THE FUTURE OF FOSSIL FUELS

KENNETH S. DEFFEYES

A **PRINCETON SHORTS** selection from *Hubbert's Peak*

As debates about the effects of fossil fuels on our climate and foreign policy intensify, the question o just how much longer we can depend on this finite source of energy becomes more and more pressin This selection from *Hubbert's Peak*, the leading book on the limits of our oil supply, forecasts wh the future will bring for fossil fuels and what the alternatives are likely to be.

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CHAPTER 9

The Future of Fossil Fuels

Years ago, a visitor to Switzerland asked how people earned a living in those high Alpine village "Each village gets paid for doing laundry for the next village." Today, an equally silly answer woul be, "Each village uses the Internet to sell toilet paper to the next village." The lesson for the glob village: we can't all work in the service economy; somebody has to be down grubbing at the base the economic pyramid. The list of fundamental activities is short: agriculture, ranching, forestr fisheries, mining, and petroleum.

Consider the names on some great art museums: Getty (oil), Guggenheim (copper), de Menil (c services), Gulbenkian (oil). Huge wealth used to be accumulated at the base of the economic syster Today's dot.com billionaires up at the apex of the pyramid may not be able to see all the way down t the base. They might have the illusion that everyone can earn a living by selling software to the ne village.

A permanent drop in oil production will pull one of the blocks out from underneath the pyrami The previous chapter strongly suggests that the drop will happen in this decade. Major disruptio likely will follow. What should we do? The question exists at two levels:

1 What can individuals and institutions do, in their enlightened self-interest, to minimize t impact of a global oil shortage?

2 As a society, how can we rearrange the global economy to lessen our dependence on oil?

Republicans choose line 1; Democrats pick line 2. The division is not that simple. I'm a registere Democrat, but I still feel authorized to protect myself while the world gets its act together. That's wh line 1 says "*enlightened* self-interest." This chapter discusses fossil fuels; chapter 10 treats alternati energy sources.

A "fossil" is the remains of an ancient organism. A fossil fuel is solar energy stored by organism in ancient times. A major lesson: the source of the world's oil accumulated over hundreds of millio of years; most of the world's oil has been discovered during my lifetime. Large-scale use of foss fuels began with the Industrial Revolution, of which coal was an integral part. In a sense, the foss fuels are a onetime gift that lifted us up from subsistence agriculture and eventually should lead us a future based on renewable resources.

A fad of 10 years ago was "finding oil on Wall Street." Publicly traded companies wit undervalued oil and gas reserves became targets for stock traders and merger-and-acquisitio specialists. An individual today could offset his or her family's petroleum consumption by purchasin oil and gas company shares. But "petroleum consumption" is not just gasoline and home heatin Many other goods and services include an energy cost. Only comparatively wealthy individuals ha the flexibility to offset future oil price rises by owning oil stocks. Many of us in the middle class ha the majority of our assets tied up in home equity and managed retirement funds; we have litt flexibility to change investments.

~~My friends would love to have a short list of trading symbols for companies with undervalu~~ U.S. oil reserves. Unfortunately, professional traders have their computers monitoring thes opportunities. Several large oil companies are ready to swallow smaller companies to acqui additional reserves. I'm not likely to find anything in a three-month-old copy of *Oil and Gas Journ* that the full-time traders have overlooked.

Colleges and universities are substantial energy users; the more fortunate schools have sizab endowments. Investing a block of the endowment, directly or indirectly, in oil and gas reserves cou be a prudent choice. I can report, however, that I got absolutely nowhere when I tried to explain that t Princeton University in 1980. Two universities have their energy problem solved in advance: th University of Texas at Austin and Texas A&M share revenues from state-owned oil lands.[1] Th University of Texas at Austin has an endowment second only to Harvard; an oil price rise increase UT Austin's income.

Here is a second limitation: we can't all buy Texaco. For years, Texaco has been a Wall Stree favorite: large oil and gas reserves, few employees, low costs. Texaco is disappearing as a investment opportunity; it is being acquired by Chevron. In fact, the entire stockholder equity for a U.S. petroleum companies combined is not large enough for all of us to offset the threatened oil pric rise. Equities are, at best, an opportunity for smart money to get in during the early rounds.

Gradually, the role of the major oil companies has changed. They are becoming more lik enormous service companies, although they do bring along their own investment capital. The majo appear to be vertically integrated companies, active in everything from exploration to marketin However, production, transportation, refining, and marketing are almost independent activities. Th oil has a defined price in between each stage. I was disappointed when I learned that the gasoline so in a Shell station might come from a Conoco refinery. Shell writes specifications and analyzes th gasoline to see that it meets the specifications, but another company may do the actual refining. The is no equivalent of a chateau-bottled wine.

In the past 10 years, major oil companies have been getting as little as 10 percent of the oil their share in new overseas ventures.[2] Much of the oil revenue goes to the producing nation, usual through the participation of government-controlled oil companies. At the marketing end, a substanti part of the price of gasoline at the pump is another round of taxes. Let's face it, oil used to be a high profitable business, and governments figured out how to cut themselves in for a big piece of th action. As world oil production decreases, some governments may feel more pain than the major o companies.

Years ago, the New York Times Company bought enough Canadian forestland to grow pulpwoo as fast as it prints newspapers. Heavy petroleum users among large corporations, like FedEx and UP could attempt a takeover of an oil company large enough to offset their consumption. In the past, useful way of insuring major producers and consumers against the effect of a price changes w purchasing futures contracts. However, the ordinary futures contracts extend for a year or two. The o problem extends for 10 years or more. Anyone who agrees to supply oil 10 years from now, for a pric agreed on today, very likely will disappear into bankruptcy before the contract matures.

The financial world has reorganized since 1980. Effects of oil price rises, during the late 1970 took months to years to spread from industry to industry; from price increases to wage demands. I the new economy, the shock of an oil price rise will spread in milliseconds. Detailed computer mode of the world economy will flash messages to buy or sell everything from AT&T to Xerox, from aluminum to zinc, from bahts to zlotys.

Oil and gas companies have split personalities. Finding a new oil field is an investment th generates income for 20 years, but Wall Street has a fixation on the most recent quarterly earning The ~~stock market has preempted the time horizon for most corporations, especially for those~~ outsi the natural resource industries. The CEO is assigned stock options on a two-year time scale. H motivation is to get the stock price up in two years: one way is to close the research lab, fire t engineers designing the upcoming product, make the quarterly profits look great, retire and cash ou Of course, I have overstated the case, but the top managers should not be given heavy person incentives to ignore long-term goals.

A second struggle about the time horizon comes from interest rates. A potential project, in an industry, is judged by the present-day discounted value of the expected future cash flow.[3] At times high inflation, and high interest rates, the future barely exists. During the 1980 oil crisis, interest rat reached 20 percent. At a 20 percent discount rate, a dollar earned 10 years in the future has a presen day value of only 11 cents. Long-term efforts, like designing a new aircraft or exploring for new o become difficult to justify. ExxonMobil is not designed to be a charity. In the existing syster ExxonMobil is not asked to take on uneconomic projects to provide us with future oil. Discounting t future is more than a problem for the oil industry. Economists and the Sierra Club have opposi philosophies.

The dichotomy between the short and long time scales affects employees, including t professional staff. Oil companies have to survive boom-and-bust cycles. This one circulated arou Denver in 1970:

Q: How do you address a petroleum geologist?
A: Waiter!

Usually at a time of low prices, all the companies in the industry are hurting simultaneously. Of t 200 largest U.S. oil and gas companies, 133 had a net loss for the year 1998. Employees who are let rarely find employment at another oil company; many of them leave the industry and never want return.

At the other extreme, around 1980 our geology undergraduates were starting out at salaries high than those of their professors. Some were very capable, but some were not our best students. Boo years can be just as distorted as lean years. However, falling oil production is not necessarily bad ne for individual petroleum geologists. My rough calculation shows that geologists' salaries amount about two cents for each barrel of U.S. oil. There's plenty of room to raise that to four cents per barr

In 1997, I looked into direct investment in wells. Could I set up a company to buy and opera wells? During 1998, inflation-corrected oil prices approached the levels of the 1930s Depression. the same time, a terrible drought was affecting the midcontinent. Rumor had it that the Oklahoma Ci police chief reported the good news that only 13 women in Oklahoma City were trying to earn a livi as prostitutes. His bad news was that 7 of them were still virgins. It seemed like a good time to shopping for oil wells.

I picked out one category of wells that might be made marginally profitable, but my maj motivation was holding the wells for five years until world oil production peaked. The search focus down to certain counties and a particular depth range. (Don't ask! Just because I am writing a boo doesn't mean I have to tell *everything*.) The potential investors I approached had two reactions: (1) was a severely depressed industry, and (2) you could make a gazillion dollars in 1997 by buyi Internet stocks. In the year 2000, potential investors told me that oil prices had recently doubled a oil wells would be too expensive to buy. So it goes.

In the long run, the eventual use for oil will be for manufacturing useful organic chemicals. ~~expect our grandchildren to ask, "You burned it? All those lovely organic molecules, you just burne~~ it?" Sorry, we burned it. Originally, the feedstock for synthesizing organic chemicals was a tar by product from treating coal. The change from coal tar to oil, roughly from 1930 to 1950, gave the nan "petrochemical" to the industry. Today, about 7 percent of world oil production goes int petrochemical manufacturing.[4]

The modern state of Israel is, in one limited sense, a product of the synthetic chemical industr During World War I, a shortage of the solvent acetone was severely limiting British production o gunpowder. Chaim Weizmann, a young chemical engineer working in England, developed a successf method for synthesizing acetone.[5] After the war, as a thank-you gift for Weizmann, the British carve out an independent country in the Middle East, which they named Palestine.

Natural crude oil consists of relatively stable molecules. No surprise, over geologic time all th unstable molecules break down. Early petroleum refineries simply sorted out those stable molecul into salable products. Oil production, and oil refineries, had been running for 50 years before th automobile was invented. Originally, their most marketable product was kerosene, primarily for lig from kerosene lanterns. The Oklahoma City oil field was discovered by the Indian Territo Illuminating Oil Company, founded before Oklahoma became a state. *Oil for the Lamps of China* w a novel and a movie of the 1930s.[6]

Introducing the automobile generated a huge market for gasoline, but the amount of gasoline th could be separated from crude oil was low, 10 or 20 percent. The original separation process wa distillation, sorting out molecules that boiled at different temperatures. Later, commerce copie nature; thermal cracking was introduced to make smaller molecules, salable as gasoline, out of larg molecules.[7]The route to petrochemicals was opened because thermal cracking produced some unstab molecules, molecules that would participate in further chemical reactions. Before World War II, bot American and German companies developed commercial petrochemical products. After the wa petrochemical production expanded enormously, in both the range of products and the tonnage produced. A whole range of plastics and synthetic fibers became part of our daily lives. (An unusu application: to clean a lens, use the freshly broken surface of a white foam-plastic packing "peanut The plastic is made from oil and gas; there is no grit in it.)

A major early petrochemical complex grew up around the Houston Ship Channel. Larg petroleum refineries supplied hydrocarbons. Salt from the salt domes was turned into hydrochlor acid, chlorine, and sodium hydroxide. Sulfur, originally from the caps of salt domes, was a source fo sulfuric acid. Bromine came from seawater. Portions of the complex were owned and operated b various companies; a local maze of pipelines conveyed intermediate products from one plant another.

We don't usually think of oil processing as a source of fertilizer. However, nitrogen compound are important in plant nutrition; the first of the three numbers on a fertilizer bag gives the nitroge content. Mineral sources of nitrogen compounds are quite rare. The obvious source is the atmospher air is 76 percent nitrogen. In 1908, Fritz Haber reacted atmospheric nitrogen with hydrogen gas produce ammonia; other nitrogen compounds could in turn be produced from the ammonia.[8] Toda the cheapest source of hydrogen gas is hydrocarbons: oil and gas. Virtually all our nitroge compounds are indirectly petrochemicals.

Major oil companies, such as ExxonMobil, are vertically integrated; they explore for oil, dri wells, transport oil, run refineries, and their gasoline hose reaches all the way to your car's fuel tan On the side, major oil companies are also petrochemical producers. Profits, or losses, happen all alon the chain from exploration to marketing. Oil-producing countries soon realized that crude oil w leaving their borders and refining and petrochemical profits were appearing elsewhere. Gradually, oi ~~producing countries arranged for the building of local refineries and petrochemical plants.~~ Toda petrochemical plants in Saudi Arabia use about 10 percent of the country's oil production.[9]

As the global economy eventually converts to renewable energy, oil and gas will continue to b produced for petrochemicals, lubricants, and specialty products. An example of a specialty produc "Vaseline," a trade name for petroleum jelly, is made by Chesebrough-Ponds. One of the companie split up in 1911 from the original Rockefeller-owned Standard Oil was Chesebrough, along wi Exxon, Mobil, Chevron, Arco, and Amoco.

If there is a continuing use for oil, what can we do to extend the supply? More oil can b squeezed out of existing fields, oil can be produced from tar sands and oil shales, and natural g production can expand.

Conventional primary and secondary recovery methods typically leave half of the oil still in th ground. A depleted oil field can be acquired cheaply; lots of clever people have devised methods fo recovering the second half of the oil. In 1980, when oil reached $37 per barrel, projects known "tertiary recovery" or "enhanced recovery" were initiated. By 1986, 512 projects were operating in th United States.[10] Tertiary recovery looked like the wave of the future. Since 1986, however, the tot amount of U.S. oil produced from these enhanced methods has been roughly constant at 700,00 barrels per day, compared with U.S. production of 6 million barrels per day. The number of operatin projects dropped from 512 (in 1986) to 199 (in 1998).[11]

Rather than listing all the tertiary recovery methods, real and imaginary, here are the mo successful methods in terms of U.S. oil production in 1998:

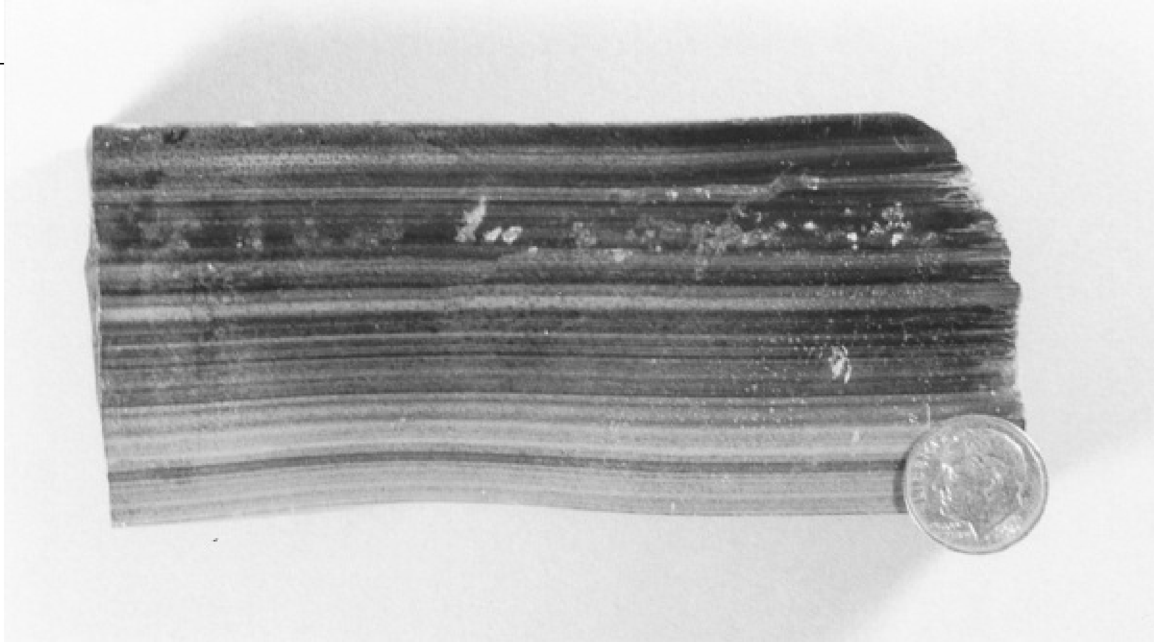
1. Steam injection, either into separate injection wells or as "huff-and-puff" intermittent injectio into production wells: 420,000 barrels per day. Steam is the oldest of the enhanced methods; it used to recover thick, viscous oil, largely in California.
2. Carbon dioxide injection to increase the volume of the oil and to reduce its viscosity: 179,00 barrels per day.
3. Hydrocarbon injection: 102,000 barrels per day.
4. Eleven other methods combined: 58,000 barrels per day.

Of course, the lack of growth was partially explained by the 1997 drop in crude oil prices. If there a major price rises associated with a drop in conventional oil production, we can expect that the methods will be dusted off and expanded once again. However, the 1980s experience shows that it not duck-soup easy to pull out the second half of the oil.

Of the unconventional sources of oil, recovery from tar sands is being expanded rapidly. A ta sand is essentially a dead oil field. When erosion brings an oil field to the surface, the small molecules evaporate, and a nearly solid tar is left in the reservoir rock. Although tar sands exi around the world, Alberta contains two enormous tar sand deposits: Athabaska and Cold Lake. Tar oil is extracted by mining the sand, contacting it with hot water, and separating the oil. To tell th truth, the oil isn't all that great; it contains a lot of sulfur. The original tar sand recovery plant, opene in 1978, was profitable in the sense that oil sales paid the operating costs, but the plant took forever pay back the capital investment.[12] Improved methods followed; as of 1999, 2 billion dollars is bein invested in new tar sand operations in Alberta. Closely related to tar sands are reservoir rocks fille with "heavy" oil, oil that is too viscous to move using ordinary production practices.

If a tar sand is a moribund oil field, an oil shale is an unborn oil field. An "oil shale" contai neither oil nor shale; it is an ordinary petroleum source rock that has never been buried into the o ~~window. A particularly large oil shale deposit exists where Utah, Colorado, and Wyoming~~ com together. As the first transcontinental railroad reached the town of Green River, Wyoming, a wor crew gathered up a circle of rocks to surround their campfire. The rocks caught fire. They were n coal; the heat from the campfire caused thermal cracking to produce oil, and it was the oil that w burning. The rock unit, the source rock, was eventually named the Green River Formation. After th formation was deposited, mountain ranges arose that broke the original lake basin into several piece The Wyoming portion is the Green River Basin, in Utah it is the Uinta Basin, and in Colorado it is th Piceance Basin. ("Piceance" is a local name, made to look French again by early map makers. Th word is pronounced "piss ants.") In the western Uinta Basin, some of the source rocks have bee buried into the oil window; two midsize oil fields produce oil whose source is the Green Riv Formation.

In the Athabaska tar sands of Alberta, huge trucks are used to haul tarimpregnated sand from open p mines to the processing plant. Economies of scale are very important in making a previously margin activity profitable. © Jonathan Blair/CORBIS.



The Green River “oil shale” is an oil source rock deposited in a nonmarine lake. The bottom water of the lake was depleted in oxygen, organic matter was preserved, and there were no bottom-dwelling animals to churn up the thin layers of sediment.

The Green River Formation turned out to be unusual in several ways. It was not marine; it was formed in a saline lake. Almost half of the world’s supply of sodium carbonate is mined from the Green River Formation.[13] Unique minerals occur in the Green River Formation. Spectacular fossils occur because no scavengers could live on the oxygen-free lake bottom. And, for our purposes, the oil that could be released from the Green River oil shale is roughly equal to all the world’s conventional oil.

When I was an undergraduate, crude oil sold for $2.50 per barrel, and everyone expected that if oil got to $5.00 per barrel, oil shale would come on the market and put conventional oil fields out of business. However, each time the price of oil increased, the imaginary oil shale price was always about $3 per barrel above the current price. I’ve been waiting for 50 years; what’s wrong? Several pilot plants have operated, mostly in western Colorado. The rock has to be mined, crushed, and heated in closed containers. The leftovers after the oil is recovered fluff up to more than their original volume; the hole where the rock was mined isn’t big enough to hold the waste. Several variations on the theme were developed, but none of them seemed economic at $25 per barrel. Research continues.

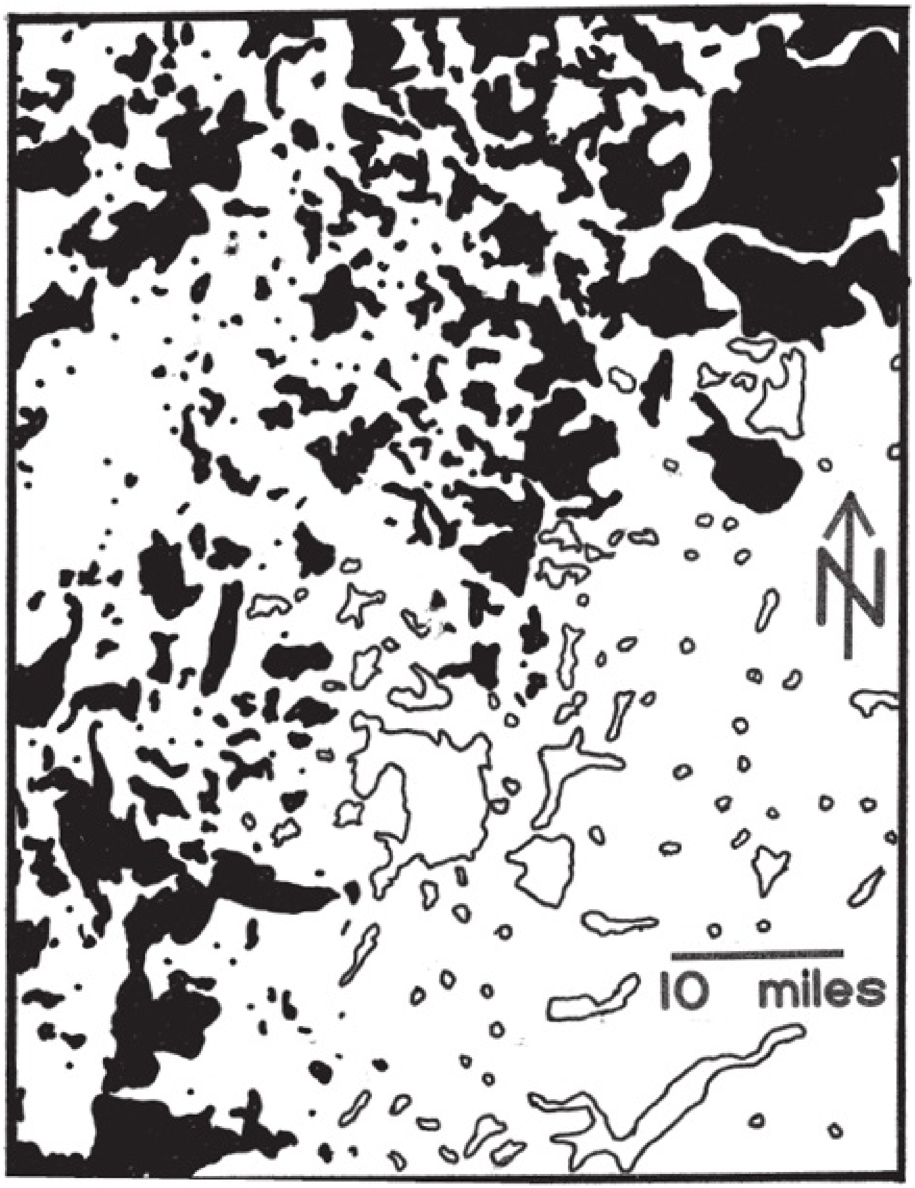
Up until 1953, natural gas sold for less than 10 cents per 1,000 cubic feet. One barrel of oil has the same energy content as 6,000 cubic feet of gas. In 1953, oil sold for $2.70 per barrel; 6,000 cubic feet of gas cost 60 cents. If you were a consumer, natural gas was a bargain. If you were drilling for oil, gas was a nuisance. Gradually, the school of hard knocks identified areas that produced only natural gas as places to stay away from. Usually, these were areas that had been buried beneath the oil window at some time in their history. Natural gas prices went above $2 in 1981. Blow the dust off the old maps; there’s a new ball game in town! Places that were now too deep, or had once been too deep, were ripe for drilling. In contrast to oil, future supplies of natural gas can be expanded by additional exploration and deeper wells.[14]

Natural gas has some advantages over the other fossil fuels. Of the fossil fuels, natural gas adds the smallest amount of carbon to the atmosphere. In natural gas there are four hydrogen atoms for each carbon; gasoline and diesel fuel average two hydrogen atoms per carbon, and coal can be almost

pure carbon. When burned, hydrogen produces water, which for the moment has not been listed as
~~harmful substance. Sulfur removal from natural gas is cheaper and more complete than sulfur remov~~
from oil or coal. As a fuel for house heating and for power generation, natural gas causes the lea
environmental damage of the fossil fuels. Not zero damage, the *least* damage.

The big advantage of gasoline is portability; the gasoline tank does not occupy much space weight in an automobile. A tank of gasoline will take the car 300 to 400 miles. The only way to mak natural gas portable is to compress it to high pressure in thick-walled tanks. Even at high pressure, car with half the trunk filled with natural gas tanks will travel only 150 miles between fuel stop Commuters, school buses, and construction vehicles typically travel much less than 150 miles per da

The eye opener is this: natural gas costs 57 cents for the equivalent of a gallon of gasoline. That based on the retail price of natural gas delivered recently to my basement for the furnace, stove, an hot water heater. At a meeting on natural gas, one of the exhibits was a compressor previously used t fill scuba divers' air tanks, modified to compress natural gas. We all crowded around that exhibi fantasizing about driving around on cheap fuel. The government hasn't figured out how to tax natur gas as a motor fuel, which made the fantasy even sweeter. In Italy and New Zealand, roadside natur gas filling stations have been around for 20 years.



Sometimes on an oil and gas map, it is possible to locate the former base of the oil window at the lin where oil and gas production changes to all gas. On this map of a portion of southeastern Oklahom oil fields are shown in solid black, and natural gas fields are outlined.

High-pressure tanks being installed to convert a conventional pickup truck to run on compresse natural gas. A typical configuration consists of two tanks at the front of the pickup bed. Addition tanks are in the background. © Sergio Dorantes/CORBIS.

Of course, I wondered about safety. What happens if I have my trunk half filled with compresse natural gas tanks and I am in a rear-end collision? I was told that the gas tanks are so strong that th car will crumple around the gas tanks like so much aluminum foil. Also, a gas flame burns upwar The ghastly hazard with gasoline is the fuel pouring down on the ground, then burning upward on th people.

Except for the portability problem, natural gas is a wonderful automotive fuel. The efficiency an ordinary automobile engine increases with the compression ratio: how much the fuel-air mixtu can be compressed before the spark plug initiates burning. However, burning can begin spontaneous and prematurely (called "pinging") if chemical bonds between carbon atoms in the fuel start to brea The compression ratio that a fuel will tolerate is the "octane" number displayed on a filling statio pump. The scale is based on two standard molecules: isooctane taken as 100 on the scale and heptan taken as 0. Regular gasoline is about 85 octane, premium gasoline is 90 octane, and top grades aviation gasoline are 100 octane. Natural gas is 135 octane. An automotive engine designed from th beginning to run on natural gas can have a high compression ratio and a high efficiency. Of course, w all respond to our gut feelings more than to numerical arguments: in the hotel lobby at a petroleu engineers meeting a year ago was a full-size, mean-looking drag racer that ran on natural gas.

Diesel engines avoid the pinging problem by compressing only air, then squirting in the fuel t initiate burning. There are hybrid diesels that compress a mixture of natural gas and air and then squi in a little diesel fuel to act as a spark plug. I thought the hybrid diesel was a really clever new idea was told that the hybrid diesel was patented by Rudolph Diesel.

As of 1965, there were two last hopes for finding an oil province that might rival the Middle Eas

Those two were western Siberia and the South China Sea. As pointed out earlier, we don't yet kno
~~about the South China Sea. Western Siberia turned out to contain entirely natural gas, almost~~ no oi
One-third of all the world's known natural gas reserves are in western Siberia.[15] The Russians c
market some of that gas in Europe, but a lot of clarification of the Russian economic and politic
situation is required before the resource is fully utilized. As with oil from Iraq and Iran, interruptio
of exploitation now may preserve a portion of the resource for future generations.

Coal is the worst possible fossil fuel. Most of the fuel value comes from carbon, with the carbo dioxide added to the atmosphere. Sulfur and mercury are difficult to remove from coal; they a released to the air in ordinary burning. However, the world has at least a 300-year supply of coal. Th United States and the former Soviet Union have the largest reserves of coal; the third world h comparatively little coal. That didn't seem fair, but I realized that the two largest industrial economi were originally built on coal.

China is going to be a particular problem with regard to coal burning. China has extensive co deposits and more than a billion people. I heard a talk presented at a geology meeting that illustrate how difficult the problem can be. In one area in China there are local coal beds, but the coal contai significant amounts of arsenic. The coal is burned on raised, but open, platforms inside the home Slides projected at geology meetings are usually quite pleasant: interesting rocks, beautif mountains. But the talk on arsenic-bearing coal was illustrated with horrible pictures of lesions o people's hands and feet from arsenic poisoning. The government had tried to sell the people stove with chimneys to get the arsenic out of the house. The stoves were rejected, in part because the ope fire did a better job of drying vegetables hung from the rafters. I have a suggestion that has only a sli chance of working. Often arsenic mineralization is associated with gold. If there is a decent trace gold in that coal, I could give them the stoves and pay them for the coal ash. They avoid the arsen poisoning and I get to keep the gold.

Our political discussions often become debates about the wrong topic. Sometimes, a subsidiary issu is a proxy for a deeper concern:

- Preserving ANWR, not because we love caribou but because we don't want the oil companies get rich from our public lands.
- Opposing disposal plans for radioactive wastes because of our fears of nuclear power plants.

Discussions about increasing the supply of crude oil get sidetracked into debates about wheth government action is needed or whether the invisible hand of economics will guide us to bigger an better oil fields. We can argue endlessly about the details without asking first whether searching fo additional crude oil would be worth the effort.

When my parents retired to a farm in Oklahoma, they hired a bulldozer and built a pond. Stocke it with bass. Good fishing, good eating. Gradually, however, they began catching fewer bass, an catching enough for dinner required longer and longer hours. There are two possible reactions:

- Buy ever more expensive fishing tackle, because there might be a great lunker of a bass st hiding deep in the pond.
- Substitute fish from the grocery store and take up something other than fishing for a hobby.

The finite supply of world oil is, in my opinion, written in stone. It's not engraved on the facade of th

Treasury Building. It's written in the reservoir rocks, in the source rocks, and in the cap rocks. N
amount of fancy fishing tackle is going to satisfy our appetite for oil.

CHAPTER 10

Alternative Energy Sources

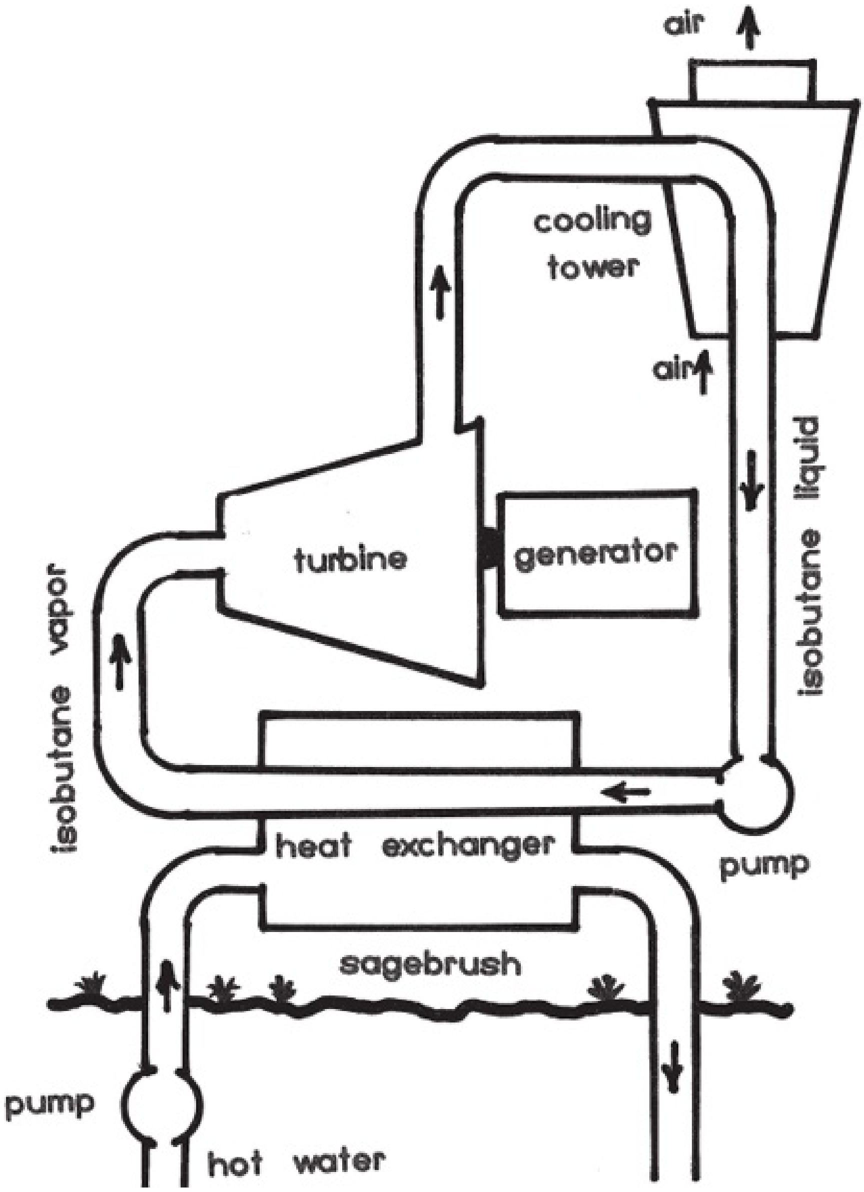
There are plenty of energy sources other than fossil fuels. Running out of energy in the long run is n the problem. The bind comes during the next 10 years: getting over our dependence on crude oil. Th chapter begins by discussing two nonrenewable energy sources, followed by the renewable resources

"Geothermal" energy is just what its name implies, heat recovered from within the Earth's crus Just as with oil fields, there are a few high-grade geothermal areas, a larger number in the middle, ar extensive low-grade heat sources that may not be economic in this century. Before 1960, three hig grade geothermal fields were generating electric power: Lardarello, Italy; the Geysers, north of Sa Francisco; and Wairakei, New Zealand (pronounced wy-RACK-ie). Each area was originally identifi from hot springs at the surface, and ordinary oil-well-drilling technology was used to exploit t resource.[1] The water from these three areas was hot enough to boil, giving an impressive yield steam. Passing the steam through turbines generated electrical power; the steam was condensed ba to water on the downstream side of the turbine to increase the energy yield. The Geysers geotherm field produces about half of the electricity used by the city of San Francisco.

There are some additional high-temperature geothermal fields, but none of them seems to be attractive as the first three. However, stepping down in both temperature and size opens up a larg number of geothermal fields. Even though the water temperature in these lesser deposits is hot enoug to boil, letting 10 percent of the water convert to steam cools the rest of the water down below t boiling temperature. Also, boiling extracts a price: dissolved minerals come out of the water and cru up the equipment. The older high-temperature deposits put up with the problem; Lardarello even so boron chemicals as a by-product.[2] For a leaner deposit, the cost of the labor and downtime f cleaning the pipes is unacceptable.

A geothermal area about 80 miles north of San Francisco, called the Geysers, generates enoug electricity to supply about half of the city of San Francisco. © Bob Rowan; Progressiv Image/CORBIS.

A clever process for recovering geothermal energy without the consequences of boiling becam commercial during the 1980s. Hot water from geothermal wells was used to boil an organic liquid, b the water itself was returned back to the ground without being allowed to boil. The organic vapor go through turbines to generate electricity, and the vapor is condensed back to liquid and circulated contact more hot water. These are called "binary" geothermal plants because both water and a lov boiling liquid are used.



A binary geothermal plant uses hot water from the ground to boil an organic liquid. The water returned to the ground, and the organic vapor goes through a turbine to generate electricity.

The beauty of a binary geothermal plant is zero emissions to the atmosphere and returning th water to the ground. You don't need an Environmental Protection Agency permit to pump arseni mercury, and antimony back into the ground if you just took the water out of an adjacent hole. Th binary process opens a range of geothermal opportunities that would not otherwise be economic. Sin the late 1980s, I have been taking 20 first-year students during fall break to study geology arour Mammoth Lakes, California. One stop on the trip is at an elegantly designed and profitable bina geothermal plant. Hot water from wells drilled into a welded tuff (with connected pores) is used boil isobutane, which boils at 11°F. One of my students asked the plant engineer what would happen one of the geothermal wells got out of control. He said that he would call a company name Halliburton. Right! Call Duncan, Oklahoma. The engineer also pointed out that the plant, over i lifetime, would replace 3 million barrels of imported oil. After he left, I had to tell the students th the United States was importing 6 million barrels of oil a *day*. That plant solves the U.S. energ problem for one half of one day.

Drilling for geothermal energy utilizes the same equipment and skills that were developed for th oil industry. It comes as no surprise that oil companies looked at geothermal resources as an extensio

of their existing activities. There are rumors that at least one major oil company is holding leases o
U.S. ~~geothermal areas as a way of extending its business into an era of energy shortage.~~

Everywhere, the temperature in the Earth's crust increases with depth; that observation underli the oil-window paradigm. In a sense, there is geothermal energy everywhere. The U.S. Department Energy sponsored one test to get energy out of hot dry rock.[3] At the edge of a major volcanic are west of Los Alamos, two vertical holes were drilled, and oil field hydrofrac equipment was used open a fracture between the two holes. Cold water was pumped down one hole, heated by the rock, ar hot water came up the other hole. When I was taken on a group tour to see this operation, someone the audience asked whether the hot water coming up carried more energy than the pumps consume The tour guide didn't know which was larger, but he gave the pump pressure in pounds per squa inch, the flow rate in gallons per minute, and the temperatures in degrees. A geophysicist, whose wo I greatly admired, turned around and started mumbling; he was trying to work the problem in his hea Game time! Could I beat him to the answer? I had recently done some similar calculations for anoth purpose. We finished at almost the same time. (I like to think that I was one second ahead.) The h water would not produce enough energy to run the pumps.

Drilling for geothermal energy has its unpleasant surprises. The federal government and the sta of California jointly sponsored a geothermal test right in the center of the Mammoth Lakes–Lo Valley volcanic area. Nearby volcanoes are only 400 years old. A drilling rig was brought i Whenever I took my students to see it, I described the rig as "medium large." In truth, that particul rig held the American depth record: drilled beyond 30,000 feet in the Anadarko Basin of Oklahom The Mammoth Lakes "geothermal" hole got down to 12,000 feet, and the drillers were not even volcanic rocks. They were drilling cold dry rock typical of the adjacent Sierra Nevada. A year ago th rig was cut up and sold for scrap iron.

Today, nuclear energy is about as unfashionable as the hoop skirt. The incidents at Three Mi Island and Chernobyl converted a widespread uneasy feeling into an almost universal fear of nucle power plants. On other side of the nuclear argument: no carbon dioxide emission to the atmosphe and a 100-year supply of uranium. It's going to be a gut-wrenching debate. Are painfully high electr bills the cure for nuclear phobia?

No press agent would have advertised nuclear power by blowing away Hiroshima and Nagasak It could have happened another way. In 1972, the French found that uranium from the Oklo Mine Gabon was missing most of its fissionable uranium 235. After some investigation, they establishe that a natural nuclear fission reaction had occurred.[4] In effect, a billion years ago in nature there we six (count them, six) water-moderated, enriched-uranium nuclear reactors. All natural ingredients. Th "enriched" uranium existed because a billion years ago less of the uranium 235 had decayed. Suppo the natural reactors at Oklo had been discovered in 1935 instead of 1972. Wow! A wonderful gift fro nature. Best thing since Prometheus discovered fire. The nuclear age would have opened with whimper instead of a bang.

Earlier, I mentioned the grip that the internal combustion engine has on the automobile and th rotary drilling rig has on the oil business. Similarly, the enriched-uranium, water-moderated nucle reactor dominates the market for nuclear power plants. Actually, the standard commercial nucle power reactors are derived from the U.S. Navy nuclear submarine reactors. However, there are about dozen fundamentally different designs for nuclear reactors.[5] I once heard Eugene Wigner lecture o reactor designs. During World War II, Wigner designed the reactors at Hanford; later he won th Nobel Prize for bringing group theory into physics. Back when new power reactors were being bui the Canadians built and operated several reactors that used natural uranium and "heavy wate (deuterium) as the moderator that slowed down the neutrons. The Canadian deuterium reactors we by the overly clever name of CANDU. The CANDU reactors had an outstanding track record f reli~~ability. I suspect that if we sat down today to reinvent the nuclear power industry, we might~~ n choose the standard American design.

Reactors have two options for their used uranium. The spent fuel elements can be disposed of their entirety as radioactive waste. Or the used uranium can be “reprocessed” to recover unburn uranium and to recover plutonium. Plutonium is evil stuff. Besides being exceedingly toxi plutonium can be used as the core of a nuclear bomb. Ted Taylor, who was the leading America designer of nuclear weapons, left Los Alamos to campaign against nuclear proliferation because l felt that it was entirely too easy to build an effective nuclear bomb out of stolen plutonium. There is continuing debate about whether you need a large staff of whizzbang scientists to build a nucle weapon or whether you could build one in your garage. No question that Ted Taylor could build one his garage.

Despite the scary aspect, some spent fuel from commercial power reactors has been reprocesse and the plutonium recycled for additional reactor fuel. A dilemma over reprocessing arose for th Australians around 1980. Huge uranium deposits had just been discovered in northern Australia; th Jabilinka deposit by itself contained more uranium that the United States had mined since 1940.[6] Th Australians preferred not to encourage worldwide growth of nuclear power plants. But as the spect of reprocessing and commercial plutonium shipments arose, the Australians switched their position. Australian uranium is cheap enough, nobody will want to reprocess spent fuel.

Very likely the safety problems and the radioactive waste problems could be handled adequate if our society were willing to make the appropriate investments. Maybe the hoop skirt will come bac The emotional problem remains. There is one possible psychological boost. The United States h been converting surplus weapons-grade uranium and plutonium, some of it purchased from th Russians, into reactor fuel. Would getting rid of nuclear weapons be an incentive for accepting nucle power plants? “They shall beat their swords into plowshares and their spears into pruning hooks. Th shall burn their warheads to warm their toilet seats.” OK, OK, so Ecclesiastes was a better writer th I am; it’s the thought that counts.

It is difficult to store electrical power. There are a few facilities that use electricity to pum water uphill to a reservoir at times of low demand and generate power when needed by running th water back down. Only a few sites are suitable for pumped storage; most electric power is generated the time it is needed. Typically, nuclear power plants carry the base load, the minimum power demar that exists all the time. At the intermediate level, hydroelectric and fossil-fuel steam-generating plan carry the normal increase. For the few peak hours, a hot summer afternoon with all the ai conditioners running, the preferred power source requires a low capital cost but can tolerate a hig fuel cost. A gas turbine, similar to a jet aircraft engine, powered by oil or natural gas is a typical peal load power generator. Some of the renewable electric sources, like solar and wind power, have the own built-in schedules; the difficulty of storing power is a serious problem.

Hydroelectric power has a number of attractions. It is renewable, you can turn it on when it needed, and it does not pollute the atmosphere. Enthusiasm for hydropower was enormous during th first half of the twentieth century. Wild rivers, salmon runs, and the glens of Glen Canyon we sacrificed in exchange for cheap electric power. Of course, mountainous areas have the greate hydroelectric opportunities. Hydroelectric power is the leading export of Kyrgyzstan; most of th country consists of the Tien Shan mountain range. Locally generated hydropower supplies electrici in remote Himalayan valleys. Aluminum ore is hauled halfway around the world to get to chea hydroelectric power at Kitimat, British Columbia.[7] Right now, there is a growing enthusiasm f tearing down dams, instead of building more. In mountainous areas with high rainfall, ne hydroelectric facilities might be acceptable, but the total of all the remaining hydroelectr opportunities will make only a modest dent in the need for electricity.

Solar and wind power participate in what I call the energy-material paradox. If materials we cheap, I could build large energy collectors. If energy were cheap, I could produce large amounts raw materials. If neither materials nor energy is cheap, I have a problem. At the moment, solar an wind power are developing in specialized areas. Neither is an immediate, large-scale solution to th energy problem.

The power per square foot in the sunshine is essentially identical to the power per square foot the wind. At first, I thought that this was just an accident, but solar energy may crank up the win velocity until the average energy density in the wind equals the average solar energy density. Win and sun don't appear together at the same place or the same time. As an example: wind often stronger at a gap in the mountains. At the southern end of the Sierra Nevada, there is a huge array windmills. They don't look like Dutch windmills, or like my grandmother's daisy wheel; they a slender, three-bladed propellers on tall stands.

The low energy density in solar and wind power requires large energy collectors. A normal-siz nuclear or fossil-fuel power plant generates 1,000 megawatts. At typical efficiencies around 1 percent, a solar or wind collector has to occupy five square miles to deliver 1,000 megawatts. I ca direct you to any of several Nevada basins where you can get the five square miles; your problem the capital cost of paving five square miles with solar collectors.

During the 1980 energy crisis, a variety of different ways were considered for converting sol energy to electric power. The two major approaches were:

The engineering design for generating electricity from windmills is not as simple as it might soun After the engineering problems were solved, large arrays of windmills could be built by replicating single design. © Bob Rowan; Progressive Image/CORBIS.

1 Trap solar heat and use the heat to generate electricity. For instance, boil a liquid with solar he and run the vapor through a turbine. High efficiency requires a large temperature differen between the solar-heated source and the air or water where the waste heat is dumped.

2 ~~Direct generation of electricity, typically by using semiconductor solar cells. In 1980~~, th efficiency of solar cells was about 6 percent; today’s cells are about 13 percent efficient.

The materials for solar and wind collectors are not scarce. Silicon (for solar cells) and aluminum (f windmills) are the second and third most abundant elements in the Earth’s crust. However, producin either silicon or aluminum from their ores requires lots of energy. It’s the energy-material dilemm that was mentioned earlier.

During the 1980 oil crisis, exotic energy schemes popped up like dandelions in my law Examples are (1) solar cells in Earth orbit, sending down solar power by microwave, and (exploiting the temperature difference between warm surface seawater and cold deep sea-water. Nor of the schemes are to be ignored, but the inventor usually wants to see an immediate full-sca implementation of the idea. It takes real judgment to sort the sheep from the goats. It is all too easy say, “It won’t work.” Rather than make decisions in a closed committee, we need an open competitio to propose detailed implementations of each concept, followed by another competition to look f serious flaws in the designs.

Chapter 9

1. Berry, M. C. (1980), The University of Texas, Austin: University of Texas Press, p. 11. Oil income from 2 million acres in we Texas is divided, two-thirds for UT Austin and one-third for Texas A&M.
2. (1999), "Azerbaijan Signs Three E&P Deals," Oil and Gas Journal, May 3.
3. Chorn, L. G., and M. Croft (2000), "Resolving Reservoir Uncertainty to Create Value," Journal of Petroleum Technolog August:52–59.
4. West, J. (1996), "Optimism Prevails in World Petrochemical Industry," in International Petroleum Encyclopedia, Tuls PennWell, pp. 5–24.
5. Reinharz, J. (1993), Chaim Weizmann, Oxford: Oxford University Press, p. 40.
6. Glasscock, C. B. (1938), Then Came Oil, New York: Grosset & Dunlap. *Oil for the Lamps of China* is the title of a book Alice Tisdale Hobart.
7. Royal Dutch/Shell staff (1983), The Petroleum Handbook, Amsterdam: Elsevier, p. 279.
8. Pauling, L. C. (1964), College Chemistry, 3d ed., San Francisco: W. H. Freeman, p. 406.
9. Tippee, B. (1999), "Saudi Arabia," in International Petroleum Encyclopedia, Tulsa: PennWell, pp. 93–94.
10. Tippee, B. (1999), Active U.S. EOR Projects, in International Petroleum Encyclopedia, Tulsa: PennWell.
11. Moritis, G. (2000), "EOR Weathers Low Oil Prices," Oil and Gas Journal, March 20, 39–61.
12. McCaslin, J. C., ed. (1987), International Petroleum Encyclopedia, Tulsa: PennWell, p. 63.
13. Garrett, D. E. (1992), Natural Soda Ash, New York: Van Nostrand Reinhold.
14. Deffeyes, K. S. (1982), "Geological Estimates of Methane Availability," in Methane, Fuel for the Future, ed. P. McGeer and Durbin, New York: Plenum Press, pp. 19–29.
15. "Worldwide Look at Reserves and Production" (2000), Oil and Gas Journal, December 18, 122–23.

Chapter 10

1. Armstead, H. T. H. (1978), Geothermal Energy, New York: John Wiley, p. 71.
2. Boron was harvested at Lardarello long before it was developed as a geothermal resource. Dickson, M. H., and M. Fan (1995), Geothermal Energy, New York: John Wiley, p. 173.
3. Smith, M. C., and G. M. Ponder (1981), "Hot Dry Rock Geothermal Energy Development Program," Los Alamos Natio Laboratory, Report LA-9287-HDR.
4. International Atomic Energy Agency (1975), Le Phenomene d'Oklo, Vienna: Agence Internaionale de L'energie Atomique.
5. Nero, A. V. (1979), Nuclear Reactors, Berkeley: University of California Press, pp. 77–132.
6. Deffeyes, K. S., and I. D. MacGregor (1980), "World Uranium Resources," Scientific American **242:**66–76.
7. Lester, M. D. (1984), "Energy's Influence on the Bauxite Industry," in Bauxite, ed. L. Jacob, New York: American Institute Mining, Metallurgical, and Petroleum Engineers, pp. 862–69.