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ABSTRACT

This is an Energy Research and Development Administration (ERDA) pamphlet which reviews economic and technical considerations for the future development of energy sources. Included are sections on petroleum, synthetic fuels, oil shale, nuclear power, geothermal power, and solar energy. Also presented are data pertaining to U.S. energy production and consumption, typical project times to complete development of various types of energy facilities, and estimated U.S. energy reserves. (SL)


THE ECONOMICS OF AMERICA'S
ENERGY FUTURE
by Henry Simmons

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THE ECONOMICS OF AMERICA'S ENERGY FUTURE

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INTRODUCTION

"The era of low cost clean energy sources is almost dead. Popeye is running out of cheap spinach," said former Secretary of Commerce Peter G. Peterson on November 14, 1972.

Within a year of this pithy appraisal of the U. S. energy outlook, Americans were to lower their home thermostats, form car pools in increasing numbers, and endure long lines at filling stations for the chance of buying higher-priced gasoline. The Arab oil embargo, with poignant and distressing force, had hastened the end of the golden age of low-cost energy.

It was a time for some hard thinking about the Nation's prodigal use of energy and its pervasive role in our society. Probably the central energy statistic was that the U. S., which has 6% of the world's population, consumes 33% of its total energy output. Before the Arab oil shock, this seemed to say only that the U. S. was preeminent among the energy-intensive advanced industrial societies. Afterwards, it became apparent that this statistic held much deeper implications.

For example, the U. S. has traditionally enjoyed low energy costs; this is because of its abundant resources of oil, coal, and natural gas, and because of an extraordinarily effective free market system for extracting, processing, and distributing these fuels. Despite the fact that the U. S. uses energy far more lavishly than other nations, only about 4% of its gross national product was actually spent on energy in 1972. At the same time, most Western European nations were spending between 8% and 12% of their GNPs for energy.

This bargain price for energy—compared with the cost of capital, labor, and raw materials—has placed an indelible mark on practically every feature of our economy and national life since World War II. Cheap energy has shaped our postwar society by such developments as the throw-away aluminum can, the frost-free refrigerator, the stove, the furnace, and hot water heater with their ever-burning pilot lights, the plastic wrapping on our food, the glassy expanse of modern office buildings that must be simultaneously heated and cooled all year round, our sprawling suburban communities based on transportation in large private automobiles instead of more energy-efficient modes of mass transit, and even our pleasure boats, snowmobiles, campers, and other recreational pastimes.

These facts of American life, of course, do not suggest some deep moral flaw in our national character. While a few social critics have detected the odor of decadence in these practices, most economists would agree that our life-style was a logical reflection of our economic circumstances. Energy *was* cheap. It seemed to be inexhaustible, now and forever. It had played a decisive role in our economic growth, and there seemed little reason why this should not continue indefinitely.

To be sure, there were some who doubted that America could keep up the energy binge indefinitely. A few economists suggested that energy was radically underpriced in our economy and that its true economic value was much greater than its market price. And there were geologists like Dr. M. King Hubbert of the Interior Department who warned (correctly) that U. S. production of crude oil would peak in the 1970s and that production from the vast Middle East oil fields will pass its peak in the last decade of this century.

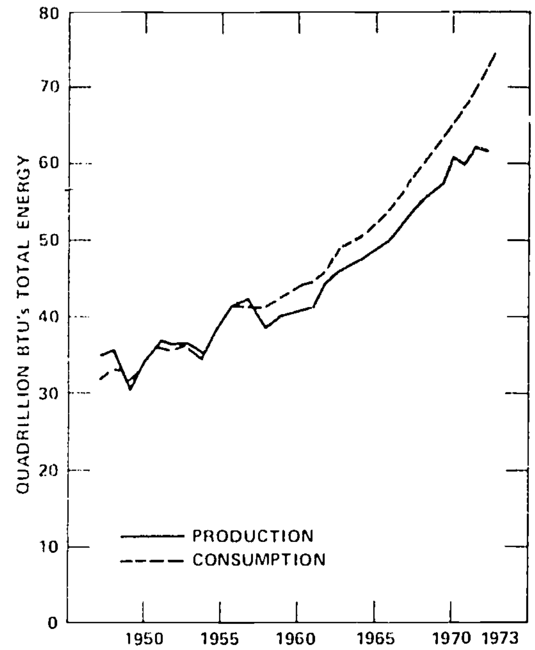
Almost alone among industrial nations, the U. S. has never had a single, comprehensive energy policy that defined the Nation's needs and objectives and the programs to achieve them. On the heels of the oil shock, the government began a far-reaching effort to achieve—hopefully in the 1980s—domestic self-sufficiency in energy through a combination of conservation and vigorous expansion of the supply of both conventional and new energy sources.

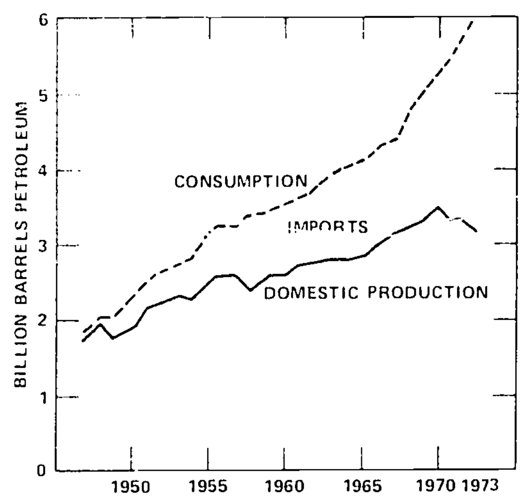
The U. S. will not only have to increase supplies of conventional fuels and take determined conservation measures, but will also have to coax gas and even synthetic crude oil from the abundant reserves of coal. It may have to extract crude oil from oil shale in the West. There is the possibility in some areas that geothermal power could be tapped on a broad scale and that the sun and winds could be harnessed in a variety of ingenious ways to meet a significant share of the energy requirement. Nuclear power will need to be accelerated—including the use of new and more efficient types of reactors. We will also need to develop thermonuclear fusion reactors which would be fueled ultimately by virtually inexhaustible heavy hydrogen in seawater. More efficient processes to convert energy to useful power will be necessary. There will also have to be a sharp improvement in the efficiency of using energy, and this calls for smaller automobiles, better insulation for buildings, refrigerators and air conditioners that provide more cooling per kilowatt-hour, and even pots and pans that capture more heat from the gas ring on the stove.

The U. S. will not return to its golden age of energy even if it uses all these measures and even if many of them succeed. Energy can no longer be as cheap or abundant as it has been in the past. At the same time, the end of the golden age does not mean an end to the American dream of a life of dignity and opportunity for all. We may discover that these objectives are not embodied in 300-horsepower automobiles or centrally air-conditioned homes. Perhaps our life-style may be altered by harsh new facts of energy scarcity and significantly higher costs in the marketplace, but our national character and particularly the adaptive and "can-do" qualities that have served us so well in the past will be major intangible assets in coping with our energy problems.

The difference between the production and consumption of energy in the United States is made up primarily by imported oil. A quarter of a century ago the U. S. was a net exporter of energy; now it imports 15%, including 35% of its oil. The figure above depicts the growing energy gap and the figure below the even wider deficit within the petroleum sector.

U.S. ENERGY PRODUCTION AND CONSUMPTION 1947-1973





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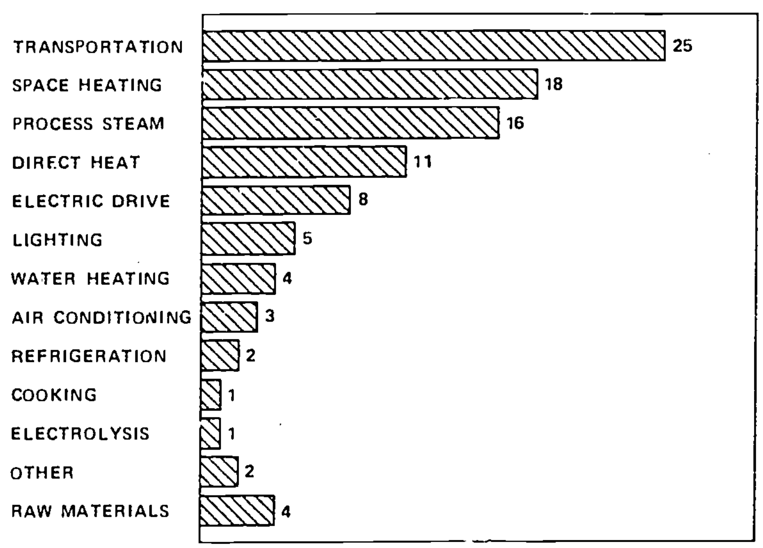
THE ROLE OF ENERGY IN AMERICAN LIFE

The U. S. is a prodigious consumer of energy in all forms. In 1973, it consumed 6.3 billion barrels of oil -- more than 17 million barrels a day. It mined and burned 600 million tons of coal. It consumed 22.2 trillion cubic feet of natural gas -- more than 60 billion cubic feet per day.

Because energy was a tremendous price bargain in the marketplace relative to the cost of labor, raw materials, and borrowed capital, the growth in total U. S. energy demand was strong and consistent in the postwar years. Over the past generation, U. S. consumption of energy increased by an average of 3.2% a year. Growth quickened to a rate of 4.3% annually in the 1960-68 period, and in the late 1960s total U. S. energy demand seemed to be growing at a rate close to 5%.

The consequences of low-cost energy have been profound for all phases of American life. There is no question, for example, that the affluence of a society is intimately related to the energy at its disposal. With the highest *per capita*

PERCENTAGE OF UNITED STATES ENERGY USE



income in the world, the U. S. also leads the world in *per capita* energy use the equivalent of 15 tons of coal or 60 barrels of oil each year for every man, woman, and child in the population. One commentator reckons that every $100 of the U. S. gross national product is associated with the energy equivalent of 1 barrel of oil — a graphic illustration of the crucial economic role of energy in our advanced industrial society.

Residential

Consider that approximately one-fifth of our total energy consumption is spent to heat, cool, and light our homes and run our major appliances. According to the Energy Policy Study of the Ford Foundation, during the 1960s the U. S. population increased 11% and households increased 17%, while our residential energy consumption rose by an astonishing 50%. The large new appliances, which appeared in the postwar years at prices within the reach of growing numbers of Americans, were primarily responsible for this surge in household energy use. Energy needs for heating and cooling rose at the relatively sedate annual rate of 2–5% during the 1960s, but energy consumption for refrigerators climbed 8% a year, clothes drying, 11%, and air conditioning, 16%.

The appliances themselves tended to be more prodigal in their energy use as larger models with new features appeared. A frost-free refrigerator requires 60% more electricity than a manual defrost model. A color television set uses 50% more power than a black-and-white model. Some appliances, such as automatic dishwashers and clothes washers, not only need electricity but also require hot water.

Commercial

The story is much the same in the commercial sector, which accounts for about 15% of U. S. energy demand. In the 1960-68 period it grew at a rate of 5.4% annually—faster than any other major sector of energy use. Heating, cooling, lighting, and the power needs of office equipment are responsible for most of the increase, with the newer office buildings requiring substantially more energy than older ones. The Ford Energy Study explained the trend by saying that the difference can be traced to higher lighting levels, sealed windows (requiring 24-hour mechanical ventilation), glass curtain walls (allowing higher levels of heat loss and gain), and the proliferation of computers, elevators, escalators, electric typewriters, and duplicating machines.

Agriculture

It has been a matter of U. S. pride that the percentage of farm workers has steadily declined during this century, so that only two full-time farmers in the U. S. today can grow enough food to support 100 of their fellow citizens. Recent studies of this remarkable growth in farm productivity have shown, however, that it rests firmly on a rising curve of fossil fuel consumption.

In 1910, for example, farms required no external "energy subsidy" to sustain their output because they relied primarily upon the muscles of men and draft animals. But the energy required in the food chain has climbed sharply because of the introduction of tractors and other mechanical devices on the farm, together with the growth of a complex processing and transportation system, centralized supermarkets, and all of the appliances in the modern home needed to store and prepare food. It is estimated that the energy equivalent of 80 gallons of gasoline is presently required to grow a single acre of corn in the U. S. Overall, it is estimated that 10 energy calories today are necessary to put 1 food calorie on U. S. dinner tables and that the complete food chain in this country accounts presently for about one-seventh of total energy use.

Transportation

About one-fourth of U. S. energy consumption is for transportation, and the automobile accounts for the largest share. Auto registrations have climbed steadily, from 62 million in 1960 to 97 million in 1972, or a rise of about 40%. Significantly, total auto mileage has increased much more rapidly, from about 550 billion miles to almost 1 trillion during this period, a jump of almost 80%. As auto use increased with the expansion of the Interstate Highway System, new models have become 20% less efficient in gasoline mileage than models of the mid-1960s.

Several factors are responsible for this loss of efficiency. Automobiles have tended relentlessly to grow in weight. Energy-costly "extras," such as power steering and automatic transmissions, have grown in popularity. Automobile air conditioning was originally a rare luxury, but now it is almost standard. Factory-installed units went into only 1 of every 14 new cars in 1960, but in 1972 they went into 7 of every 10 new models. Increased weight and energy-consuming equipment have caused current models of U. S. automobiles to get 10% to 12% less mileage than those of the mid-1960s.

Another factor that has impaired the energy efficiency of automobiles has been the pollution control measures adopted by the government. The extra weight of the emission control devices and the lower compression ratios and richer fuel mixtures required to curb emissions have cut the fuel efficiency of 1973 and 1974 models by another 10% compared to those of the mid-1960s. Overall, these trends have penalized the performance of U. S. automobiles at a time of potential fuel scarcity and rising costs. While the average U. S. auto in 1960 realized about 14.3 miles per gallon of gasoline, this dropped to less than 12 mpg in 1973.

The American automobile, which is twice as heavy and consumes twice as much gasoline as its European and Japanese counterparts, vividly illustrates the effects of low-cost energy in one particular segment of our lives. Its impact has been far more pervasive and subtle, however, than we generally realize. For example, it was the overwhelming convenience of the car coupled with the expanding highway system that destroyed the interurban rail transit systems of the 1920s and 1930s. It is the car that has severely eroded urban mass transit in the postwar years, despite the greater energy efficiency of the latter modes of transport. It was the car that made possible the sprawling and sparsely populated residential suburb, which requires more energy for people to get from their homes to stores, services, and places of work. The car today accounts for 95% of our urban passenger traffic and 85% of our intercity traffic. In freight movements, railroads have steadily lost business to trucks and air transport, despite the four-fold energy efficiency advantage of trains over trucks and the 63-fold advantage over aircraft in terms of energy requirements per ton-mile.

"Quads" of Energy

Because we use energy and fuels in widely diverse forms in our society, it is helpful to establish a single quantitative measure for energy, whatever the type. One convenient measure is the British Thermal Unit or BTU, which is the amount of heat required to raise the temperature of 1 pound of water by 1°F.

It is estimated that in 1973, the U. S. consumed 74.7 quadrillion BTUs of all forms of energy. This is such an awkward number to express numerically—74,700,000,000,000,000 – that energy experts generally resort to scientific notation – 74.7×10^{15} BTUs—or sometimes simply 74.7 "quads" of energy. By way of comparison, it is estimated that the rest of the world is using about twice as much energy as the U. S.—about 150 "quads" of BTUs in 1973.

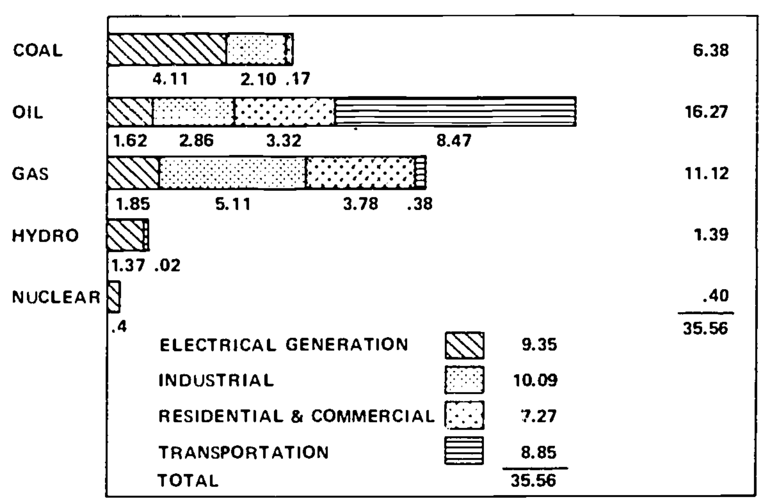
TRENDS IN U. S. ENERGY SUPPLY

It is hardly an exaggeration to say that the U. S. today is powered by fluid hydrocarbons. Oil and natural gas filled 77% of the Nation's energy needs in 1973. Coal, a solid hydrocarbon, supplied 18%, hydroelectric generation, 4%, and nuclear energy, 1%.

The pattern of the U. S. energy supply has evolved with the Nation's economy and technology. For most of the first century of U. S. history, wood fires, windmills, and waterwheels provided the bulk of the Nation's mechanical energy. It was not until the arrival of coal-burning locomotives and the steel industry after the Civil War that coal began to figure prominently in the U. S. energy supply mix. Oil was first discovered in a shallow Pennsylvania field in 1859, but coal remained dominant until the opening of the fabulous Texas Spindletop field in 1901; this field and others assured cheap oil for automotive uses and a steady expansion of petroleum in the energy supply mix. After World War II, gas grew rapidly in importance as pipelines stretched from southwestern producing fields to the major cities of the north and east.

It is significant to an understanding of the current U. S. energy problem that coal and the fluid hydrocarbons have essentially reversed their shares of the Nation's energy mix over the past 50 years. In 1920, coal supplied 78% of the Nation's energy, while petroleum and natural gas supplied only 18%. As recently as 1947, coal supplied 48% of total U. S. energy, but by 1973, its share had dropped to 18% and petroleum was dominant at 46% followed by natural gas at 31%.

THE PATTERN OF UNITED STATES PRIMARY FUEL USE (1973)
Oil Equivalents–millions of barrels per day

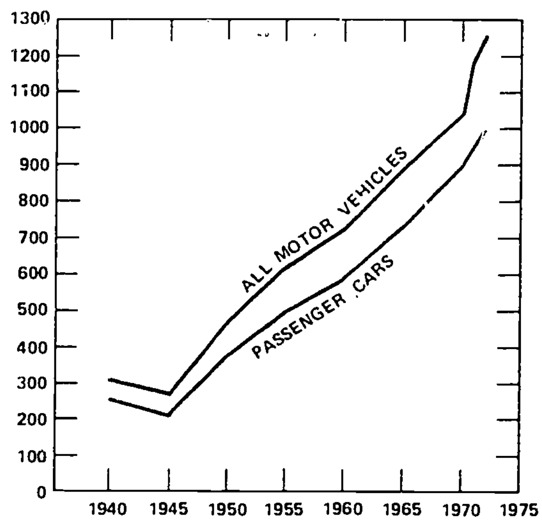


Viewed historically, the U. S. shift away from coal might seem illogical. Coal, after all, constitutes the most abundant component of U. S. reserves of hydrocarbon fuel. Proven reserves of coal amount to about 200 billion tons (1000 quads of BTUs), while total estimated recoverable coal, according to a Cornell University study, may amount to 1.6 trillion tons (about 34,000 quads). In BTUs, these reserve and potential recovery estimates are 15 to 25 times the reserves and recovery potential of domestic natural gas and oil, and they are clearly sufficient to support total U. S. energy requirements for centuries.

Nevertheless, coal gave way to petroleum and natural gas. Coal is difficult to extract from deep underground mines. When the coal seams are close to the surface, strip-mining results in damage that causes permanent desolation or is costly to repair. Coal is expensive to transport and awkward to handle. Its combustion is a dirty process with problems of ash disposal and the emission of a variety of pollutants—sulfur dioxide, nitrogen oxides, and particulates. Petroleum and natural gas by contrast are easy to extract and cause little damage to the landscape. They burn in a clean fashion, and leave behind no solid residues.

A number of potent factors tended to accelerate the shift to the more convenient hydrocarbons in the postwar years: The great surge in ownership of private automobiles, the growth of diesel truck and airline operations, the conversion of the railroads from coal to diesel power, and the rapid growth of oil- and gas-fired electrical generation capacity. This trend was reinforced with the opening in the early 1950s of incredibly rich new oil fields in the Persian Gulf. These were so productive that a single well could produce as much as 10,000 barrels of oil per day at a wellhead cost as low as $0.05 a barrel. Oil from these fields easily undersold U. S. crude in world markets; in fact, it could be delivered to U. S. ports more cheaply than domestic oil. Although the U. S. in 1959 established import quotas to prevent excessive reliance on the low-cost foreign oil, these were politically unpalatable and their effectiveness gradually eroded, particularly in the northeastern U. S., which became more and more dependent upon imported crude oil and refined products. Early in 1973, when it became obvious that the U. S. no longer could meet its petroleum demand from domestic and Western Hemisphere sources, the quota system was formally abandoned.

GROWTH IN VEHICLE MILES 1942–1972, (BILLIONS)



U. S. domestic production of crude oil had actually peaked in 1970 at an average daily output of 9.6 million barrels. (The absolute peak was reached in November of that year, when domestic wells produced 10,045,000 barrels per day.) Since 1970, however, U. S. oil production has been declining steadily, despite the enormous stimulus to drilling and production activities brought on by the four-fold jump in the world oil price in 1973. By mid-1974 U. S. production had drifted downward to 8.9 million barrels a day, and the Nation was importing crude and refined products at the rate of 6.5 million barrels a day.

Coupled with the decline in U. S. domestic output of oil has been a growing deficit in refinery capacity. In the 1960s the petroleum industry experienced a chronic excess in refinery capacity. It was the refinery overruns of gasoline and other products that allowed the so-called "independents" to buy products cheaply from the "majors" and compete vigorously for retail sales. In the late 1960s, mounting environmental resistance to new refineries and uncertainties over the operation of the quota system ended the over-capacity situation, and now the U. S. finds itself increasingly dependent upon overseas sources for both crude and refined products.

Natural gas increased its share of the energy market even more rapidly than oil in the postwar years. Initially burned off (or "flared") as a useless by-product of oil production, natural gas came into its own with the construction of the pipeline network and rapidly replaced the "town gas" used in most U. S. cities. (Town gas is a mixture of hydrogen and carbon monoxide baked out of coal at innumerable local "gas works"; it contains only about half as much energy per cubic foot as natural gas, and, of course, it was considerably more expensive.)

A significant factor in the development of natural gas has been government price regulation. In 1953 the Supreme Court ordered the Federal Power Commission to regulate the wellhead price of natural gas sold in interstate commerce in relation to its actual production costs. The effect of this was to maintain the price of gas at a disproportionately low rate for the next two decades and also to discourage the development of new domestic gas supplies. The FPC in 1974 allowed the price of all gas sold across state lines to increase from an average of $0.23 to $0.42 per thousand cubic feet, but, on a BTU basis, the new price was still equivalent to oil at $2.35 a barrel at a time when the average price of domestic oil was $7 a barrel and the world price was $10 and rising.

Because the price of interstate gas is controlled at levels far below equivalent energy prices, demand has soared, exploration and production have declined, proven reserves have fallen below a 12-year supply, and major gas users are finding interruptions of service increasingly frequent. One expert, Dr. Henry R. Linden of the Institute of Gas Technology, has warned that the U. S. faces a further decline in gas production in the next several years and that this could lead to a "collapse of the interstate gas supply".

Despite its great promise, nuclear generation of electricity has been extremely slow to come on line. The first commercial generation of nuclear electricity occurred at Shippingport, Pennsylvania, in 1957 when a reactor originally designed for submarine propulsion went into operation with an initial electrical output of 60 megawatts. Utilities today are installing power reactors of 1000 megawatts and more, and a major manufacturing and construction industry has grown up in the past decade to supply the nuclear demand. However, determined opposition from environmentally concerned citizens, protracted licensing hearings, construction delays and poor labor productivity, adverse court decisions, environmental legislation, and exasperating "teething" problems with pumps, valves, and other components of the complex new systems have stretched the average lead time for bringing a new plant into service to almost 10 years. As a result, by mid-1975, only about 55 nuclear power plants, generating about 5% of the Nation's central station electrical power, were in commercial operation in the U. S. This is equivalent to 1% of the Nation's total energy supply— or about the same as firewood, as one frustrated government energy official has remarked.

Although hydroelectric power currently supplies only about 4% of total U. S. energy needs, it is generally regarded as a mature industry. The most desirable sites for high dams, mainly in the Pacific Northwest, have been exploited. It is expected that further expansion will take the form of pumped storage systems to provide peaking power for utilities.

THE ARAB OIL EMBARGO

In October 1973 the Arab oil exporting countries declared an embargo on oil shipments to the U. S. because of its support for Israel in the 17-day Fourth Arab-Israeli War. Before 1970 the Arab embargo would have had little effect on the U. S. Though the Nation lost its self-sufficiency in oil in the late 1940s and became a net importer of energy in 1958, the great bulk of its imports were from relatively secure Western Hemisphere sources—Venezuela, Canada, and Mexico—plus some from Africa and the Far East. By 1973, however, the U. S. was importing more than 6 million barrels of oil per day, and the Arab states had become an important source. When the oil embargo was fully effective in the first quarter of 1974, the government estimated that it cut U. S. supplies by 2.7 million barrels a day—about 14% of the anticipated oil demand.

The fuel crisis was not painless, of course. Lost forever were the millions of man-hours spent by motorists in long lines at gasoline stations. In addition, the tourist industry and the unique American roadside culture of motels and fast food shops suffered real economic loss. Fortunately, the embargo was relatively short, so that total U. S. economic activity was not significantly affected. But it signaled a harsh new energy reality for both the U. S. and the rest of the world.

The cutoff of Arab oil vividly underlined the growing American dependence on foreign sources of energy. At the time of the embargo, the U. S. was importing about 33% of its total oil supply—equivalent to 17% of its total energy needs. More ominous, the growth in U. S. energy demand was falling almost entirely upon imported oil and, if this continued, the U. S. by 1980 would be dependent for half its total oil consumption on foreign sources—the Mid-East in particular, where more than half of the world's total oil reserves are located.

Another jarring aspect of the Arab oil cutoff was the four-fold inc[illegible] in the world price of oil exacted by the Organization of Petroleum Exporting Countries (OPEC) over a period of little more than 1 year. Because of its still substantial domestic production, this would not affect the U. S. as severely as Japan and the industrial countries of Western Europe, which are far more dependent on imported oil. It was estimated that the OPEC group would garner more than $100 billion from their customers in 1974, including $20 billion from the U. S. These oil imports exerted tremendous pressures on the balance of payments of the industrial countries. Moreover, the severe inflationary pressures induced in Western economies by the oil price hike, the prospect of mounting deficits in international trade and balances of payments, the possibility of restrictive trade practices, and unmanageable economic disruption were seen as definite threats to the West unless the world oil price receded.

As difficult as the new oil prices were for the West, they represented a far greater threat to the undeveloped world. Countries like India, Bangladesh, and the drought-stricken nations of central Africa have become vitally dependent upon imported oil and fertilizers to maintain bare subsistence levels. To a number of experts extreme deprivation and even starvation seem possible because there is simply no prospect that they could generate the additional foreign exchange to continue importing the more costly oil and energy-intensive products at customary rates.

U. S. ENERGY GOALS

The unfolding of the Nation's energy predicament gave birth to three major national energy goals to restore U. S. energy self-sufficiency by 1985: (1) reduction of oil imports in the short-term future; (2) an end to U. S. vulnerability to economic disruption by foreign suppliers of energy by 1985; and (3) development of U. S. energy technology and resources so that this Nation would have the ability to supply a significant share of the energy needs of the Free World by the end of this century.

By 1985 the United States' expansion of energy production would be accomplished primarily by:

- 200 major nuclear power plants
- 250 major new coal mines
- 150 major coal-fired power plants
- 30 major new oil refineries
- 20 major new synthetic fuel plants
- Many thousands of new oil wells
- Millions of new automobiles, trucks, and buses that use much less fuel.

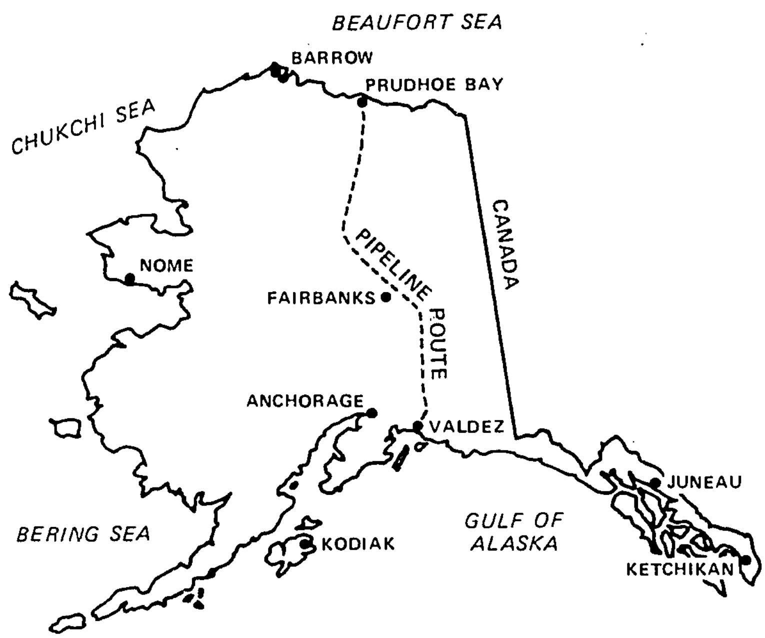
Theoretically, higher fuel and energy costs in the long run would tend to restrain the growth in our consumption of energy. It is not clear, however, how high prices must go in order to achieve significant reductions in energy demand. Rather than attempt to hold outlays for energy at a fixed level, using less and less as the price increases, it is possible that Americans will tend to sacrifice other consumption in order to maintain *per capita* energy consumption near traditional levels. Economists call this behavior "price inelasticity," and it has clearly been the case with respect to higher gasoline prices. Although gasoline prices in 1974 were about 40% higher than a year earlier, demand for motor gasoline lagged only about 3% below 1973.

Yet if the U. S. is to prevent ever-increasing dependence upon insecure foreign energy sources, let alone achieve self-sufficiency, it is clear that the recent growth rate in energy demand must be cut back sharply. One energy scenario suggested a growth rate of 2%, but even lower growth rates have been proposed by the Ford Foundation's Energy Policy Study and other expert groups.

Gasoline mileage for American cars could be increased by smaller cars, electronic ignitions, radial tires, and eliminating or reducing energy-costly accessories like automatic transmissions and air conditioners. It is not clear, however, that this could be achieved by voluntary methods or through market price pressure alone. Various regulatory and taxation schemes have been proposed to discourage large wasteful cars and encourage small efficient models. The government is funding measures to improve the technology of energy conservation, including automotive fuel economy, and the efficiency of railroad, bus, ship, and air transportation.

Economic Problems of Expanding Energy Supply in the Short Term

For the near-term, at least until 1985, energy independence requires a vigorous effort to expand conventional domestic energy supply—oil, gas, coal, and the current generation of nuclear light-water reactors (LWRs). A variety of legislative and administrative measures have been initiated or proposed, such as the creation off the coasts of deep-water "superports" for huge tankers bringing oil from Alaska and foreign sources, a second Alaskan pipeline to bring gas as well as crude oil from the rich North Slope field, stepped-up leasing of promising tracts on the Outer Continental Shelf of the Atlantic and Gulf coasts, elimination of tax incentives for American companies producing oil overseas, tax incentives for oil companies to make new energy investments, a temporary relaxation in the standards of the Clean Air Act to allow greater use of domestic fuels in power plants, an acceleration in the siting and licensing of nuclear power plants to cut lead times from as much as 10 years to as little as 5 years, special incentives to stimulate the production of crude oil from huge reserves of oil shale in the western states, and the manufacture of synthetic gas and oil from coal.



The 800-mile Trans-Alaska pipeline, which will cross three mountain ranges and miles of tundra and permafrost, will carry oil from Alaska's North Slope to the ice-free port of Valdez. Construction work on the $4.5 billion project is expected to be completed in 1977. The pipeline will have an ultimate capacity of 2 million barrels of oil a day.

Steel pipe to be used in the Trans-Alaska oil pipeline was bent at this testing facility to make certain the pipe is flexible enough to follow land contours and occasional turns in the 800-mile pipeline route.

Expanding energy supplies is a costly business. Various expert study groups have concluded that the capital investment required to achieve energy sufficiency would range from $600 billion to perhaps $1 trillion. The higher figure is roughly equivalent to the entire gross national product of the U. S. in 1970.

One estimate of the energy and related investment required to reach energy sufficiency was made by the National Academy of Engineering (NAE). It put the total at $700 billion with the goal to be achieved in 1985. It would imply an annual investment of $60 billion (1974 dollars). Some idea of the relative scale of this investment may be drawn from the fact that it is more than half the total present annual rate of U. S. industrial investment; almost one-third the net new funds raised in the capital markets for all purposes by states and municipalities, corporations, and the Federal Government, and about three-fourths the rate of personal savings and retained corporate earnings.

A more optimistic conclusion could be drawn from data presented by the Federal Energy Administration in a report that was published in November 1974. Historically, as the report notes, total business investment has been about 10% of the gross national product. Of this, the investment required to finance the expansion of energy production (in the major sectors of coal, oil, gas, and electric utilities) has averaged about 23% of the total. During spans of several years—notably most of the 1950s and since 1970—business has been able to make substantial increases in capital expenditures for energy, up to about 26% or 27% of total investment. But even if we only continue the 23% average since World War II, projected economic growth would raise the total dollars available during the 1975-84 period to $435 billion. Some think this amount might come close to being enough. Moreover, there are policies that the government can adopt to encourage certain kinds of investment.

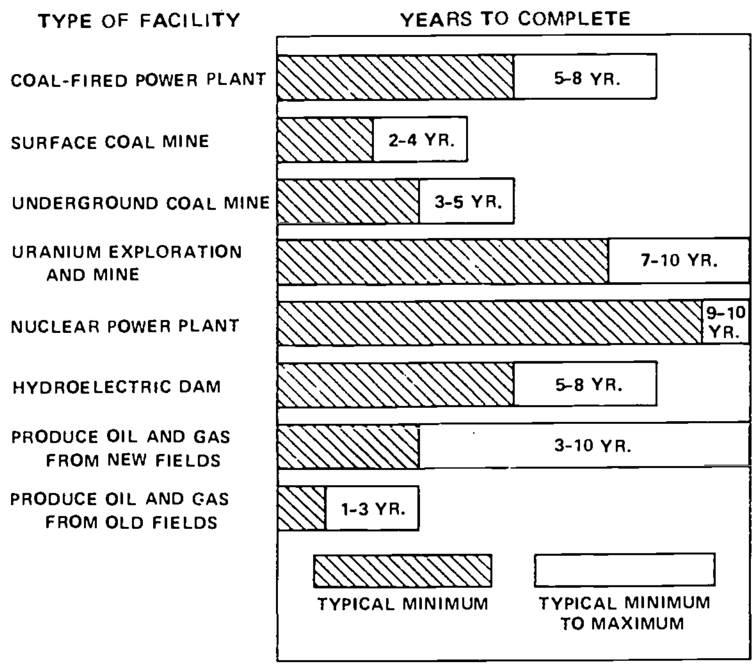
Total investment figures fail to reflect the difficulties that could be posed for specific sectors of the energy industry. Consider the Nation's electric utilities. Under the NAE scenario, they would have to come up with half of the new capital—$350 billion in all, $30 billion a year through 1985, or about three times their current rate of investment. But the harsh fact is that they cannot even carry out their present construction schedules, let alone increase them. With high interest rates and a shortage of investment funds, utilities have encountered difficulties in financing new projects with bond issues and have tended to postpone major projects. A survey by the National Economic Research Associates disclosed that by October 1974, major U. S. utilities had trimmed their construction budgets by about $14 billion for the 1974-78 period, postponing or cancelling some 132,000 megawatts of nuclear and fossil fuel generating capacity.

Even if the energy expansion could be capitalized at the required pace for early self-sufficiency, there would be severe shortages of engineers, technicians, and skilled labor along with bottlenecks in manufacturing capacity. For example, the NAE scenario would require an increase of 230,000 workers in the primary energy industries, including 30,000 more trained engineers, 125,000 coal miners (to double coal production to 1260 million tons by 1985), and 192,000 more pipefitters, welders, boilermakers, and electricians. This would more than double the Nation's present force of 149,000 skilled construction craftsmen. It should be noted that membership in AFL-CIO unions representing these skills has grown quite slowly in recent years, mobility and productivity of building construction labor has been declining, and the energy sector will have to compete with other demands for the skilled outdoor construction work force.

In addition to competing for capital and labor, expanding the domestic energy base will require overcoming limitations in manufacturing capacity and shortening lead times for materials and heavy equipment. For example, steel plate and structural shapes, large forgings and castings, and large bearings are required over the entire spectrum of energy production. One consortium of oil companies that paid $210 million for a Colorado oil shale tract found that it could not get large draglines to stripmine the shale until 1978 or 1979. (It later abandoned the project.) Another company found it could not get bids from domestic suppliers for pressure vessels needed in a coal gasification project with less than a 4-to-5 year delivery lead time. Shortages of tubular goods and castings are plaguing the U. S. oil drilling industry. Overseas, the picture is much the same, where, for example, the effort to bring oil ashore from the North Sea fields has been slipping steadily behind schedule because of similar difficulties in getting materials and equipment.

There are other serious economic problems related to achieving complete energy sufficiency. It is clear, for example, that the real costs of domestic U. S. oil production are significantly higher than the cost of producing oil from the extravagantly productive fields of the Middle East. Programs to extract oil from shale and synthetic gas and liquid hydrocarbons from coal would mean even greater cost

TYPICAL PROJECT TIMES
(From go-ahead to production)



disadvantages for the U. S. fuels. As the U. S. reduced its reliance on cheaper foreign energy supplies, the international oil cartel might reduce the world price to some level below the real costs of domestic fuels. To protect energy investment and maintain progress toward sufficiency, the U. S. would then have to impose tariffs or quotas on the lower-cost foreign oil products.

MIDTERM OUTLOOK FOR DOMESTIC ENERGY

"Beyond 1985 looms an ominous prospect of even greater demand for energy from ever-increasing and ever-rising expectations at home and abroad," the NAE Energy Task Force has observed. "Unless innovative ways are developed for conserving and using energy and substantial new sources and new technologies are found for increasing energy supplies, the strategies presented by the Task Force (for the near term) would only postpone a grim future of energy scarcity."

The problem for the midterm is centered on the disquieting fact that not only the U. S. but the entire world is exhausting its reserves of pumpable fuels—gas and oil—at a prodigious rate. These convenient, easily extractable hydrocarbons were laid down by slow natural processes over the past 600 million years, and mankind has been consuming them in recent years at least one million times faster than the rate at which they formed.

An American petroleum geologist, Dr. M. King Hubbert of the U. S. Geological Survey, has been warning for more than a decade that the U. S. and the world are facing an imminent depletion of these reserves. In fact, Dr. Hubbert has forecast that U. S. domestic production of gas and oil would peak in the 1970s and then decline inexorably. This indeed appears to have happened for both fuels. And there is growing pessimism that the U. S. will be able to bring in enough oil and gas from Alaska or new offshore fields to reverse the decline, although the new supplies may be able to maintain production at the present level of 8.9 million barrels a day for a few years longer.

More ominously, Dr. Hubbert has forecast that the growth rate in world oil demand—even stronger than U. S. demand in recent years—indicates that production in the Middle East and elsewhere will peak by the end of this century and then go into a rapid decline. Significantly, even if the sharply higher oil prices restrain demand growth, Hubbert's model suggests a delay of only a decade or two in reaching the point of declining production.

This means that the U. S., and ultimately the rest of the world, will have to shift from oil-based energy resources to other, more difficult forms of energy. According to Dr. Ralph Lapp, a well-known energy analyst, "There is no alternative in the long run to primary reliance for our energy needs upon coal and atomic power. Simultaneously, we are going to have to move toward an 'all-electric' economy, perhaps even to the extent of eventually substituting electric automobiles for gasoline-burning ones."

Estimated Proved Reserves*

Fuel	Definition	Orig. Units	BTU × 10^{15}	% of Total
1. Coal	In seams at least 42 in. thick at less than 1000 ft overburden	200×10^9 s tons	4200	86.0
2. Liquid fuels	Proved reserves of oil and natural gas liquids	43.10^9 bbl	202	4.1
3. Natural gas	Proved reserves of dry gas	267×10^{12} cu ft	275	5.6
4. Uranium†	Reasonable assured at less than \$15/lb U_3O_8	520×10^3 s tons	208	4.3
Total			4885	100.0

*Proved reserves are limited to materials in known deposits available for recovery under existing economic and technological conditions.

†Calculated at 400 × 10^9 BTU per short ton U_3O_8.

It should be pointed out that neither Dr. Hubbert's dire prophecies of oil and gas depletion nor Dr. Lapp's prescription for meeting the energy crisis by increased reliance on coal and nuclear power are universally accepted. Many expert geologists in the petroleum industry and the Geological Survey itself believe that recoverable supplies of oil and gas are much greater than Dr. Hubbert forecasts and that there is little danger of early depletion.

Environmentalists quarrel with the idea of mining more coal and accelerating the construction of nuclear power plants. They have urged a moratorium on nuclear plant construction, abandonment of nuclear research, and an all-out national effort to harness such "gentle" technologies as solar power to meet future national needs.

It can be fairly stated that no technological challenge the Nation has ever faced in its history has been as critical as these new tasks. What is required in a span of a few decades is nothing less than a massive roll-over of our energy base from fluid to solid hydrocarbons coupled with a radical increase in the role of electricity in our energy supply mix. Our national prosperity, our hopes for economic growth, our role in world affairs, and perhaps even our chances of survival as an affluent industrial society are vitally dependent upon the success with which we master these new technologies. They will not come easily, and the energy we can expect from them will be far more costly than anything we have experienced. While there should be vigorous debate over the relative roles of conservation and expanded domestic production in the solution of our energy problems, it seems clear that we must at a minimum have the new technologies in hand if we are to avoid the bleak consequences of energy scarcity.

SYNTHETIC FUELS FROM COAL

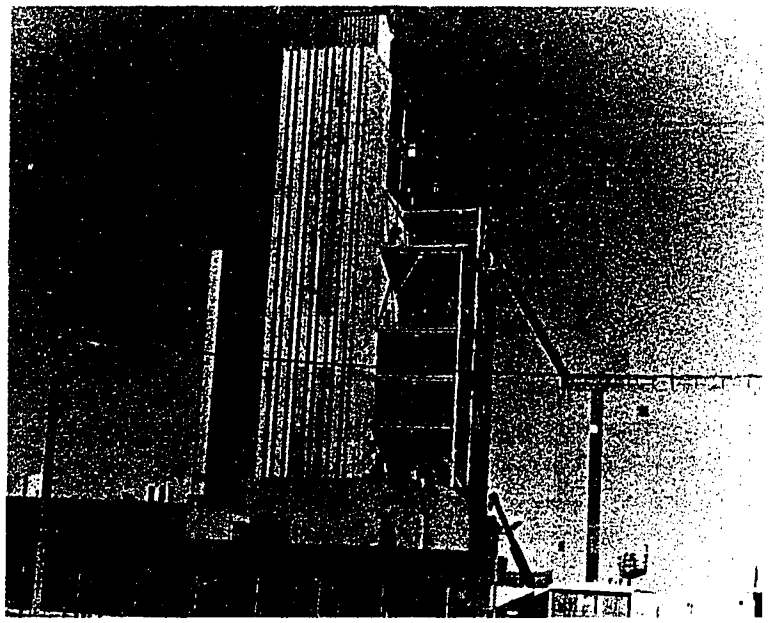
Fossil fuels release energy when their hydrogen content is oxidized by combustion. Whether in liquid, gaseous, or solid form, all such fuels are mixtures of carbon and hydrogen. By altering the ratios of carbon and hydrogen and by reforming these atoms into different molecules, it is possible to tailor synthetic fuels of desirable properties. There are a dozen or more processes under study for conversion of coal to more convenient forms—clean, low-BTU gas (less than 200 BTUs per cubic foot) for electric power generation; synthetic gas of pipeline quality (1000 BTUs per cubic foot), which can substitute for our present methane natural gas; methanol, also known as wood or methyl alcohol, which could serve as a future motor fuel in place of gasoline; synthetic crude oil, which could be used as refinery feedstock; and even a clean solid fuel with a low ash and sulfur content and a higher energy value than most of our present coals.

It must be emphasized that since all of these processes involve very large plants in order to realize economies of

While high-BTU gas could replace the natural gas now used in stoves and furnaces, it is more likely that a low-BTU synthetic gas will come into increasing use for generating electricity. Since the low-BTU gas has only one-fifth the heating value of methane, it cannot be transported economically over long distances by pipeline; instead it must be consumed close to the point of production. However, no oxygen is required to produce it, and other steps necessary in the high-BTU gasification process can be eliminated. Hence its cost at the plant gate would be about 20% less than high-BTU gas, or about $0.90 per million BTUs using the cheapest western coals, according to the Cornell Workshop study. As shortages of natural gas become increasingly acute, it is expected that electric utilities and industrial users, who now account for two-thirds of all natural gas consumption, will shift increasingly to the cheaper low-BTU gas, and leave natural gas and the high-BTU synthetic product to residential users.

Processes for the manufacture of methanol and "syncrude" from coal involve more elaborate chemical treatment than gasification. Capital costs are expected to range from $1400 to $1600 for each million BTUs of daily production capacity, according to a 1972 study of new energy forms conducted by the National Petroleum Council. At that time it reckoned that a methanol plant using the most modern technology could produce methanol at a cost of $1.50 to $2.00 per million BTUs. However, since liquid fuels are cheaper to transport over long distances than gaseous fuels, the ultimate cost of methanol or syncrude to the user would not bear the same 30% differential over syngas expected in the manufacturing process itself.

Methanol is of particular interest because of its potential for replacing motor gasoline and diesel fuels. Although it has only about one-half the energy per pound as gasoline and would provide only about 55% to 60% as much mileage per gallon as gasoline, a manufacturing cost of about $0.15 per gallon, based on the price of coal before the oil embargo, could be competitive on a BTU basis with the refinery cost of gasoline derived from crude costing $7 to $10 a barrel. One difficulty with methanol is cold weather starting, but many experts believe this can be solved. Methanol will burn more cleanly than gasoline, emitting only a fraction of the carbon monoxide and nitrogen oxides that come from engines burning gasoline.



An ERDA plant at Rapid City, South Dakota, is testing a process to convert lignite and other more reactive coals to high BTU gas. This concept, called the CO_2 Acceptor Process, involves the reaction of crushed limestone with carbon dioxide, one of the byproducts of gasification. The reaction, which releases the heat needed to keep the gasification process going, results in a synthetic gas enriched in methane and hydrogen.

A number of schemes have been proposed for establishing a synthetic fuel industry based on coal gasification and liquefaction. Some would require massive amounts of government assistance. For example, one proposal calls for building 66 plants to produce oil and gas from coal, with a total production capacity equivalent to about 4.1 million barrels of oil per day. The cost is estimated at $98 billion. Common to this and other proposals is an agreement by the government to buy the plant's entire output over its useful life at a floor price—say, $1.50 per million BTUs. The operator would be free to sell his product on the open market if the price is higher than the government-guaranteed level. But if energy prices remain relatively high or continue their upward trend, the market price would stay above the floor price and the government would not have to subsidize the production of synthetic fuel.

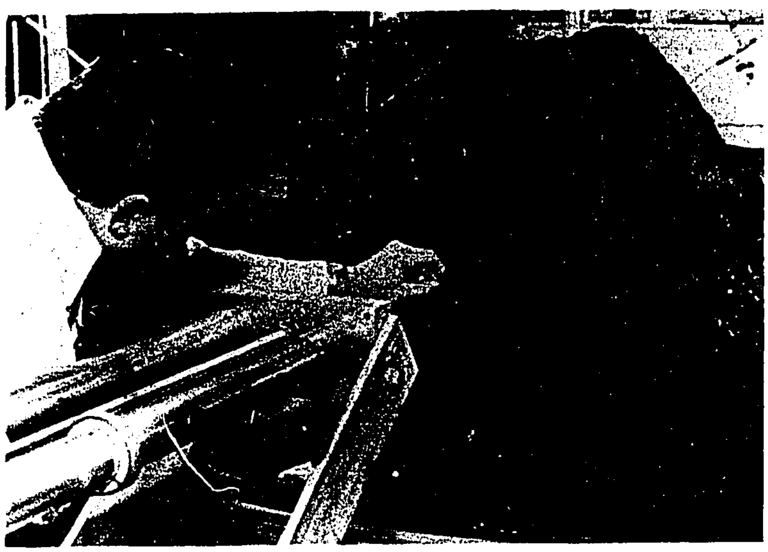
It should be pointed out that ambitious plans for such crash programs could provide only a minor fraction of present and projected energy needs. For example, one plan under consideration by the Cornell Workshops proposed 36 synthetic fuel plants at a cost of about $500 million each—24 plants producing 250 million cubic feet of high-BTU gas per day and 12 others extracting shale oil at the rate of 100,000 barrels per day. Such an array would produce a volume of gas and oil equal to only about 6% of total U. S. energy consumption in 1973, and less than 4% of the projected consumption for 1985.

Improved technology can significantly reduce the costs of converting coal into more desirable fuels. Coal is hydrogen-poor, compared to the other fuels, but all conversion processes exact an energy penalty. In the case of gasification, for example, about 35% of the original heat content of the coal is lost. It may ultimately be possible to make up some of this loss through the introduction of combined cycle power generation processes, in which gas turbines and steam turbines are coupled in tandem so that the jet exhaust of the former raises steam in the boiler of the latter. It is thought that such systems might achieve overall energy efficiencies of 50% or more, compared to 42% for the best single-stage power stations today, but is doubtful that the energy penalty of converting coal to gas can be reduced much below 20%.

The high costs for coal-derived energy must necessarily persist according to the National Petroleum Council, since coal handling, gas handling, processing, scrubbing, and compression are far more capital-intensive than the handling of hydrogen-rich liquids such as petroleum. The NPC said, "It is fundamentally incorrect to believe that capital requirements for producing gaseous energy forms from coal can ever be reduced to levels which are typical for refining liquid petroleum fractions."

Another problem in estimating the costs of synthetic fuels is the extreme sensitivity of their costs to the price of coal. The 1972 NPC study of the cost of synthetic fuels assumed prices as low as $0.20 per million BTU for western coals during the 1975-82 period, and $0.25 for the 1982-2000 period. However, coal prices on long-term contracts have increased quite sharply, so many of the earlier forecasts have become outdated.

Because of the sharp increases in coal prices and the inflationary price increases occurring throughout the whole capital goods sector of the economy, earlier optimism that synthetic fuels might compete with gas and oil at present



In research at ERDA's Lawrence Livermore Laboratory on the feasibility of underground coal gasification, water is being pumped into a coal sample to test its porosity and permeability.

world prices has diminished. Although synthetic fuels may not be economic in the short-term future, they may become more competitive as the supply of petroleum and natural gas diminishes. Moreover, it is also desirable for the U. S. to build them on a major scale for reasons of national security and political independence in world affairs. A synthetic fuel industry is, therefore, an integral part of achieving self-sufficiency in energy.

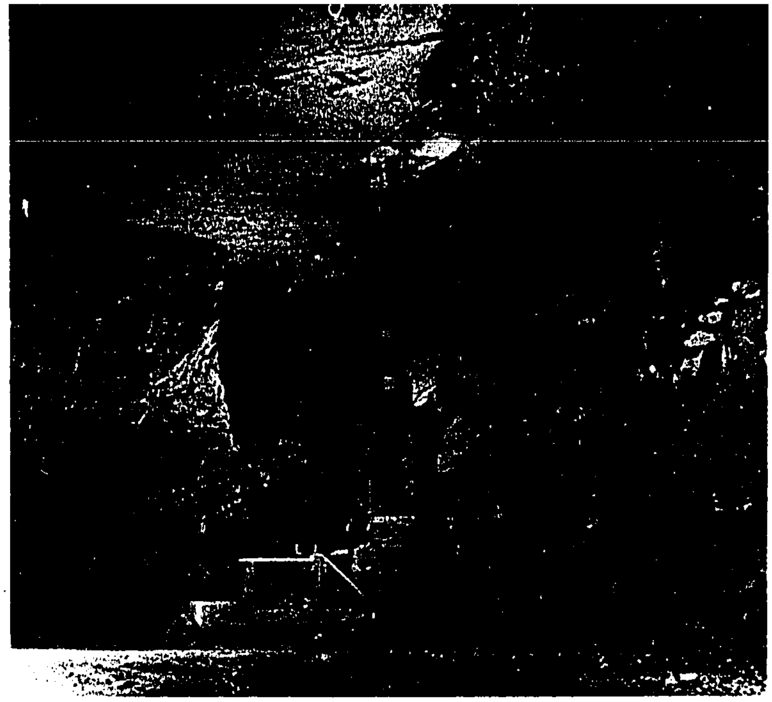
OIL SHALE

In three states of the western U. S.—Colorado, Wyoming, and Utah—there are deposits of shale containing about 1.4 trillion barrels of oil—about six times the proven, probable, and speculative U. S. reserve of both on- and off-shore oil. According to the U. S. Bureau of Mines, this shale oil occurs in deposits at least 10 feet in thickness and yields 10 to 25 gallons of crude oil per ton of shale.

The thickest and richest deposits of shale are in the Piceance Basin of western Colorado; these range more than 10 feet in thickness and 20 gallons or more per ton. Underlying an area of about 600 square miles, this shale contains a total of 720 billion barrels of oil, according to the Interior Department. It represents a major U. S. energy resource.

Two methods are under consideration for extracting shale oil. One calls for mining the shale, crushing it, and then retorting the material to a temperature of about 900°F to decompose the solid organic material (kerogen) to crude oil. This technique would require vast amounts of water to dispose of spent material, and it would pose severe environmental problems.

A second method for shale oil extraction is *in situ* retorting. This would be accomplished by drilling and excavation to prepare a body of shale for underground retorting and pumping the liquid oil yield to the surface. The underground technique would involve handling only about one-fourth as much material as the surface method, and it



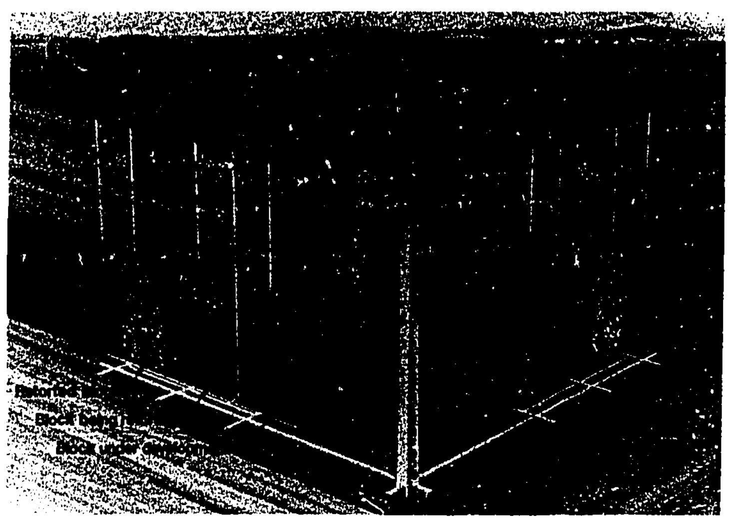
An underground oil shale mine.

Water availability may ultimately place a ceiling of 3 to 5 million barrels a day on shale oil production, according to government estimates. If the bulk of this oil is obtained by mining and surface retorting, it will present a severe materials handling problem. For every 1 million barrels of oil of daily production capacity, it is estimated that 570 million tons of material will have to be mined each year. This would be as much as all of the material handled by the entire U. S. coal-mining industry in 1973. Compounding the problem is the fact that the shale must be handled twice—first it must be mined and then it must be disposed of in an environmentally acceptable manner.

Another problem is the technology of extracting oil from shale. While this has proven in surface retorts on a scale of 1000 tons per day, commercial retorts would have to be at least 10 times larger. With respect to *in situ* extraction, demonstrations have been conducted on a very much smaller scale, with output of only about 35 gallons a day.

If shale oil can make a major contribution to national energy needs, its price is expected to be significantly less than oil synthesized from coal. The Cornell Workshops Study estimated a cost of $0.80 per million BTUs for shale oil extracted from the richest beds (yielding more than 35 gallons per ton), and it has suggested that this might be driven downward to perhaps $0.70 as the industry becomes experienced in the new operation.

It is not clear how rapidly shale oil production can come into operation. According to the National Academy of Engineering report, "The lead times and the serious problems facing the industry force the Task Force to conclude that *the maximum target production rate by 1985 cannot realistically exceed 0.5 million barrels per day.* Even this target is an extremely large undertaking, involving the capital expenditure of some $3 billion to $5 billion in a new and unfamiliar technology."



One concept for extracting energy from oil shale involves removing the oil by retorting the resource in place, rather than mining the material and processing it above ground. Successful development of this technique on a scale applicable to a major portion of the Nation's vast oil shale deposits would significantly lower environmental degradation as well as reduce U. S. dependence on foreign oil supplies.

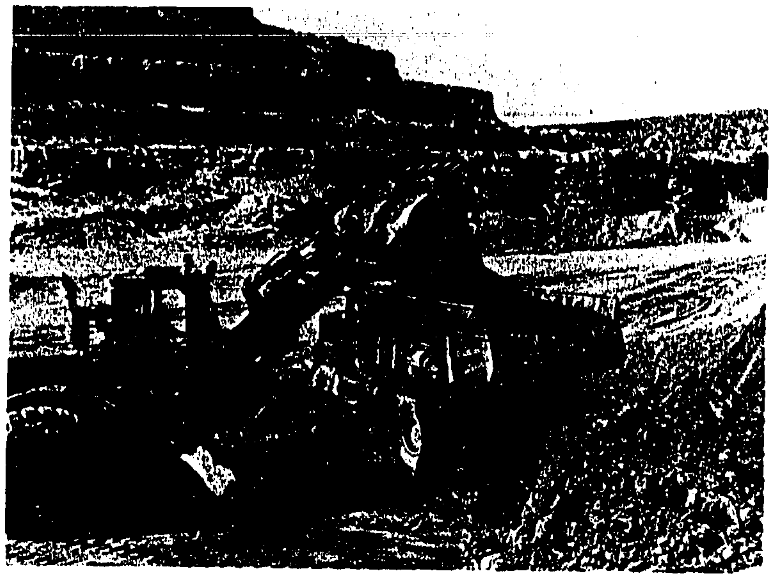
UPGRADING THE GENERATION OF NUCLEAR POWER

Plans for expanding domestic electric supply call for increasing nuclear power. As of December 31, 1974, the U. S. had an installed nuclear capacity of about 36,000 megawatts, equal to about 7.5% of total electrical generating capacity, compared to 5.5% at the end of 1973.

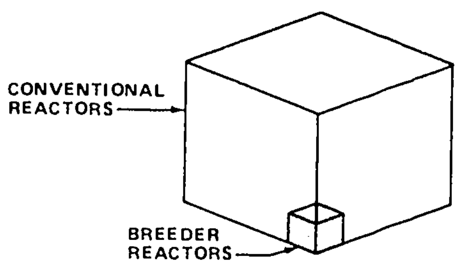
Through 1985, and probably longer, the bulk of nuclear capacity will come from light-water reactors that burn uranium enriched with the fissionable isotope uranium-235. Present LWRs, however, have two drawbacks: They discharge about 30% more heat to the environment than modern coal-fired stations of equivalent capacity, and they are able to convert only about 1% to 2% of the potential energy of uranium into boiler heat for steam generation.

Of the two problems, the more severe is the inefficiency with which LWRs burn their fuel. This could create a problem of growing severity in the mining, milling, and enrichment of uranium fuel. Current uranium requirements are modest, with 1974 production of about 12,000 tons of uranium oxide (U_3O_8) (also known as "yellowcake") sufficient to meet all demands. However, the rapid growth anticipated in nuclear generation by the LWRs means that very much larger amounts of yellowcake will be required in the future—between 25,000 and 35,000 tons annually by 1980, 70,000 to 120,000 tons annually by 1990, and 100,000 to 200,000 tons a year by 2000.

Present U. S. uranium reserves that can yield yellowcake at $8 per pound or less are calculated at 277,000 tons with another 450,000 tons potentially available at the same cost. The expansion of nuclear power with LWRs will rapidly exhaust these rich reserves; this means that uranium mining and milling operations in the 1980s will have to resort to ores of steadily decreasing uranium assays. It is estimated that the U. S. has proved reserves of 520,000 tons of uranium that can be extracted at $15 per pound and 700,000 tons that can be obtained at a cost up to $30 a pound, with the potential of an additional 1 million tons and 1.7 million tons, respectively, at those cost levels.



Above, uranium is excavated from an open pit mine. Below, for every 100 cubic feet of uranium ore required to fuel conventional reactors, only 1 cubic foot would be required to fuel breeders.



Far greater amounts of uranium ore are available in shales and granites in the continental U. S., but the uranium concentration is quite low, on the order of 50 parts per million, or about 2% of the uranium content of present ores. Uranium extracted from such lean ores would cost \$100 to \$200 per pound, and it would exact a considerable environmental cost. For example, to satisfy an annual demand for 150,000 tons of yellowcake, more than 4 billion tons of the so-called Chattanooga Shales would have to be mined every year—about seven times the volume of the material now handled by the entire U. S. coal industry. Hundreds of new milling plants would be required, together with hundreds of thousands of workers.

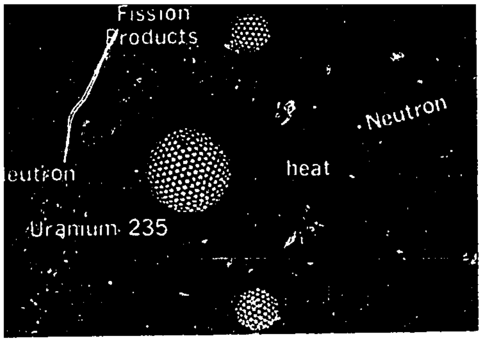
"The anticipated growth of the nuclear industry cannot be maintained with any credibility beyond the mid-1990s if it is to remain based on current generation converters [LWRs]," concluded Dr. Peter Auer of the Cornell Workshops on Energy Research and Development. "In fact, we may observe in this connection that were we forced to utilize ore grades as low as 50 parts per million of U_3O_8 in present day converters, the energy content per unit weight of rock would be comparable to coal. As a consequence, one of the attractions of nuclear energy—minimal impact on land due to mining—would be sacrificed."

One action that might ease future demand for yellowcake and enriched uranium fuel for light-water reactors would be the recycling of plutonium as part of their fuel charge. Like uranium-235, plutonium-239 is fissile, and it can release energy in a nuclear chain reaction. Plutonium-239 is produced in the normal course of reactor operations as a result of neutron collisions with "fertile" uranium-238 isotopes, which constitute about 97% of the fuel charge of LWRs, and the plutonium can be recovered in the reprocessing of reactor fuel elements. Fabricating this recovered plutonium into new reactor fuel elements might relieve future uranium mining and milling requirements as well as enrichment needs by as much as 30%. The use of plutonium for commercial enrichment of reactor fuel is now being actively investigated, and some plutonium-enriched fuel is now being tested in a few reactors.

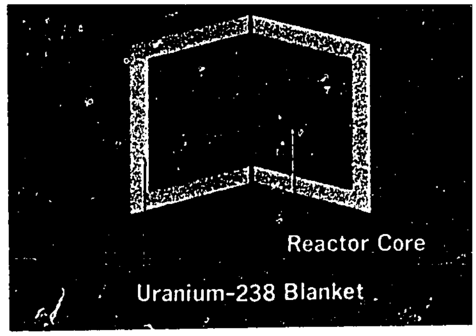
While plutonium recycling may ease the uranium supply problem, the ultimate solution to this problem will require new and fundamentally different reactor concepts, which would broaden the base of available fuels for nuclear reactors and use existing fuels with far greater efficiency.

Two reactor concepts under development will be able to use thorium and the fissile uranium-233 isotope in their fuel cycle. These are the High Temperature Gas Reactor (HTGR) and the Light Water Breeder Reactor (LWBR). Their initial fuel charge would consist of thorium and uranium enriched in uranium-235. As the reaction proceeded, some of the fertile thorium-232 would be transmuted by neutron bombardment into fissile uranium-233. The latter would then be recovered during fuel element reprocessing and recycled into the reactors in subsequent fuel charges. In the case of the HTGR, the use of uranium-233 would sharply reduce lifetime requirements for natural and enriched uranium, while for the LWBR it is thought that uranium-233 can support the reactor fissile fuel requirements entirely after the first 10 years of operation. The successful mastery of the thorium/uranium-233 fuel cycle would approximately double the amount of low-cost ($10 per pound) fuels available for nuclear power generation.

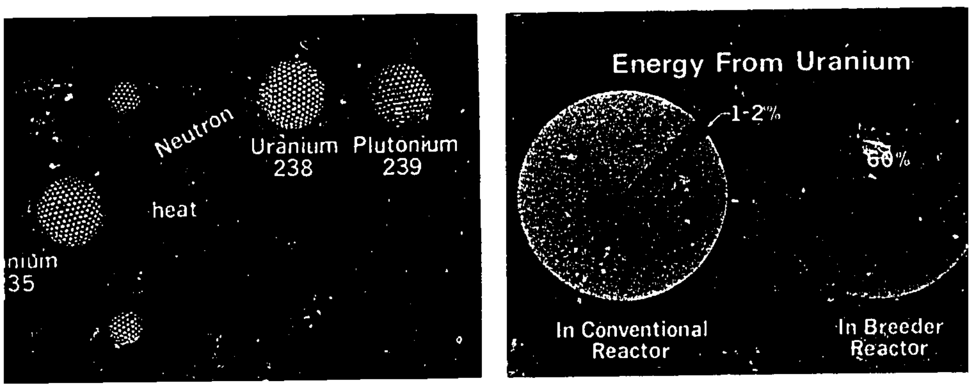
Even with advanced converters like the HTGR and the LWBR, the time would eventually come when low-cost uranium and thorium would be depleted, and these fuels would increase in cost. To surmount this problem the U. S. Energy Research and Development Administration (ERDA) is pressing the development of the Liquid Metal Fast Breeder Reactor (LMFBR), which will generate more fuel than it consumes. The sodium-cooled LMFBR would operate on a core of plutonium fuel derived from LWR production, and this core would be surrounded by a blanket of fertile uranium-238. The fast neutrons generated in the core transmute the uranium-238 into fissile plutonium-239 faster than the fissile plutonium is "burned" in the core. Subsequent fuel cores for the LMFBR would use the plutonium-239 of its own manufacture while producing additional fuel to start up new LMFBRs. It is expected that the process can eventually be made so efficient that the original fuel charge of fissile fuel will be doubled in as little as 10 years, thus providing fuel charges for additional breeder reactors and reducing the need for additional uranium mining, milling, and enrichment to a negligible scale.



(a) The fission process in a conventional, or light water, reactor uses from 1% to 2% of the energy in uranium.



(b) The core of the breeder reactor contains fissionable uranium-235 or plutonium-239 surrounded by a blanket of uranium-238.



(c) The production of plutonium fuel in a breeder reactor could enable us to use 60% of the energy in uranium.

HOW THE BREEDER BREEDS. Nuclear fuel consists of fissionable atoms whose nuclei can be broken apart (fissioned) by the impact of atomic particles called neutrons. Certain elements, called fertile materials, can be made fissionable. The LMFBR would have a fuel core containing plutonium-239, a fissionable material, and uranium-238, a fertile material. The core would be surrounded by a blanket of uranium-238. In the blanket, fertile uranium-238 would be turned into fissionable plutonium-239 when the nuclei of the uranium-238 atoms absorbed the neutrons generated by the plutonium. Meanwhile the heat from the fissioning of the plutonium or uranium nuclei in the core would be used to produce steam for driving turbogenerators to produce electricity, and the plutonium-239 formed in the blanket could be used in the future to fuel other reactors. The breeder will produce about 5 pounds of fuel for every 4 pounds it consumes.

Since the breeder fuel cycle would be 30 to 50 times more efficient in its use of fuel than the current generation of LWRs, nuclear power could become essentially insensitive to rising fuel costs, and the fast breeder could assure ample nuclear electricity for centuries to come. The LMFBR has

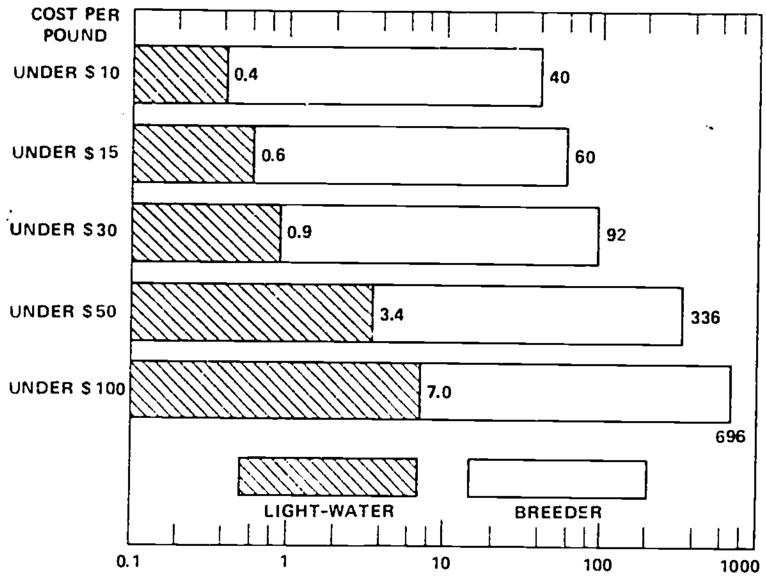
This array of instruments will monitor the behavior of nuclear fuel during reactor operations. It is one component of the Fast Flux Test Facility now being constructed at Hanford, Washington. This original and innovative research and development facility will provide experience in designing, fabricating, and operating liquid metal fast breeder reactors, which would hold down the cost and extend the supply of uranium fuel.

accordingly been assigned the top nuclear reactor development priority by the government. In partnership with a group of utilities ERDA is presently building a demonstration plant on the Clinch River in Tennessee, which will be the first U. S. large-scale (380 gross electrical megawatts) LMFBR power plant.

There has been considerable debate concerning the high priority and funding level assigned to the LMFBR. The primary justification for the funding level and development schedule is the anticipated depletion of uranium fuel resources that are extractable at acceptable economic and environmental costs. Without the LMFBR more and more LWRs would come on line with their added uranium demands. Because of lengthening lead times for nuclear plants and problems for utilities seeking to raise capital, however, projections for nuclear power have tended to erode. In 1971, for example, the government anticipated 151,000 megawatts of nuclear generation capacity for the U. S. by the end of 1980. In 1972, this was lowered to 132,000 megawatts, and in 1974, it was further trimmed to 102,000 megawatts.

Although near-term LWR demand on the uranium supply is somewhat diminished by these reduced estimates of LWR capacity, the fact remains that uranium demand for the longer term must increase inexorably. It is estimated that 700,000 to 950,000 tons of yellowcake must be produced to satisfy LWR requirements between 1973 and 1991 and that a stable nuclear power industry in 1990 would require an 8-year forward reserve assurance of another 1 million tons of uranium supply to justify investment in new milling facilities and forward delivery contracts for yellowcake. Thus there is little question in the long run that the breeder will ultimately be required to deal with the uranium supply problem. If we have learned anything from our current and prospective energy problems, it is the wisdom of a policy that is forehanded in meeting our needs.

COMPARISON OF TOTAL URANIUM ENERGY WITH LIGHT-WATER AND BREEDER REACTORS
(Btu × 10^{18})



GEOTHERMAL POWER

There are several hundred hot springs, fumaroles (openings in volcanic areas from which smoke and gases arise), and geyser complexes located mainly in the western states of the U. S. Geological studies of these regions have disclosed the existence of subsurface steam and pressurized hot water that can be drilled into so that the energy can be either converted to electric power by means of steam turbines and generators or used directly for other purposes.

The Geysers field near San Francisco is the only geothermal site presently in commercial use in the U. S. It has a capacity of 400 electrical megawatts and a scheduled expansion to 900 megawatts by 1977. A single well in this field can produce more than 100 tons of steam an hour at a temperature of 400°F and a pressure of 140 pounds per square foot. The cost of this steam, including the disposal of the spent steam, has been reckoned at about $0.35 a ton, or only one-third the cost of comparable steam generated in a conventional power plant burning fuel oil at a cost of $7 a barrel.

The success of The Geysers as a geothermal power source has raised expectations that significant amounts of power can be extracted from other geothermal sources in the U. S. and that this new industry will expand rapidly because of cost

Electric generating plants at The Geysers, a natural steam field in California, now have a capacity of 400 megawatts. The total potential geothermal capacity at this location is estimated to be in the range of 1000 to 4000 megawatts, enough to serve one half the present needs of the greater San Francisco metropolitan area. The technology is limited in its application, however, because additional dry steam fields are not now known and are not believed likely to exist in the U. S.

advantages of geothermal heat compared to heat produced by nuclear reactions and fossil fuels. The National Petroleum Council has estimated that 19,000 megawatts of geothermal power capacity—all of it in California and Nevada—could be on line in the U. S. by 1985. Other estimates of the potential have ranged up to 132,000 megawatts by 1985, or about 15% of total anticipated U. S. installed electrical capacity at that time. To spur the exploitation of this new energy resource the Congress has enacted the Federal Geothermal Leasing Act to make available millions of acres of promising federal lands for prospecting and development.

Several caveats should be noted with respect to geothermal power. In the first place, The Geysers and two of the other geothermal power sites now in operation in the rest of the world produce dry steam, which is the most desirable product. Some geologists estimate that relatively few geothermal sites will yield dry steam. A larger number produce hot water or a mixture of steam and water. An even larger number of hot dry rock reservoirs contain no usable quantities of water, but might be used to produce heat if water were passed through them. While low-pressure steam can be separated from the flow and additional steam of still lower pressure can be obtained by a flashing process, the capital costs and therefore the ultimate cost of electrical kilowatts produced from these fields will be greater than for dry-steam fields. Low-pressure turbines will cost more per kilowatt of generating capacity because the use of steam in large quantities at pressures and temperatures far below steam produced in conventional fuel-burning plants requires large turbines to transform the heat to mechanical energy.

A second problem with geothermal power relates to the impurities in the wet steam produced at many sites. For example, wells drilled in parts of the Salton Sea area of California can produce 60 tons of steam an hour from a brine containing 20% to 30% by weight of dissolved salts and other solids. Not only do these mineral impurities cause corrosion and the buildup of deposits in pipes and equipment, but they also present a severe disposal problem. It appears, however, that the latter problem can be solved in many fields by according to the NPC. However, millions of quads of BTUs, supplied by tectonic processes and radioactive decay in the earth itself, are held by hot water in sedimentary basins at depths of more than 2 miles, by the heat trapped in rocks down to a depth of 6 miles, and by magma chambers within a few miles of the earth's surface.

In the case of the water in deep, permeable sedimentary basins, the NPC suggests that the total detectable heat stored in such basins in the U. S. at depths below 2 miles may equal the heat of combustion of 10 trillion barrels of oil, or about 100 times the Nation's total petroleum reserves. "It seems conceivable that (the heat) may overshadow even the overall total for oil," the NPC observed, but it remains to be seen whether this energy can be harnessed for practical use.

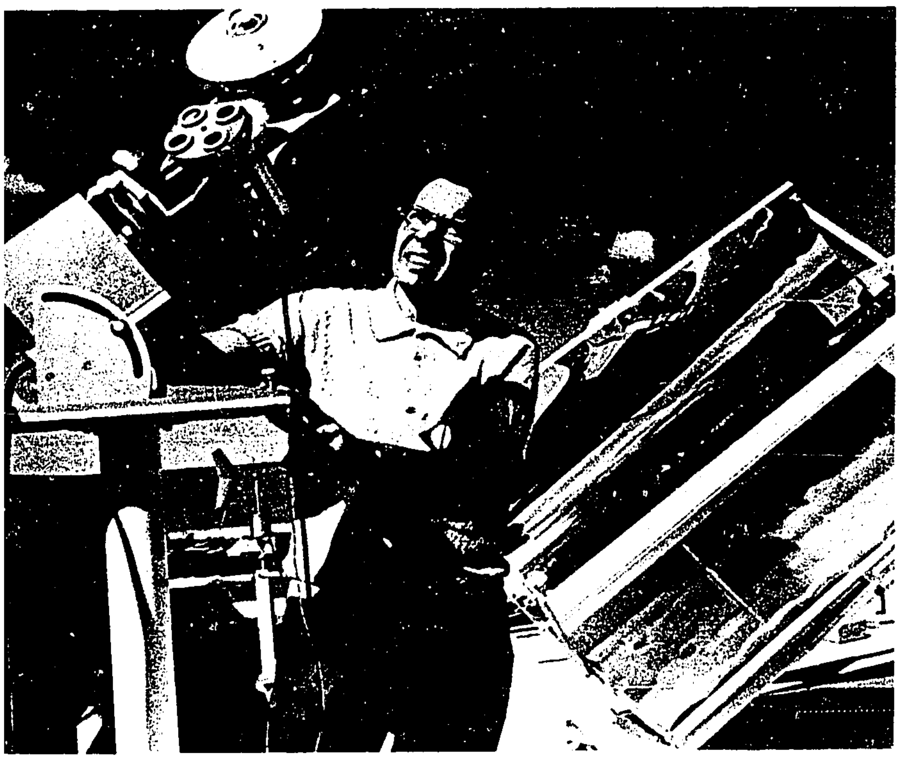
SOLAR ENERGY

No source of energy is as clean, abundant, and inexhaustible as sunlight and some of its secondary effects, such as the winds and the differences in temperature between the tropical ocean surface and the waters in the depths. The idea of harnessing this energy is inherently attractive because it is a "gentle" technology that emits almost zero pollutants and exacts a far smaller penalty on our environment than some other energy-production activities.

Historically, solar energy has played a major role in civilization. Up to the 20th century, for example, it was the wind that propelled most of the world's ocean commerce, and until the 1940s the wind provided electricity for tens of thousands of American homes. Ironically, low-cost fossil fuels drove wind-generated electricity out of business. More recently, silicon photovoltaic cells have been employed in camera light meters and to generate electricity for spacecraft.

In theory, an earth-based solar collector $\frac{1}{500}$th of the area of the United States (an area slightly smaller than Massachusetts) receives an amount of solar energy that, if converted at 20% efficiency, would provide for all of the Nation's present consumption of electricity. Statistics like these have caused some people to conclude that much higher priority should be assigned to solar energy and that some present approaches to energy needs should be dropped or sharply curtailed.

In fact, however, there are technical, economic, and institutional barriers to the immediate and widespread use of solar energy. Overcoming these barriers will take decades of work. Thus it would be irresponsible and foolhardy for the United States to ignore other opportunities to satisfy its short-term energy needs.



At the U. S. Energy Research and Development Administration's Sandia Laboratories in New Mexico, this device is used to measure the intensity of the sun. Temperatures are recorded by the pyroheliometer and are then compared with those from solar energy collectors. The efficiency of various collectors is determined in this way.

The technical barriers to using solar energy are associated with two facts about the sun's rays: They are spread diffusely over the surface of the earth and they are intermittent: the sun shines only by day and is frequently obscured by clouds. To harness large amounts of solar energy, collectors must be spread over a large area, and the larger the facility, the higher the cost. With most techniques, only a portion of the collected solar energy is used immediately. The rest must be stored. The cost of storage is usually a significant fraction of the cost of operating the installation. Thus one of the major areas of research and development that must be pursued to improve the outlook for solar energy utilization has to do with finding ways to store large amounts of energy at low cost.

The economic barriers to utilization of solar energy result from the fact that high initial costs are required for solar energy facilities, even though the operating costs are low. Someone has to borrow money to build these facilities. This is often a problem even for governments and large businesses. For individual homeowners, it is even more of a problem.

The institutional barriers of using solar energy result from outmoded thinking. People and institutions do not usually give serious consideration to lifetime energy costs when they construct a facility or a residence. Because of the historic low costs of fossil fuels, there has been no economic incentive to establish industries that manufacture, install, guarantee, and maintain solar energy equipment. Consequently, the banks and other lending institutions have nowhere to turn for advice if someone wants a loan for a solar installation.

To alleviate economic and institutional barriers, governments may offer special financial incentives such as guaranteed loans to encourage the use of the new technology. A number of other measures can also be adopted; for example, revision of building and zoning codes, rapid amortization allowances for federal income tax purposes, and local property tax exemptions for buildings with solar plants.

Six major approaches to using this energy source are being followed in the national solar energy program under the leadership of ERDA. Two approaches involve the direct utilization of the sun's light and heat. The others are techniques for converting solar energy into electricity. The six, listed in order of their potential for large-scale near-term benefits, are:

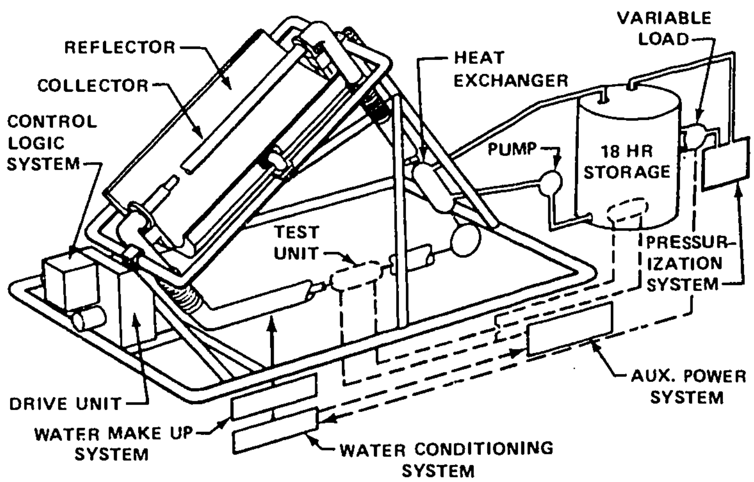
- Heating and cooling
- Wind energy conversion
- Bioconversion to fuels
- Solar thermal conversion
- Photovoltaic conversion
- Ocean thermal energy conversion.

Solar energy for heating and cooling is the most immediately promising application because it is technically simple and because roughly one quarter of all United States energy consumption is for space heating, water heating, and air conditioning—at a cost of more than $25 billion a year. Furthermore, the use of air conditioning is continuing to increase. In 1974, the government began major efforts to demonstrate solar heating and cooling on a large scale and to carry out necessary research and development. Several initial installations have been made in public school buildings.

Also in 1974, the Solar Heating and Cooling Demonstration Act was passed. This legislation provides for major demonstrations of solar heating technology within 3 years and combined solar heating and cooling technology within 5 years.

In early 1975, ERDA completed an interim report on a national plan to achieve the purposes of this legislation. The plan, submitted to the Congress, called for the construction and operation of systems in a large number of residential and commercial buildings, both publicly and privately owned. Cooperative efforts by 13 federal departments and agencies would lead to the installation of units in 400–2400 buildings. In addition, the plan provided for research and development, collection, and widespread dissemination of information on solar heating and cooling, and activities to remove obstacles based on economic factors and traditional ways of thinking. With the creation of a government-supported market through 1979, the plan pointed toward achieving conditions under which a solar heating and cooling industry can develop.

Wind is another area that promises relatively short-range use of solar energy if economic and institutional barriers can be overcome. If ways can be found to use wind-generated energy directly or to store it at low cost, this source can provide needed additional electrical generating capacity in areas of the country where there are relatively high winds.



SOLAR COLLECTOR SYSTEM

Highly reflective curved metal plates cause the sun's rays to converge on the glass tube in the center. *Fluid in the tube is heated by the sun and circulates through the tubes. The fluid goes through the heat exchanger where the heat is stored and the fluid is recirculated to pick up more heat.*

A series of experimental wind energy machines are now being built. In the near future more advanced versions of these machines will be installed at generating facilities at various locations. The purpose will be to learn how to solve the problem of introducing electricity generated from the varying winds into utility grids requiring steady service to customers and to verify the technical and economic characteristics of such systems.

Still another technique of using solar energy is to accentuate the natural processes of photosynthesis in plant life. There are many ways to do this; again the problems are mainly economic and institutional.

The ERDA program of bioconversion to fuels is working to establish the commercial practicability of producing significant quantities of plant materials at feasible costs. The goal is to convert these materials and other organic products now considered wastes into clean fuels. The four major sources of materials being examined are urban solid wastes, agricultural residues, and terrestrial and marine crops. End products that may result include synthetic natural gas, alcohol fuels, solid fuels, heat, electricity, ammonia nitrogen fertilizer, and petrochemical substitutes.

The economic analysis of bioconversion has one interesting aspect. If the entire cost of production has to be recovered by the sale of the end products, solar energy might find it difficult to compete with conventional energy. But if a portion of the cost is charged to environmental protection and disposal of wastes, the prospects for solar energy systems seem more promising.

Numerous bioconversion experiments and studies are under way with ERDA support. One study involves the growth of giant kelp as an ocean energy crop. Under examination is a plan to place a 7-acre kelp farm off the California coast to determine operating and performance characteristics of kelp beds on floating structures. An important feature of this work is the design of the artificial supports that would be necessary and the determination of whether this could be done at sufficiently low cost to make the plan economically attractive. Another type of project now being designed is a pilot plant to evaluate a process for producing pipeline quality fuel gas from urban solid wastes.

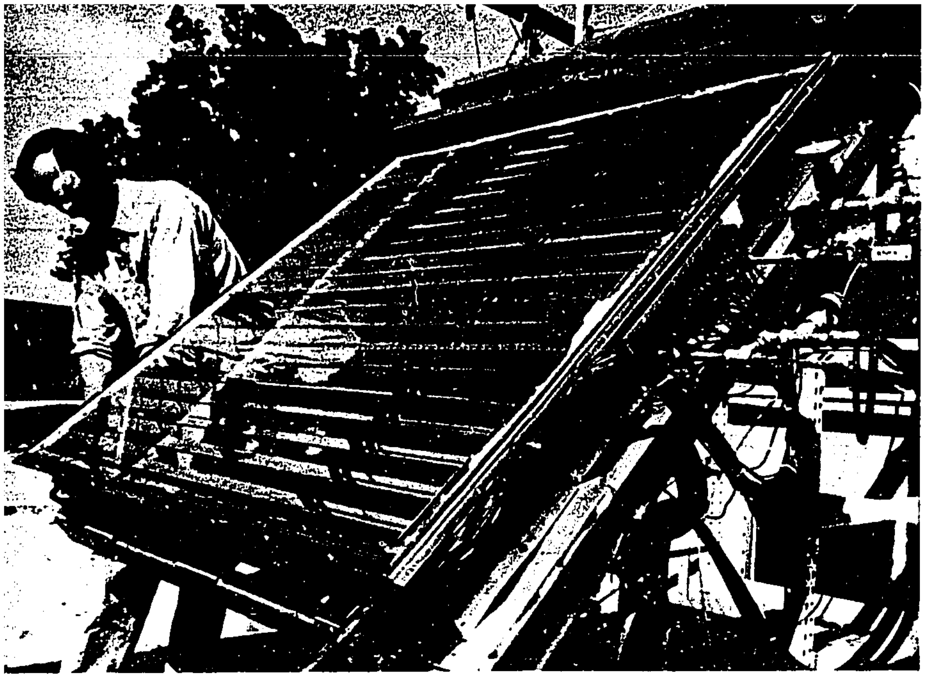
Somewhat longer time scales are associated with the other techniques for generating electricity from solar energy. One such approach will employ high-temperature thermal conversion. Experiments are under way to use various means to collect and concentrate the sun's rays on pipes coated with materials that would absorb the sunlight as completely as possible and reduce re-radiation of heat outward. But this application illustrates some of the economic barriers very graphically. A 1000-megawatt power plant of this design would require a collection area of about 10 square miles if located in the southwestern United States, where solar radiation is high. Estimates of the cost of such installations vary widely. For example, one estimate suggests that such capacity might be constructed for about $750 per kilowatt, which would result in costs of about $0.02 per kilowatt-hour for electric power at the bus bar.* Other estimates run as high as three to four times as much. No one will really be able to estimate such costs with any degree of accuracy before demonstration plants are built and operated for a period of time.

Another long-range potential contributor of electric power is the photovoltaic technique used in photographic light meters and solar cells in space. The cost challenge is illustrated by the solar cell array on the Skylab space station orbited in 1973 and occupied by teams of astronauts for periods ranging up to 84 days. The array was designed to produce 10 kilowatts and cost about $2 million per kilowatt to build. This is about 4000 times the cost of power generation capacity using coal-fired or nuclear plants on earth.

Of course, systems designed for use in space must meet much higher quality-control standards than would be necessary on earth, where equipment can be maintained periodically and repaired when necessary. It is estimated that present mass production techniques might produce silicon solar cell arrays at a cost of $10,000 per kilowatt and that this could be reduced to $2500 by developing an inexpensive process for producing cadmium sulfide cells. The goal of the photovoltaic program is to drive costs down ultimately to about $500 per kilowatt.

The longest-range application of solar energy involves making use of differences of 40°F or more between the temperatures at the tropical ocean surface and a half-mile

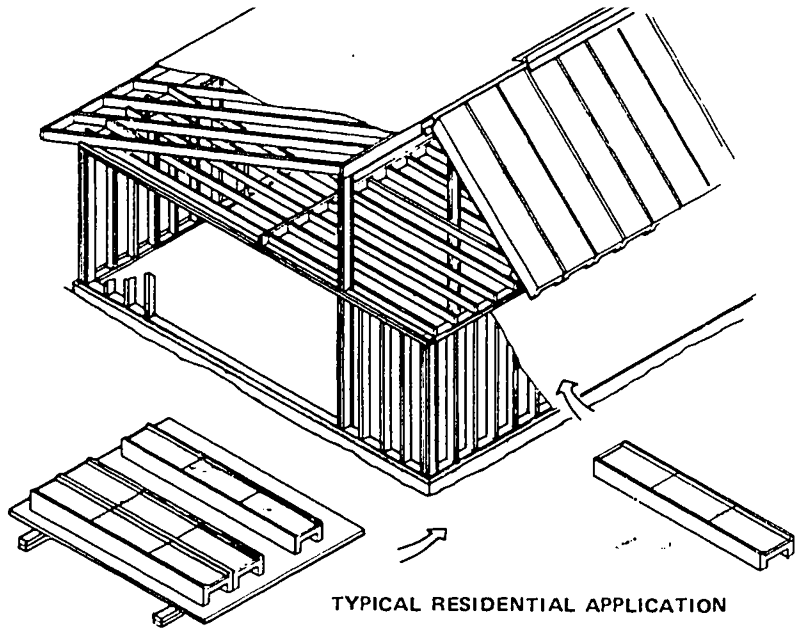
*A bus bar is one of the main bars or conductors carrying an electric current.



A prototype of compound parabolic concentrator at the ERDA's Argonne National Laboratory in Illinois is designed to intensify the sun's rays to achieve temperatures high enough for efficient direct electrical conversion from sunlight.

below. These differences can be used to drive turbines that operate through the boiling and condensation of liquids such as propane or ammonia. Research has progressed through the solution of some design problems. and engineering organizations have evaluated the feasibility of various concepts. Planning is based on the construction of demonstration plants by the mid-1980s and commercial implementation by the end of that decade.

In summary, the sun provides at least six techniques by which clean and abundant supplies of energy can be provided to meet *some* of our needs. The utilization of these opportunities will involve efforts to overcome technical and institutional as well as economic barriers over the next few decades.



The flat plate solar collector unit can be architecturally integrated into a building (cutaway view above). The unit is weathertight ard insulated. It is easily installed and maintained by building craftsmen.

Timonium Elementary School in Maryland is heated by a solar energy system. Glass panels on the roof trap the sun's warmth, which then heats piped water.

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ENERGY FOR THE LONG PULL

One curious aspect of the energy crisis is that the problems of the next several decades seem more acute than those we will face in the next century and beyond. This rests in part on the conviction that by 2000 we will have mastered the technology of extracting synthetic hydrocarbon fuels of all types from coal and also that we will have firmly in hand a breeder reactor technology that is both commercially acceptable and provides a short doubling time for the production of nuclear fuel. Our domestic recoverable coal reserve is sufficient to meet our requirements for several centuries, and an efficient breeder technology would make our uranium reserves sufficient for a thousand years or longer. While geothermal power and solar energy (and possibly oil extracted from shale) are expected to make important additional contributions to the total energy supply, most energy experts believe that coal and the breeder reactor must provide the major share of our needs for the next quarter century.

Of course, our civilization will eventually run out of coal and fissile nuclear materials if energy consumption continues at its present and projected rates. But there is a potent solution on the horizon for even this eventuality, and the growing confidence that it, too, can be mastered also contributes to the fairly optimistic view that we can meet our energy needs indefinitely, even after the exhaustion of all recoverable nuclear and fossil fuels.

This solution is the controlled thermonuclear reaction— nuclear fusion. Since it is the same process that produces the enormous energy release of the sun and stars and the hydrogen bomb, it is apparent that it has an enormous potential as a power source. This is because the supply of deuterium in the world's oceans is effectively infinite from the standpoint of man's energy needs.

In comparison with the nuclear fission process for generating power, fusion offers many other striking advantages. There is no possibility of a major nuclear accident. Transportation, handling, and storing of radioactive materials is minimal. The risk of radiation release is quite low. In case of sudden shutdown, there is only a minor problem in handling the heat load in a fusion reactor.

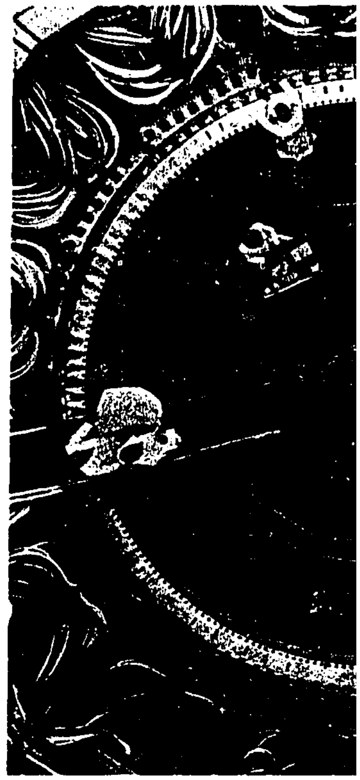
Because of these attractive qualities, it has been proposed that the U. S. forget about sophisticated new reactors like the fast breeder and concentrate instead on the fusion process. Unfortunately, however, the scientific feasibility of the fusion process has yet to be demonstrated, despite more than two decades of effort in this country, the Soviet Union, and elsewhere.

The theory of the fusion process is relatively straightforward: If a fully ionized plasma of deuterons and tritons* can be heated to a temperature of 100 million degrees, if it is sufficiently dense, and if it can be confined for a sufficient length of time, the collisions of the nuclei will fuse a sufficient number of these particles to release hundreds of times more energy than is required to operate the process.

Progress in achieving these conditions has been slow and beset with severe difficulties. Beginning in 1951, the U. S. launched an effort to achieve fusion by means of magnetic confinement of hot, dense deuterium-tritium plasmas. For almost 20 years, the research effort was plagued by plasma turbulence, instabilities, and oscillations that caused it to wriggle out of the magnetic confinement and extinguish itself when it touched the cold walls of the containment vessel. By the late 1960s, however, most of these problems had been solved, and the Soviet development of the powerful "tokamak" design led to renewed optimism.

Meantime, a second line of fusion effort began in 1969, which is based on the idea that immensely powerful laser beams might be used to vaporize and implode tiny pellets of deuterium and tritium and produce in less than a billionth of a second the pressures and temperatures of a miniscule thermonuclear explosion. The process would rely on simple inertial forces, rather than complex magnetic fields, to hold the plasma together long enough for fusion reactions to take place. Repeated several times a second in a reactor vessel of

*A triton is the nucleus of a tritium (^3H) atom.



Part of ERDA's fusion research
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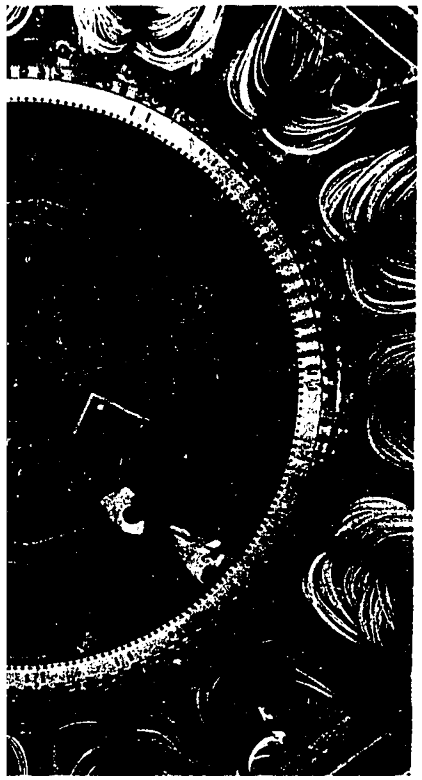

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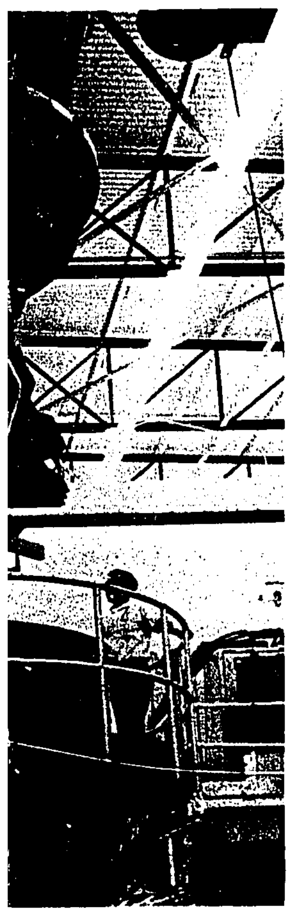

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A future energy economy based on thermonuclear fusion could be self-sufficient indefinitely. Even if all conventional fuels were depleted, the availability of electric power at relatively fixed cost would allow the manufacture of hydrogen by electrolysis or a variety of other techniques. It should also make possible the synthesis of hydrocarbon fuels drawing upon the great carbonate beds on the sea floor or even the carbon dioxide in the atmosphere.

It has been conjectured that hydrogen might replace the natural gas in our present energy mix and that in liquid form at $-423°F$ it might even serve as a fuel for aircraft, trucks, and automobiles. Hydrogen does pose some problems, however, it contains by volume only about one-third the heating value of methane (1031 BTU per cubic foot); so we would have to handle much larger quantities of it to do the same job as methane. Fortunately, the viscosity of hydrogen is only about one-third that of methane, so we might be able to pump about three times as much hydrogen gas through our 225,000-mile natural gas transmission network. With modifications in the burners of stoves, furnaces, and water heaters, we could use it for the same tasks that natural gas presently performs.

Hydrogen might be rather awkward to use as a transportation fuel. While its combustion in air is much cleaner than gasoline and it is capable of about 50% greater thermal efficiency than gasoline, its density is so low that quite large volumes would be required, even if it were cooled to a liquid state. For example, about 60 gallons of hydrogen would be required to equal the energy content of a 17-gallon automobile gasoline tank. Furthermore, this "tank" would really be a large, super-insulated thermos bottle called a "dewar" to prevent the cryogenic hydrogen from boiling away. Under these circumstances, many believe that fuels like methanol or even synthetic gasoline will be the preferred fuels for transportation except where electric cars come into vogue. Hydrogen storage might prove feasible, however, for larger vehicles, such as buses or trucks.

While a fusion energy economy might encounter no insurmountable barriers in replacing with synthetics all the conventional hydrocarbon fuels we burn today, we should not regard fusion as some kind of Aladdin's Lamp, which could solve our energy problems in a single stroke. Fusion reactors will be costly and at least as difficult to construct as large fission reactors. To manufacture hydrogen with the same total energy content as the natural gas we presently consume would require 1 million megawatts of additional electric power. This figure is 2.5 times greater than the Nation's total installed electrical generating capacity in 1972, and almost 10 times the new generating capacity that the Nation added to the power grid over the last 5 years. In shifting to a fusion energy base, we would thus face the same great challenges in raising capital and in carrying out large-scale construction that we now perceive in our midterm outlook for energy.

CONCLUSION

Whatever the Nation's final response to its energy problems, it is clear that there are no easy answers. (As one veteran engineer has remarked of energy, "Some SOB has run off with all the easy problems.") The sad reality is that all energy problems are extremely complex, and all feasible solutions must be equally complex and difficult. Moreover, all the solutions are flawed in one way or another—economic and environmental cost, technological complexity, political acceptability, and the like.

Yet, as a nation, we will have to select a mixture of these difficult options if we are to cope intelligently with our energy future. The decisions we make on energy are really decisions on the style of our future lives, the stature we expect of this Nation in foreign affairs, our prospects for economic stability and growth, and our commitment to equal opportunity for all. So the energy debate, complex and difficult as it is, requires our participation as citizens because its resolution will so fundamentally affect our individual and national future.

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A word about ERDA . . . .

The mission of the U. S. Energy Research & Development Administration (ERDA) is to develop all energy sources, to make the Nation basically self-sufficient in energy, and to protect public health and welfare and the environment. ERDA programs are divided into six major categories:

- CONSERVATION OF ENERGY—More efficient use of existing energy sources, development of alternate fuels and engines for automobiles to reduce dependence on petroleum, and elimination of wasteful habits of energy consumption.
- FOSSIL ENERGY—Expansion of coal production and the development of technologies for converting coal to synthetic gas and liquid fuels, improvement of oil drilling methods and of techniques for converting shale deposits to usable oil.
- SOLAR, GEOTHERMAL, AND ADVANCED ENERGY SYSTEMS—Research on solar energy to heat, cool, and eventually electrify buildings, on conversion of underground heat sources to gas and electricity, and on fusion reactors for the generation of electricity.
- ENVIRONMENT AND SAFETY—Investigation of health, safety, and environmental effects of the development of energy technologies, and research on management of wastes from energy production.
- NUCLEAR ENERGY—Expanding medical, industrial and research applications and upgrading reactor technologies for the generation of electricity, particularly using the breeder concept.
- NATIONAL SECURITY—Production and administration of nuclear materials serving both civilian and military needs.

ERDA programs are carried out by contract and cooperation with industry, university communities, and other government agencies. For more information, write to USERDA–Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

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