dense because long, straight chains of molecules can be packed tightly, resulting in a large mass per unit volume. (b) They also make it difficult for the molecules to flow past one another, making the crude oil more viscous (slower to flow and harder to pump). In addition, many sulfur compounds might be present in these oils. They are called young-shallow crudes: young, because they have not had the time to be broken down by the high temperatures inside the earth; and shallow, because they have not been buried deeply. Typically, young-shallow crudes are highly viscous, high-density materials with a high sulfur content. Crude oil found in portions of southern California, for example near Ventura (see Investigation 8-14), are young-shallow crudes.

As the oil is buried more deeply inside the earth's crust, it is exposed to higher temperatures. As a result, the molecules can break apart to a greater extent, and some of the molecules containing sulfur will be destroyed. These ‘young-deep’ crudes will have moderate viscosities, densities and sulfur contents. If the oil has not been buried very deeply, it will not experience the same temperatures as a young-deep crude. However, over very long time periods, the same chemical transformations that occur in a short time at high temperatures can also occur at relatively low temperatures. Thus an ‘old-shallow’ oil might have the same properties as a young-deep one. The analogy with the expression that “time is money” is very appropriate. We know that we can shorten the time required to do something if we are willing to spend more money to do it. (Remember also our definition and discussion of power, in Chapter 2.) In geology “time is temperature:” as temperature increases, the time needed to accomplish a particular change decreases. Crude oils of the young-deep or old-shallow quality occur both in California, around Oxnard, and in Texas, in the vicinity of Scarborough.

If a crude oil is buried deeply and for a long time, extensive breaking apart of the carbon chains can occur. At the same time, most of the sulfur compounds in the oil are broken down. Therefore an ‘old-deep’ crude oil has low viscosity, low density, and very low sulfur content. This combination of properties makes the old-deep crudes the most desirable: they require little refining to remove sulfur and they can be converted to large quantities of high-quality products such as gasoline (see below). Unfortunately, less than 5% of the world's remaining petroleum reserves are of this quality. Some of the best quality crude oils are found in northwestern Pennsylvania, in the vicinity of Bradford, and the term *Pennsylvania crude* is used as a standard of quality for crude oils. Overseas, old-deep crudes occur in Morocco.

Illustration 8-1. Calculate the atomic C/H ratio in a Pennsylvania crude oil that has the following elemental composition: 84.9% C; 13.7% H; 1.4% O (+N). Compare it to the C/H ratio in octane.

Solution.

$$\frac{C}{H} = \frac{84.9\text{ g C}}{13.7\text{ g H}} = \left(\frac{84.9\text{ g C}}{13.7\text{ g H}}\right)\left(\frac{1\text{ g H}}{1\text{ mol H}}\right)\left(\frac{1\text{ mol C}}{12\text{ g C}}\right) = 0.52\,\frac{\text{mol C}}{\text{mol H}} \quad \text{(PA oil)}$$

$$\frac{C}{H} = \frac{8\text{ atoms C}}{18\text{ atoms H}} = \frac{0.44\text{ atoms C}}{1\text{ atom H}} = 0.44\,\frac{\text{mol C}}{\text{mol H}} \quad (\text{octane, } C_8H_{18})$$

It is seen that this crude oil has less hydrogen than octane. Indeed, one of the results of crude oil refining is a more hydrogenated product, that is, a product containing more hydrogen. Also, petroleum contains more hydrogen than coal; see Illustration 7-1. This issue will be pursued further in our discussion of synfuels in Chapter 10.

Petroleum Utilization

Petroleum utilization is a much more complex process than coal utilization. This is illustrated in Figure 8-5. In particular, the preparation of petroleum before it is sold to the consumers is very extensive. The reason for this is that, despite their similar elemental composition, the chemical structure of different crude oils may be very different, as discussed above. Furthermore, a large number of different products is obtained from the petroleum refinery. This is illustrated in Figure 8-6. Most of them are used as fuels. A small but very important fraction is used as the basis for the (petro)chemical industry which gives us such indispensable products as plastics, pharmaceuticals and textiles.

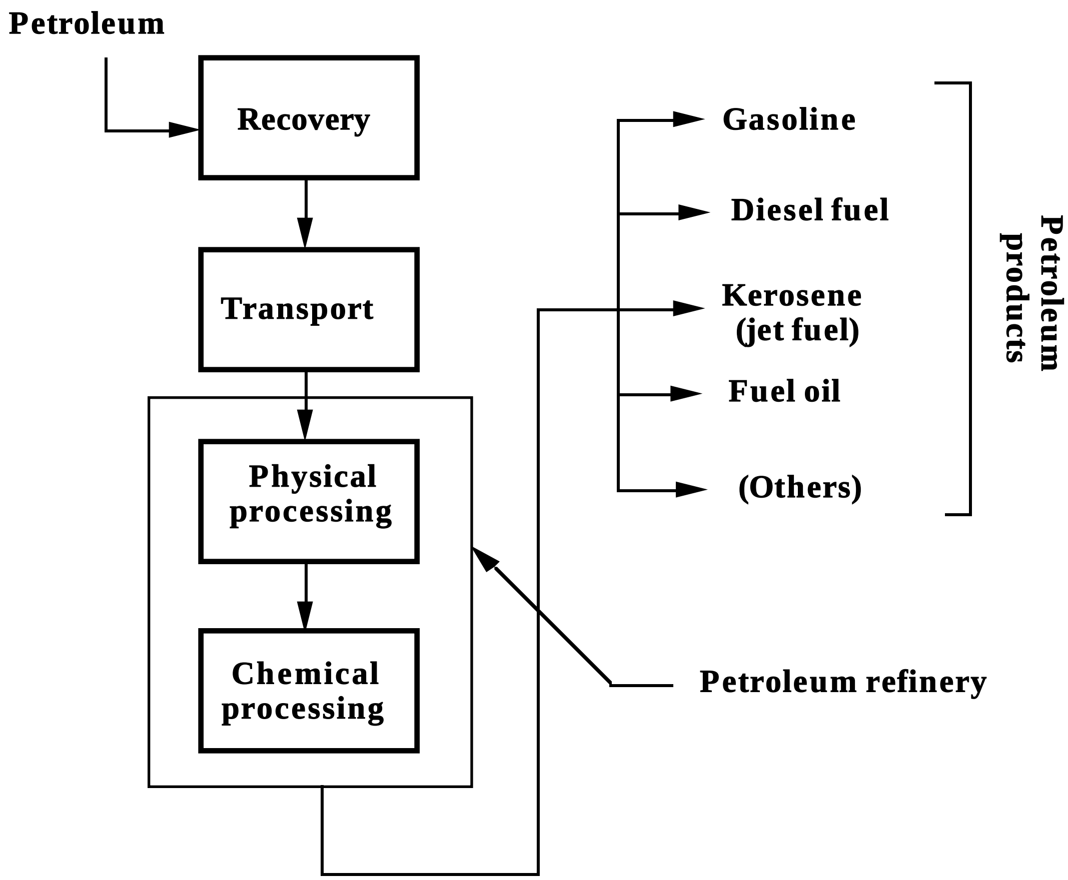


FIGURE 8-5. Pathways to petroleum utilization.

Oil Recovery (Drilling). After geologists of an oil company have located the general area in which petroleum is thought to occur, a well is drilled. Selecting the site for drilling requires detailed knowledge of the geologic features under the earth's surface. We can see from Figure 8-7 that of the three wells shown, all of which are reasonably close to the oil pool, only well B would actually produce oil. Drilling is also done to determine the extent of the reserves. Once the oil has been located, additional drilling might be done over an area around the first producing well to assess the geographic extent of the oil pool and its depth. This information allows geologists to estimate the amount of oil in the pool (see also Figure 5-9).

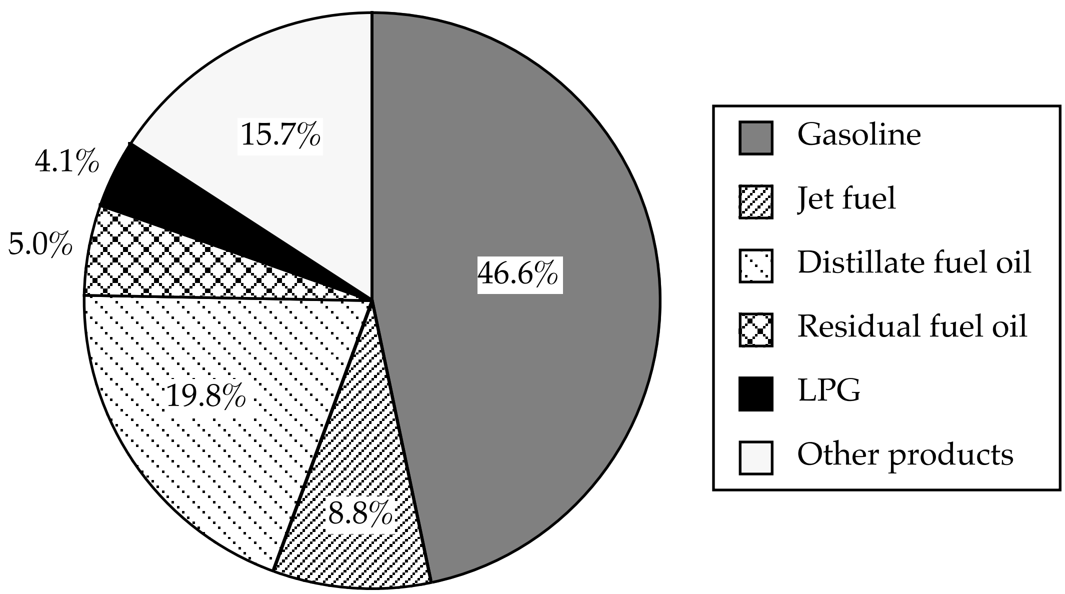


FIGURE 8-6. Distribution of products of petroleum refining in the United States. [Source: Energy Information Administration.]

When a drilling site has been selected, the first job is to *rig up*, or to assemble the drilling rig derrick. This is routinely taken as a sign of activity of the entire oil exploration industry, and is periodically reported among the economic indicators. Figure 8-8 shows the changes in the number of active rigs in the period 1970-1990. A comparison with Figure 20-3 will show the logical existence of a positive correlation with the price of oil.

The next step is to begin the actual drilling; in the industry jargon, the well is *spudded in*. The drill bit, which grinds through the rock to cut the hole, is attached to sections of pipe called the *drill stem*. The portion of this stem sticking out of the ground is the *kelly*. The kelly is turned by an engine to provide the rotary motion needed for the drill bit to do its job. As the drill bit moves further into the earth's crust, the kelly gradually sinks in. At some point, the crew must stop drilling to add a new section of pipe to the drill stem and reattach the kelly. A top-notch crew can add a 30-foot section of pipe in 45 seconds.

The drill bit is lubricated by mud. The hole is lined with *casing*, a steel pipe lining that prevents the upper portions of the well from caving in on top of the bit. Eventually, the drill bit will be worn to the point that it no longer cuts rock effectively. At that point, there is no alternative but to replace it, a job that requires *pulling the pipe,* meaning removing the kelly and all of the sections of pipe comprising the drill stem. On a very deep well, this chore can involve pulling up 10,000 feet or more of pipe, in thirty-foot sections. The drilling mud is examined for traces of oil, to determine when the reservoir has been penetrated. Once oil has been found, the drill pipe is pulled out, leaving the casing to protect against cave-ins.

The first oil well in the United States, drilled by Edwin Drake in Titusville, PA, was only 69 feet deep. Today it is common to drill oil wells several thousands of feet deep, in some cases to an extreme of 25,000 feet (almost 5 miles!). The deeper the well, the more expensive it becomes, because of the labor involved in the drilling operation, the need to replace worn-out drill bits, and the cost of the pipe put down the drill hole.

If oil is found, there are two general classes of recovery methods for bringing it to the surface. Conventional or *primary recovery*, usually recovers about 30% of the oil from a reservoir. There are two kinds of primary recovery. *Flush production* requires no work.

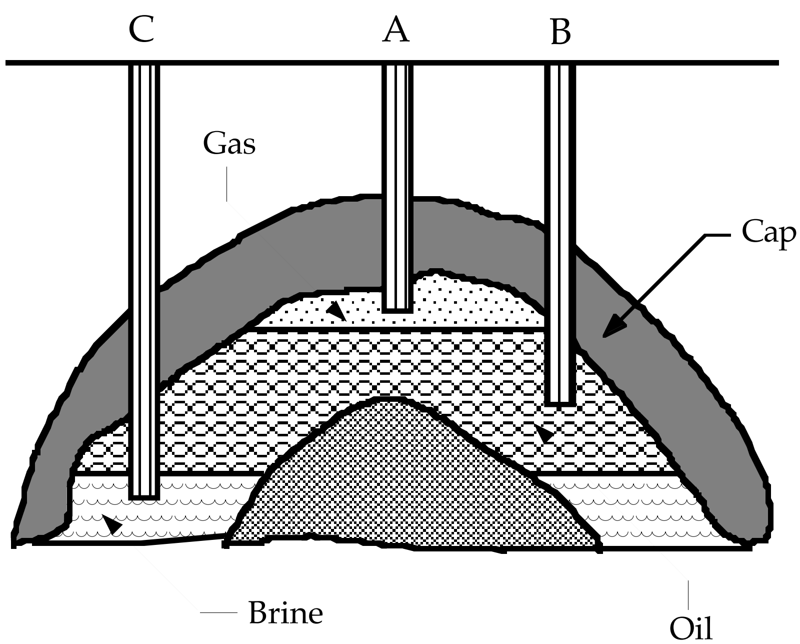


FIGURE 8-7. Selection of a site for petroleum drilling.

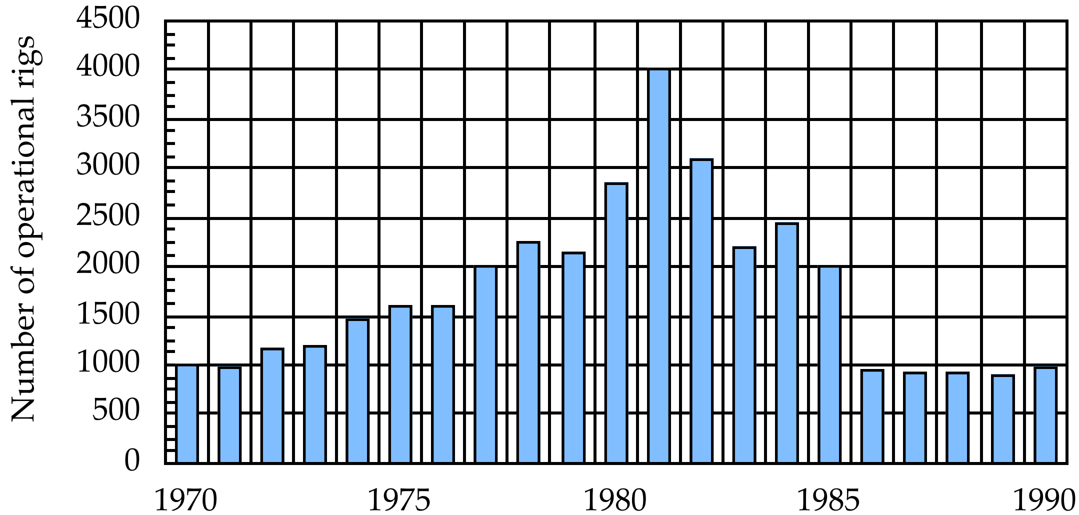


FIGURE 8-8. Average number of oil (and gas) drilling rigs in operation in the U.S. [Source: *Time*, August 27, 1990, p. 47.]

In this case, the oil in the reservoir is under pressure and will come to the surface by natural flow. The force responsible for the flow of oil may be a water drive, in which water lying under the oil pushes it to the surface, or a gas cap drive, in which a bubble of gas pushing down on the oil forces it to the surface. *Settled production* occurs when oil has to be pumped from the reservoir.

Enhanced recovery is used when it is no longer possible to pump the oil with conventional techniques. Enhanced oil recovery techniques are sometimes divided into secondary and tertiary recovery. In secondary production, conditions similar to flush production are created. Instead of relying on naturally occurring water or gas to force the oil out, the oil field is flooded with water pumped down into wells to force the oil out, or gas is pumped down a well to create an artificial version of gas cap drive. This is shown in Figure 8-9.

Secondary recovery methods extract an additional 10 to 20% of the available oil from a well. Because we cannot rely simply on natural forces, as in flush production, but instead must provide pumps and associated piping to force gas or water underground, secondary recovery is more expensive than primary recovery. Tertiary recovery is even more expensive. In general, it is usually necessary to decrease the viscosity of the oil to achieve further recovery. Since the viscosity of any liquid drops as its temperature increases, tertiary recovery often involves heating the oil underground, such as by injecting steam into the wells. As an alternative, special chemicals (surface-active agents) can be injected into wells to reduce the viscosity.

In the United States, many oil fields have lost most of their associated gas. Consequently, little gas pressure remains to force the remaining oil to the surface in gas cap drive. It is necessary to resort to the more expensive methods of secondary and tertiary recovery. Because gas and oil have been pumped from oil fields in the U.S. for many years, and because there is a greater need for enhanced recovery, many active oil wells in the United States actually produce very little oil. There are about 500,000 oil wells in the United States, but the average production is only about 16 barrels per well per day. In comparison, there are no more than 1000 wells in Saudi Arabia, but each one of them produces, on average, 10,000 barrels of oil per day.

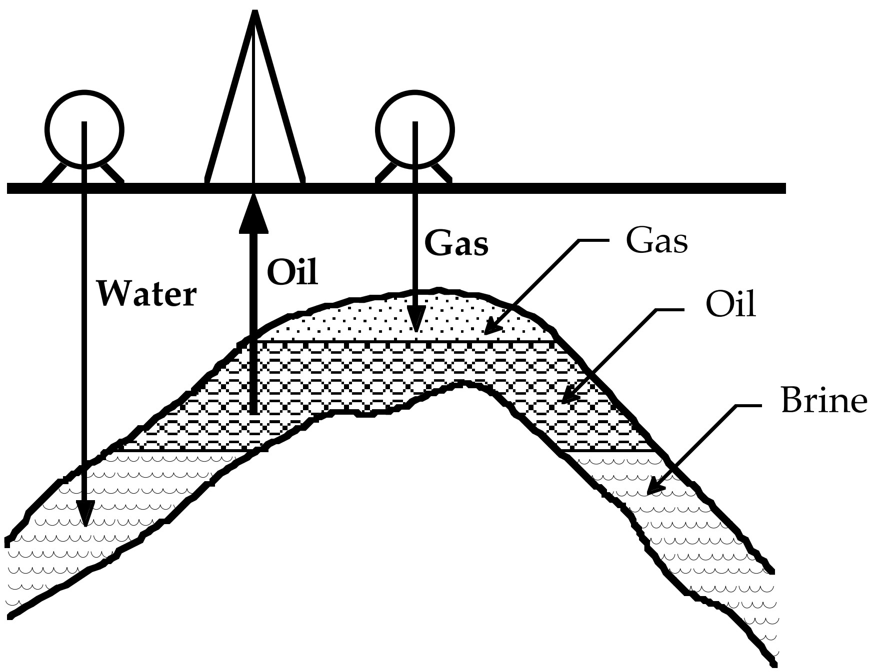


FIGURE 8-9. Enhanced oil recovery techniques: secondary recovery.

In some cases, oil is under such a high pressure underground that drilling creates a *gusher*, in which oil and gas may shoot out of the well up into the air for days or even weeks. An uncontrolled gusher is very wasteful, since there is no way to collect and recover the oil spewed out of the well. It also harms the environment, since the oil is sprayed into the air and onto the ground. A very dangerous situation occurs when an oil well catches fire. In a gusher, the oil and gas may shoot out of the well with such speed that small rocks can be carried along. If one of these rocks strikes sparks from steel piping, a fire could start.

Some oil occurs in pools underneath the sea floor (in the Point Arguello field, California, for example). Extracting that oil from the earth requires the expensive and dangerous process of undersea drilling. The process requires that a stable platform holding the drilling rig be floated into position on the surface of the sea, and anchored in the spot where it is intended to drill. Once the drilling platform has been located and anchored, legs are installed to support the platform from the sea floor. People, their food and clothing and all the necessary supplies must be transported to the drilling rig. In some cases the drilling rigs are large enough to have a helicopter landing pad, so that the transportation of people and materials is done by helicopter. The rig must be anchored and supported well enough to resist the wave and wind action of severe storms at sea (see Investigation 8-6). Precautions are needed to prevent ships from blundering into the rig and to avoid leakage of oil. If a leak occurs in the undersea well or in the piping bringing the oil to the ocean surface, severe ecologic damage can result. The crude oil leaking into the ocean can destroy marine life. Any of the oil that washes ashore can ruin beaches. This is precisely the point of contention between oil firms and environmentalists in the ongoing debate about the development of the Point Arguello field, near Santa Barbara, California, the largest domestic oil discovery since Alaska's Prudhoe Bay (see Investigation 8-14). Such debates will probably increase as the number of offshore rigs increases both in the U.S. (Figure 8-10) and elsewhere in the world.

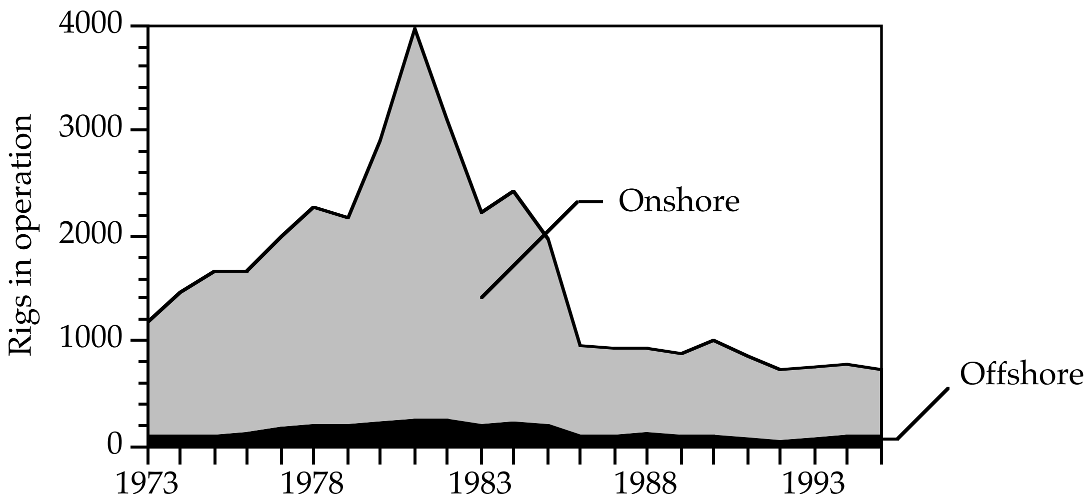


FIGURE 8-10. Oil and gas drilling activity in the United States.
[Source: Energy Information Administration.]

Many factors determine how valuable a particular crude oil deposit is. First is the location of the reservoir – its depth, and the hardness of the intervening rock layers. These factors determine the drilling costs necessary to reach the reservoir. Second is the size of the reservoir; the number of barrels of oil that can be recovered together with the prevailing crude oil price give an indication of the amount of money that can be obtained from selling the oil. The quality of the oil is also an important consideration. First is the question of how easily it can be gotten from the ground. Does it flow readily, or will expensive secondary and tertiary recovery methods be needed? Chemical composition is also an indicator of quality. Suppose an oil company wishes to produce large quantities of gasoline. Gasoline consists mainly of molecules having from five to about nine carbon atoms (see below), and has a very low sulfur content. Given a choice of two crudes, one with molecules mainly having 13-17 carbons and 3% sulfur, and one with molecules mainly having 9-12 carbon atoms and 1% sulfur, the latter would require less refining to obtain high yields of gasoline and would be the more valuable feedstock for a gasoline refinery. Indeed, the best crudes would seem to be those having relatively small molecules (both for low viscosity flow and for high yields of gasoline) and having low sulfur contents. As mentioned previously, the old-deep crudes of Pennsylvania, where oil exploration started, but where there is hardly any oil left, have these characteristics. Today, most of the drilling activity in the U.S. is concentrated in the Gulf states, California and Alaska, as illustrated in Figure 8-11. Six states (Texas, Alaska, Louisiana, California, Oklahoma and Wyoming) accounted for more than 85% of the petroleum produced in 1992.

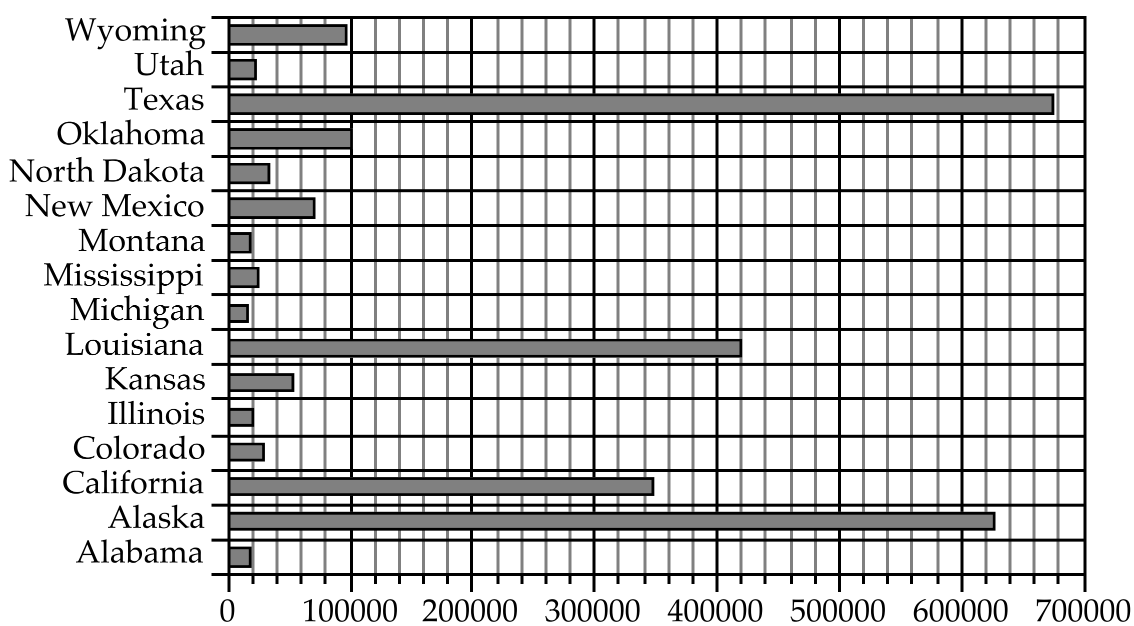


FIGURE 8-11. Production of petroleum in the U.S. by states (in thousands of barrels). [Source: American Petroleum Institute, “Basic Petroleum Data Book,” July 1995.]

Transportation. Once the oil has been pumped out of the ground, it must then be transported to the users. Two major methods are used for petroleum transportation. About 200,000 miles of oil pipelines exist in the United States. The best known is the Trans-Alaskan pipeline, which runs for 800 miles from the oil fields on the north slope of Alaska at Prudhoe Bay to a ship terminal at the (now well known) port of Valdez. The pipeline was completed in 1977 at a total cost of fifteen billion dollars. Its capacity is some 1.2 million barrels of oil per day, almost 20% of U.S. production. Its construction represents one of the largest civil engineering projects of this century.

The second transportation method uses ships – oil tankers and the huge, ocean-crossing supertankers. The supertankers are very economical. They can carry as much as 50 million barrels of oil across the oceans, equivalent to about a three-day oil consumption in the U.S. One problem in their use is that they cannot pass through the Panama Canal. Hence, the oil from Alaska needs to be transferred to smaller vessels for transportation to the East Coast. Another problem became apparent in the spring of 1990 (on a Good Friday!), when the 1000-ft long supertanker Exxon Valdez collided with a reef and spilled some 250,000 barrels of oil into Prince William Sound. (The cleanup costs amounted to several billion dollars.) Several other significant oil spills have been reported by the media since then (see Investigation 8-17). As international transport of oil becomes increasingly important, this potential problem must be added to the growing list of environmental problems associated with fossil fuel utilization (see Chapter 11).

Petroleum Refining. We have seen that coal requires little processing before its (conventional) use for direct combustion purposes. We shall also see that natural gas requires little or no processing. In comparison, when crude oil is pumped from the ground, it may contain several hundred individual components, which range from liquids of very low boiling points to solid waxes. Crude oil could be used as a boiler fuel to make steam for process heating or electric power generation, but it is only marginally more desirable than coal (because of the convenience of handling liquids rather than solids). No other device can make efficient use of a substance having such a complex mixture of components. For example, imagine getting Vaseline (a petroleum-derived product) into the fuel injector or carburetor of your car! Imagine trying to pave a road with gasoline!

As illustrated in Figure 8-5, the approach to making the best use of petroleum is first to separate it into a small groups of compounds. This is done in a petroleum refinery, schematically (and simplistically) illustrated in Figure 8-12. The numbers given in parentheses for the yields of different products are only approximate. They can vary considerably with the type of crude oil refined and with the conditions of operation of the refinery.

In principle, it is possible to separate each component of petroleum one-by-one, though this might take many repetitive distillation operations. However, to do so would be both very wasteful and prohibitively expensive. For example, suppose we had a supply of crude oil that contained 0.5% octane. Octane, C_8H_{18}, is a component of gasoline. If for some reason we wanted to use pure octane as a motor vehicle fuel, we would require 4.8 million barrels (some 200,000,000 gallons) of crude oil to produce 1,000,000 gallons of pure octane, after many distillation steps to purify the octane. On the other hand, 20% of a good crude oil might yield gasoline on simple distillation. Making 1,000,000 gallons of gasoline would require only 119,000 barrels of crude oil. Currently, pure octane can be purchased from chemical supply companies at about $100 per liter, which is equivalent to some $400 per gallon. In contrast, gasoline costs about $1.30 per gallon. Few of us would drive very far if we had to pay $400 for a gallon of fuel! Hence, a compromise is reached by separating petroleum into groups of components having reasonably similar properties. In that way, it is possible to make products having consistently uniform properties without incurring in the expense of separating the petroleum into individual chemical compounds. This upgrading of crude oil into products tailored to meet specific consumer needs is what we mean by *refining.*

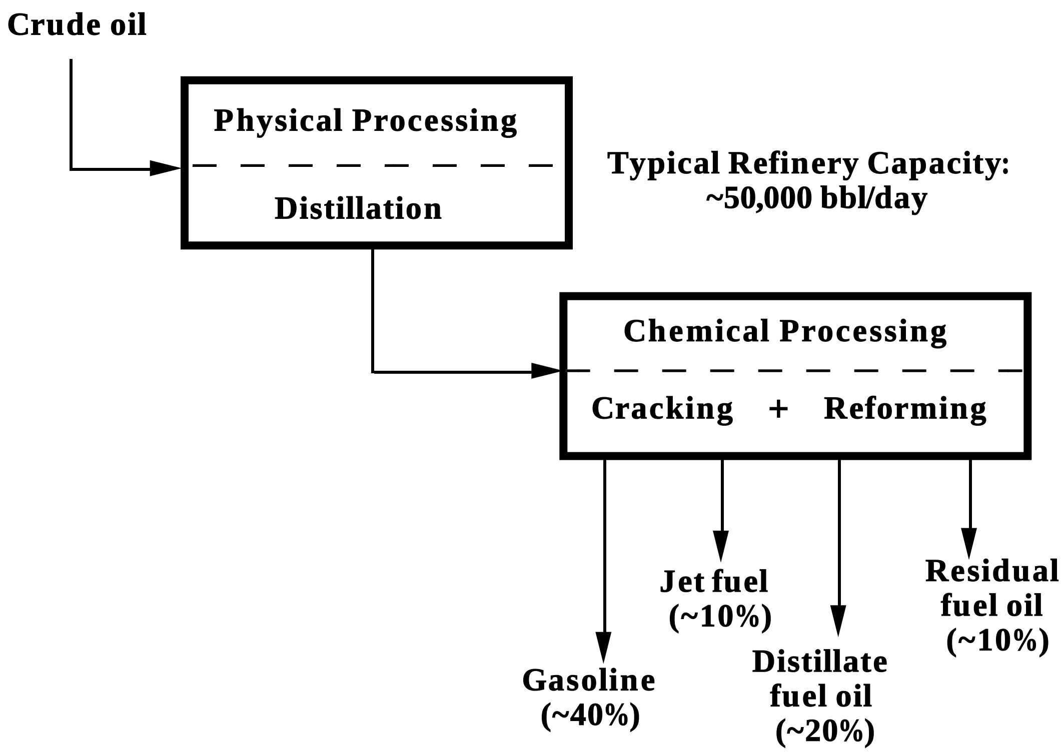


FIGURE 8-12. Schematic representation of a petroleum refinery.

The key step in refining is distillation. *Distillation* is the separation of materials based on differences in their volatility (as indicated by their boiling points). This operation is carried out in a distillation tower (or column) illustrated in Figure 8-13. Vapors from the heated crude oil rise and recondense continuously as they ascend within the column. The more volatile substances – those with the lower boiling points – become relatively enriched near the top of the column. Substances with very high boiling points are enriched near the bottom. At any given location in the column, there is a mixture of vapors corresponding to a liquid of particular composition and volatility. These vapors can be withdrawn from the column and condensed to form a liquid product. Such a liquid is still a mixture of many components, but in this case the components have fairly similar boiling points. The separation of crude oil by distillation is a physical process based on the fact that different chemical compounds have different boiling points. For example, pentane, C_5H_{12}, boils at 36 °C, while nonane, C_9H_{20}, boils at 128 °C. Because the separation is based only on a physical process – boiling – no chemical bonds are broken during distillation and no chemical reactions take place at this stage.

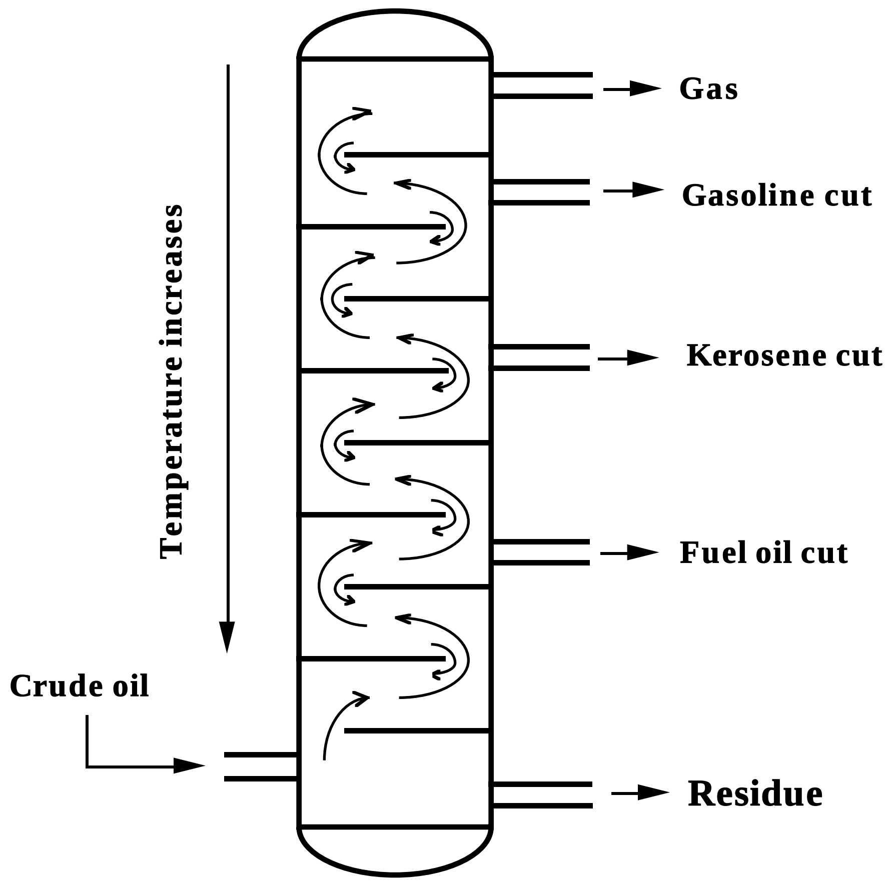


FIGURE 8-13. Schematic representation of a distillation tower.

Petroleum Products. Five broad categories of products are obtained by distillation of crude oil. Their primary use is shown in Table 8-1. Their historical output from U.S. refineries is summarized in Figure 8-14.

Gases are mainly propane, C_3H_8, and butane, C_4H_{10}, that were dissolved in the oil. They can be liquefied and sold as the useful fuel LPG (liquefied petroleum gas); see Chapter 9. Gasoline produced by distillation of crude oil is called *straight-run gasoline*.

TABLE 8-1
Principal energy-related uses of the products of petroleum refining

Product	Main Use
Gases	Industrial and residential fuel
Gasoline	Fuel in spark-ignition engines
Diesel fuel	Fuel in compression-ignition engines
Jet fuel (Kerosene)	Fuel for jet engines and gas turbines
Fuel oils	Industrial or residential fuel

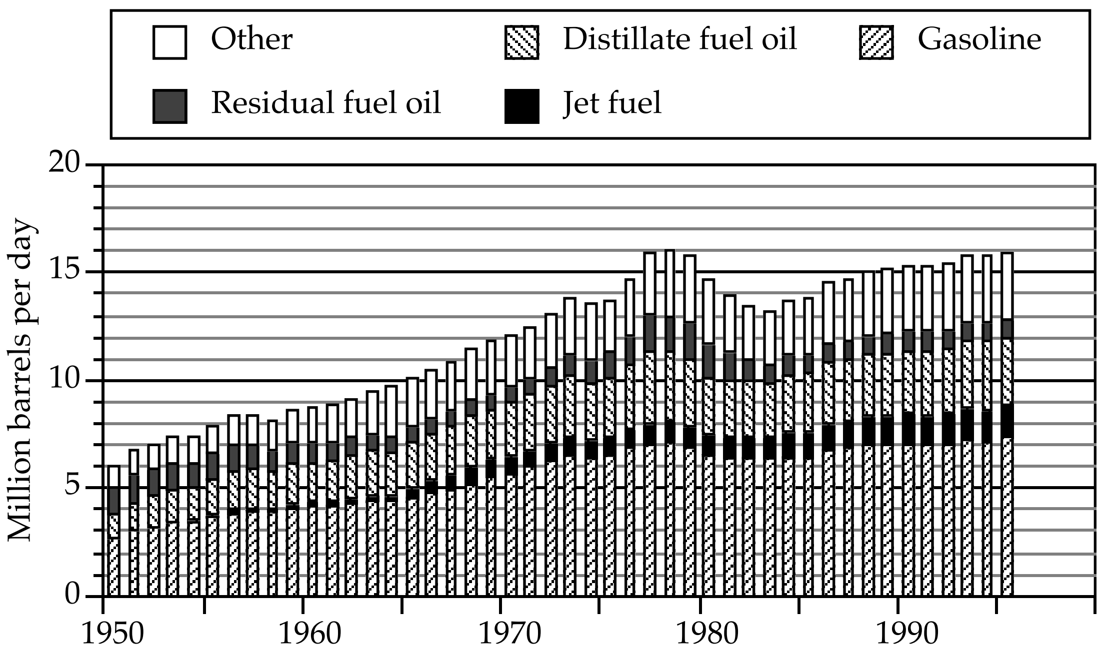


FIGURE 8-14. Output of petroleum products from U. S refineries.
[Source: Energy Information Administration.]

This mixture boils in the range 25-150°C. The major chemical components of straight-run gasoline are straight-chain paraffins in the range of pentane to nonane. *Kerosene* consists mainly of compounds with ten to twelve carbon atoms, boiling in the range of 170-300 °C. *Fuel oil* boils at temperatures above 300°C and consists of molecules with twelve or more carbon atoms. The residue is the material that doesn't boil at all in the distillation operation. In the petroleum business, it is often referred to as the *resid*. Special treatments of the resid can produce heavy fuel oils, asphalt, waxes and greases.

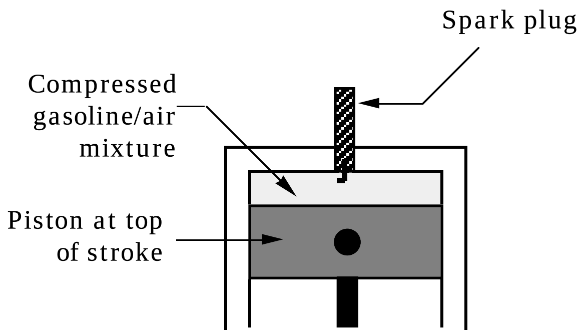
Gasoline is the most important product of a petroleum refinery. A good quality old-deep crude oil may yield 20% straight-run gasoline upon distillation. That is, every 100 barrels of crude oil distilled would provide 20 barrels of gasoline. However, today's market demand for gasoline is such that we need to produce more like 40-50 barrels of gasoline from 100 barrels of crude (see Figure 8-7). We have seen that gasoline components typically have five to nine carbon atoms, while the higher-boiling distillation products have larger molecules. We have also seen that the gradual heating of petroleum inside the earth converts large molecules having long chains of carbon atoms to smaller molecules (compare a young-shallow with an old-deep crude). To increase the amount of gasoline produced during refining, we adopt nature's process for reducing the size of molecules by heating. The formation of an old-deep crude in nature takes thousands of years. To accelerate this process and make it commercially useful in an oil refinery, we use much higher temperatures than are encountered in a typical petroleum reservoir.

The process of *thermal cracking* uses thermal energy (heat) to break chemical bonds. For example, dodecane, $C_{12}H_{26}$, which occurs in fuel oil, might break apart to butane, C_4H_{10}, and octane, C_8H_{18}. Since octane contains eight carbon atoms, we would expect it to be a component of gasoline. In this way, a fuel oil can be cracked to increase the yield of gasoline. Thermal cracking processes were first developed around the time of World War I, to help meet the increased demand for gasoline for military vehicles and aircraft. A disadvantage of the thermal cracking process is that it can produce a lot of carbon-rich solid (also called *coke*, even though this material is not identical with metallurgical coke produced from coal). Converting some of the carbon in the fuel oil to the low-value coke rather than the high-value gasoline represents a waste of material.

As automobile design and technology continued to evolve in the 1920s and 30s, automotive engineers came to realize that not only is the amount of gasoline available to consumers an important concern, but so too is its combustion performance in the engine. To see how and why oil refiners developed processes to produce the kinds of gasoline we can buy today, we must digress a bit to consider how gasoline actually burns in an automobile engine.

Almost all automobile engines operate on a four-stroke cycle. This will be discussed in Chapter 20. The gasoline/air mixture is first compressed and is then ignited. At the instant the spark plug ‘fires’, the gasoline/air mixture in the immediate vicinity of the spark plug tip is ignited. This burning gasoline cloud ignites the surrounding mass of gasoline. The products of combustion occupy a greater volume than the original gasoline and air. For example, suppose we assume that gasoline were pure octane. We could then write the following chemical reaction:

$$2\ C_8H_{18} + 25\ O_2\ \text{Æ}\ 16\ CO_2 + 18\ H_2O$$



In this process 27 volumes of gaseous reactants form 34 volumes of products. The effect of this change is to increase the pressure inside the engine cylinder. Since heat is being liberated from the burning of the gasoline, the temperature also increases. The increasing temperature will also increase the pressure inside the cylinder. Therefore, the unburned gasoline/air mixture is compressed even further. With a well-tuned engine under normal operation, the combustion of the gasoline/air mixture will continue smoothly by igniting successive layers of the mixture until the piston has been pushed to the bottom of its stroke, ready to begin the exhaust stroke. Sometimes, however, the remaining, unburned gasoline/air mixture is compressed so much that it explodes instead of burning smoothly. The explosion is so violent that we can actually hear it inside the car – we call it *engine knock*. Engine knock is undesirable because it wastes gasoline. If your engine knocks regularly, your ‘mileage’, the number of miles driven per gallon of gasoline, will be less than you could get from a smoothly running engine. It is also undesirable because the engine is subjected to increased mechanical stresses when this happens; this can lead to premature wear and physical damage of the engine and, eventually, to some sizeable repair bills. We'll come back to these issues in Chapter 20.

Automotive engineers learned that straight-chain paraffins have a much higher tendency to knock than do branched-chain paraffins. The tendency of a particular gasoline to knock is expressed by its *octane number* (ON).

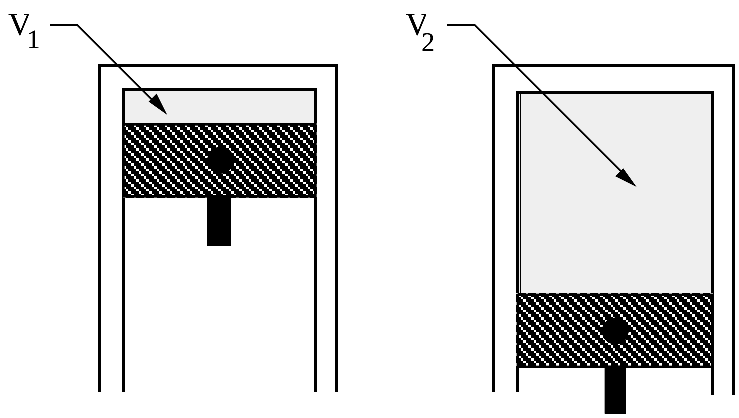
Heptane
ON = 0

Iso-octane
ON = 100

The straight-chain paraffin heptane, C_7H_{16}, is arbitrarily assigned an octane number of 0. The highly branched paraffin formally called trimethylpentane, C_8H_{18}, is assigned an octane number of 100. The name "octane number" derives from the fact that the formal chemical name is abandoned, for convenience, and the compound is referred to as iso-octane, and more often simply as 'octane'.

To determine the octane number, the combustion performance of a gasoline is compared in a standardized test engine with various blends of heptane and iso-octane. The octane number of the gasoline is equal to the percentage of iso-octane in the blend that gives the same knock performance as the gasoline being tested. For example, a gasoline with ON=87 has the same engine performance as a blend of 87% iso-octane and 13% heptane. The higher the octane number, the less likely it is that a gasoline will cause engine knock.

$$\textbf{Compression Ratio} = \frac{V_2}{V_1}$$



The driving performance of a car depends on the *compression ratio* of the engine. This is the ratio of the cylinder volume when the piston is at the bottom of its stroke to the volume remaining when the piston is at the top of its stroke. Although, strictly speaking, the ratio would be expressed as a number, say, 8, it is customary to write the compression ratio as 8:1 and refer to it as "eight to one." The efficiency of an engine is proportional to its compression ratio. The higher the compression ratio is, the greater will be the efficiency of conversion of chemical energy of the fuel to kinetic energy of the engine; in other words, the engine's power will be greater. Since *power* is the rate of doing work, and work must be accomplished to move the vehicle down the road, we experience 'power' as a rapid acceleration of the car and high driving speeds.

If an engine has a high compression ratio, the gasoline/air mixture is compressed to a higher pressure than would be experienced in a different engine of lower compression ratio. Since the gasoline/air mixture is already at a higher pressure in the high-compression-ratio engine, it is easier and more likely to be compressed to the pressures that cause knocking during combustion. In other words, the higher the compression ratio of the engine is, the more likely it is to knock with a given grade of gasoline. Consequently, the higher the compression ratio of the engine, the higher the octane number of gasoline that is required to avoid engine knock.

Straight-run gasoline has an octane number of about 55. In contrast, most modern automobile engines require gasolines with octane numbers in the range of 87-93. Not only must refiners increase the total amount of gasoline produced from a barrel of crude, but they must also seek ways to increase the octane number. Three options are available for improving the octane number. First, straight-chain paraffins can be converted to branched chain compounds (see below). Second, ring-containing aromatic compounds can be blended into the gasoline, because many aromatic compounds have very high octane numbers. Third, special *antiknock compounds* can be added to the gasoline in small quantities. The use of aromatic compounds in gasoline is on the decline because of Clean Air Act regulations: these compounds tend to contribute much more than paraffins to soot and smoke formation, and with increased concern about air pollution from vehicle exhausts, future gasoline formulations are likely to contain fewer, not more, aromatics. In addition, the simplest aromatic compound, benzene, is thought to be responsible for causing leukemia in laboratory animals, suggesting that long-term exposure to gasoline vapors containing benzene might cause leukemia in humans. The most widely used and most controversial antiknock additive is tetraethyllead (for convenience called ‘lead’). The use of tetraethyllead in gasoline is now almost completely discontinued because of environmental concerns. Lead compounds that are produced when tetraethyllead burns in the engine destroy the effectiveness of the catalytic converters in the engine exhaust system. This in turn works against society's efforts to curb the pollution caused by vehicle exhausts (see Chapter 11). Furthermore, lead compounds leaving the exhaust system of the car get into the environment. Most lead compounds are poisonous to humans and other animals. Thus the best strategy for improving the octane number of gasoline is to convert straight-chain paraffins to branched-chain compounds.

In the 1940s, it was discovered that carrying out the cracking operation in the presence of solid materials containing silicon and aluminum oxides, called *catalysts*, not only broke large paraffin molecules apart into smaller ones, but the carbon chains were also changed from straight to branched structures. A catalyst is a substance that increases the rate of a chemical reaction, but is not itself consumed in the reaction. Many catalysts not only increase the rate of a reaction, but they also allow the overall chemical reaction to be carried out at lower temperatures or pressures by altering the specific molecular processes that take place during the course of the reaction. Essentially, catalysts make it easier to carry out a particular chemical process. The *catalytic cracking* process in a refinery increases both the total number of gallons of gasoline produced from a barrel of crude oil and the octane number of the product. Catalytic cracking also generally produces less coke than thermal cracking, and wastes less oil. This is today the standard process for improving gasoline yield, and thermal cracking processes are used only to a limited extent.

All crude oils will produce some straight-run gasoline on distillation. This product has too low an octane number for today's cars, but it would be extremely wasteful to throw it away. Straight-run gasoline is, of course, already a gasoline, so it does not need cracking to improve its properties. Rather, all that is needed is for the straight chains of carbon atoms to be rearranged into branched chains or aromatic rings. The shape, and not the size, of the molecules needs to be changed. In other words, the molecules need to be 're-formed' and indeed the process by which we do this is called *reforming*. Like catalytic cracking, reforming is carried out in the presence of a catalyst. The essential difference is that reforming changes only the molecular shape, while catalytic cracking changes both the shape and size of the carbon chains.

In summary, then, we have seen that relying only on distillation, about 20% of a barrel of high-quality crude oil could be converted to gasoline with a relatively low octane number (for example, ON=55). Using modern refinery technology that includes catalytic cracking and catalytic reforming, almost 50% of a barrel of crude can be converted to gasoline with octane number well into the 90s.

Kerosene is used today mainly as a fuel for jet engines and gas turbines. In years past it was widely used for domestic lighting (in kerosene lamps). That market was essentially wiped out by the increasing spread of electric power networks, especially into rural areas, in the first three decades of this century. There is still a small market for kerosene for domestic use, particularly for auxiliary heaters ("space heaters").

Diesel fuel partially overlaps in boiling range with the fuel oils. The boiling range of diesel fuel is 190-380 °C. In contrast to the traditional automobile engines, in which the fuel/air mixture is ignited by a spark plug, diesels have no spark plugs; they rely on extreme compression to ignite the fuel/air mixture. Both automobile and diesel engines are examples of *internal combustion engines*, meaning that the fuel is ignited and burned inside the engine. We can differentiate the two by referring to the traditional automobile engine as a *spark-ignition engine* and the diesel as a *compression-ignition engine*. The compression ratio of a diesel engine is in the range 13:1 to 20:1, whereas a high-performance spark-ignition engine might have a compression ratio of 9.5:1; in smaller, economy car engines it might be about 8:1.

Since the diesel engine is a compression-ignition engine, we want (in fact, we need) the fuel to 'knock'. Thus the straight-chain paraffins, which are undesirable in gasoline, are highly desirable components in diesel fuels. The standard of performance of a diesel fuel is the *cetane number*. The cetane number is determined in analogous fashion to the octane number. In this case, the two reference compounds are hexadecane ('cetane'), $C_{16}H_{34}$, and methylnaphthalene, $C_{11}H_{10}$.

Cetane is assigned a cetane number of 100 and 1-methylnaphthalene, an aromatic compound very unlikely to knock, is assigned a cetane number of 0. Most commercially available diesel fuels have cetane numbers in the range 30-60. For automobiles or light trucks with diesel engines a fuel with cetane number 52-54 is appropriate.

Cetane Methylnaphthalene

Fuel oils have a wide range of uses. Some of the major uses include domestic heating, generation of heat or mechanical power in industrial processes, steam generation in electric power plants, and running the engines on ships. The entire spectrum of fuel oil products sold commercially covers a wide boiling range. Commercial fuel oils are usually assigned a number to indicate the fuel quality. These are summarized in Table 8-2.

TABLE 8-2
Classification of fuel oils by numbers

Number	Name	Color	Calorific value (BTU/gal)
1	Kerosene	Light	137,000
2	Distillate	Amber	141,000
4	Very light residual	Black	146,000
5	Light residual	Black	148,000
6	Residual (“Bunker C”)	Black	150,000

Number 2 fuel oil is the common home heating oil. Number 6, or Bunker C oil, is a commonly used industrial heating oil; however, Bunker C usually has such a high viscosity that it must be warmed before it can flow through the fuel system into the furnace. As a rule, the viscosity and the sulfur content of fuel oils increase as the classification number increases. The *flash point,* the temperature at which the vapors ignite, and the *pour point*, the lowest temperature at which an oil will still flow, also increase as the number increases.

Lubricating oils (or “lube oils”) exit from the distillation column below the heating oils. In automobile engines, their performance directly affects the efficiency: their role is to minimize the conversion of mechanical energy (of pistons, shaft, etc.) back to thermal energy (through friction). Although lube oils may constitute no more than 2% of the crude, they are very desirable products, since they can often be sold at high profit. (Compare the cost of a *quart* of lube oil with a *gallon* of gasoline.) Lube oils are carefully refined to insure desirable lubricating characteristics. These characteristics include a low viscosity at low temperatures (so that the oil can flow into the moving parts even on very cold days), low volatility at high temperatures (so that the oil does not vaporize away when the engine is running at high speed) and a resistance to decomposition at the high temperatures of the engine.

Table 8-3 and Figure 8-15 summarize the data on the various commercially available motor oils, which the reader should find useful. The SAE (Society of Automotive Engineers) oils are designated by their viscosity or pour point. The lower the pour point (for, say, oil 5W), the lower the viscosity and the more likely it is that the oil will flow (and thus lubricate the engine) at low temperatures. In very cold climates, one needs to use oils like 5W-20 or 5W-30 to make sure that they will flow at the very low temperatures. There exist also ‘year-round’ oils, for most climates, such as SAE 10W-40 and 10W-50. (These oil designations have found their way even into comics. Here is the dialogue from a 1995 B.C. cartoon: “I have this terrible recurring dream that involves numbers and letters,” says the patient to “Dr. Peter, the head shrinker.” “What are they?,” asks Dr. Peter. “10W-30,” responds the patient.)

TABLE 8-3
Properties of common lubricating (engine) oils

SAE Number	Pour Point (°C)	Viscosity*
5W	-	3.8
10W	-28	4.1
15W	-	5.6
20W	-24	5.6
20	-	5.6
30	-20	9.3
40	-16	12.5
50	-10	16.3

* in mm^2/s, at 100 °C
Note: Commercial motor oils are mixtures of the ones shown in the table.

Finally, asphalt – which is normally a non-distillable portion of crude oil – is most commonly used for paving roads. Waxes can be extracted from asphalt using special solvents. Waxes have a variety of important - though mundane - uses in society, including candles, waxed paper, wax coatings on cardboard food containers and the paraffin wax used for sealing jars when preserving food by home canning.

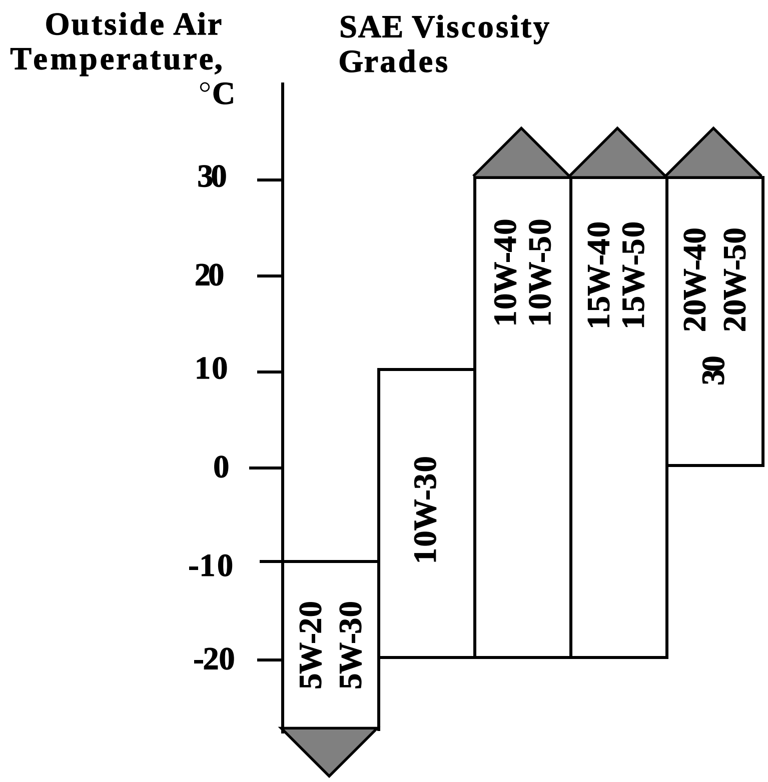


FIGURE 8-15. Examples of viscosity grades for passenger car engine oils. [Source: Society of Automotive Engineers Handbook, 1986.]

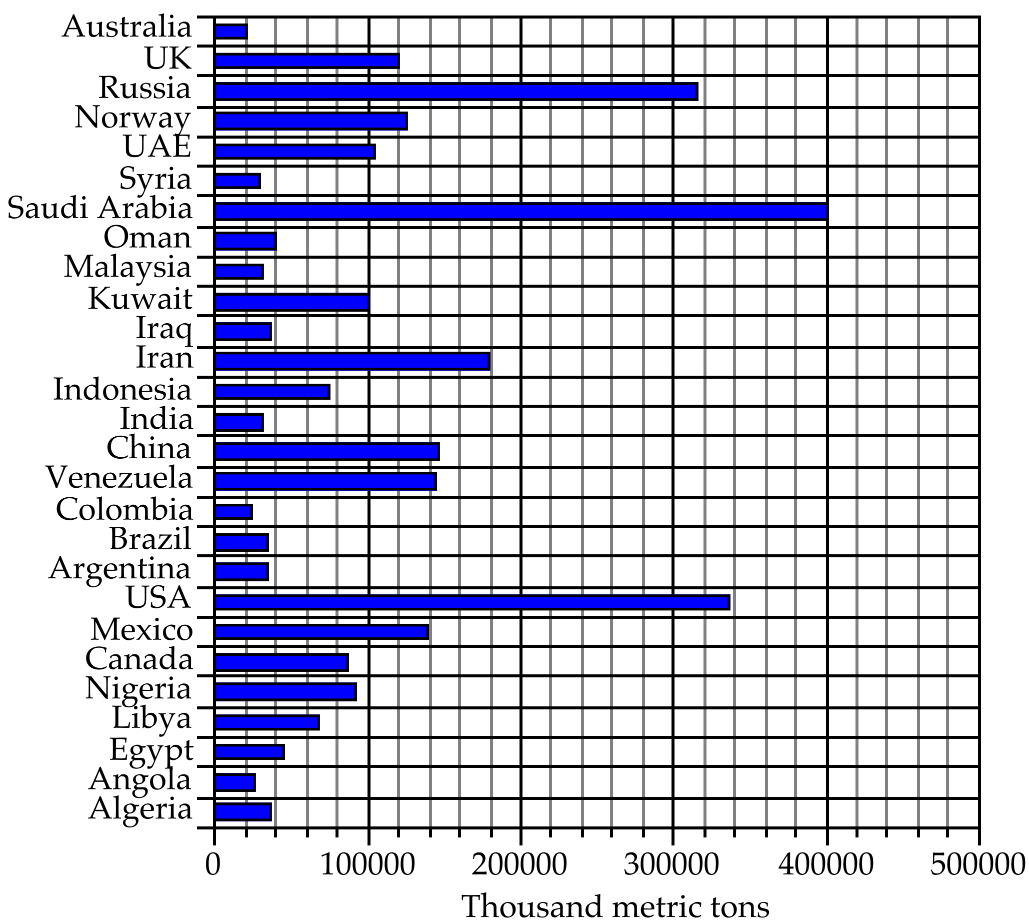
REVIEW QUESTIONS

8-1. The Department of Energy has provided the following data for the U.S. proven reserves of oil in the period 1984-1994 (in billions of barrels): 28.4, 28.4, 26.9, 27.3, 26.8, 26.5, 26.2, 24.7, 23.7, 22.9, 22.5. Make a graph with these data and comment on the trend observed. Compare this information with that published in the *Economist* of 7/20/96 (p. 88) according to which the U.S. has 10 years of reserves remaining.

8-2. Each one of the tankers from a fleet that bring imported oil to the U.S. carries 5 million barrels of oil. How many of these need to be unloading their cargo in any given day to keep the U.S. refineries busy?

8-3. Recently hailed as one of the largest discoveries since Prudhoe Bay (see NYT of 11/22/96, “Petrobrás Finds Big Deep-Water Oilfield”), a field 80 miles off the coast of the state of Rio de Janeiro (owned by Petrobrás, the state-owned Brazilian oil company), is said to contain 1.3 billion barrels of oil. Indeed, in the last decade there has been no larger discovery (see the *Economist* of 5/18/96, “From major to minor”). At current oil consumption levels (less than 2 quads per year), how long would this oil last in Brazil. Were it to be consumed in the U.S., how long would it last?

8-4. The “1994 Energy Statistics Yearbook” of the United Nations reports that the world oil production was 3.03 billion metric tons of oil.
(a) Compare this amount, in energy units, with the production of coal (see Review Question 7-2).



(b) What percentage of this production is accounted for by the countries shown on the graph (p. 163)?
(c) What fraction is accounted for by the U.S., Russia and Saudi Arabia?
(d) Compare the information in this graph with that provided in Figure 8-3. Is the agreement good?

8-5. Do the numbers for U.S. reserves shown in Figures 8-1 and 8-2 agree with each other? Explain your answer.

8-6. By regularly changing the lubricating oil, the average efficiency of a car is kept at 30 miles per gallon. If the oil is not changed regularly, the average efficiency slips to 27 miles per gallon. The car is driven 15,000 miles every year and a gallon of gasoline costs $1.30. (a) How much money is saved by changing the oil? (b) Is this enough for 3 annual oil changes (at $20 per oil change)?

8-7. How many pounds of carbon dioxide are produced by burning a pound of gasoline and a pound of diesel fuel? Which fuel produces more CO_2? Assume that gasoline can be represented as octane and that diesel fuel can be represented as cetane.

8-8. Indicate whether the following statements are true or false:
(a) A gasoline that has an octane number of 92 contains 92% iso-octane and 8% heptane.
(b) In the past 30 years domestic oil production has exceeded domestic consumption.
(c) Distillation of crude oil is a chemical process.
(d) Reforming of crude oil does not change the number of carbon atoms in the molecule chain.
(e) Cracking of crude oil does not change the number of carbon atoms in the molecule chain.

8-9. Explain why all cars made in the U.S. since 1975 use unleaded gasoline.

INVESTIGATIONS

8-1. Find out where the Exxon Corporation is looking for oil these days. See NYT of 10/20/91 (“Oil's Field of Dreams Is Usually Foreign”), 9/19/94 (“Exxon's Go-Slow Strategy: Some analysts worry growth is threatened”) and 6/30/95 (“Exxon Expected to Sign Deal For Russian Oilfields Today”). Where are the other major oil companies drilling for oil? See *Time* of 7/4/94 (“Black Gold Rush: One of history's great oil scrambles is under way as new fields open up abroad”); BW of 1/13/92 (“Big Oil's Slippery Slope”) and 8/8/94 (“Remaking Big Oil”); NYT of 7/19/92 (“The Shrinking of the American Oil Industry”), 9/11/92 (“Exxon and Mobil in Russia Venture”), 11/1/93 (“East China Sea Opened to Oil Exploration”), 11/9/93 (“Oil Companies Shifting Exploration Overseas”), 3/20/94 (“For Oil Industry, That Next ‘Elephant’ Proves Elusive” and “In Russia, Turning Oil Into Money Is Actually Hard”), 3/25/94 (“Group Sets Oil Project For Russia”), 4/12/94

("Siberian Oil Venture by 4 Companies"), 9/1/94 ("Conoco Starts Pumping Deep in Arctic Russia"), 9/21/94 ("Huge-Scale Caspian Oil Deal Signed"), 10/31/94 ("Long-Term Oil Strain Is Seen"), 3/12/96 ("Shell Makes a Big Oil Discovery Off Nigeria"), 9/24/96 ("Market Place: Arco looks to Russia to fill its vast appetite for oil reserves"); WSJ of 9/11/92 ("Exxon and Mobil Agree to Search Jointly For Large Oil Fields in Western Siberia"), 9/1/94 ("Conoco Tests the Tundra for Oil Profits"), 10/10/94 ("Foreign Oil Companies Find Risks in Exploring China's Tarim Basin"), 11/24/94 ("Texaco-Led Consortium Nears Russian Oil Agreement"); *Economist* of 5/18/96 ("From major to minor: The world's big oil firms are engaged in an increasingly desperate scramble for giant, low-cost reserves"). See also *Fortune* of 9/10/90 ("The Beginning of the End for Oil").

8-2. Alaska has become almost as hooked on revenues from oil as some of the OPEC countries. Investigate the importance of oil in Alaska's economy. Are Alaskans in favor of opening the Arctic National Wildlife Refuge for oil exploration? See NYT of 1/27/91 ("Hickel Wants New Alaska Gold Rush"), 10/9/96 ("Payday in Oil-Rich Alaska: Questions Over a Windfall"); BW of 8/6/90 ("Why Alaska needs to break its oil habit") and the *Economist* of 1/29/94 ("Alaska's budget: Now, the diet"). See also Investigation 21-1.

8-3. Since the breakup of the Soviet Union, Azerbaijan has emerged as an important player on the international oil market, just as it was a century ago in the times of Ludwig Nobel, the "oil king of Baku" (see Chapter 3 in Yergin's *The Prize*, Further Reading, p. 461). Find out who is exploring for oil in and around Baku, how much is expected to flow from these fields, and through which pipelines. See NYT of 9/21/94 ("Huge-Scale Caspian Oil Deal Signed"), 2/15/95 ("Getting This Oil Takes Drilling and Diplomacy"), 9/13/95 ("Pipeline Politics"), 10/4/95 ("U.S. and Russia at Odds Over Caspian Oil"), 10/10/95 ("Lessened Russian Role in Azerbaijani Oil"), 10/27/95 (Caspian's Sun on Rise, Chasing Russian Shadow"); *Economist* of 11/14/92 ("Azerbaijani oil: Almost an oil rush"), 3/25/95 ("Of pipedreams and hubble-bubbles: Like just about everything that happens in Azerbaijan, last week's attempted coup had oily ramifications"); and BW of 7/17/95 ("The Great Game Comes to Baku: Who will tap–and transport–the Caspian sea of oil?").

8-4. The North Sea oil has been a big factor in reducing the clout of OPEC in the last fifteen years. Find out how much oil is flowing from these fields, who is producing it and who is using it. See NYT of 4/12/94 ("Risks Rise in North Sea As Oil's Price Declines"), 2/28/95 ("Shell and Exxon in North Sea Oil Venture") and 10/19/95 ("New Oilfield Lifts Output From Norway").

8-5. Colombia, known for its vast reserves of high-quality coal (see Investigation 7-11) and as a former oil importer, has become a new oil power. Investigate how much oil is expected to flow from its oil fields and how much of it is exported. See NYT of 8/4/93 ("As Colombia Oil Flow Spurts, So Do Worries About Money"), 8/22/94 ("Oil Companies Buy an Army To Tame Colombia's Rebels"), 3/20/95 ("Colombia Becoming an Oil Power in Spite of Itself") and 10/7/96 ("Land Clash Pits Indians Vs. Oilmen in Colombia"). See also the *Economist* of 7/31/93 ("Colombia: And now oil").

8-6. Offshore drilling in the Gulf of Mexico has been important for the U.S. oil industry since the 1960s (see Figure 8-10). Find out about some of the recent activities of oil companies in the area. How much oil is expected to be recovered? Is offshore drilling permitted elsewhere in the U.S.? See BW of 5/15/95 ("The Undersea World of Shell Oil: It's discovering vast reserves in the Gulf of Mexico"), 10/30/95 ("Pulling Oil from Davy Jones' Locker: New technologies cut the cost of deep-sea production"); USNWR of 7/3/95 ("Coastal Drilling? Don't Bet On It"); *Economist* of 8/19/95 ("Offshore Oil: Murky waters"); NYT of 10/28/90 ("Lawmakers Agree to Curb Exploration for Offshore Oil"), 2/10/91 ("Interior Dept. Backs New Drilling For Oil and Gas at Offshore Sites"), 4/24/94 ("2,860 Feet Under the Sea, a Record-Breaking Well"), 12/7/94 ("Oil Companies Drawn to the Deep"), 9/19/95 ("Oil and Gas Finds by Texaco Give It Hope in Gulf of Mexico"), 9/26/95 ("Geochemist Says Oil Fields May Be Refilled Naturally"), and 11/28/95 ("Shell to Seek Oil Beneath Gulf of Mexico Salt"). See also *National Geographic* of 7/92 ("America's Third Coast").

8-7. Geologists are drilling for oil in increasingly remote areas. An offshore platform is a remarkable engineering achievement. It better be! A typical cost is a billion dollars, similar to that of a 1000-megawatt electric power plant. Find out more about new ways of oil drilling and about the challenges of maintaining offshore platforms. See *National Geographic* of 8/89 ("The Quest for Oil"); NYT of 10/21/92 ("How the Offshore Rigs Rode Out Gulf's Storm"), 4/8/96 ("A New Way to Seek Undersea Oil, Via Satellite"); and USNWR of 7/10/95 ("Drilling deep for dollars").

8-8. In Latin America, Venezuela is the oil 'super-power'. But there are other important oil players as well. Prepare two bar graphs, one showing the proven reserves of oil in Latin American nations and the other showing their current oil production. See NYT of 7/11/93 ("Latin America's Oil Rush: Tapping Into Foreign Investors") and the *Economist* of 5/15/93 ("Oil in Latin America: A sacred limping cow") and 6/1/96 ("Energy in Latin America: Even oil is growing less sacred").

8-9. The Chevron Corporation has been interested in exploiting oil in Kazakhstan. How much oil is expected to flow from the Tengiz oil field? Summarize the recent developments in this potentially huge deal. See NYT of 12/29/92 ("Caspian Oil Date Is Set By Chevron"), 4/7/93 ("Kazakhstan And Chevron Start Venture"), 10/4/95 ("U.S. and Russia at Odds Over Caspian Oil"), and 11/19/96 ("Pipeline Set To Expedite Kazakstan Oil").

8-10. The eight-hour TV series "The Prize," based on Daniel Yergin's book (see Further Reading, p. 461), was a major energy-related media event. Read the reviews and summarize the opinions of the critics. See *Time* of 1/11/93 ("Historical Gusher"), and NYT of 1/10/93 ("Oil Becoming the Substance of Saga") and 1/11/93 ("The Epic of World Oil

As a Catalyst of Conflict"). See also the review of the book in the NYT Book Review of 12/9/90.

8-11. As the country itself, Russian oil industry has gone through quite a turmoil in the last decade. Review some of the events as reported by the media. See NYT of 9/6/90 ("Effect of Fall in Soviet Oil Output"), 5/19/91 ("Oil Facts and Follies: U.S. ignores drop in Soviet exports"), 2/11/92 ("Siberia: Rich in Oil, but Not 'Oil-Rich'"), 7/12/92 ("Russians Line Up for Gas as Refineries Sit on Cheap Oil"), 9/11/92 ("Exxon and Mobil in Russia Venture"), 10/22/92 ("Market Place: Searching for Oil Beyond Moscow"), 12/13/92 ("Russia's Oil Industry, the New Domino"), 3/20/94 ("In Russia, Turning Oil Into Money Is Actually Hard"), 3/25/94 ("Group Sets Oil Project for Russia: $10 Billion Investment in Sakhalin Island Field"), 4/12/94 ("Siberian Oil Venture by 4 Companies"), 9/1/94 ("Conoco Starts Pumping Deep in Arctic Russia"), 9/4/94 ("Siberia Awaits the Onslaught"), and 6/30/95 ("Exxon Expected to Sign Deal For Russian Oilfields Today"); WSJ of 8/22/90 ("A Host of Problems Plague Soviet Union's Oil Industry"), 9/1/94 ("Conoco Tests the Tundra for Oil Profits"), 11/24/94 ("Texaco-Led Consortium Nears Russian Oil Agreement"); *Economist* of 7/16/94 ("Lukoil: Vagit Rockefeller"), 12/10/94 ("Russian oil: A gusher under ice"), and 4/1/95 ("Russian oil: The refined chaos").

8-12. Asia is poised for rapid economic development in the 21st century. Do Asian nations have enough oil? Prepare a graph that compares their production and consumption of oil. See the *Economist* of 8/15/92 ("Asian energy: Quenching the tigers' thirst").

8-13. Find out more about the Strategic Petroleum Reserve. Retrieve the relevant data from the Web site of the Energy Information Administration (www.eia.doe.gov). Make an appropriate graph. How long would this oil last in the case of cessation of imports (if the current consumption trends continued)? See also NYT of 9/28/90 ("Delivering Oil From Strategic Reserves to Consumers"), 1/6/91 ("Using an Oil Reserve to Control Prices"); WSJ of 9/14/90 ("Increase in Strategic Petroleum Reserve To One Billion Barrels Is Voted by House"); *Oil & Gas Journal* of 4/8/96 ("The SPR and the budget").

8-14. Despite the fact that the Los Angeles Basin is notorious for its smog, California is well known for its tough environmental regulations. A case in point is Chevron's exploitation of Point Arguello oil field (close to Santa Barbara), one of the largest reserves found since Alaskan Prudhoe Bay. Find out more about this odyssey. See NYT of 11/28/90 ("Chevron Sets California Oil Plan") and 11/29/90 ("Breaking Logjam on California Oil"), as well as WSJ of 11/12/90 ("Oil Firms and Environmentalists Seem No Closer To Agreement in Drawn-Out Fight in California"). How would you go about getting a quick update on this situation?

8-15. Catalytic cracking is a process that revolutionized the production of transportation fuels from petroleum. Find out how it also helped win the Second World War. See the *Journal of Chemical Education*, August 1984, p. 655.

8-16. Kuwait's oil fields have been devastated during the 1990/91 invasion by Iraq; see *National Geographic* of 8/91(“After the Storm”) and 2/92 (“Persian Gulf Pollution”). They appear to have recovered admirably. Summarize the important indicators that illustrate this recovery. See NYT of 11/6/94 (“Kuwait's Oil Industry Rises From the Ashes of War”).

8-17. International transport of crude oil is very important for the United States and the world (see Review Question 8-2). It has been under closer scrutiny since the Exxon Valdez spill. Find out about some of the insurance and market issues. See NYT of 12/12/94 (“Insurance Shift for Oil Tankers May Disrupt Flow to U.S.”).

8-18. In a series of advertisements on the current exploration and utilization of oil, the Mobil Corporation makes the point that it is “getting ready for a changing world” (NYT of 8/29/96). The changes involve both going to new places to find oil and using modern technology to find it and refine it. Find out about some of these new developments. See *USA Today* of 11/12/92 (“High technology: A premium asset”); NYT of 10/3/96 (“A different kind of power”), 10/10/96 (“Staying the course vs. cut and run”), 11/7/96 (“High drama once again in the age of oil”), 11/15/96 (“New tools for today's oil prospectors”), and 11/20/96 (“Managing molecules”).

8-19. In another series of advertisements on the current exploration for oil, Mobil talks in more detail about its many international partners. Find out about some of these partners. See NYT of 8/31/95, 9/21/95, 10/26/95, 11/16/95, 1/18/96, and 2/8/96.

8-20. It is understandable that Mobil and other oil companies are not thrilled by the prospects of “alternative fuels.” In an advertisement entitled “Running out of oil?,” Mobil argues against forcing the market to make the transition to alternative fuels prematurely. What alternative fuels is Mobil talking about? Summarize the arguments against these alternative fuels. See NYT of 4/13/95.

8-21. Once upon a time, independent oil producers – the so called ‘wildcatters’ – were very important for the domestic oil supply. What are their fortunes these days? See *Time* of 8/27/90 (“Gushing With Enthusiasm”) and *Smithsonian* of 3/91 (“There are new signs of energy out in the Kansas oil patch”).

8-22. There has never been more publicity given to oil than in September 1990. Browse through some of the newspapers and weekly magazines of the time and find out why.

8-23. In addition to discussing the geopolitics of oil, the *National Geographic* of 5/88 (“The Persian Gulf: Living in Harm's Way”) has important information on the oil reserves in the region. Do the numbers quoted agree with the information in Figures 8-1 and 8-2 What fraction of Middle East's reserves is in the Persian Gulf countries?

8-24. As far as “big oil” is concerned, it all started with Colonel Edwin Drake in Titusville, Pennsylvania in 1859. Find out about today's oil cities in Pennsylvania. See NYT of 7/26/95 (“Inside Oil City, Hope Runs Dry”).