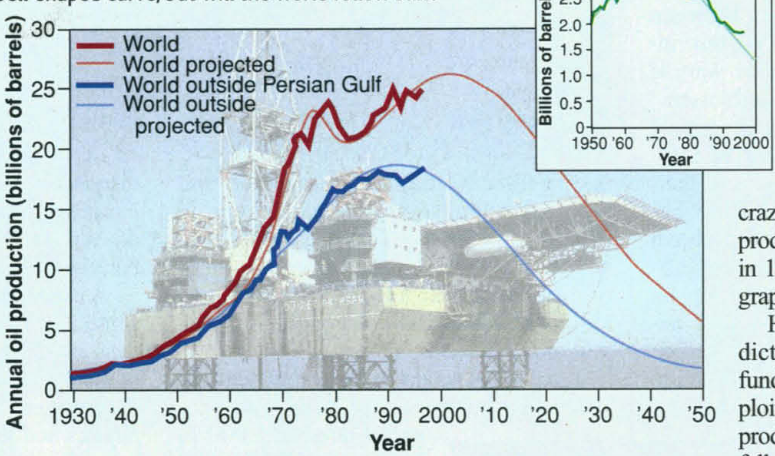
Many economists foresee another half-century of cheap oil, but a growing contingent of geologists warns that oil will begin to run out much sooner—perhaps in only 10 years

The Next Oil Crisis Looms Large—and Perhaps Close

Nature took half a billion years to create the world's oil, but observers agree that humankind will consume it all in a 2-century binge of profligate energy use. For now, as we continue to enjoy the geologically brief golden age of oil, the conventional outlook for oil supply is bright: In real dollars, gasoline has never been cheaper at the pump in the United States—and by some estimates there are a hefty trillion barrels of readily extractable oil left in known fields. Thanks to new high-tech tricks for finding and extracting oil, at the moment explorationists are adding to oil reserves far faster than oil is being consumed. So, many who monitor oil resources, especially economists, see production meeting rising demand until about 50 years from now—plenty of time for the development of alternatives.

Comforting thinking—but wrong, according to an increasingly vociferous contingent, mainly geologists. They predict that the world will begin to run short of oil in perhaps only 10 years, 20 at the outside. These pessimists gained a powerful ally this spring when the Paris-based International Energy Agency (IEA) of the Organization for Economic Cooperation and Development (OECD) reported for the first time that the peak of world oil production is in sight. Even taking into account the best efforts of the explorationists and the discovery of new fields in frontier areas like the Caspian Sea (see sidebar on p. 1130), sometime between 2010 and 2020 the gush of oil from wells around the world will peak at 80 million barrels per day, then begin a steady, inevitable decline, the report says.

"From then on," says consulting geologist L. F. Ivanhoe of Novum Corp. in Ojai, California, "there will be less oil available in the next year than there was in the previous year. We're not used to that." Scarce supply, of course, means a higher price, especially because optimists and pessimists alike agree that the Organization of Petroleum Exporting Countries (OPEC), which triggered the oil crises of 1973 and 1979, will once again dominate the world oil market even before world oil production peaks (see sidebar on p. 1129). At the peak and shortly thereafter, as more expensive fuel sources such as hard-to-extract oil deposits, the tarry sands of Canada, and synfuels from coal are brought on line, prices could soar. "In the 5 to 10 years during the switch, there could be some very considerable price fluctuations," says an IEA official. "Then we will plateau out at a higher but not enormous price level." In other words, gas lines like those of the Arab oil embargo 25 years ago could return temporarily, followed by permanently expensive oil.



Crude accounting. U.S. oil production in the lower 48 states (upper right) peaked in 1970, as predicted by a bell-shaped curve, but will the world follow suit?

The down side of the curve

The debate over just when the end of cheap oil will arrive pivots on an interplay of geology and technology. There's only so much oil in the ground, geologists and technology-loving economists agree, but how much of it geologists can find and engineers can extract at a reasonable cost is much in contention. Geologists considering the past record of finding and extracting oil see a fixed, roughly predictable amount left to be produced and put the production peak sooner rather than later. Their case for the past being the best predictor of the future depends heavily on their success in predicting the oil production peak of the lower 48 states of the United States, the only major province whose oil production has already peaked.

For projections of future oil production, many geologists rely on a kind of analysis pioneered by the late geologist M. King Hubbert. In 1956, when he was at Shell Oil Co., he published a paper predicting that, based on the amount and rate of past production, output in the lower 48 states—which was then increasing rapidly from year to year—would peak between 1965 and 1970 and then inexorably decline. "The initial reaction to this conclusion was one of incredulity—'The man must be crazy!' " Hubbert later recalled. But production peaked right on schedule in 1970 and has declined since (see graph inset).

Hubbert based his successful prediction on what seemed to him a fundamental law governing the exploitation of a finite resource—that production will rise, peak, and then fall in a bell-shaped curve. He constructed his curve by noting that extraction of oil begins slowly and then accelerates as exploration finds more of the huge fields that are too big to miss and that hold most of the oil. That's the ascending side of his bell-shaped curve.

PREDICTED PEAK IN WORLD OIL PRODUCTION

SOURCE	PEAK DATE
F. Bernabe, ENI SpA (1998)	2000–2005
C. Campbell and J. Laherrére, Petroconsultants (1998)	2000–2010
J. MacKenzie, World Resources Institute (1996)	2007–2014
OECD's International Energy Agency (1998)	2010–2020
J. Edwards, University of Colorado, Boulder (1997)	2020
DoE's Energy Information Administration (1998)	>2020

OPEC's Second Coming

Everyone over 30 has a memory of the oil crisis 25 years ago: gasoline prices up 40% in a few months, crude oil prices more than doubled, and Western politicians helpless to do anything about it. Now, as geologists and economists hotly debate when oil will begin to run short (see main text), there's general agreement that despite today's dirt-cheap oil, the oil-consuming nations of the world had best take heed from the lessons learned a quarter-century ago. The domination of the market by the Organization of Petroleum Exporting Countries (OPEC)—which spawned the '70s crisis—will soon return, probably in the next decade.

Last time around, of course, all the gloomy predictions of permanently expensive oil came to nothing. "What saved us was that regions like Mexico and the North Sea could increase production," says economist Robert Kaufmann of Boston University. Next time, however, production from non-OPEC regions will be dropping, not rising, notes Kaufmann. OPEC dominance—and potential chaos in the oil market—is inevitable.

Dominance of the world oil market has changed hands repeatedly this century. In the 1930s, the state of Texas, in the form of a regulatory body called the Texas Railroad Commission, was able to dampen boom-and-bust cycles in oil prices by turning on production when prices rose and turning off fields when prices fell. The commission managed to keep the price of oil steady and relatively low—to avoid the appearance of price gouging and any retaliation—right through the formation of OPEC in 1960 and its first attempt at dominance in 1967.

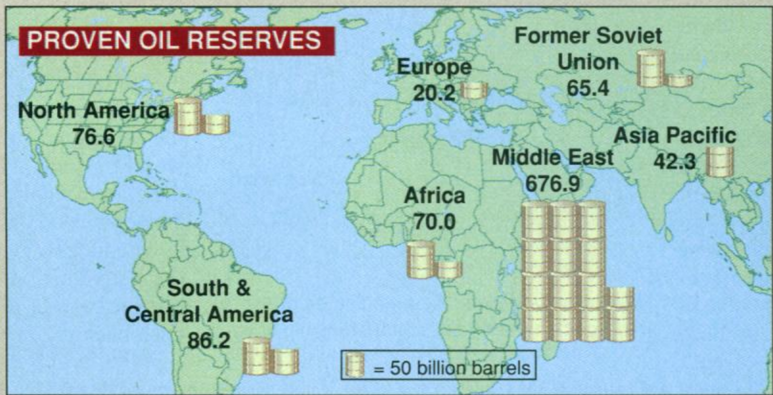
Then, Texas began running short of oil. In the late '60s, the commission opened up field after field, to no avail; none could deliver oil fast enough to maintain Texan dominance. By the time of the Arab-Israeli War of 1973, OPEC was producing more than half of the world's oil, and the pivotal Middle East members of OPEC—Iran, Iraq, Kuwait, Saudi Arabia, and the United Arab Emirates—were producing 36% of it. The Arab members of OPEC cut off oil shipments to countries friendly to Israel and quadrupled the price of Middle East oil. Texas was powerless to increase production as oil jumped from \$13 a barrel (1997 dollars) to \$33 a barrel.

At the next crisis in 1979, when the Iranian revolution cut off that country's supplies, oil-consuming nations were still at the mercy of OPEC. Price pressures had lowered demand and the supply from oil provinces discovered in the 1960s such as the North Sea, Mexico, and Alaska was steadily increasing, but OPEC countries still produced 44% of world oil. Prices jumped to \$53 a barrel (1997 dollars). Some thought dominance of the market might eventually slip away from OPEC, but as news editor Allen Hammond wrote in *Science* in the spring of 1974, "the betting here is that high energy prices will endure." But those dire predictions missed the steadily rising production of non-OPEC oil and high prices' dampening effect on demand. Prices declined steadily until 1986, when they collapsed back to \$20 a barrel as OPEC's contribution sank to 32% of world production.

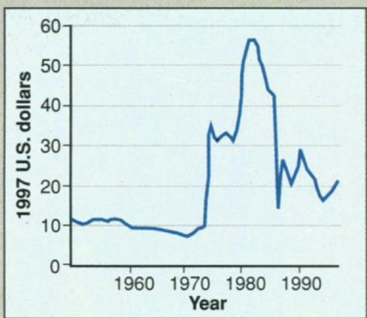
Soon, however, the non-OPEC world, like Texas, will begin to run short of oil. This spring the Paris-based International Energy Agency projected that production outside Middle East OPEC countries would peak next year. By 2009, the subsequent decline there and a projected production increase in the Middle East would give that region 50% of world production, supported by its control of 64% of the world's oil reserves. That's an even stronger position than the one the Middle East enjoyed in 1973. Even upbeat analyses of the world oil supply, such as that from the Energy Information Agency (EIA) of the U.S. Department of Energy, call for OPEC as a whole to be producing about half the world's oil by 2015; that's the percentage it controlled in 1973.

What will OPEC do with its dominant role? Kaufmann believes that OPEC too may have learned a lesson—that huge price increases lead to decreased demand and switching to expensive but more reliable supplies, factors that helped lead to the 1986 price collapse. Economic self-interest for OPEC nations would dictate modest price increases in the next 5 to 10 years, says Kaufmann. The EIA agrees, projecting a steady rise of only about 30% in real prices by 2020. But most would agree with the EIA that "one can expect volatile [price] behavior to recur because of unforeseen political and economic circumstances." In other words, if Middle East supplies are disrupted by war or politics, those gas lines will be back. **–R.A.K.**

BRITISH PETROLEUM



BRITISH PETROLEUM



Cartel control. Middle East OPEC members control a huge amount of oil (*above*). Those reserves allowed them to boost prices in the 1970s (*left*) and will give them that power again.

After this fast start, production begins to stall. By this point, exploration has turned up most of the easy-to-find huge fields. The smaller fields, although far more numerous, are harder to find, more expensive to drain, and can't match the volume of the big fields. At the same time, the gush of oil from the big fields slows. Oil in a reservoir lies in pores whose surfaces hold onto it like a sponge, so that wells first gush, then slow toward a trickle. The declining rate of oil discoveries and slowing production from big, early finds combine to force overall production to peak—the top of Hubbert's curve—at about the time that half of all the oil that will ever be recovered has been pumped. From then on, production drops as fast as it rose, creating Hubbert's idealized symmetrical bell-shaped curve.

When applied to world oil production, Hubbert's curve traces out a relatively grim future. During the oil crisis of 1979, Hubbert himself made a rough estimate of a turn-of-the-century world peak. At that time,

Big Oil Under the Caspian?

Geologists have been discovering less and less oil since the 1960s, but hope springs eternal in the oil industry. Optimists now pin their hopes for staving off the impending shortage of oil (see main text) in part on deposits of as-yet-unknown size under the Caspian Sea. "The Caspian Basin is an area of vast resource potential," pronounces the U.S. Energy Information Administration (EIA). But not everyone thinks this deposit will rescue the world.

Oil was first found under the Caspian in the last century, but there are still promising unexplored areas. Explorationists have drilled into about 30 billion barrels of oil that are ready to be pumped out, about half the amount found under the North Sea. But estimates of how much will ultimately be discovered rely on guesswork. Seismic images reveal geologic structures big enough to hold lots of oil, but there's no sure way to tell whether the rock in those structures is porous enough to hold much oil, and whether they are sealed well enough to hold in oil.

How big a bonanza? Caspian Sea oil provinces (red) look promising but require long pipelines.

Considering these uncertainties, geologist Gregory Ulmishek of the U.S. Geological Survey in Denver guesses that there may be another 50 billion barrels of oil to be found in the Caspian. But the EIA quotes a figure of 186 billion barrels—an amount equal to about a third of the oil known to remain in all of the Middle East. Only new wells in unexplored areas—which may be drilled in the next year or two—will tell who's right.

In the near term, pumping big volumes of Caspian oil will take cooperation in politics as well as luck in geology. The three countries controlling the potentially big fields—Azerbaijan, Kazakhstan, and Turkmenistan—are all landlocked and will have to pipe oil across neighboring nations, projects that have been delayed by political wrangling in this unstable region.

And even if the Caspian does prove to rival the largest oil provinces, it won't save the world for long. Many geologists estimate that there are roughly one trillion barrels of easily extractable oil left to be pumped. According to calculations by physicist Albert Bartlett of the University of Colorado, Boulder, every billion barrels discovered beyond that will push back the inevitable shortfall in world oil supplies by 5.5 days. By that reckoning, even the most generous estimates of the Caspian Sea could push the crisis, expected sometime between 10 and 50 years from now, back by 3 years at most.

–R.A.K.

though, geologists were slightly underestimating just how much oil Earth contains, and Hubbert's forecast was too gloomy—but perhaps not by much. In recent years, a half-dozen Hubbert-style estimates have been made, and they all cluster around a world oil production peak near 2010 (see table on p. 1128). Half the world's conventional oil has already been pumped, these geologists say, so the beginning of the end is in sight.

One of the most pessimistic recent analyses comes from former international oil geologists Colin Campbell and Jean Laherrére, who are associated with Petroconsultants in Geneva; Campbell was an adviser to the IEA on its latest estimate. "Barring a global recession, it seems most likely that world production of conventional [easily extracted] oil will peak during the first decade of the 21st century," they wrote in the March issue of *Scientific American*.

Campbell and Laherrére's early peak prediction is drawn in part from their low estimates of existing reserves. Of the trillion barrels of oil that countries have reported finding but not yet extracted—their proven reserves—Campbell and Laherrére accept only 850 billion barrels. Much of the rest they view as "political reserves"—overly generous estimates made for political reasons. For example, reserves jumped by 50% to 200% overnight in many OPEC countries in the late 1980s—perhaps because OPEC rules allow countries with more declared reserves to pump more oil and so make more money, says Campbell.

Not all Hubbert-type estimates are quite so pessimistic. "I'm an optimist," says former oil industry geologist John Edwards of the University of Colorado, Boulder. "I think there's a lot more oil to be found. I used optimistic numbers [near the high end of estimated reserves], but I'm still at 2020" for the world production peak. "Conventional oil is an exhaustible resource. That's just the bottom line."

Technology to the rescue?

But other geologists and many economists put more faith in technology. Oil will eventually run out, these self-described optimists agree, but not so soon. "We're 30, maybe even 40, years before the peak," says oil geologist William Fisher of the University of Texas, Austin. Fisher has lots of support from the latest international energy outlook prepared by the U.S. Department of Energy's Energy Information Administration (EIA). "We don't see the peak happening until after the limit of our outlook," in 2020, says the EIA's Linda Doman. "We think technology and developing Middle East production capacity will provide the oil."

In the optimists' view, it doesn't matter that there are few if any huge new fields left out there to find. What does matter, they say, is how much more oil the industry can find and extract in and around known fields. Even as the world consumes 26 billion barrels a year, in their opinion reserves are growing rapidly. They argue that much of OPEC's reserve growth is real, and that OPEC and others are boosting reserves not so much through the discovery of new fields as through the growth of existing fields—and technology is the key. Technology might double the yield from an established field, they say. "Technology has managed to offset the increasing cost of finding and retrieving new resources," says economist Douglas Bohi of Charles River Associates in Washington, D.C. "The prospect is out there for an amazing increase in the [oil] reserve base."

Three currently used technologies are helping drive this boost in reserves, Bohi and others say. Aided by supercomputers, explorationists are using the latest three-dimensional seismic surveying to identify likely oil-containing geologic structures, yielding a sharp picture of potential oil reservoirs. A second technology involves first drilling down and then sideways, punching horizontally through a reservoir so as to reduce the number of wells needed, and therefore the expense, by a factor of 10. Finally, technology that allows wells to be operated on the sea floor many hundreds of meters down is opening up new areas in the Gulf of Mexico, off West Africa, and in the North Sea.

All these new technologies can slow or delay what Hubbert saw as an inexorable production drop in older fields, the optimists say. Indeed, such technological achievements have already helped arrest the decline of U.S. oil production during the past 3 to 4 years, says Edwards.

But the pessimists are unmoved. "Much of the technology is aimed to increase production rates," says Campbell. "It doesn't do much for the reserves themselves." And what new technology does do for reserves, it has been doing since the oil industry began in the 19th century, he says. New technologies for better drilling equipment and seismic probing have been developed continually rather than in a sudden leap and so have been boosting the Hubbert curves all along. The shape of the curve therefore already incorporates steady technology development, he and other pessimists note.

As a result, they argue that today's technological fixes will make only slight changes to the curve. "All these things the economists talk about are just jiggling in a minor way with the curve," says Albert Bartlett, a physicist at the University of Colorado, Boulder, who calculates a 2004 world peak. "You can get some bumps on the [U.S.] curve by breaking your back, but the trend is down." For example, when oil hit $40 a barrel in the early 1980s, the U.S. production curve leveled out in response to a drilling frenzy—but it soon went right back down again. And besides, the pessimists note, when high prices drive increased production, the oil pumped is not cheap oil. Economist Cutler Cleveland of Boston University has found that the price-driven drilling frenzy of the late 1970s and early '80s produced the most expensive oil in the history of the industry. So, such production is a hallmark of the end of the golden age and the beginning of the transition stage of expensive oil.

The next few years should put each side's theory to the test. If technology can greatly boost reserves, then the U.S. production curve should at least stabilize, while if the pessimists are right, it will soon resume its steep downward slide. Production from the North Sea should tell how middle-aged oil provinces will fare; pessimists expect it will peak in the next few years. But it is the world production curve that will finally reveal whether the world is due for an imminent shortfall or decades more of unbounded oil.

–RICHARD A. KERR

MOLECULAR EVOLUTION

How the Genome Readies Itself for Evolution

Built into the genome's DNA sequences are regions that can promote rapid and extensive genetic change

The renowned author and cancer scientist Lewis Thomas once wrote: "The capacity to blunder slightly is the real marvel of DNA. Without this special attribute, we would still be anaerobic bacteria and there would be no music." Like many others—Nobel laureate Barbara McClintock was a notable exception—Thomas thought that genetic change, and hence the evolution of new species, results from small, random mutations in individual genes. But a growing wealth of data, much of it presented at a recent meeting,* indicate that mainstream biologists need to consider genomes, and the kinds of evolutionary changes they undergo, in a much different light.

The work shows that the mutations leading to evolutionary change are neither as small nor as rare as many biologists have long assumed. Sometimes they involve the movements of relatively large pieces of DNA, like transposable elements, the stretches of mobile DNA originally discovered in maize by McClintock. They can even take the form of wholesale shuffling or duplication of the genetic material (see p. 1119). All these changes can affect the expression of genes or free up duplicated genes to evolve new functions.

What's more, these changes may not be totally random. Researchers have found, for example, that some stretches of DNA are more likely to be duplicated or moved to another place than others, depending on the nature of their sequences. They are also learning that the enzymes that copy and maintain the DNA introduce changes in some parts of the genome and not others, creating hotspots of mutation that increase the efficiency of evolution. As James Shapiro, a bacterial geneticist at the University of Chicago, puts it, "Cells engineer their own genomes."

ZOYA MASLAK

Venom generator. Predatory cone snails have diverse venoms because of hypermutatable sections of DNA.

Findings such as these are leading to what Lynn Caporale, a biotechnology consultant based in New York City, describes as a "paradigm shift." In the past, researchers assumed that genomes evolve to minimize mutation rates and prevent random genetic change. But the new findings are persuading them that the most successful genomes may be those that have evolved to be able to change quickly and substantially if necessary. Or as McClintock said in her 1983 Nobel lecture, the genome is "a highly sensitive organ of the cell, that in times of stress could initiate its own restructuring and renovation."

Nature's genetic engineers

One of the oddest examples of how the genome can restructure itself comes from David Prescott, a molecular geneticist at the University of Colorado, Boulder. For the past 25 years, he has studied the genetic makeup of a group of single-celled organisms called hypotrichous ciliates, whose genomes are truly bizarre.

In addition to its large working nucleus, called the macronucleus, which contains multiple copies of all the genes, every ciliate has one or more micronuclei, each of which carries two copies of all the genes. The micronuclear genes, which are normally inactive, are split into multiple sections, with lots of interrupting DNA, called internal eliminated sequences, between the coding regions. In three of the 10 genes analyzed thus far, the coding regions are also in the wrong order.

These micronuclear genes have to undergo a dramatic change during sexual reproduction when the micronuclei from the two partners fuse and give rise to both a new micronucleus and a new macronucleus. As the macronucleus takes shape, not only is the DNA between gene coding regions removed, but the coding regions have to be put into the correct order—"all in a matter of hours," Prescott notes.

Although having the gene-coding regions shuffled and split up in the micro-

* "Molecular Strategies in Biological Evolution," 27 to 29 June, organized by the New York Academy of Sciences, in New York City.