Prognosis for Expanded U.S. Production of Crude Oil

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The future production of crude oil will depend upon a variety of parameters, some of which relate to the geology of the earth and to the techniques for oil production but many of which are dependent upon economics, governmental regulations, material supply, and similar factors. A prediction of future oil suppliers will be found in a composite assessment of several questions, namely: (i) How much oil is there to be found? (ii) How fast can unfound oil be located? (iii) How much of the oil that has been found or will be found will be produced? and (iv) How fast can known oil be produced? The answer to every one of these questions is an estimate, and the uncertainties in the estimates arise from both nonphysical and physical elements.

Since its beginning in 1859 the U.S. oil industry has produced 100×10^9 barrels (1.6×10^{13} liters) of crude oil, and of the total oil discovered to date only about 38×10^6 barrels remain as proved reserves. Meanwhile, consumption has increased markedly until today domestic production of crude oil supplies only a little more than one half of the demand for all liquid petroleum.

To place this problem in proper perspective, it is necessary to recognize that for approximately 20 years the U.S. petroleum industry has experienced diminishing activity. During this period certain trends have been observed. (i) The percentage of the world crude oil reserves in the United States has decreased from 14 to 7 percent while that of the Middle East has decreased from 66 to 56 percent, although the U.S. crude oil reserves have increased from 30×10^9 barrels to 38×10^9 barrels. (ii) The percentage of the world crude oil produced in the United States has decreased from 44 to 19 percent while that of the Middle East has increased from 24 to 40 percent, although the U.S. production rate has increased from 2.2×10^9 to 3.3×10^9 barrels per year. (iii) The U.S. demand for crude oil in this period has increased from 2.56×10^9 to 4.30×10^9 barrels per year, an increase of 70 percent. The U.S. domestic crude oil reserves based on the latest demand rate have decreased from an equivalent 12-year supply to an equivalent 7-year supply. (iv) The total number of producing oil wells has declined from 594,000 to 504,000. (v) The total number of wells drilled per year has decreased from 57,000 to 27,000, but of more consequence is the fact that the number of exploratory wells has decreased from 16,000 to 8,000 per year and the total footage drilled has decreased from 235×10^6 feet (71×10^6 meters) to 140×10^6 feet. Unquestionably, the net effort of all the forces acting on petroleum exploration and production has not provided the impetus to develop a continuing reserve and productivity.

The Oil-Finding Process

The finding of oil in the past has depended upon a complex industry which has been dominated by small business interests and individuals who may have owned a drilling rig, who may have dealt in real estate holdings and mineral interests, who may have been geological consultants, or who may have had investment capital. Inasmuch as the risks were high, the system was sensitive to economic factors, tax incentives, and governmental regulations which may have changed the probabilities of financial return. Over the past 20 years, the number of independents engaged in drilling and production operations has decreased from 40,000 to less than 4,000 and the total number of drilling rigs has decreased from 5,300 to 1,400.

Geophysical tools are available which make it possible to interpret the structure of the earth from its surface and geological analyses provide for establishing the probability that petroleum may be found in a given situation, but the oil is not found except by drilling. It order to drill a well, there are two minimal requisites: first, the right to drill, and, second, the hardware to drill. The right to drill for oil must be obtained from the owner, usually in the form of a lease which conveys the power to explore and produce oil in exchange for monetary compensations and a share of the oil that is subsequently produced.

The most attractive areas for leasing are the large unleased government lands, principally on the continental shelf. Land held onshore and in nongovernmental hands is not so likely to be in large parcels. It takes time to assemble small leases into sufficiently large groups to make the risk of exploratory drilling worth the cost, and it is becoming increasingly difficult to assemble such tracts.

In the most favorable economic and political climate, the implementation of petroleum resource development requires at least a 5-year lead time. Geological and geophysical surveys must be conducted to identify favorable prospects; adequate funding and participations must be arranged; lands must be leased; drilling equipment must be acquired (or designed and built for special conditions); adequate manpower must be acquired and trained; well drilling and completion must be accomplished; and production and transportation facilities must be installed and product sales contracted.

A desirable strategy would be to commence exploratory drilling in all favorable areas simultaneously. However, this is not possible because of the limited number of drilling rigs and the limited manpower presently available. The alternate strategy is to evaluate and rate undeveloped resource areas according to their potential for success. Decisions must also be made on the assignment of drilling rigs to exploratory or development drilling, or both, because there is a great need for development drilling in fields already dis-

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← *Courtesy Standard Oil Company, Cleveland, Ohio* covered. All of the 1400 U.S. drilling rigs are committed for the next 18 months, and it is difficult for these rigs to operate efficiently because of the shortage of metal goods used in drilling and production.

Without question, any breakthrough in drilling technology could accelerate the rate of discovery of petroleum. Although drilling technology has steadily improved, there have been no major innovations in the past 50 years, in spite of the expenditure of hundreds of millions of dollars in drilling research. Although many exotic drilling techniques have been proposed and are being investigated, the rotary drilling technique still remains the most efficient and economic method for drilling in the earth's crust.

Domestic Oil Reserves

How much oil is there in the unexplored parts of the earth to attract the discoverer and developer? Studies indicate that thus far approximately half of the oil in place in the United States and its territorial waters has been discovered. More than half of this remaining oil is expected to be found in the offshore areas and Alaska, but it is to be expected that drilling will proceed at a slower rate in these hostile environments.

Rather widely known are the estimates of total oil production for the United States made by Hubbert (*1, 2*) and illustrated in Fig. 1. The basic assumptions of his approach are that the total amounts of oil resources are finite and that constantly increasing demand results in maximum annual production, Q. Consequently, the annual production curve accurately reflects, at any given time, a percentage of the total reserves that can be produced. When the rate of change, dQ/dt, decreases and then becomes negative, projection of the curve becomes increasingly more reliable for the prediction of the total ultimate oil resource.

For U.S. oil production it is seen that the curve has recently changed slope and that the rate of change is decreasing. If the rate of change has reached zero, then half of the total ultimate reserve will have been produced and the remaining curve will be essentially a mirror image of past production. The total ultimate recovery, Q_u, of oil may be estimated as the area under the curve. This recovery, according to Hubbert, will be about 200×10^9 barrels. Therefore, about 100×10^9 barrels remain as a combination of oil already discovered and oil that remains to be discovered. Of this amount it is estimated that 38×10^9 barrels are identifiable as recoverable reserves from known reservoirs. Consequently, there would be about 62×10^9 barrels of oil remaining to be discovered.

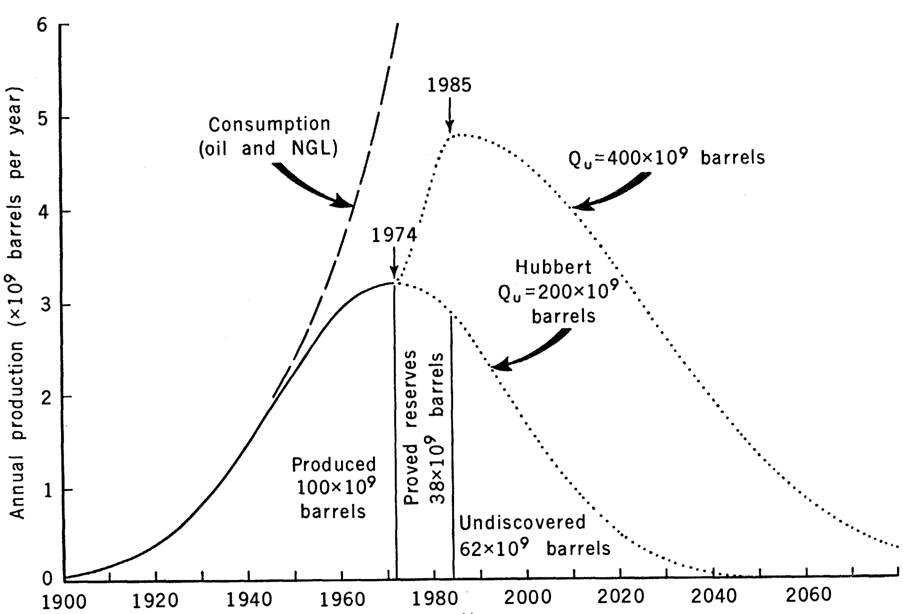


Fig. 1. Total oil production history for the United States, including Alaska, of ultimate recovery, $Q = 200 \times 10^9$ barrels [Hubbert (*1*)] and a possible recovery, $Q_u = 400 \times 10^9$ barrels. The consumption curve includes not only crude oil but also natural gas liquids (*NGL*), which account for about 15 percent of consumption.

Hubbert's estimates of ultimate production are among the lowest, and the depletion concept on which they are based has been soundly defended, as, for example, by Cook (*3*). Other estimates are larger. The National Petroleum Council (*4*) has estimated that there are 727×10^9 barrels of oil in place, and, if we use their average recovery figure of 31.4 percent, the ultimate recoverable oil should be 228 $\times$ 10^9 barrels (Table 1). This would mean an undiscovered resource of about 90×10^9 barrels.

The American Association of Petroleum Geologists (*5*) has estimated a total resources of 824×10^9 barrels in place, with an ultimate recoverable supply of 258×10^9 barrels at 30 percent recovery. This would mean that the recoverable oil to be found is 120×10^9 barrels. These estimates were based on detailed evaluations of producing areas by geologists who are intimately familiar with the various aspects of exploration and production potential of their areas. But none of these estimates includes undiscovered resources of some of the more speculative land and offshore areas that remain largely unexplored.

The U.S. Geological Survey (*6*) has estimated a larger amount of discoverable oil in place, which yields an ultimate recoverable volume of 568 $\times$ 10^9 barrels if recovery averages 30 percent. This estimate is based largely on volumes of sedimentary rock available for exploration in the land and offshore areas of the United States and on the amount of expected oil that can be obtained from such volumes, based on past production experience.

The total area of the U.S. continental shelf and slope to a water depth of 8000 feet is approximately equal to the land area from which most of our past and present production has come, and it is logical to assume that the Hubbert figures should be extended for this reason. On the basis of geological similarities, it may be assumed that the shelves will yield about the same amount of oil as has already been produced or is expected to be produced from our land areas, that is, an additional 200×10^9 barrels of oil. The total estimate of 400×10^9 barrels of oil as the ultimate amount of producible oil falls within the range of estimates of other recent studies.

If the exploration effort for new oil is expanded immediately, particularly on the continental shelf and in Alaska, it is estimated that at least 5 years will be required before significant production can be established, and 10 years until peak production is achieved. Superimposing the additional resources of 200×10^9 barrels of oil on the Hubbert production curve (Fig. 1), therefore, shows that the total annual production for the United States might be increased to nearly 5×10^9 barrels per year in about 10 years. If these estimates are reasonable, the United States can become self-sufficient in oil production only if the demand for crude oil also decreases sharply. Even if the estimated figure of 400×10^9 barrels is somewhat low, this conclusion is not altered significantly.

It is generally conceded that virtually all of the giant onshore U.S. oil fields have been discovered and that future inland discoveries will be confined to small stratigraphic trap fields which are located most efficiently by drilling. Such field additions are expected to add ultimately to U.S. reserves and productivity, but what is needed now is a giant oil field discovery which could complement immediately the petroleum reserve and productivity. The best prospect for such fields lies in the U.S. offshore territorial waters and in Alaska. These areas remain relatively unexplored and should be the subject for accelerated geological and geophysical reconnaissance.

Additional oil from continental shelves or from deeper strata on dry land will be most difficult and expensive to find and produce. The professional exploration talent is available, however. About 15,000 geologists are now engaged in petroleum exploration, 5,000 geophysicists interpret the required geophysical surveys, and more than 20,000 engineers apply the technology for oil production. (These figures are based on various society memberships.) To this pool of imaginative and experienced manpower can be added in future years the thousands of students now being trained in our universities.

Table 1. Some estimates of ultimate oil recovery in the United States. Undiscovered recoverable reserves have been estimated by subtracting the present cumulative production of 100×10^9 barrels and the expected reserves of 38×10^9 barrels from the ultimate recoverable reserves.

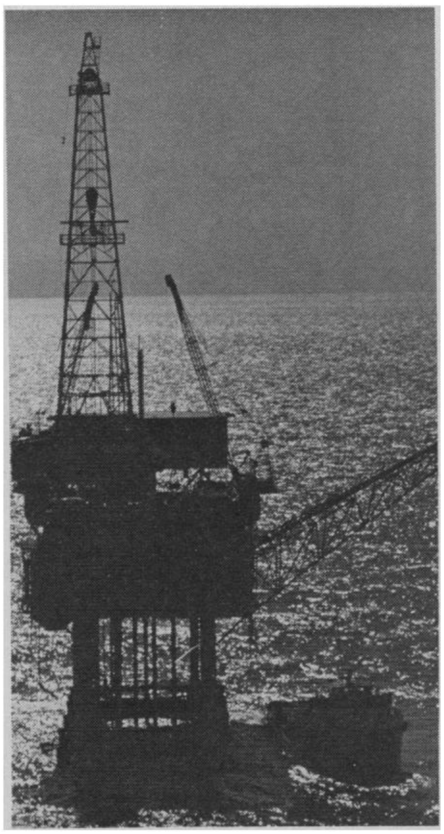
Reference	Oil in place ($\times 10^9$ barrels)	Ultimate recoverable reserves ($\times 10^9$ barrels)	Undiscovered recoverable reserves ($\times 10^9$ barrels)
Hubbert (*1, 2*)		190	62
National Petroleum Council (*4*)	727	228 (31%)	90
American Association of Petroleum Geologists [Cram (*5*)]	824	258 (30%)	120
U.S. Geological Survey [Theobald *et al.* (*6*)]	1895	568 (30%)	430

Future Oil Recovery

Once new oil has been found, many factors determine how much of it is available to us. Our history of oil production to date demonstrates that we will recover about 30 percent of what we have found. The reasons for this lie in the nature of oil occurrence, in the efficiency of recovery systems, in economic factors, and in government regulations.

An oil reservoir occurs in those favorable geological situations which permit oil to accumulate in the interstices of rocks. The reservoir container is the rock itself, and its containing capacity (porosity) is expressed as a percentage of the total rock volume. It is unusual to find a reservoir with a porosity of more than 30 percent, and it is common to find commercially productive reservoirs with porosities of less than 10 percent.

Not all of the containing capacity of the reservoir will be filled with oil, however. Generally, water coexists with the oil. It is unusual to find a reservoir with less than 15 percent of its pore spaces filled with water, and some reservoirs may have in excess of 50 percent water. Consequently, in a reservoir with 15 percent porosity and 30 percent water, each cubic foot of oil found requires about 10 cubic feet of rock volume (1 cubic foot = 0.028 cubic meter). A reservoir having sufficient oil to make it economically attractive to spend large amounts of money to find therefore represents a large rock volume.



Offshore drilling drifting platform, Gulf of Mexico, 1974. [Courtesy Tenneco Inc., Houston, Texas]

Reservoirs which produce oil in commercial quantity in the continental United States may range from a few thousand barrels to several billion barrels of oil in place. Historically, only one exploratory well in ten has found oil in sufficient quantities to justify production at all (that is, to justify the further costs of completing the well after it has been drilled). Only about one well in 50 has found an oil reservoir of sufficient size to repay its total costs.

An oil reservoir is not only a container, it is also a conduit through which the fluid must move. The well is a cylindrical hole in the reservoir rock, perhaps 6 inches (15.2 centimeters) in diameter, and oil may move into the well from an areal extent of thousands of feet depending upon the physical parameters of the rock and the oil. The rate at which oil will move through the reservoir rock to the well is dependent upon the capacity of the reservoir rock to transmit fluid (its permeability), upon the viscosity of the oil, and upon the pressure differentials that are available for movement. Many oils are very viscous even at the elevated temperatures of most oil reservoirs and often cannot be commercially

Cranes used in the unloading of barges which bring bulk supplies to Prudhoe Bay during the summer from Houston, Seattle, and other points. The ice moves off the Arctic coast for less than 2 months each summer and the barges have to slip through the moving ice and hurriedly deliver their supplies to avoid being frozen in for the winter. [Courtesy BP Alaska, Inc., Anchorage, Alaska]

produced for this reason. Techniques of heating have been used successfully in some instances, and attempts have been made to produce heavy oils through a process in which part of the oil is burned in place in order to provide heat for producing the remainder.

Whatever may be the physical nature of the reservoir rock, its oil, or its producing pressures, the removal of oil from a reservoir is a process that ordinarily extends over a number of years. The Bradford oil field which was discovered in the late 1800's is still producing some oil, as is the East Texas oil field which was discovered in 1930. Both of these are large oil fields, but it is not the size which leads to long production periods. The long periods are a result of (i) the relatively low capacity of most reservoir rocks to transmit fluid, (ii) the geometry of the well producing system whereby the fluids must flow to a small hole from a wide area, (iii) the declining amounts of driving energy that are available as the oil is produced, and (iv) the physics of fluid flow in porous materials.

Although a reservoir may be discovered and its potential may be estimated from a single discovery well, the true extent of the reservoir, its form, and its capacity to produce will not have been determined until many wells have been drilled. It is not unusual for development to proceed over a 2- or 3-year period before the reservoir has been adequately delineated and an appropriate number of wells have been drilled and completed to drain the reservoir efficiently. The reservoir's structural features (areal extent and thickness), rock properties (porosity and permeability), and fluid content (oil, water, and gas) must be ascertained in order to estimate the volume of petroleum in place. Each oil field is unique not only with respect to these characteristics but also with respect to the natural forces which will be effective in displacing the oil from the reservoir into wells. These natural forces may produce a very efficient or very inefficient recovery of oil, and it is necessary to identify them in order to achieve the most effective utilization of this natural energy. Often it is necessary to supplement the natural energy in the reservoir through fluid injection.

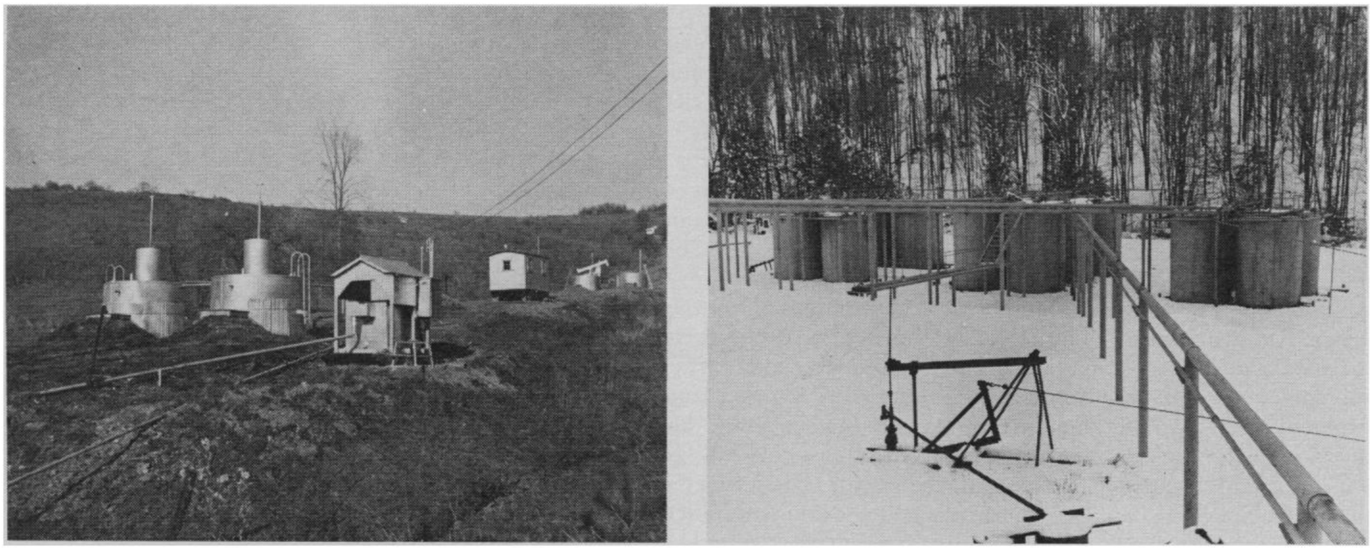
Oil recovery technology has passed through a period in which secondary recovery techniques have been and are being applied to reservoirs which were produced only with the native energy available in the reservoir. These techniques require the introduction of fluids, usually water or gas, to provide a driving force to move additional oil to producing wells. Such procedures require the drilling of injection wells to introduce fluid into the reservoir. New oil reservoirs are being produced in which the best recovery techniques are used from the start so that in more recently discovered reservoirs the secondary recovery phase will not need to be incorporated.

Since oil production is a dynamic process, it is rate-sensitive. There is not only an optimum rate of production to achieve maximum oil recovery but also an optimum rate of production to achieve maximum economic return. These rates are seldom the same. In general, oil production rates are not established at either of these extremes but lie somewhere between and most frequently closer to those corresponding to the optimum for maximum economic return.

The fraction of oil that can be taken from reservoirs will be quite variable, ranging from essentially zero to as high as 80 percent, but, overall, the average has been about 30 percent. Many fundamental problems which might be solved by technology could increase the amount of oil that can be recovered from a given reservoir. One problem is the "efficiency of displacement." This efficiency is the amount of oil that is moved out when the pores of a rock are swept by water or gas. Attempts to increase this efficiency have included the use of detergents, foams, high-velocity displacement agents, solvents, and combustion.

Another problem is "sweep efficiency." This is a measure of the oil that is bypassed in a reservoir because of the geometry of the reservoir and the location of wells at which withdrawals and injections are made. Attempts to increase this efficiency include high-viscosity displacement fluids, fracturing techniques, and well location arrangements. A third problem is "reservoir heterogeneity." Geological formations in many situations are layered with interconnecting and interlocking strata that may vary markedly in their characteristics for fluid flow. It is important in the development of a reservoir to recognize these variables as early as possible and to take them into consideration in the well location and completion decisions.

In all instances of production, however, the continuation of production and the application of new techniques are



(Left) Tank battery with crude oil manifold lines and old style pumping jack in foreground. (Right) Stock tanks, pump building, and electric pumping unit in the background. [Courtesy Pennzoil Company, Bradford, Pennsylvania]

sensitive to regulations and to economic conditions. It is convenient to classify oil fields as (i) producing or (ii) abandoned. Simply stated, this means that for producing fields it is economical to continue to produce oil whereas for abandoned fields it is not. Abandoned fields may be reactivated to producing status if economics—such as an increase in the price of oil—are favorable.

The conditions which contribute to the abandonment of a producing field are directly associated with the costs of producing and treating the oil and the selling price of the oil. As an oil field is depleted and loses its energy, the oil must be lifted to the surface by various means. The oil becomes contaminated with other fluids or materials and must be treated to provide an oil which will comply with pipeline quality standards. All of the factors which impact on the cost of lifting and treating the oil will influence the rate at which oil will be produced. Of primary importance are the costs of equipment, energy, treating materials, and labor. A producing oil field, for example, that is being stimulated by water injection may become uneconomical and the field may be abandoned when the produced ratio of water to oil becomes 5 to 1 and the price of oil is $3 per barrel. However, this same field might be reactivated to producing status if the price of oil increases to $4 or $5 per barrel.

Unquestionably, over one half of the oil discovered in past years in the United States remains economically unrecoverable at this time. Oil recovery technology is highly developed and sophisticated, and secondary or tertiary oil recovery methods capable of recovering a high percentage of the oil remaining in abandoned fields are known. Many remain untried on a field basis because of the lack of economic incentives.

Summary and Conclusions

It is estimated that less than one half of the oil in place has been discovered to date in the United States and its territorial waters. Although some new oil will be discovered inland, it is anticipated that most new oil will be found offshore and in Alaska. Estimates of the total vary, but from all the evidence there appears little probability that within the next 10 years the United States can produce enough crude oil to meet our liquid hydrocarbon needs, unless there is a change in the life-style of its people.

The drilling rate (footage drilled annually), the finding rate (volume of petroleum discovered per unit of drilling), and access to favorable petroleum provinces are the principal factors controlling the discovery of petroleum. Hence, oil will not be found unless an oil-finding capacity is maintained and further developed. There is a long time lag in the finding of oil because of the need for geological and geophysical evaluations, for leasing arrangements, and for hardware to do the drilling. The risks of oil finding are especially sensitive to the marketplace.

The immediate exploration effort that is needed for the discovery and development of new reserves on the continental shelves will be expensive, perhaps even beyond the means of the largest oil companies. Furthermore, this exploration effort should be made in the public interest for the eventual benefit of the entire nation. For these reasons, a committee of geologists (7) has proposed that the federal government consider assuming the burden of initial exploration costs, primarily those of geophysical surveys of the continental shelves, and that the data so obtained be made available to the public.

Of the oil that is found, not all can be produced. The development of technology for improving oil recovery efficiency will require much research and much fieldwork. If techniques could be developed to raise the recovery average to 60 percent, this would double the estimated reserves we would have at our disposal. The reserves available will be produced over an extended number of years because the depletion of an oil reservoir requires time. Producing rates must be balanced between the maximum which the reservoir will allow and the maximum for achieving the most efficient oil recovery. For the next 10 years, domestic production will be obtained primarily through a continuation of the production methods that we have used heretofore. However, oil production by secondary and tertiary techniques is expected to constitute an ever-increasing percentage of the total domestic production of oil.

If we assume the current continuing downtrend in both drilling rate and finding rate, it is expected that domestic crude oil production 10 years hence will provide less than one half of the U.S. demand if demand continues to increase linearly. If it is assumed that the drilling rate will grow linearly for the next 10 years and equal the maximum achieved in 1956, that the finding rate will increase to correspond to the higher finding rates of the past, and that economic and political conditions will be favorable, it is expected that the U.S. domestic production could provide approximately 75 percent of the demand if that demand continues to increase linearly. Any technological breakthrough in exploration, drilling, production, or oil recovery; the discovery of a giant field; or substantial improvement in the economic incentives will reduce the gap between domestic crude oil production and demand.

There is a need, therefore, for urgency and commitment by government and industry to cooperate to solve this problem. It is essential to have a stable, satisfactory economic and governmental regulatory climate. Positive incentives are needed to expand exploration activities and to apply improved oil recovery techniques. More specifically, risk capital is needed to expand activities. This requires a fair return on total investment as well as anticipation of attractive earnings on current and future investments. Price incentives may provide part of the stimulus for such capital.

Complementing and supplementing these incentives, the government should provide a consistent and stable policy directed to encourage accelerated development of oil reserves and increased productivity. Of particular importance are policy issues relating to leasing, including government lands; to environmental conservation and ecological impairment; to production and product regulation; to import quotas; to price regulation, including petroleum, materials, and labor; and to taxation. The seriousness of the energy crisis necessitates practical "trade-offs" which must be instituted to stimulate activity and which can be modified as the solution to the problem evolves.

References and Notes

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Problems of Expanding Coal Production

John Walsh

Coal is dirty fuel, dangerous to mine underground, expensive to transport, and awkward to handle. It retains, in other words, the disadvantages that caused it to lose markets to oil and natural gas after World War II. In addition, a rapid increase in surface mining operations in recent years has inflicted environmental damage which has incited a campaign for effective controls that could limit expansion of strip mining. Now, of course, waning domestic supplies of oil and natural gas and rising international fuel costs have made coal relatively attractive again.

If the United States is to gain energy self-sufficiency—however defined—by the end of the decade, a prodigious increase in the production and consumption of coal will be necessary. The country has huge reserves of good quality coal. Conservative estimates put at 150 billion tons the coal recoverable by current mining methods. Project Independence, the federal government's plan for becoming "reasonably self-sufficient" by 1980, calls for an increase in coal production from 602 million tons in 1973 to 962 million tons per year in 1980. However, expanding the supply and use of coal, particularly in the short run, requires the successful clearing of a formidable array of environmental, technical, social, and economic hurdles.

These problems have been exacerbated by a lag in research in the coal industry. Attainable technologies, for conversion of coal to synthetic fuels, for example, have not been brought to maturity because of indifferent research and development programs. A defeatist attitude has contributed to the lag. Coal was dethroned by oil and natural gas after World War II, and the conventional wisdom was that nuclear energy was the long-term energy source. It is still hard to convince coal industry veterans that coal is the fuel of the future rather than the fuel of the past.

For the coal industry and for the electric power industry that uses about two-thirds of the coal consumed domestically, the major immediate issue is air pollution. One of the chief accomplishments of the environmental movement, which crested in the 1960's, was fostering the passage of the Clear Air Act of 1970. Provisions of the act scheduled to go into effect next year set standards for sulfur emissions which, in effect, would rule out the use of a major portion of the coal from the fields that now supply power plants in the East. The chances that the Clean Air Act would be fully enforced on schedule virtually vanished in the winter energy shortage. Several states have already relaxed their own air

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