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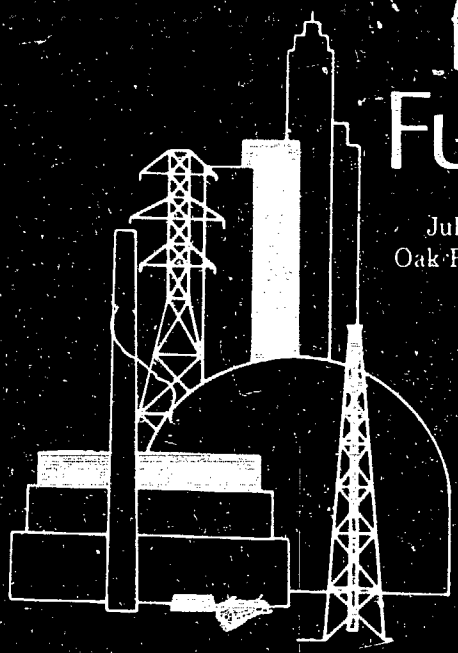
Energy Sources for the Future



July 7-25, 1975
Oak Ridge, Tennessee

Oak Ridge Associated Universities
U.S. Energy Research and Development Administration,
Division of Biomedical and Environmental Research

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Symposium on

ENERGY SOURCES FOR THE FUTURE

July 7-25, 1975
Oak Ridge, Tennessee

Edited by
Jerome L. Duggan
North Texas State University
and
Roger J. Cloutier
Oak Ridge Associated Universities

Symposium Conducted by Special Training Division of Oak Ridge Associated Universities/Sponsored by U.S. Energy Research and Development Administration, Division of Biomedical and Environmental Research

PREFACE

For several summers the Special Training Division of Oak Ridge Associated Universities has conducted a three-week program on *Energy Sources for the Future*. Sponsored by the U.S. Energy Research and Development Administration, the program is designed for college professors teaching or planning to teach energy courses. Participants have represented most branches of science.

The invited lecturers have also represented most scientific disciplines. Although expert in specific fields, the speakers have endeavored to present their topics in a manner comprehensible to scientists and educators unacquainted with the speaker's disciplines. In doing this, the speakers distributed numerous handouts, graphs, charts, etc., that have already found their way into many lectures.

Since the first summer energy program, participants have encouraged the course coordinators to compile the material for wider distribution. Although this volume represents only about half of the material presented during the July 1975 symposium, it will provide the reader with useful facts and respected opinions about this nation's energy status.

We hope that these proceedings will enable teachers everywhere to give their students a better understanding of our energy problems and possible solutions.

Jerome L. Duggan
North Texas State University

Roger J. Cloutier
Oak Ridge Associated Universities

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Survey of World Energy Resources

by

M. King Hubbert

United States Geological Survey, Washington, D. C.

ABSTRACT

The present large-scale use of energy and power by the human species represents a unique event in the billions of years of geologic history. Furthermore, in magnitude, most of the development has occurred during the present century. In the United States, the peak in the rate of petroleum production occurred in 1970 and that for natural gas is imminent. The peak in the world production of crude oil is expected to occur at about the year 2000 and that for coal production at about 2150 or 2200. For other sources of energy and power, water power, geothermal power and tidal power are inadequate to replace power from fossil fuels. Nuclear power, based on the breeder reactor and utilizing low-grade deposits of uranium and thorium, has a larger potential than the fossil fuels, but it also constitutes a large perpetual hazard. The largest source of energy available to the earth is solar radiation. This source has a life-expectancy of a geologic time scale, is nonpolluting and is larger in magnitude than any likely requirements by the human species.

In consequence of the large supplies of available energy, the period since 1800 has been one of an unprecedented exponential industrial growth. This also has been accompanied by a world-wide ecological disturbance, including that of the human population. It can easily be seen that such a period of growth must be ephemeral in character and, in fact, is now almost over. One aspect of this transition from a state of exponential growth to a state of nongrowth is the present alarm over an "energy crisis." Actually, the world's present problems are by no means unmanageable in terms of present biological and technological knowledge. The real crisis confronting us is, therefore, not an energy crisis but a cultural crisis. During the last two centuries, we have evolved what amounts to an exponential-growth culture, with institutions based on the premise of an indefinite continuation of exponential growth. One of the principal consequences of the cessation of exponential growth will be an inevitable revision of some of the tenets of that culture.

INTRODUCTION

By now, it has become generally recognized that the world's present civilization differs fundamentally from all earlier civilizations in both the magnitude of its operations and the degree of its dependence on energy and mineral resources--particularly energy from the fossil fuels. The significance of energy lies in the fact that it is involved in everything that occurs on the earth--everything that moves. In fact, in the last analysis, about as succinct a statement as can be made about terrestrial events is the following: The earth's

surface is composed of the 92 naturally occurring chemical elements, all but a minute radioactive fraction of which obey the laws of conservation and of non-transmutability of classical chemistry. Into and out of this system is a continuous flux of energy, in consequence of which the material constituents undergo either continuous or intermittent circulation.

The principal energy inputs into this system are three (Fig. 1): (1) $174{,}000 \times 10^{12}$ thermal watts from the solar radiation intercepted by the earth's diametrical plane; (2) 32×10^{12} thermal watts conducted and convected to the earth's surface from inside the earth; and (3) 3×10^{12} thermal watts of tidal power from the combined kinetic and potential energy of the earth-moon-sun system. Of these inputs of thermal power, that from solar energy is overwhelmingly the largest, exceeding the sum of the other two by a factor of more than 5,000.

Of the solar input, about 30%, the earth's albedo, is directly reflected and scattered into outer space, leaving the earth as short-wavelength radiation; about 47% is directly absorbed and converted into heat; and about 23% is dissipated in circulating through the atmosphere and the oceans, and in the evaporation, precipitation and circulation of water in the hydrologic cycle. Finally, a minute fraction, about 40×10^{12} watts, is absorbed by the leaves of plants and stored chemically by the process of photosynthesis whereby the inorganic substances, water and carbon dioxide, are synthesized into organic carbohydrates according to the approximate equation

$$\text{Light energy} + CO_2 + H_2O \rightarrow |CH_2O| + O_2.$$

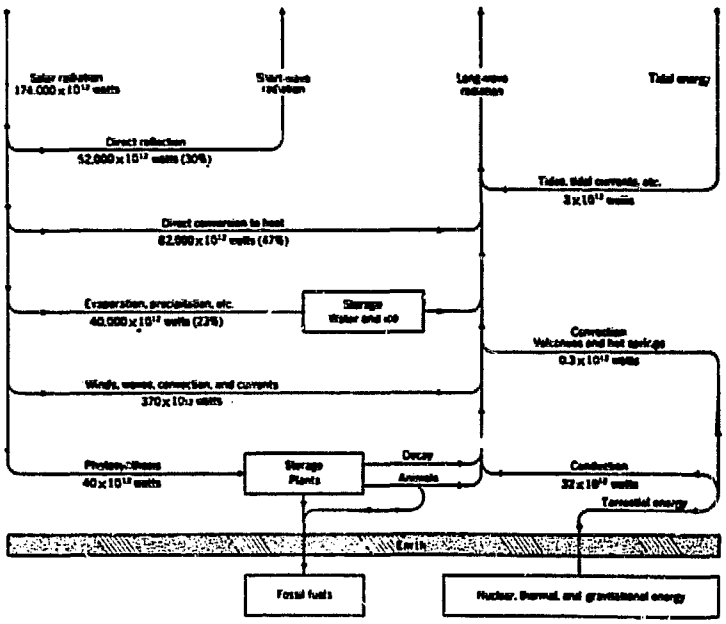


FIGURE 1 - World energy flowsheet.

All figures are used courtesy of The Canadian Mining and Metallurgical Bulletin, July, 1973.

Small though it is, this fraction is the energy source for the biological requirements of the earth's entire populations of plants and animals.

From radioactive dating of meteorites, the astronomical cataclysm that produced the solar system is estimated to have occurred about 4.5 billion years ago and microbial organisms have been found in rocks as old as 3.2 billion years. During the last 600 million years of geologic history, a minute fraction of the earth's organisms have been deposited in swamps and other oxygen-deficient environments under conditions of incomplete decay, and eventually buried under great thicknesses of sedimentary muds and sands. By subsequent transformations, these have become the earth's present supply of fossil fuels: coal, oil and associated products.

About 2 million years ago, according to recent discoveries, the ancestors of modern man had begun to walk upright and to use primitive tools. From that time to the present, this species has distinguished itself by its inventiveness in the progressive control of an ever-larger fraction of the available energy supply. First, by means of tools and weapons, the invention of clothing, the control of fire, the domestication of plants and animals and use of animal power, this control was principally ecological in character. Next followed the manipulation of the inorganic world, including the smelting of metals and the primitive uses of the power of wind and water.

Such a state of development was sufficient for the requirements of all premodern civilizations. A higher-level industrialized civilization did not become possible until a larger and more concentrated source of energy and power became available. This occurred when the huge supply of energy stored in the fossil fuels was first tapped by the mining of coal, which began as a continuous enterprise about 9 centuries ago near Newcastle in northeast England. Exploitation of the second major fossil-fuel supply, petroleum, began in 1857 in Romania and 2 years later in the United States. The tapping of an even larger supply of stored energy, that of the atomic nucleus, was first achieved in a controlled manner in 1942, and now the production of nuclear power from plants in the 1,000-megawatt range of capacity is in its early stages of development.

In addition to increased energy sources, energy utilization was markedly enhanced by two technological developments near the end of the last century: the development of the internal-combustion engine, utilizing petroleum products for mobile power, and the development of electrical means for the generation and distribution of power from large-scale central power plants. This also made possible for the first time the large-scale use of water power. This source of power derived from the contemporary flux of solar energy has been in use to some degree since Roman times, but always in small units--units rarely larger than a few hundred kilowatts. With electrical generation and distribution of hydropower, first accomplished at Niagara Falls about 1895, progressively larger hydropower stations have been installed with capacities up to several thousand megawatts.

ENERGY FROM FOSSIL FUELS

To the present the principal sources of energy for industrial uses have been the fossil fuels. Let us therefore review the basic facts concerning the exploitation and utilization of these fuels. This can best be done by means of a graphical presentation of the statistics of annual production.

World Production of Coal and Oil

Figure 2 shows the annual world production of coal and lignite from 1860 to 1970, and the approximate rate back to 1800, on an arithmetic scale. Figure 3 shows the same data on a semilogarithmic scale. The significance of the latter presentation is that straight-line segments of the growth curve indicate periods of steady exponential growth in the rate of production.

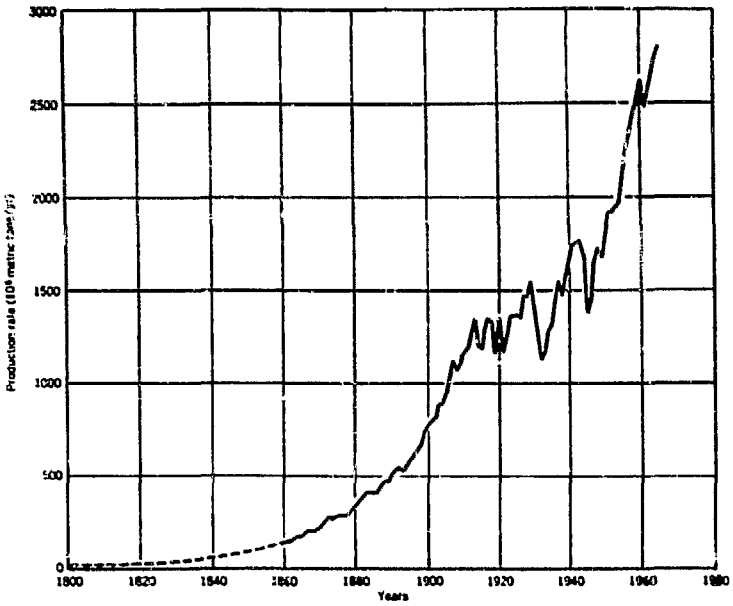


FIGURE 2 - World production of coal and lignite (Hubbert, 1969, Fig. 8.1).

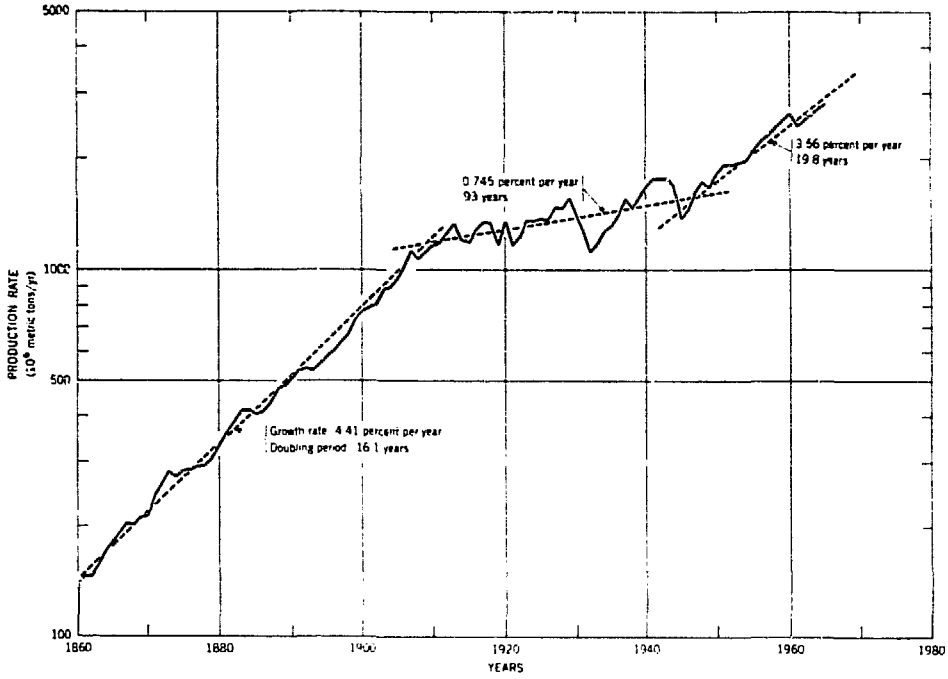


FIGURE 3 - World production of coal and lignite (semilogarithmic scale) (Hubbert, 1971, Fig. 4).

Annual statistics of coal production earlier than 1860 are difficult to assemble, but from intermittent earlier records it can be estimated that from the beginning of coal mining about the 12th century A.D. until 1800, the average growth rate of production must have been about 2% per year, with an average doubling period of about 35 years. During the 8 centuries to 1860 it is estimated that cumulative production amounted to about 7×10^9 metric tons. By 1970, cumulative production reached $140 \cdot 10^9$ metric tons. Hence, the coal mined during the 110-year period from 1860 to 1970 was approximately 19 times that of the preceding 8 centuries. The coal produced during the last [illegible] period from 1940 to 1970 was approximately equal to that produced during all preceding history.

The rate of growth of coal production can be more clearly seen from the semilogarithmic plotting of Figure 3. The straight-line segment of the production curve from 1860 to World War I indicates a steady exponential increase of the rate of production during this period at about 4.4% per year, with a doubling period of 16 years. Between the beginning of World War I and the end of World War II, the growth rate slowed down to about 0.75% per year and a doubling period of 93 years. Finally, after World War II a more rapid growth rate of 3.56% per year and a doubling period of 19.8 years was resumed.

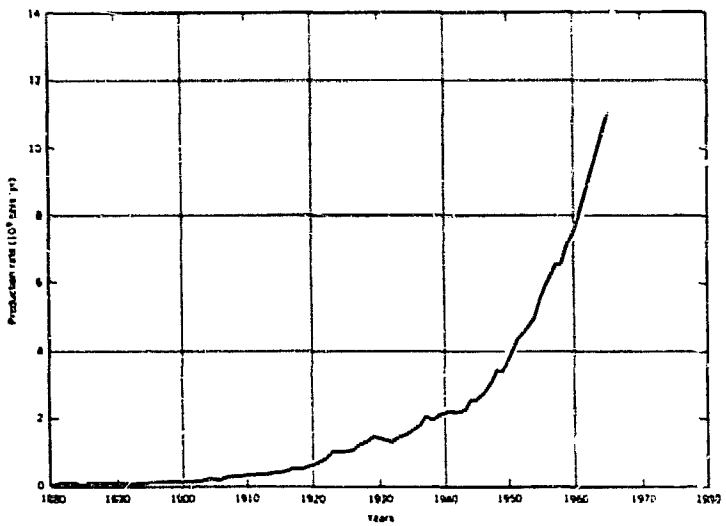


FIGURE 4 - World production of crude oil (Hubbert, 1969, Fig. 8.2).

Figure 4 shows, on an arithmetic scale, the annual world crude-oil production from 1880 to 1970. Figure 5 shows the same data plotted semilogarithmically. After a slightly higher initial growth rate, world petroleum production from 1890 to 1970 has had a steady exponential increase at an average rate of 6.94% and a doubling period of 10.0 years. Cumulative world production of crude oil to 1970 amounted to 233×10^9 barrels. Of this, the first half required the 103-year period from 1857 to 1960 to produce. the second half only the 10-year period from 1960 to 1970.

When coal is measured in metric tons and oil in U. S. 42-gallon barrels, a direct comparison between coal and oil cannot be made. Such a comparison can be made, however, by means of the energy contents of the two fuels as determined by their respective heats of combustion. This is shown in Figure 6, where the energy produced per year is expressed in power units of 10^{12} thermal watts. From this it is seen that until after 1900 the energy contributed by crude oil

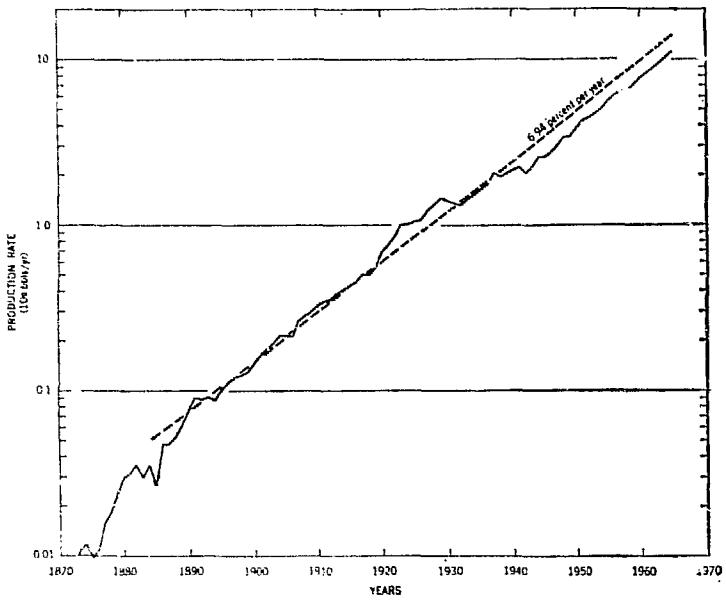


FIGURE 5 - World production of crude oil (semilogarithmic scale) (Hubbert, 1971, Fig. 6).

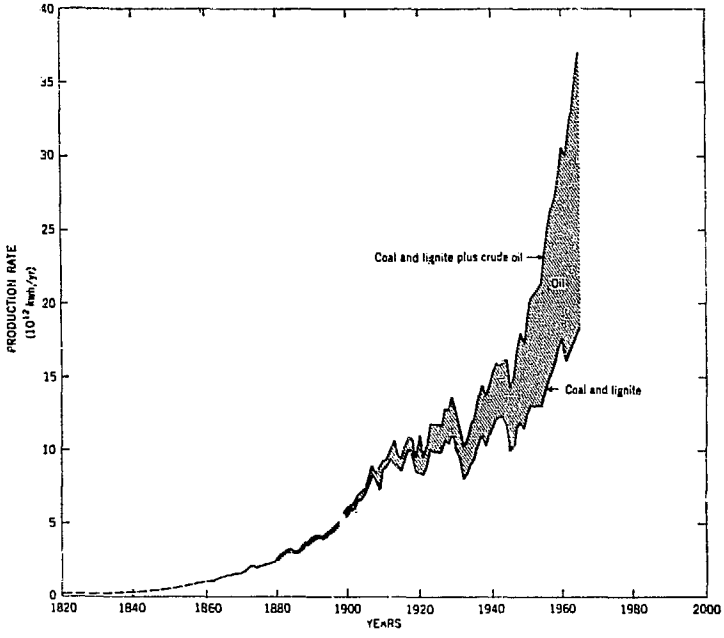


FIGURE 6 - World production of thermal energy from coal and lignite plus crude oil (Hubbert, 1969, Fig. 8.3).

was barely significant as compared with that of coal. By 1970, however, the energy from crude oil had increased to 50% of that from coal and oil combined.

Were natural gas and natural-gas liquids also to be included, the energy from petroleum fluids would represent about two-thirds of the total.

U. S. Production of Fossil Fuels

The corresponding growths in the production of coal, crude oil and natural gas in the United States are shown graphically in Figures 7 to 9. From before 1860 to 1907 annual U. S. coal production increased at a steady exponential rate

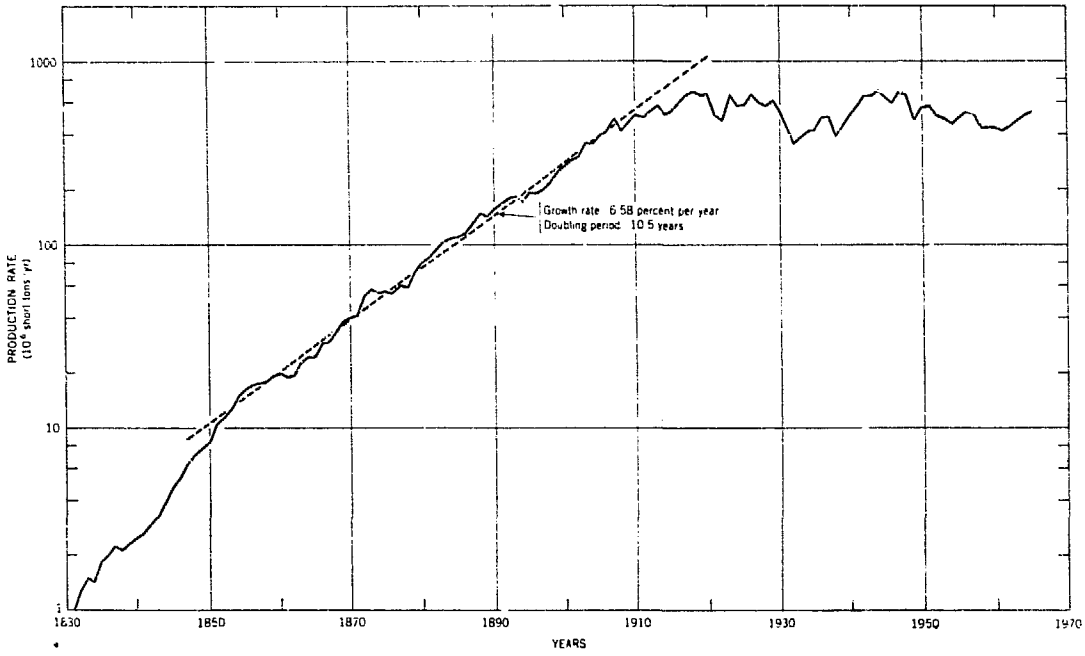


FIGURE 7 - U. S. production of coal (semilogarithmic scale).

of 6.58% per year, with a doubling period of 10.5 years. After 1907, due largely to the increase in oil and natural-gas production, coal production fluctuated about a production rate of approximately 500×10^6 metric tons per year. After an initial higher rate, U. S. crude-oil production increased steadily from 1870 to 1929 at about 8.27% per year, with a doubling period of 8.4 years. After 1929, the growth rate steadily declined to a 1970 value of approximately zero. From 1905 to 1970 the U. S. production of natural gas increased at an exponential rate of 6.6% per year, with a doubling period of 10.5 years.

Finally, Figure 10 shows the annual production of energy in the United States from coal, oil, natural gas, and hydro- and nuclear power from 1850 to 1970. From 1850 to 1907, this increased at a steady growth rate of 6.9% per year and doubled every 10.0 years. At about 1907, the growth rate dropped abruptly to an average value from 1907 to 1960 of about 1.77% per year, with a doubling period of 39 years. Since 1960, the growth rate has increased to about 4.25% per year, with the doubling period reduced to 16.3 years.

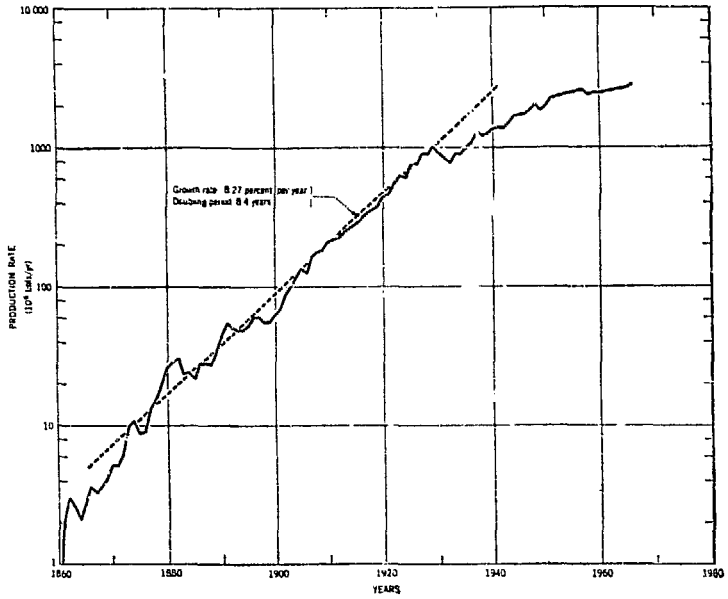


FIGURE 8 - U. S. production of crude oil, exclusive of Alaska (semilogarithmic scale).

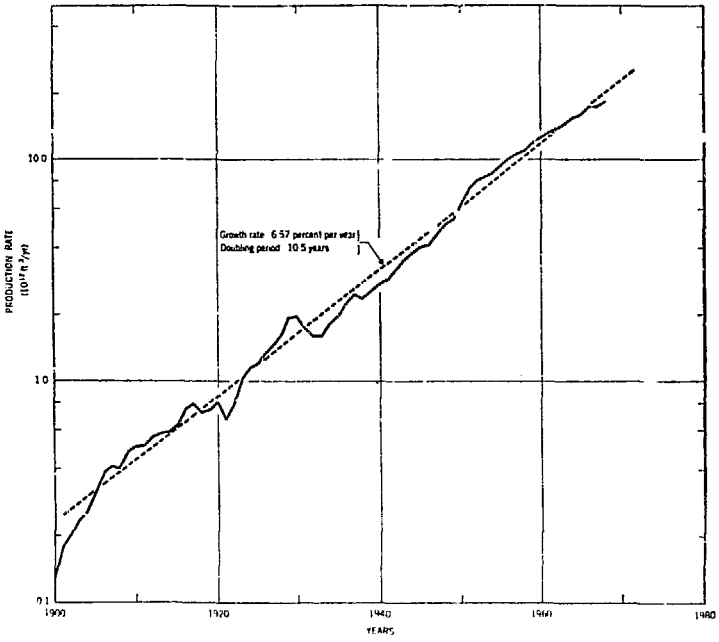


FIGURE 9 - U. S. net production of natural gas (semilogarithmic scale).

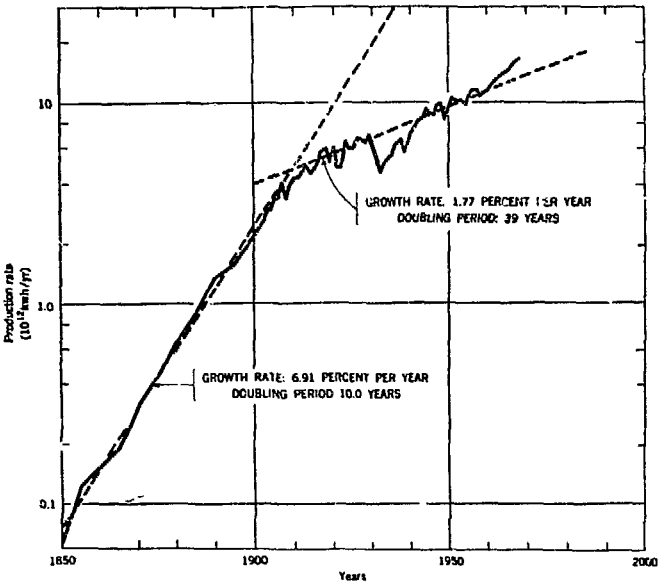


FIGURE 10 - U. S. production of thermal energy from coal, oil, natural gas, water power and nuclear power (semilogarithmic scale).

DEGREE OF ADVANCEMENT OF FOSSIL-FUEL EXPLOITATION

The foregoing are the basic historical facts pertaining to the exploitation of the fossil fuels in the world and in the United States. In the light of these facts we can hardly fail to wonder: How long can this continue? Several different approaches to this problem will now be considered.

Method of Donald Foster Hewett

In 1929, geologist Donald Foster Hewett delivered before the AIME one of the more important papers ever written by a member of the U. S. Geological Survey, entitled "Cycles in Metal Production." In 1926, Hewett had made a trip to Europe during which he visited 28 mining districts, of which about half were then or had been outstanding sources of several metals. These districts ranged from England to Greece and from Spain to Poland. Regarding the purpose of this study, Hewett stated:

> I have come to believe that many of the problems that harass Europe lie in our path not far ahead. I have therefore hoped that a review of metal production in Europe in the light of its geologic, economic and political background may serve to clear our vision with regard to our own metal production.

In this paper, extensive graphs were presented of the production of separate metals from these various districts showing the rise, and in many cases the decline, in the production rates as the districts approached exhaustion of their ores. After having made this review, Hewett generalized his findings by observing that mining districts evolve during their history through successive stages analogous to those of infancy, adolescence, maturity and old age. He sought criteria for judging how far along in such a sequence a given mining district or region had progressed, and from his study he suggested the successive culminations shown in Figure 11. These culminations were: (1) the quantity of

exports of crude ore; (2) the number of mines in operation; (3) the number of smelters or refining units in operation; (4) the production of metal from domestic ore; and (5) the quantity of imports of crude ore.

Although not all of Hewett's criteria are applicable to the production of the fossil fuels, especially when world production is considered, the fundamental principle is applicable; namely, that like the metals, the exploitation of the fossil fuels in any given area must begin at zero, undergo a period of more or less continuous increase, reach a culmination and then decline, eventually to a zero rate of production. This principle is illustrated in Figure 12, in

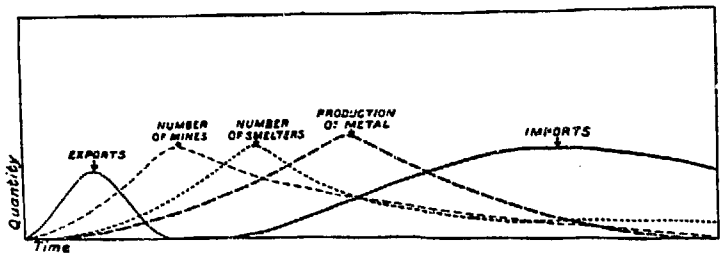


FIGURE 11 - Fig. 7 from D. F. Hewett's paper, "Cycles in Metal Production" (1929).

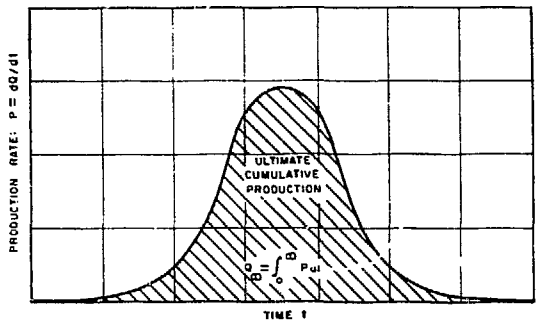


FIGURE 12 - Mathematical relations involved in the complete cycle of production of any exhaustible resource (Hubbert, 1956, Fig. 11).

which the complete cycle of the production rate of any exhaustible resource is plotted arithmetically as a function of time. The shape of the curve is arbitrary within wide limits, but it still must have the foregoing general characteristics.

An important mathematical property of such a curve may be seen if we consider a vertical column of base Δt extending from the time axis to the curve itself. The altitude of such a column will be the production rate

$$P = \Delta Q/\Delta t$$

at the given time, where ΔQ is the quantity produced in time Δt. The area of the column will accordingly be given by the product of its base and altitude:

$$P \times \Delta t = (\Delta Q/\Delta t) \times \Delta t = \Delta Q.$$

Hence, the area of the column is a measure of the quantity produced during the time interval Δt, and the total area from the beginning of production up to any given time t will be a measure of the cumulative production up to that time. Clearly, as the time t increases without limit, the production rate will have gone through its complete cycle and returned to zero. The area under the curve after this has occurred will then represent the ultimate cumulative production, Q^{∞}. In view of this fact, if from geological or other data the producible magnitude of the resource initially present can be estimated, then any curve drawn to represent the complete cycle of production must be consistent with that estimate. No such curve can subtend an area greater than the estimated magnitude of the producible resource.

Utilization of this principle affords a powerful means of estimating the time scale for the complete production cycle of any exhaustible resource in any given region. As in the case of animals where the time required for the complete life cycle of, say, a mouse is different from that of an elephant, so in the case of minerals, the time required for the life cycle of petroleum may differ from that of coal. This principle also permits a reasonably accurate estimate of the most important date in the production cycle of any exhaustible resource, that of its culmination. This date is especially significant because it marks the dividing point in time between the initial period during which the production rate almost continuously increases and the subsequent period during which it almost continuously declines. It need hardly be added that there is a significant difference between operating an industry whose output increases at a rate of 5 to 10% per year and one whose output declines at such a rate.

Complete Cycle of Coal Production

Because coal deposits occur in stratified seams which are continuous over extensive areas and often crop out on the earth's surface, reasonably good estimates of the coal deposits in various sedimentary basins can be made by surface geological mapping and a limited amount of drilling. A summary of the current estimates of the world's initial coal resources has been published by Paul Averitt (1969) of the U. S. Geological Survey. These estimates comprise the total amount of coal (including lignite) in beds 14 inches (35 cm) or more thick and at depths as great as 3,000 feet (900 m), and in a few cases as great as 6,000 feet. Averitt's estimates as of January 1, 1967, for the initial producible coal, allowing 50% loss in mining, are shown graphically in Figure 13 for the world's major geographical areas. As seen in this figure, the original

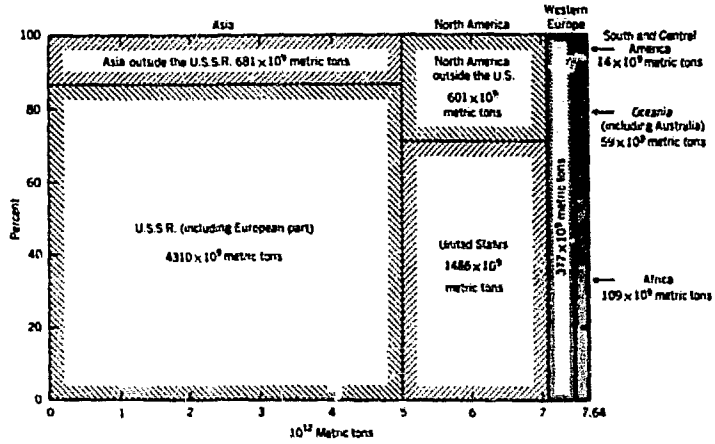


FIGURE 13 - Averitt (1969) estimate of original world recoverable coal resources (Hubbert, 1969, Fig. 8.24).

recoverable world coal resources amounted to an estimated 7.64×10^{12} metric tons. Of this, 4.31×10^{12}, or 56%, were in the USSR, and 1.49×10^{12}, or 19%, in the USA. At the other extreme, the three continental areas, Africa, South and Central America, and Oceania, together contained only 0.182×10^{12} metric tons, or 2.4%, of the world's total.

Figure 14 shows two separate graphs for the complete cycle of world coal production. One is based on the Averitt estimate for the ultimate production of 7.6×10^{12} metric tons. These curves are also based on the assumption that

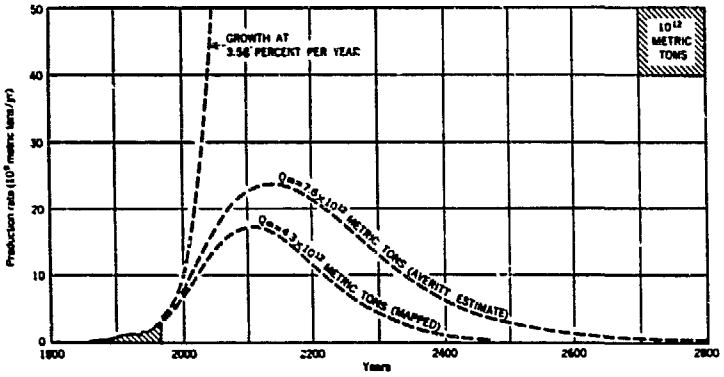


FIGURE 14 - Complete cycle of world coal production for two values of Q^{∞} (Hubbert, 1969, Fig. 8.25).

not more than three more doublings, or an 8-fold increase, will occur before the maximum rate of production is reached. The dashed curve extending to the top of the drawing indicates what the production rate would be were it to continue to increase at 3.56% per year, the rate that has prevailed since World War II. For either of the complete-cycle curves, if we disregard the first and last 10-percentiles of the cumulative production, it is evident that the middle 80% of Q^{∞} will probably be consumed during the three-century period from about the year 2000 to 2300.

Figure 15 shows the complete cycle of U. S. coal production for the two values for Q^{∞}, 1486×10^{9} and 740×10^{9} metric tons. Here too the time required to consume the middle 80% would be the 3 or 4 centuries following the year 2000.

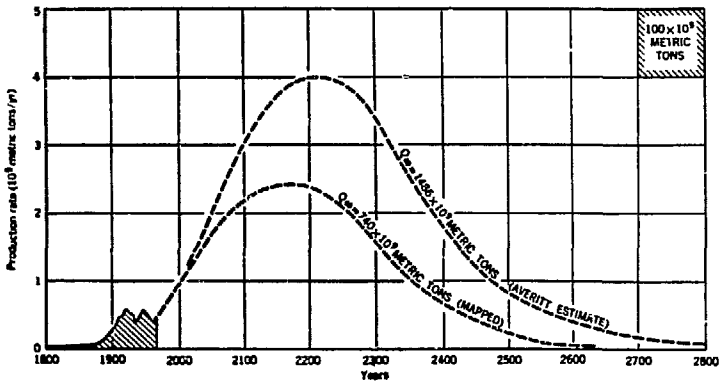


FIGURE 15 - Complete cycle of U. S. coal production for two values of Q^{∞} (Hubbert, 1969, Fig. 8.26).

A serious modification of the above coal-resource figures has been given by Averitt (cited in Theobald, Schweinfurth and Duncan, 1972). Here, Averitt, in February 1972, has given an estimate of the amount of coal remaining in the United States that is recoverable under present economic and technological conditions. This comprises coal in seams with a minimum thickness of 28 inches and a maximum depth of 1000 feet. The amount of coal in this category is estimated to be 390×10^9 short tons or 354×10^9 metric tons. Adding the 37×10^9 metric tons of coal already produced gives 391×10^9 metric tons of original coal in this category. This amounts to only 26% of the 1486×10^9 metric tons assumed previously. Of this, 9.5% has already been produced. If we apply the same ratio of 26% to the previous world figure of 7.6×10^{12} metric tons, that is reduced to 2.0×10^{12} metric tons. Of this, 0.145×10^{12} metric tons, or 7.2%, has already been produced.

Revisions of Figures 14 and 15 incorporating these lower estimates of recoverable coal have not yet been made, but in each instance the curve for the reduced figure will encompass an area of only about one-quarter that of the uppermost curve shown, and the probable time span for the middle 80% of cumulative production will be cut approximately in half.

Estimates of Petroleum Resources

Because oil and gas occur in limited volumes of space underground in porous sedimentary rocks and at depths ranging from a few hundred feet to 5 or more miles, the estimation of the ultimate quantities of these fluids that will be obtained from any given area is much more difficult and hazardous than for coal. For the estimation of petroleum, essentially two methods are available: (1) estimation by geological analogy; and (2) estimation based on cumulative information and evidence resulting from exploration and productive activities in the region of interest.

The method of estimating by geological analogy is essentially the following. A virgin undrilled territory, Area B, is found by surface reconnaissance and mapping to be geologically similar to Area A, which is already productive of oil and gas. It is inferred, therefore, that Area B will eventually produce comparable quantities of oil and gas per unit of area or unit of volume of sediments to those of Area A.

Although this is practically the only method available initially for estimating the oil and gas potential of an undrilled region, it is also intrinsically hazardous, with a very wide range of uncertainty. This is illustrated in Table 1, in which the estimates made in 1953 for the future oil discoveries on the continental shelf off the Texas and Louisiana coasts are compared with the results of subsequent drilling.

TABLE 1 — Petroleum Estimates by Geological Analogy: Louisiana and Texas Continental Shelves
(crude oil, 10^9 bbls)

	U.S. Geological Survey estimates, 1953	Cumulative discoveries to 1971
Louisiana	4	ca. 5
Texas	9	Negligible

In 1953, the U. S. Geological Survey, on the basis of geological analogy between the onshore and offshore areas of the Gulf Coast and the respective areas of the continental shelf bordering Texas and Louisiana, estimated future discoveries of 9 billion barrels of oil on the Texas continental shelf and 4 billion on that of Louisiana. After approximately 20 years of petroleum exploration and drilling, discoveries of crude oil on the Louisiana continental shelf have amounted to approximately 5 billion barrels; those on the continental shelf off Texas have been negligible.

The second technique of petroleum estimation involves the use of various aspects of the Hewett criterion that the complete history of petroleum exploration and production in any given area must go through stages from infancy to maturity to old age. Maturity is plainly the stage of production culmination, and old age is that of an advanced state of discovery and production decline.

In March 1956, this technique was explicitly applied to crude-oil production in the United States by the present author (Hubbert, 1956) in an invited address, "Nuclear Energy and the Fossil Fuels," given before an audience of petroleum engineers at a meeting of the Southwest Section of the American Petroleum Institute at San Antonio, Texas. At that time the petroleum industry in the United States had been in vigorous operation for 97 years, during which 52.4 billion barrels of crude oil had been produced. A review of published literature in conjunction with inquiries among experienced petroleum geologists and engineers indicated a consensus that the ultimate amount of crude to be produced from the conterminous 48 states and adjacent continental shelves would probably be within the range of 150 to 200 billion barrels. Using these two limiting figures, the curves for the complete cycle of U. S. crude-oil production shown in Figure 16 (Hubbert, 1956) were constructed. This showed that if the ultimate cumulative production, Q^{∞}, should be as small as 150×10^9 bbls, the peak in the rate of production would probably occur about 1966--about 10 years hence. Should another 50×10^9 bbls be added, making $Q^{\infty} = 200 \times 10^9$ bbls, the date of the peak of production would be postponed by only about 5 years. It was accordingly predicted on the basis of available information that the peak in U. S. crude-oil production would occur within 10-15 years after March 1956.

This prediction proved to be both surprising and disturbing to the U. S. petroleum industry. The only way it could be avoided, however, was to enlarge the area under the curve of the complete cycle of production by increasing the magnitude of Q^{∞}. As small increases of Q^{∞} have only small effects in retarding the date of peak production, if this unpleasant conclusion were to be avoided, it would be necessary to increase Q^{∞} by large magnitudes. This was what happened. Within the next 5 years, with insignificant amounts of new data, the published values for Q^{∞} were rapidly escalated to successively higher values--204, 250, 372, 400 and eventually 590 billion barrels.

In view of the fact that values for Q^{∞} used in Figure 16 involved semi-subjective judgments, no adequate rational basis existed for showing conclusively that a figure of 200×10^9 bbls was a much more reliable estimate than one twice

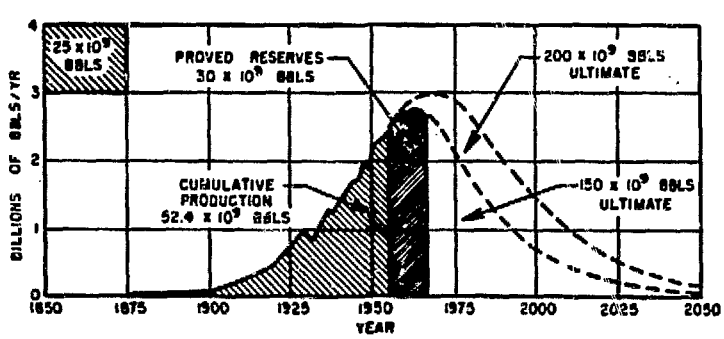


FIGURE 16 - 1956 prediction of the date of peak in the rate of U. S. crude-oil production (Hubbert, 1956, Fig. 21).

that large. This led to the search for other criteria derivable from objective, publicly available data of the petroleum industry. The data satisfying this requirement were the statistics of annual production available since 1860, and the annual estimates of proved reserves of the Proved Reserves Committee of the American Petroleum Institute, begun in 1937. From these data cumulative production from 1860 could be computed, and also cumulative proved discoveries defined as the sum of cumulative production and proved reserves after 1937.

This type of analysis was used in the report, Energy Resources (Hubbert, 1962), of the National Academy of Sciences Committee on Natural Resources. The principal results of this study are shown in Figures 17 and 18, in which it was found that the rate of proved discoveries of crude oil had already passed its peak about 1957, proved reserves were estimated to be at their peak in 1962 and the peak in the rate of crude-oil production was predicted to occur at about the end of the 1960 decade. The ultimate amount of crude oil to be produced from the lower 48 states and adjacent continental shelves was estimated to be about 170 to 175 billion barrels.

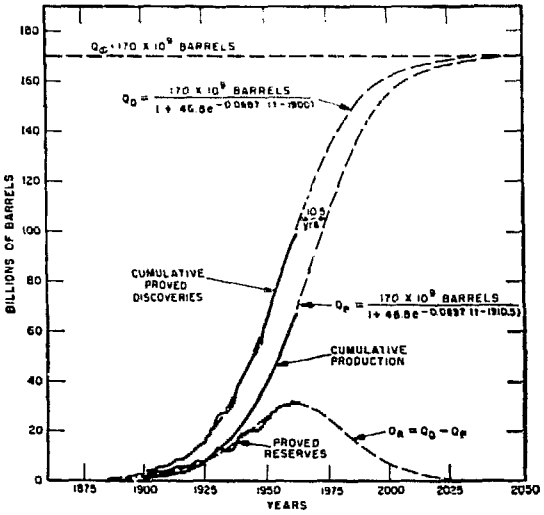
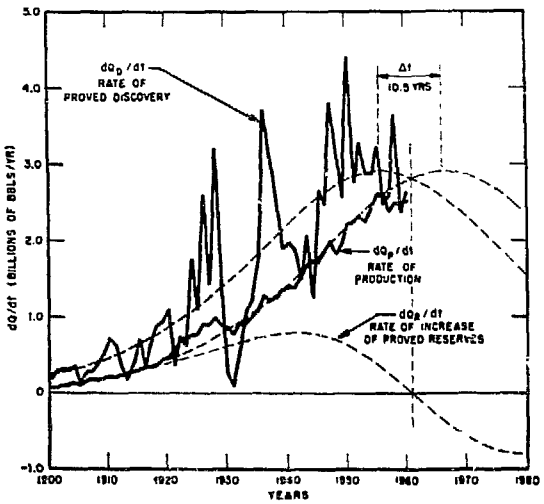


FIGURE 17 - Curves of cumulative proved discoveries, cumulative production and proved reserves of U. S. crude oil as of 1962 (Hubbert, 1962, Fig. 27).

FIGURE 18 - Curves showing the rates of proved discovery and of production, and rate of increase of proved reserves of U. S. crude oil as of 1961. Note prediction of peak of production rate near the end of 1960 decade (Hubbert, 1962, Fig. 28).



The corresponding estimates for natural gas are shown in Figures 19 and 20 (Hubbert, 1962). From these figures it will be seen that the rate of proved

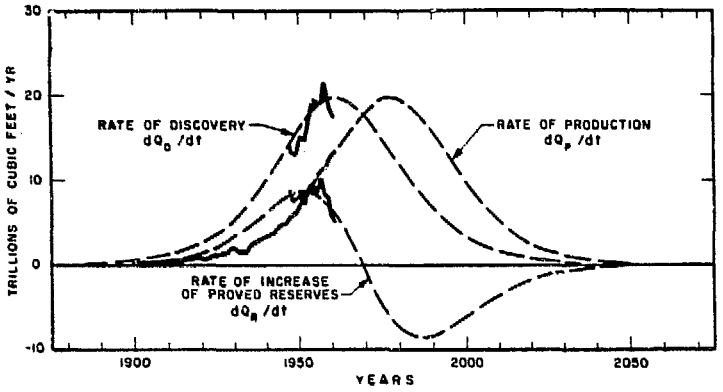


FIGURE 19 - 1962 estimates of the dates of the peaks of rate of proved discovery, rate of production and proved reserves of U. S. natural gas (Hubbert, 1962, Fig. 46).

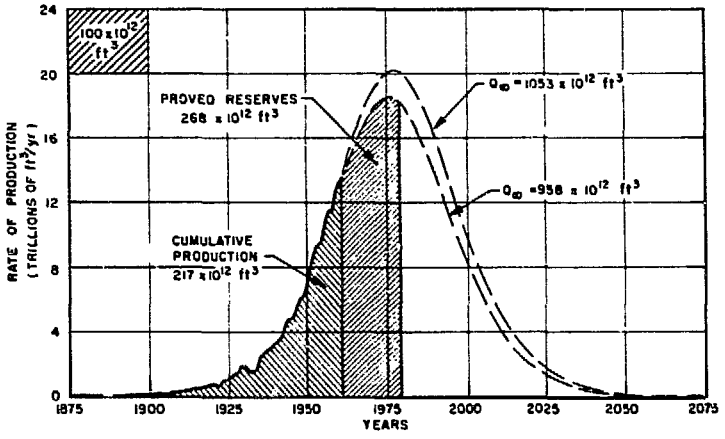


FIGURE 20 - 1962 estimates of ultimate amount of natural gas to be produced in conterminous United States, and estimates of date of peak production rate (Hubbert, 1962, Fig. 47).

discoveries was estimated to be at its peak at about 1961. Proved reserves of natural gas were estimated to reach their peak ($dQ_r/dt = 0$) at about 1969, and the rate of production about 1977.

At the time the study was being made, the U. S. Geological Survey, in response to a Presidential directive of March 4, [illegible], presented to the Academy Committee estimates of 590×10^9 bbls for crude oil and 2650 ft^3 for natural gas as its official estimates of the ultimate amounts of these fluids that would be produced from the lower 48 states and adjacent continental shelves.

These estimates were, by a wide margin, the highest that had ever been made up until that time. Moreover, had they been true, there would have been no grounds for the expectation of an oil or gas shortage in the United States

much before the year 2000. These estimates were cited in the Academy Committee report, but because of their wide disparity with any available evidence from the petroleum industry, they were also rejected.

As only became clear sometime later, the basis for those large estimates was an hypothesis introduced by the late A. D. Zapp of the U. S. Geological Survey, as illustrated in Figure 21 (Hubbert, 1969). Zapp postulated that the

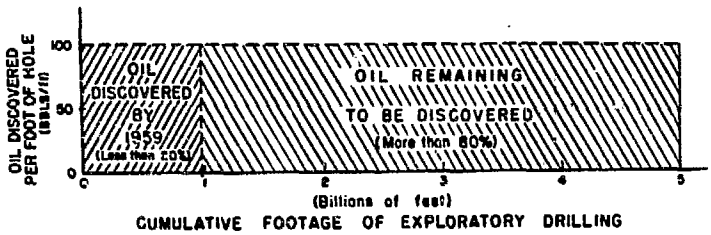


FIGURE 21 - Zapp (1962) hypothesis of oil discoveries per foot versus cumulative footage of exploratory drilling for conterminous United States and adjacent continental shelves (Hubbert, 1969, Fig. 8.18).

exploration for petroleum in the United States would not be completed until exploratory wells with an average density of one well per each 2 square miles had been drilled either to the crystalline basement rock or to a depth of 20,000 ft in all the potential petroleum-bearing sedimentary basins. He estimated that to drill this pattern of wells in the petroliferous areas of the conterminous United States and adjacent continental shelves would require about 5×10^9 feet of exploratory drilling. He then estimated that, as of 1959, only 0.98×10^9 feet of exploratory drilling had been done and concluded that at that time the United States was less than 20% along in its ultimate petroleum exploration. He also stated that during recent decades there had been no decline in the oil found per foot of exploratory drilling, yet already more than 100×10^9 barrels of oil had been discovered in the United States. It was implied, but not expressly stated, that the ultimate amount of oil to be discovered would be more than 500×10^9 bbls.

This was confirmed in 1961 by the Zapp estimate for crude oil given to the Academy Committee. At that time, with cumulative drilling of 1.1×10^9 feet, Zapp estimated that 130×10^9 bbls of crude oil had already been discovered. This would be at an average rate of 118 bbls/ft. Then, at this same rate, the amount of oil to be discovered by 5×10^9 feet of exploratory drilling should be 590×10^9 bbls, which is the estimate given to the Academy Committee. This constitutes the "Zapp hypothesis." Not only is it the basis for Zapp's own estimates, but with only minor modifications it has been the principal basis for most of the subsequent higher estimates.

The most obvious test for the validity of this hypothesis is to apply it to past petroleum discoveries in the United States. Has the oil found per foot of exploratory drilling been nearly constant during the past? The answer to this is given in Figure 22 (Hubbert, 1967), which shows the quantity of oil discovered and the average amount of oil found per foot for each 10^9 ft of exploratory drilling in the United States from 1860 to 1965. This shows an initial rate of 194 bbls/ft for the first unit from 1860 to 1920, a maximum rate of 276 bbls/ft for the third unit extending from 1929 to 1935 and then a precipitate decline to about 35 bbls/ft by 1965. This is approximately an exponential decline curve, the integration of which for unlimited future drilling gives an estimate of about 165×10^9 for Q_∞, the ultimate discoveries.

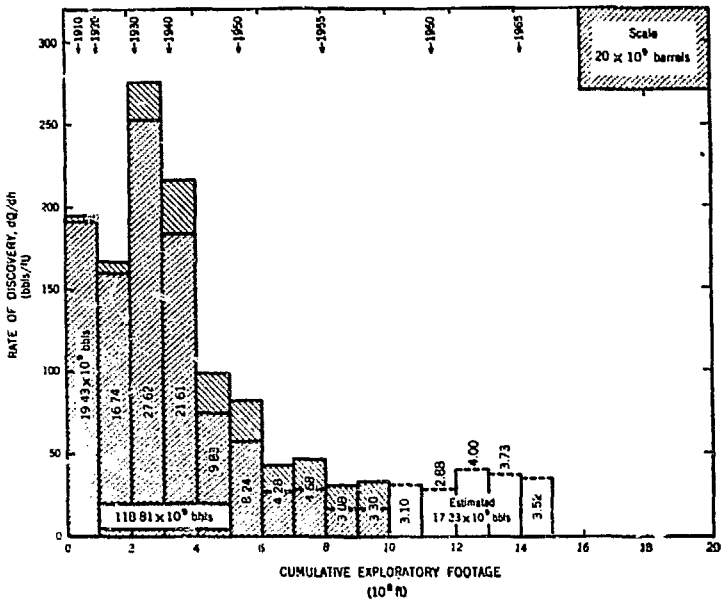


FIGURE 22 - Actual U. S. crude-oil discoveries per foot of exploratory drilling as a function of cumulative exploratory drilling from 1860 to 1965 (Hubbert, 1967, Fig. 15).

The superposition of the actual discoveries per foot shown in Figure 22 on the discoveries per foot according to the Zapp hypothesis of Figure 21 is shown in Figure 23 (Hubbert, 1969). The difference between the areas beneath the two curves represents the difference between the two estimates--an apparent overestimate of about 425 × 10^9 bbls.

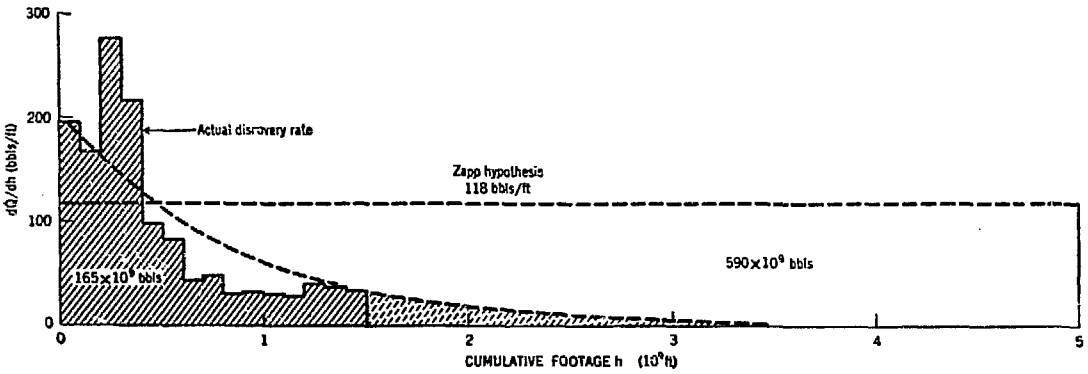


FIGURE 23 - Comparison of U. S. crude-oil discoveries according to Zapp hypothesis with actual discoveries. The difference between the areas beneath the two curves represents an overestimate of about 425 billion barrels (Hubbert, 1969, Fig. 8.19).

To recapitulate, in the Academy Committee report of 1962, the peak in U. S. proved crude-oil discoveries, excluding Alaska, was estimated to have occurred at about 1957, the peak in proved reserves at about 1962 and the peak in production was predicted for about 1968-1969. The peak in proved reserves did occur

in 1962, and the peak in the rate of production occurred in 1970. Evidence that this is not likely to be exceeded is afforded by the fact that for the six months since March 1972, the production rates of both Texas and Louisiana, which together account for 60% of the total U. S. crude-oil production, have been at approximately full capacity, and declining.

As for natural gas, the Academy report estimated that the peak in proved reserves would occur at about 1969 and the peak in the rate of production about 1977. As of September 1972, the peak of proved reserves for the conterminous 48 states occurred in 1967, 2 years ahead of the predicted date, and it now appears that the peak in the rate of natural-gas production will occur about 1974-1975, 2 to 3 years earlier than predicted. In the 1962 Academy report, the ultimate production of natural gas was estimated to be about 1000×10^{12} ft^3. Present estimates by two different methods give a low figure of 1000×10^{12} and a high figure of 1080×10^{12}, or a mean of 1040×10^{12} ft^3.

Because of its early stage of development, the petroleum potential of Alaska must be based principally on geological analogy with other areas. The recent Prudhoe Bay discovery of a 10-billion-barrel field--the largest in the United States--has been a source of excitement for an oil-hungry U. S. petroleum industry, but it still represents less than a 3-year supply for the United States. From present information, a figure of 30×10^9 bbls is about as large an estimate as can be justified for the ultimate crude-oil production from the land area of Alaska, although a figure greater than this is an admitted possibility. Adding this to a present figure of about 170×10^9 bbls for the conterminous 48 states gives 200×10^9 as the approximate amount of crude oil ultimately to be produced in the whole United States.

Canada's Resources

For the present paper, it has not been possible to make an analysis of the oil and gas resources of Canada. However, Figure 24, from R. E. Folinsbee's Presidential Address before the geological section of the Royal Society of Canada (1970), provides a very good appraisal of the approximate magnitude

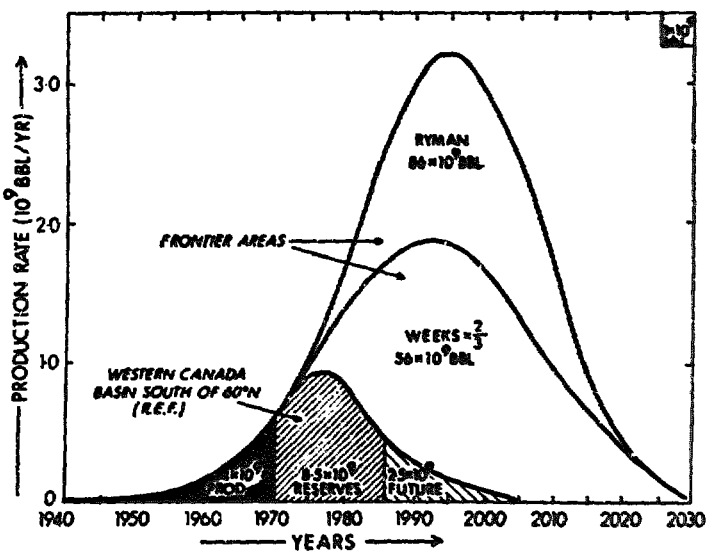


FIGURE 24 - Complete cycles of crude-oil production in Canada (Folinsbee, 1970, with permission).

of Canadian crude-oil resources. According to this estimate, the ultimate production of crude oil from Western Canada south of latitude 60° will be about 15×10^9 barrels, of which 12.5×10^9 have already been discovered. The peak in the production rate for this area is estimated at about 1977. This figure also shows a maximum estimate of 86×10^9 barrels of additional oil from the frontier areas of Canada. Should this be exploited in a systematic manner from the present time, a peak production rate of about 3×10^9 bbl/yr would probably be reached by about 1995.

As of 1973, however, the proved reserves for Canadian crude oil and natural-gas liquids both reached their peaks in 1969; those for natural gas in 1971. Therefore, unless development and transportation of oil and gas from the frontier provinces begins soon, there may be a temporary decline in total Canadian production of oil and gas toward the end of the present decade.

World Crude-Oil Production

In the present brief review, only a summary statement can be made for the petroleum resources of the world as a whole. Recent estimates by various major oil companies and petroleum geologists have been summarized by H. R. Warman (Warman, 1971) of the British Petroleum Company, who gave 226×10^9 bbls as the cumulative world crude-oil production and 527×10^9 bbls for the proved reserves at the end of 1969. This totals 753×10^9 bbls as the world's proved cumulative discoveries. For the ultimate recoverable crude oil, Warman cited the following estimates published during the period 1967-1970:

Year	Author	Quantity (10^9 bbls)
1967	Ryman (Esso)	2090
1968	Hendricks (USGS)	2480
1968	Shell	1800
1969	Hubbert (NAS-NRC)	1350-2100
1969	Weeks	2200
1970	Moody (Mobil)	1800

To this, Warman added his own estimate of $1200\text{-}2000 \times 10^9$ bbls. A recent unpublished estimate by the research staff of another oil company is in the mid-range of $1900\text{-}2000 \times 10^9$ bbls.

From these estimates, there appears to be a convergence toward an estimate of 2000×10^9 bbls, or slightly less. The implication of such a figure to the complete cycle of world crude-oil production is shown in Figure 25 (Hubbert, 1969), using two limiting values of 1350×10^9 and 2100×10^9 bbls. For the higher figure, the world will reach the peak in its rate of crude-oil production at about the year 2000; for the lower figure, this date would be about 1990.

Another significant figure for both the U. S. and the world crude-oil production is the length of time required to produce the middle 80% of the ultimate production. In each case, the time is about 65 years, or less than a human lifetime. For the United States, this subtends the period from about 1937 to 2003; for the world, from about 1967 to 2032.

Another category of petroleum liquids is that of natural-gas liquids which are produced of a by-product of natural gas. In the United States (excluding Alaska), the ultimate amount of natural-gas liquids, based on an ultimate amount of crude oil of 170×10^9 bbls, and 1040×10^{12} ft of natural gas, amounts to

about 36 × 10^9 bbls. Corresponding world figures, based on an estimate of 2000 × 10^9 bbls for crude oil, would be about 400 × 10^9 bbls for natural-gas liquids, and 12,000 ft^3 for natural gas.

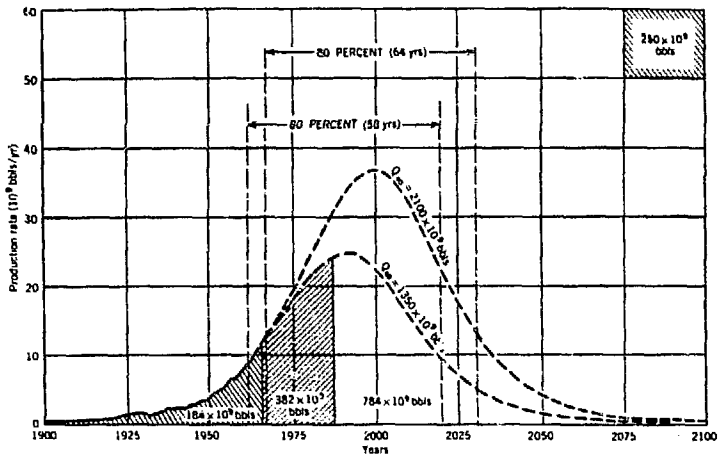


FIGURE 25 - Complete cycle of world crude-oil production for two values of Q^{∞} (Hubbert, 1969, Fig. 8.23).

Other Fossil Fuels

In addition to coal, petroleum liquids and natural gas, the other principal classes of fossil fuels are the so-called tar, or heavy-oil, sands and oil shales. The best known and probably the largest deposits of heavy-oil sands are in the "Athabasca Tar Sands" and two smaller deposits in northern Alberta containing an estimated 300 × 10^9 bbls of potentially producible oil. One large-scale mining and extracting operation was begun in 1965 by a group of oil companies, and others doubtless will follow as the need for this oil develops.

Unlike tar sands, the fuel content of which is a heavy, viscous crude oil, oil shales contain hydrocarbons in a solid form known as kerogen, which distills off as a vapour on heating and condenses to a liquid on cooling. The extractible oil content of oil shales ranges from as high as 100 U. S. gallons per short ton for the richest grades to near zero as the grades diminish. When all grades are considered, the aggregate oil content of the known oil shales is very large. However, in practice, only the shales having an oil content of about 25 gallons or more per ton and occurring in beds 10 feet or more thick are considered to be economical sources at present. According to a world inventory of known oil shales by Duncan and Swanson (1965), the largest known deposits are those of the Green River Formation in Wyoming, Colorado and Utah. From these shales, in the grade range from 10 to 65 gallons per ton, the authors estimate that only 80 × 10^9 bbls are recoverable under 1965 economic conditions. Their corresponding figure for oil shales outside the United States is 110 × 10^9 bbls.

The absolute magnitude of the world's original supply of fossil fuels recoverable under present technological and economic conditions and their respective energy contents in terms of their heats of combustion are given in Table 2. The total initial energy represented by all of these fuels amounted to about 83 × 10^{21} thermal joules, or 23 × 10^{15} thermal kilowatt-hours. Of this, 64% was represented by coal and lignite, 17 and 16%, respectively, by

TABLE 2 — Approximate Magnitudes and Energy Contents of the World's Original Supply of Fossil Fuels Recoverable Under Present Conditions

Fuel	Quantity	Energy Content		Per Cent
		10^{21} thermal joules	10^{15} thermal kwh	
Coal and lignite	2.35×10^{12} metric tons	53.2	14.80	63.78
Petroleum liquids	2400×10^{9} bbls	14.2	3.95	17.03
Natural gas	$12{,}000 \times 10^{12}$ ft^3	13.1	3.64	15.71
Tar-sand oil	300×10^{9} bbls	1.8	0.50	2.16
Shale oil	190×10^{9} bbls	1.1	0.31	1.32
TOTALS		83.4	23.20	100.00

petroleum liquids and natural gas, and 3% by tar-sand and shale oil combined. Although the total amount of coal and lignite in beds 14 or more inches thick and occurring at depths less than 3,000 feet, as estimated by Averitt, are very much larger in terms of energy content, than the initial quantities of oil and gas, the coal practically recoverable under present conditions is only about twice the magnitude of the initial quantities of gas and oil in terms of energy content. Therefore, at comparable rates of production, the time required for the complete cycle of coal production will not be much longer than that for petroleum--in order of a century or two for the exhaustion of the middle 80% of the ultimate cumulative production.

To appreciate the brevity of this period in terms of the longer span of human history, the historical epoch of the exploitation of the fossil fuels is shown graphically in Figure 26, plotted on a time scale extending from 5000

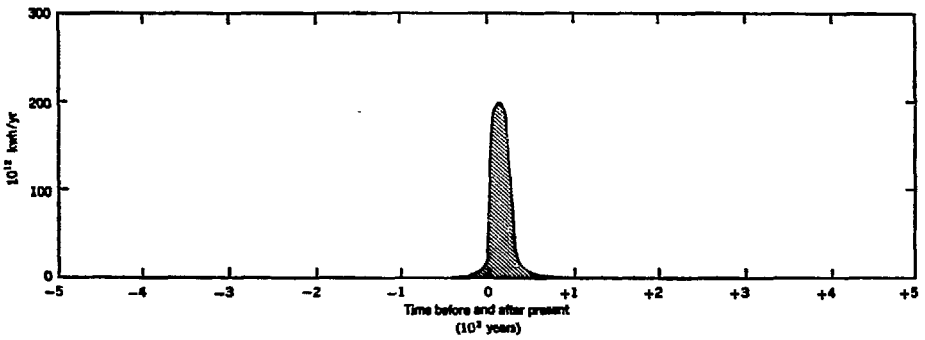


FIGURE 26 - Epoch of fossil-fuel exploitation in perspective of human history from 5000 years in the past to 5000 years in the future (modified from Hubbert, 1962, Fig. 54).

years in the past to 5000 years in the future--a period well within the prospective span of human history. On such a time scale, it is seen that the epoch of the fossil fuels can be only a transitory or ephemeral event--an event, nonetheless, which has exercised the most drastic influence on the human species during its entire biological history.

OTHER SOURCES OF INDUSTRIAL ENERGY

The remaining sources of energy suitable for large-scale industrial use are principally the following.

1. Direct use of solar radiation.
2. Indirect uses of solar radiation.
   (a) Water power.
   (b) Wind power.
   (c) Photosynthesis.
   (d) Thermal energy of ocean water at different temperatures.
3. Geothermal power.
4. Tidal power.
5. Nuclear power.
   (a) Fission.
   (b) Fusion.

Solar Power

By a large margin, the largest flux of energy occurring on the earth is that from solar radiation. The thermal power of the solar radiation intercepted by the earth, according to recent measurements of the solar constant, amounts to about $174{,}000 \times 10^{12}$ thermal watts. This is roughly 5,000 times all other steady fluxes of energy combined. It also has the expectation of continuing at about the same rate for geological periods of time into the future.

The largest concentrations of solar radiation reaching the earth's surface occur in desert areas within about 35° of latitude north and south of the equator. Southern Arizona and neighbouring areas in the southwestern part of the United States are in this belt, as well as northern Mexico, the Atacama Desert in Chile, and a zone across northern Africa, the Arabian Peninsula and Iran. In southern Arizona, the thermal power density of the solar radiation incident upon the earth's surface ranges from about 300 to 650 calories per cm^2 per day, from winter to summer. The winter minimum of 300 calories per cm^2 per day, when averaged over 24 hours, represents a mean power density of 145 watts per square meter. If 10% of this could be converted into electrical power by photovoltaic cells or other means, the electrical power obtainable from 1 square km of collection area would be 14.5 megawatts. Then, for an electrical power plant of 1,000 megawatts capacity, the collection area required would be about 70 km^2. At such an efficiency of conversion, the collection area required to generate 350,000 megawatts of electrical power--the approximate electric-power capacity of the United States at present--would be roughly 25,000 km^2 or 9,000 square miles. This is somewhat less than 10% of the area of Arizona.

Such a calculation indicates that large-scale generation of electric power from direct solar radiation is not to be ruled out on the grounds of technical infeasibility. It is also gratifying that a great deal of interest on the part of technically competent groups in universities and research institutions has arisen during the last 5 years over the possibility of developing large-scale solar power.

Hydroelectric Power

Although there has been continuous use of water power since Roman times, large units were not possible until a means was developed for the generation and transmission of power electrically. The first large hydroelectric power

installation was that made at Niagara Falls in 1895. There, ten 5,000-hp turbines were installed for the generation of A.C. power, which was transmitted a distance of 26 miles to the city of Buffalo. The subsequent growth of hydroelectric power in the United States is shown in Figure 27 and that for the world in Figure 28.

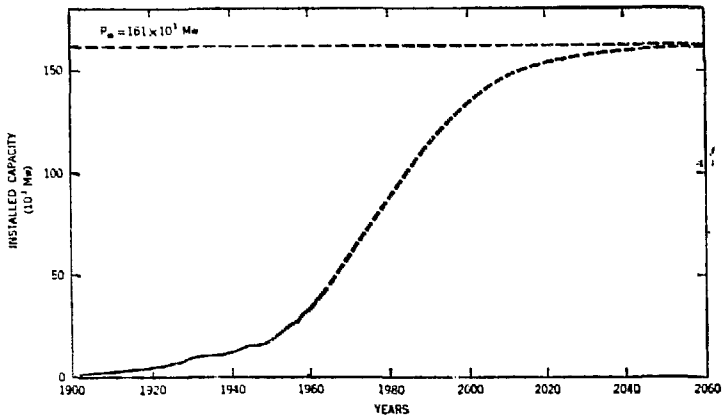


FIGURE 27 - Installed and potential hydroelectric-power capacity of the United States (Hubbert, 1969, Fig. 8.28).

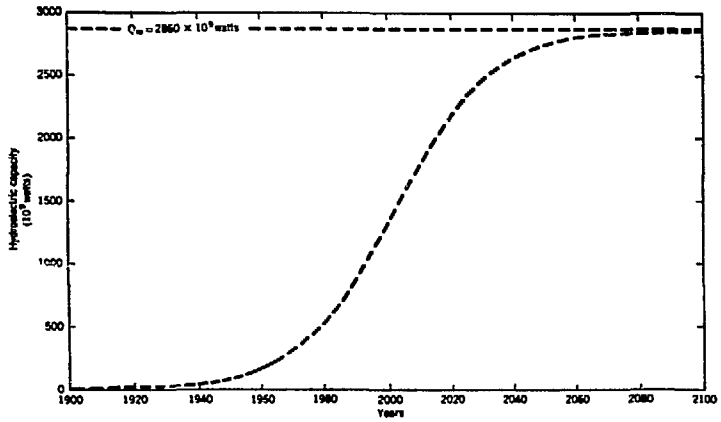


FIGURE 28 - Installed and potential world hydroelectric-power capacity.

In the United States, by 1970, the installed hydroelectric power capacity amounted to 53,000 megawatts, which is 32% of the ultimate potential capacity of 161,000 Mw as estimated by the Federal Power Commission. The world installation, by 1967, amounted to 243,000 Mw, which is 8.5% of the world's estimated potential hydroelectric power of 2,860,000 Mw. Most of this developed capacity is in the highly industrialized areas of North America, Western Europe and the Far East, especially Japan.

The areas with the largest potential water-power capacities are the industrially underdeveloped regions of Africa, South America and Southeast Asia, where combined capacities represent 63% of the world total.

The total world potential water power of approximately 3×10^{12} watts, if fully developed, would be of about the same magnitude as the world's present

rate of utilization of industrial power. It may also appear that this would be an inexhaustible source of power, or at least one with a time span comparable to that required to remove mountains by stream erosion. This may not be true, however. Most waterpower developments require the creation of reservoirs by the damming of streams. The time required to fill these reservoirs with sediments is only 2 or 3 centuries. Hence, unless a technical solution of this problem can be found, water power may actually be comparatively short-lived.

Tidal Power

Tidal power is essentially hydroelectric power obtainable by damming the entrance to a bay or estuary in a region of tides with large amplitudes, and driving turbines as the tidal basin fills and empties. An inventory of the world's most favorable tidal-power sites gives an estimate of a total potential power capacity of about 63,000 Mw, which is about 2% of the world's potential water power capacity. At present, one or more small pilot tidal power plants of a few megawatts capacity have been built, but the only full-scale tidal plant so far built is that on the Rance estuary on the English Channel coast of France. This plant began operation in 1966 with an initial capacity of 240 Mw and a planned enlargement to 320 Mw.

One of the world's most favorable tidal-power localities is the Bay of Fundy region of northeastern United States and southeastern Canada. This has the world's maximum tides, with amplitudes up to 15 meters, and a combined power capacity of nine sites of about 29,000 Mw. Extensive plans have been made by both the United States and Canada for the utilization of this power, but as yet no installations have been made.

Geothermal Power

Geothermal power is obtained by means of heat engines which extract thermal energy from heated water within a depth ranging from a few hundred meters to a few km beneath the earth's surface. This is most practical where water has been heated to high temperatures at shallow depths by hot igneous or volcanic rocks that have risen to near the earth's surface. Steam can be used to drive steam turbines. At present, the major geothermal power installations are in two localities in Italy with a total capacity of about 400 Mw, the Geysers in California with a planned capacity by 1973 of 400 Mw and at Wairakei in New Zealand with a capacity of 160 Mw. The total world installed geothermal power capacity at present is approximately 1,500 Mw.

What the ultimate capacity may be can be estimated at present to perhaps only an order of magnitude. Recently, a number of geothermal-power enthusiasts (many with financial interests in the outcome) have made very large estimates for power from this source. However, until better information becomes available, an estimation within the range of 60,000 to 600,000 Mw, or between 2 and 20% of potential water power, is all that can be justified. Also, as geothermal-power production involves "mining" quantities of stored thermal energy, it is likely that most large installations will also be comparatively short-lived--perhaps a century or so.

Nuclear Power

A last major source of industrial power is that of atomic nuclei. Power may be obtained by two contrasting types of nuclear reactions: (1) the fissioning of heavy atomic isotopes, initially uranium-235; and (2) the fusing of the isotopes of hydrogen into heavier helium. In the fission process, two stages are possible. The first consists of power reactors which are dependent

almost solely on the rare isotope, uranium-235, which represents only 0.7% of natural uranium. The second process is that of breeding whereby either the common isotope of uranium, uranium-238, or alternatively thorium, is placed in a reactor initially fueled by uranium-235. In response to neutron bombardment, uranium-238 is converted into plutonium-239, or thorium-232 into uranium-233, both of which are fissionable. Hence by means of a breeder reactor, in principle, all of the natural uranium or thorium can be converted into fissionable reactor fuel.

Uranium-235 is sufficiently scarce that, without the breeder reactor, the time span of large-scale nuclear power production would probably be less than a century. With complete breeding, however, it becomes possible not only to consume all of the natural uranium, or thorium, but to utilize low-grade sources as well.

The energy released by the fissioning of a gram of uranium-235 or plutonium-239 or uranium-233 amounts to 8.2×10^{10} joules of heat. This is approximately equivalent to the heat of combustion of 2.7 metric tons of bituminous coal or 13.4 barrels of crude oil. For the energy obtainable from a source of low-grade uranium, consider the Chattanooga Shale, which crops out along the western edge of the Appalachian Mountains in eastern Tennessee and underlies, at minable depths, most of several midwestern states. This shale has a uranium-rich layer about 16 feet or 5 meters thick with a uranium content of 60 grams per metric ton, or 150 grams per cubic meter. This is equivalent to 750 grams per square meter of land area. Assuming only 50% extraction, this would be equivalent in terms of energy content to about 1,000 metric tons of bituminous coal or to 5,000 barrels of crude oil per square meter of land area, or to one billion metric tons of coal or 5 billion barrels of oil per square kilometer. In this region, an area of only 1,600 km^2 would be required for the energy obtainable from the uranium in the Chattanooga Shale to equal that of all the fossil fuels in the United States. Such an area would be equivalent to that of a square 40 km, or 25 miles, to the side, which would represent less than 2% of the area of Tennessee.

The fusion of hydrogen into helium is known to be the source of the enormous amount of energy radiating from the sun. Fusion has also been achieved by man in an uncontrolled or explosive manner in the thermonuclear or hydrogen bomb. As yet, despite intensive efforts in several countries, controlled fusion has not been achieved. Researchers, however, are hopeful that it may be within the next few decades.

Should fusion be achieved, eventually the principal raw material will probably be the heavy isotope of hydrogen, deuterium. This occurs in sea water at an abundance of 1 deuterium atom to each 6,700 atoms of hydrogen. The deuterium-deuterium, or D-D, reaction involves several stages, the net result of which is:

$$5\,{}_1^2D \rightarrow {}_2^4He + {}_2^3He + H + 2n + 24.8\ MeV;$$

or, in other words, 5 atoms of deuterium, on fusion, produce 1 atom of helium-4, 1 atom of helium-3, 1 atom of hydrogen and 2 neutrons, and in addition release 24.8 billion electron volts, or 39.8×10^{-13} joules.

It can be computed that 1 liter of water contains 1.0×10^{22} deuterium atoms, which upon fusion would release 7.95×10^9 joules of thermal energy. This is equivalent to the heat of combustion of 0.26 metric tons of coal or 1.30 barrels of crude oil. Then, as 1 km^3 of sea water is equivalent to 10^{12} liters, the heat released by the fusion of the deuterium contained in 1 km^3 of sea water would be equivalent to that of the combustion of 1300 billion barrels of oil or 260 billion tons of coal. The deuterium in 33 km^3 of sea water would be equivalent to that of the world's initial supply of fossil fuels.

From the foregoing review, what stands out most clearly is that our present industrialized civilization has arisen principally during the last 2 centuries. It has been accomplished by the exponential growth of most of its major components at rates commonly in the range of 4 to 8% per year, with periods of doubling from 8 to 16 years. The question now arises: What are the limits to such growth, and what does this imply concerning our future?

What we are dealing with, essentially, are the principles of ecology. It has long been known by ecologists that the population of any biologic species, if given a favorable environment, will increase exponentially with time; that is, that the population will double repeatedly at roughly equal intervals of time. From our previous observations, we have seen that this is also true of industrial components. For example (Fig. 29), the world electric-power capacity is now growing at 8% per year and doubling every 8.7 years. The world automobile population and the miles flown per year by the world's civil-aviation scheduled flights are each doubling every 10 years. Also, the human population is now doubling in 35 years (Fig. 30).

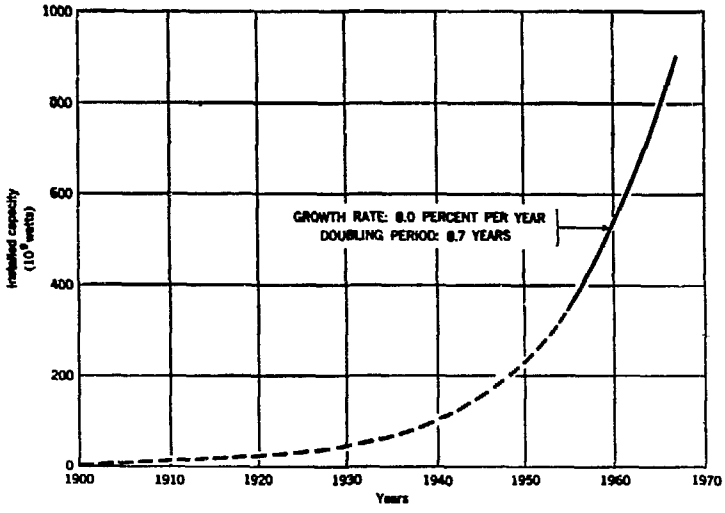


FIGURE 29 - World electric generating capacity as an example of exponential growth (Hubbert, 1971, Fig. 2).

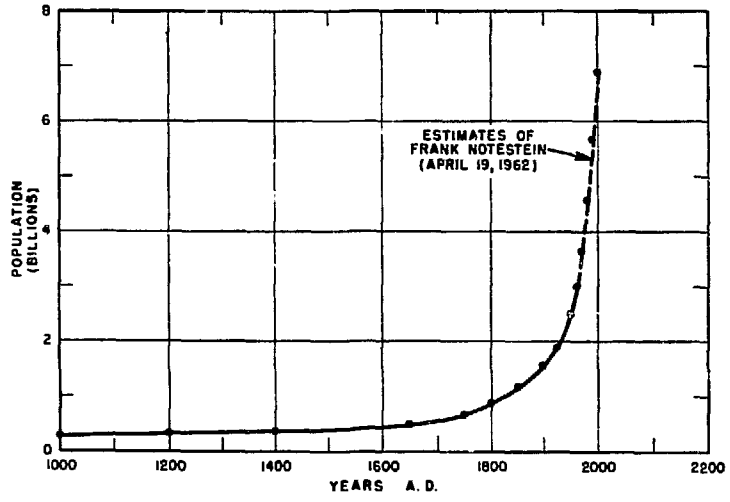


FIGURE 30 - Growth of human population since the year 1000 A.D. as an example of an ecological disturbance (Hubbert, 1962, Fig. 2).

The second part of this ecological principle is that such exponential growth of any biologic population can only be maintained for a limited number of doublings before retarding influences set in. In the biological case, these may be represented by restriction of food supply, by crowding or by environmental pollution. The complete biologic growth curve is represented by the logistic curve of Figure 31.

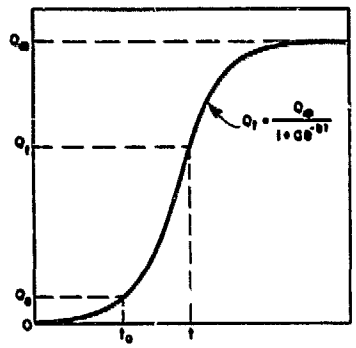


FIGURE 31 - The logistic growth curve showing both the initial exponential phase and the final slowing down during a cycle of growth.

That there must be limits to growth can easily be seen by the most elementary arithmetic analysis. Consider the familiar checkerboard problem of placing 1 grain of wheat on the first square, 2 on the second, 4 on the third and doubling the number for each successive square. The number of grains on the nth square will be 2^{n-1}, and on the last or 64th square, 2^{63}. The sum of the grains on the entire board will be twice this amount less one grain, or $2^{64}-1$. When translated into volume of wheat, it turns out that the quantity of wheat required for the last square would equal approximately 1,000 times the present world annual wheat crop, and the requirement for the whole board would be twice this amount.

It follows, therefore, that exponential growth, either biological or industrially, can be only a temporary phenomenon because the earth itself cannot tolerate more than a few tens of doublings of any biological or industrial component. Furthermore, most of the possible doublings have occurred already.

After the cessation of exponential growth, any individual component has only three possible futures: (1) it may, as in the case of water power, level off and stabilize at a maximum; (2) it may overshoot and, after passing a maximum, decline and stabilize at some intermediate level capable of being sustained; or (3) it may decline to zero and become extinct.

Applied to human society, these three possibilities are illustrated graphically in Figure 32. What stands out most clearly is that our present phase of exponential growth based on man's ability to control ever larger quantities of energy can only be a temporary period of about 3 centuries' duration in the totality of human history. It represents but a brief transitional epoch between two very much longer periods, each characterized by rates of change so slow as to be regarded essentially as a period of non-growth. Although the forthcoming period poses no insuperable physical or biological difficulties, it can hardly fail to force a major revision in those aspects of our current culture the tenents of which are dependent on the assumption that the growth rates which have characterized this temporary period can somehow be sustained indefinitely.

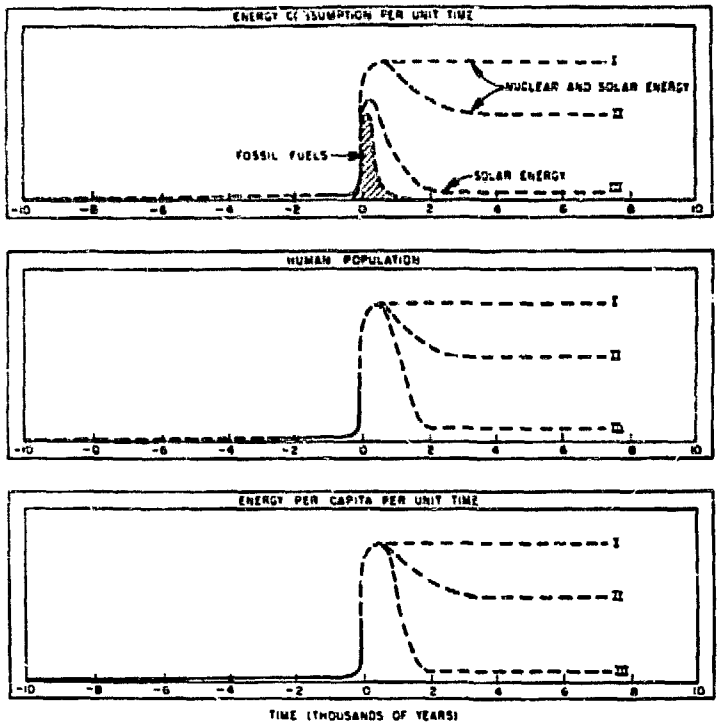


FIGURE 32 - Epoch of current industrial growth in the context of a longer span of human history (Hubbert, 1962, Fig. 61).

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ENERGY DEMAND GROWTH: INFLUENCE OF POPULATION GROWTH, EFFICIENCY OF USE, AND PRICING POLICIES

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University of Tennessee Environment Center

Paper presented at the ORAU Conference on
"Energy Sources for the Future", July 1975

The intent of this paper is to present the case that the "energy problem" is more than a shortage of gas and oil - it is western man's confrontation with the finitude of our natural resources and limitations of our technologies. It is one of the most clear-cut signals to western man that we cannot forever continue to try to solve problems through expansionism. The energy problem is the problem of growth - growth of population and growth of per capita consumption. World population has been growing at a rapidly accelerating rate over the past century (figure 1). Indeed, the rate of increase of population growth is in itself accelerating. Projections of world population by the end of the century indicate a total number of more than 6,000 million people, more than 2,500 million more than live today. History shows that we have usually tended to underestimate population growth. For example, in 1950 world population in 1985 was predicted to be about 3,300 million people. In fact the world has already passed that number! All world citizens are not equal energy consumers (an American uses 50 times the energy consumed by an East Indian). However it is clear that the total number of people on the planet influences in some measure the total energy demand. As long as population exponeniates, particularly at such a high rate, it is folly to hope to expand significantly the energy availability per capita.

While world population is expanding at an ever increasing rate, the use of natural resources is accelerating even faster. In figure 2 we show the world consumption of iron ore in comparison with world population growth. Clearly the growth of demand for iron ore (similarly, energy and other resources) has been sharply greater than that of world population growth. On the average resource demand is growing at 2 to 3 times population growth rates. It is for this reason that Commoner and others see the energy/environment debate centered around resource use, whereas Ehrlich and others focus on population growth. Clearly the rate of increase of per capita consumption is currently the most significant factor in the Western world; however population ultimately becomes the most important issue to deal with.

There is another kind of growth that has exacerbated environmental problems associated with man's activities and that is the growth in "unit size". While we have witnessed an explosion in the number of people in the world we simul-

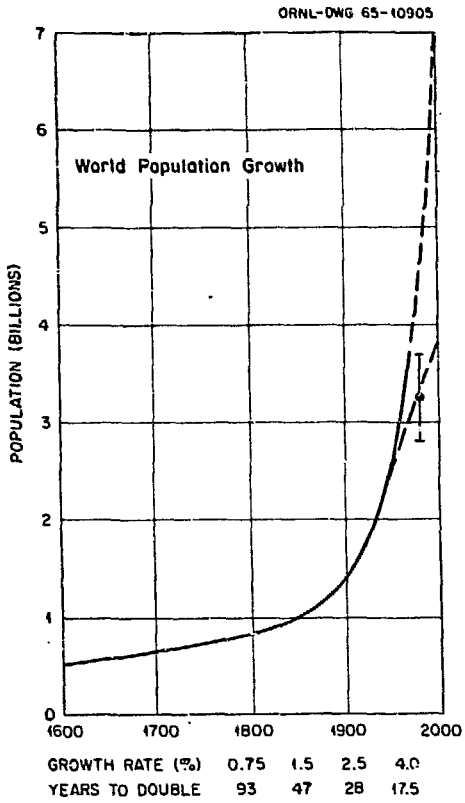


Figure 1

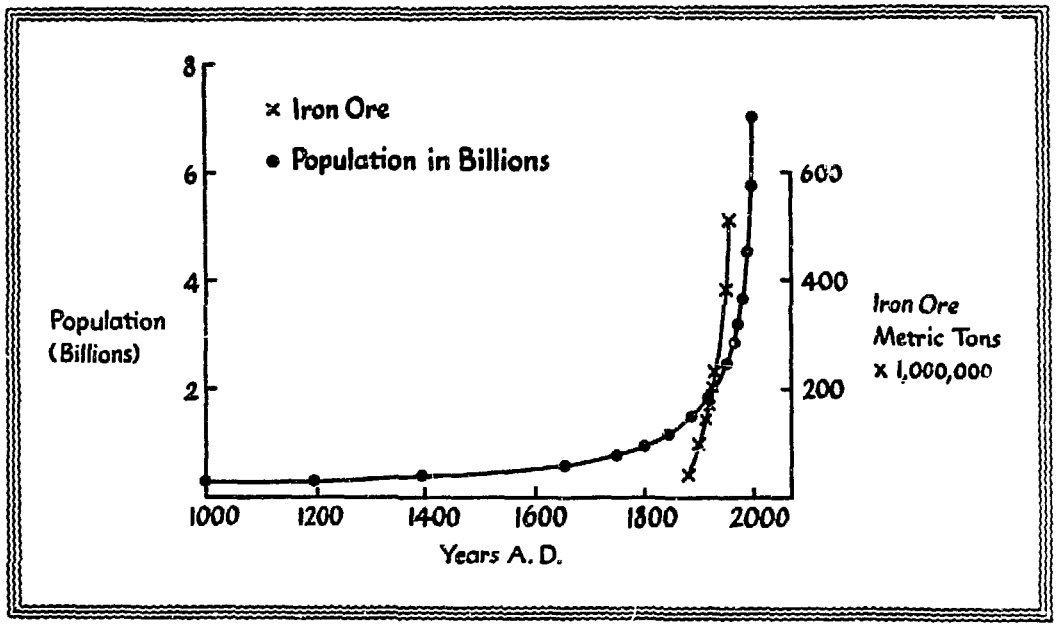


Figure 2

taneously witness an implosion of man's activities into small areas. This has been the result of two phenomena:

(1) The growth of cities has caused a massive redistribution of population. In the U.S. more than three-fourths of all the people now reside in "urban" areas, up from one-fourth only two generations back. Cities have brought improvements in education, availability of cultural and other services to a broader segment of our population, and greater efficiency to our commercial and industrial system. At the same time the growth of cities has not been without major socio-economic problems! The growth also pushed our energy system toward one of greater energy intensiveness.

(2) The second "implosion" factor has been the growth in unit size of industrial activities (especially electric power plants). The advance of high technology plus economic factors in the private market place have coused such a growth of unit size that the natural assimilative capacity of the environment that once "handled" most pollution emissions has been overwhelmed by the concentration of the emissions. We illustrate this point in figure 3. Maximum unit size for a single electrical generator has changed with incredible speed over the last twenty years, leading to rapidly escalating power plant size.

It is clear that we can no longer get away with the tolerance for emissions of pollutants that we were able to do only a quarter century ago. The scale of our activities, combined with the physical concentration of those activities, simply preclude the continuance of such policies.

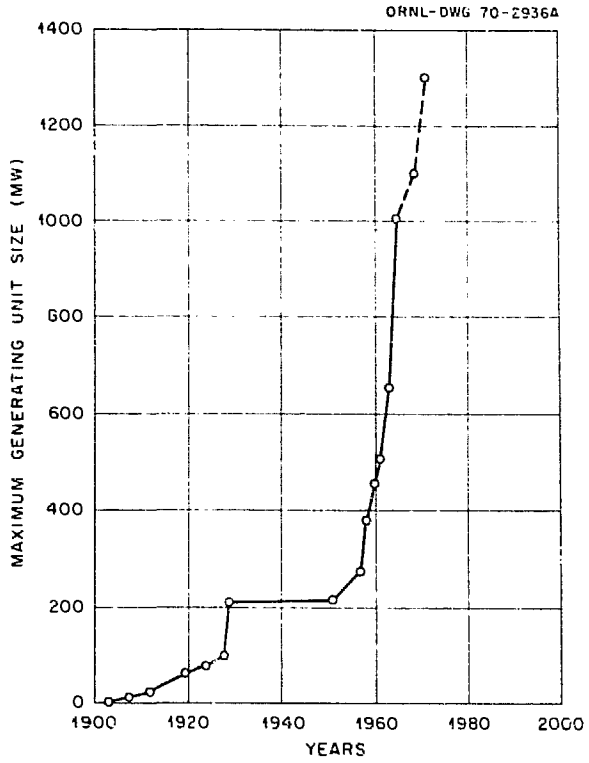
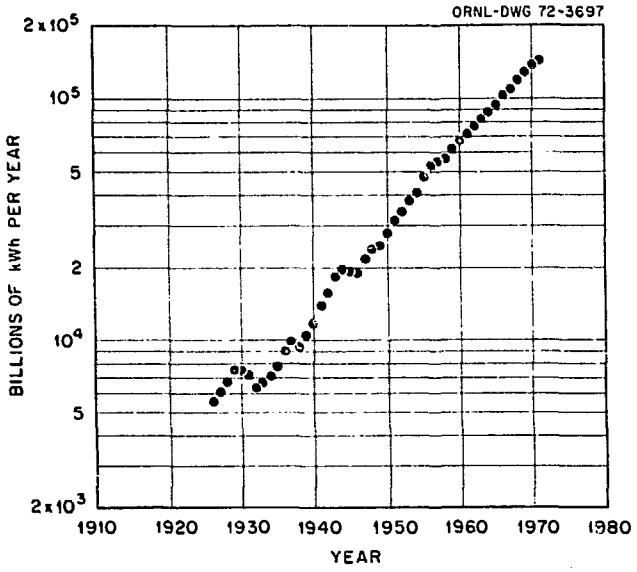


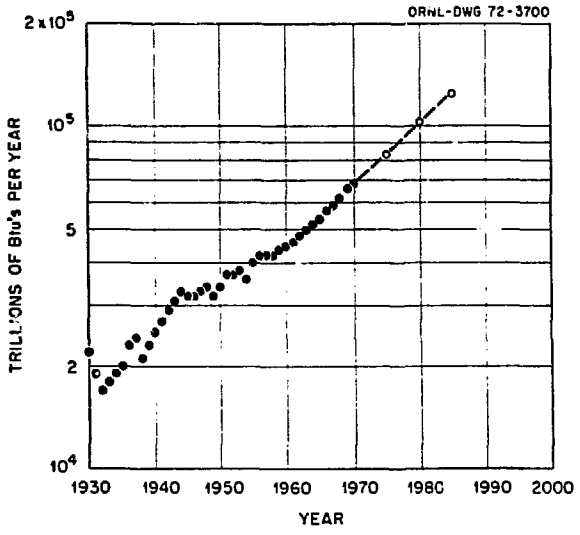
Figure 3

A cursory examination of energy demand growth shows that for many years the exponential has been closely followed. Total sales of electricity in the United States (figure 4) show a remarkably consistent pattern from the end of World War II until 1974. A more detailed examination shows the rate of growth of electrical demand actually increased to over 7% per annum. In figure 5 the total U.S. consumption of energy resources is plotted to 1970, again showing an exponential growth (accelerating from about 2% per year in 1950 to about 4.5% per year in 1970). It is both tempting and very dangerous to extrapolate such past history into the future (as indicated by the dotted line in the figure).



Total U.S. Sales of Electricity.

Figure 4



Projected U.S. Consumption of Energy Resources (from U.S. Energy Outlook, a 1971 Report of the National Petroleum Council).

Figure 5

The old adage that "what is past is prologue" must not be interpreted to mean that what has happened in the past will continue to happen in the future. For example one of the main reasons that energy consumption expanded at such a high rate during the last 20 years is because it's "real" price was constantly decreasing throughout that entire period of time. When a commodity becomes cheaper and cheaper over time the economic consumer will respond by using it more and more compared to other goods and services. That is precisely what happened to energy in the U.S. during the period 1950-1973. Given such a consistent rate of expansion of energy demand it was easy, if sloppy, for energy planners to assume that such a rate of expansion would continue into the future. In figure 6 we illustrate the point. This information was presented to the Congress by the Atomic Energy Commission in 1968 to defend the need for its nuclear power program. In the last column a population of 320 million people was projected for the turn of the century. Also a very healthy expansion of per capita consumption was assumed. On the basis of these numbers it was "shown" to be imperative to expand the nuclear power program (figure 7) in order to maintain exponential growth.

U.S. ELECTRIC UTILITY POWER STATISTICS RELATING TO POPULATION AND CONSUMPTION

	1950	1968	Est. for 1980	Inter. Proj. for 2000
POPULATION (millions)	152	202	235	320
TOTAL POWER CAPACITY (millions of kilowatts)	65	290	600	1,352
KW CAPACITY / PERSON	0.6	1.4	2·½	~ 4·¼
POWER CONSUMED PER PERSON PER YEAR (kilowatt-hours)	2,000	6,500	11,500	~ 25,000
TOTAL CONSUMPTION (kilowatt-hours)	325 billion	1.3 trillion	2.7 trillion	~ 8 trillion
NUCLEAR POWER CAPACITY % OF TOTAL	0	< 1%	25%	~ 69%

Figure 6

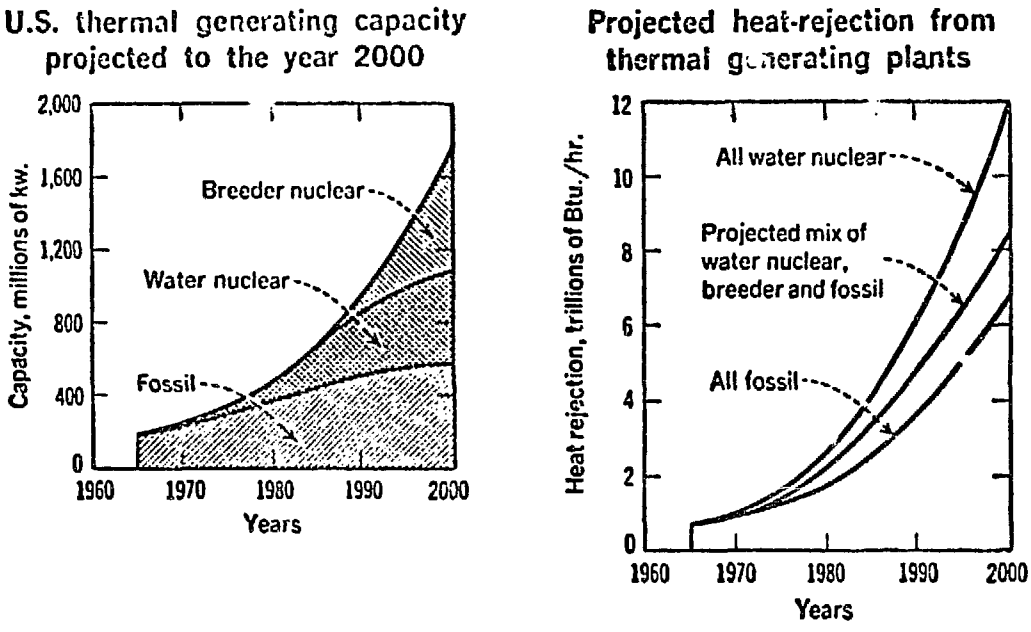


Figure 7

Thus the arguments derived from an assumed continuation of rapid growth played an important role in establishing U.S. energy policy and funding decisions during recent years. At the same time it is already quite clear that these assumptions are simply wrong. For example the population growth assumed (figure 6) has now been reestimated at a dramatically lower figure (about 260 million rather than 320 million) at the turn of the century. Other studies have shown that market saturation of appliances and other factors will cause energy demand growth to taper off appreciably during the next twenty years.

It is interesting to note that some of the most urgent questions raised about meeting energy demand growth has to do with the capital demands that would be imposed on our capital markets. Other questions arose about the capacity of our environment to handle such rapidly expanding activities for any extended period of time. During the late 1960's we came to a national concensus that we simply cannot endure the continued external environmental impact of energy production and use that had attained during the previous quarter century. We also were confronted by the overwhelming problem of handling such straight-forward problems as heat loads from waste heat produced by electrical generation. Waste heat loads for only 50 years following 1970 were projected to be nearly ten times the already difficult problem encountered in 1970 (figure 8).

Year	Approximate Condenser Heat Loads, 10^{12} Btu/yr
1970	7,700
2000	35,000
2020	67,000

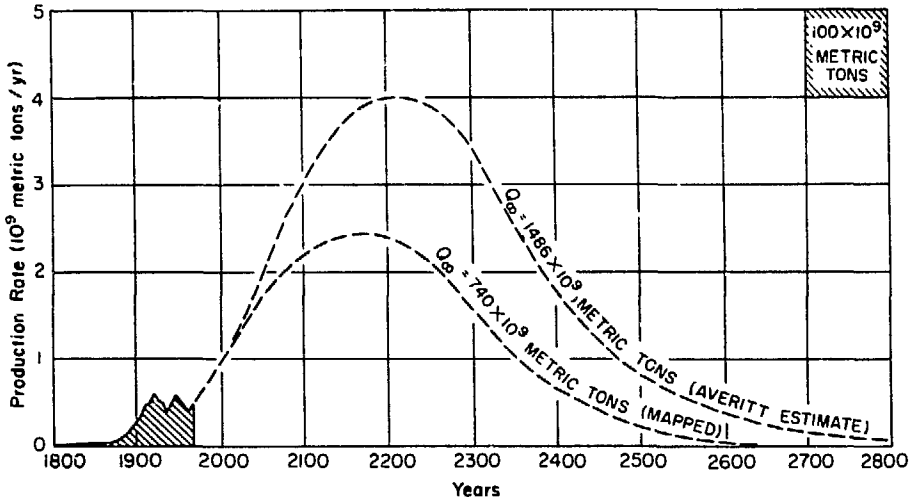
Figure 8

During the same time that arguments were made about how to continue the rapid exponentiation of energy consumption it became increasingly clear that our "bountiful" fossil fuel supplies were not nearly as bountiful as we had once thought. We are on the downward path in terms of world production of natural gas. We are nearing the peak in the production of oil. We are within 100-200 years of peaking in our use of coal. That doesn't leave us much time to restructure our energy system. In figure 9 we reproduce results of one of M. King Hubbard's studies on coal and in figure 10 we illustrate the fact that, in terms of world history, the "age" of fossil fuels will turn out to be more an "incident" than "age". At the present time we consume fossil fuels at a rate between 100,000 and one million times faster than these fuels were created through their natural production rate. It is folly to think that one can keep up such a growth of consumption for many more decades.

It is little wonder that arguments about "limits to the growth" of man's activities began to surface during these past ten years. Models describing the interaction between resources, consumption, and quality of life have moved through an age of infancy to one of credibility; all of us are left much more uneasy about the ability of technology and institutions to deal with the problems of growth. In the cartoon strip "Peanuts" Lucy exclaims to Linus: "... This generation has been given the works. All the world's problems are being shoved at us by the last generation". Linus: "What do you think we should do about it?". Lucy: "We'll stick the next generation!". We have been deferring costs of affluence from one generation to

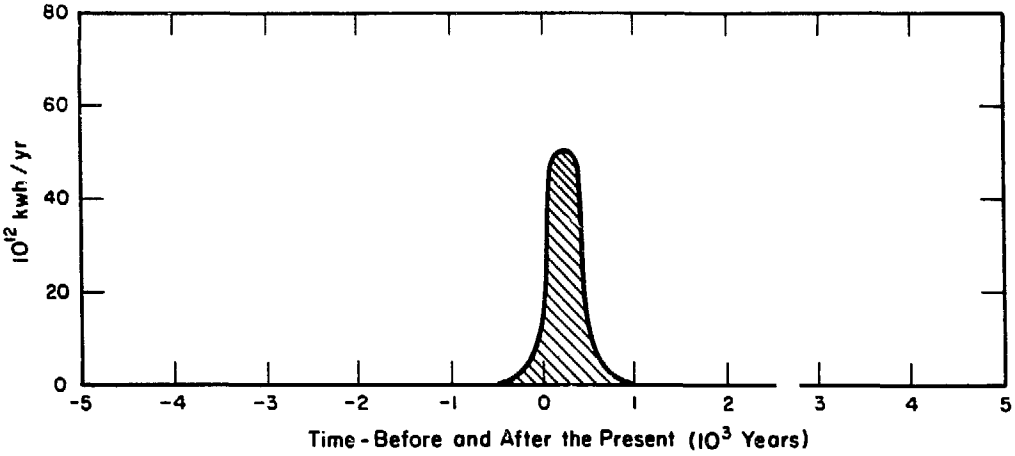
another for many years. Witness the degradation of air and water quality; the poisoning of rivers and wildlife with long lived pestisides; the grossly inefficient use of natural gas and other energy resources; the ravaged landscape left behind in surface mining; the one billion dollar per year bill we now pay for black lung benefits that was incurred years ago by people buying "cheap" coal. Over the past decade we have instituted environmental standards and other devices to cause the true cost of our affluence to be more adequately reflected in its market price. It is true that the "price" has gone up but it is also equally clear that the current price is a better approximation of the real cost than it was a decade ago.

During the 1960's our subsidy of energy prices was further increased by



Complete cycles of United States coal production for two values of Q_∞.

Figure 9



Epoch of exploitation of fossil fuels in historical perspective from minus to plus 5,000 years from present. (From Hubbert, 1962, Figure 54, p. 91.)

Figure 10

allowing ourselves to become heavily dependent upon imported oil. The U.S. changed from almost complete self-sufficiency in oil in 1960 to a dependence on imports for about 35 percent of its oil by 1973. At the time of the most recent Arab oil embargo our imports were rising at the annual rate of one million barrels per day. Our decision to depend on oil imports gave us a short term advantage of very cheap oil (2 to 3 dollars per barrel) but an ultimately unacceptable dependence on the vagries of an international cartel. Bolstered by these cheap imports, our national energy consumption efficiency continued to fall and demand growth accelerated.

At the same time that imports began to rise we began to insist on paying more completely for environmental costs associated with domestic energy production and use. Several pollution control bills were passed by the Congress in the late 1960's which are designed to internalize these environmental costs. This decision raised the price of domestic energy and tended to make consumers think more carefully about the efficiency of use. At the same time it gave energy companies an even greater incentive to buy and refine oil overseas.

The Arab oil embargo (1973-4) and the OPEC cartel price on international oil that followed the embargo has had a dramatic effect on U.S. and world energy strategies. Prior to the price rise the price of energy was generally placed below its true cost. Oil was sold at a moderate mark up from its average cost of discovery - a figure far less than the average price of newly discovered oil. The price of inter-state natural gas was controlled at a figure very much less than it would attain in a free market environment. The price of coal, set to compete with cheap oil, still did not contain much of the environmental and health costs associated with its production. The new world oil price instituted by OPEC brought the price of oil up to a level approximating the cost of "new" oil. This, in turn, has resulted in a general escalation of other energy costs. As a consequence the price of coal is no longer cost-based and profit margins are now sufficiently high that essentially all health and environmental externalities can be incorporated into its price and still leave a respectable profit margin. As a consequence of this new price system a number of

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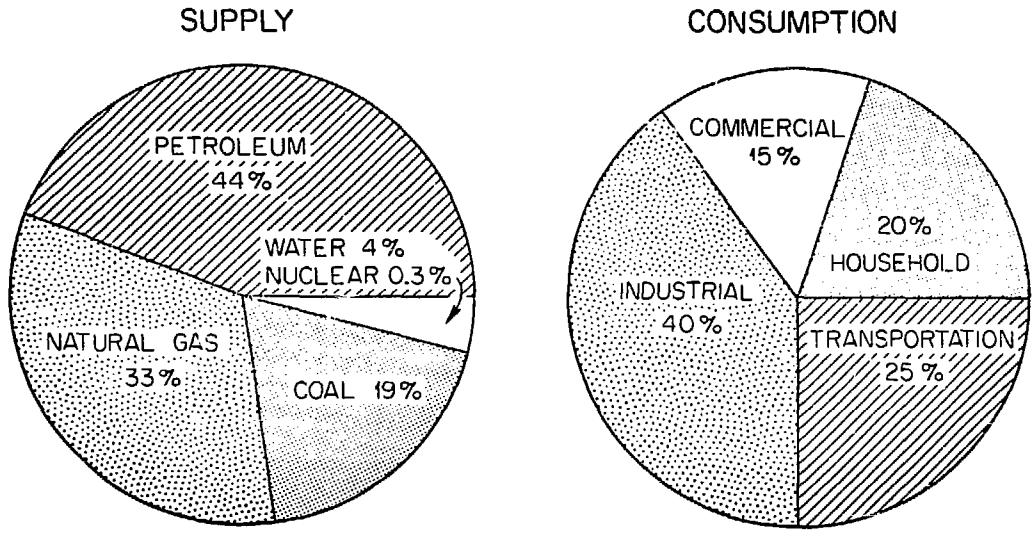

Figure 11

energy supply technologies will be developed that heretofore were simply not competitive. In the long run our energy supply system will become much more diverse and, as a consequence, more stabilized. Therefore in the long run the new higher price for energy is probably good news for mankind.

But what about energy consumption? Our consumption system results from decades of continually decreasing energy prices. How should this system change in response to the new price? How fast can we make that response? Current energy supply and consumption patterns are summarized in figure 11. Petroleum and natural gas now comprise more than three-fourths of our entire energy supply. With natural gas on the decline and with petroleum production peaking it is obvious that our supply picture will be changing markedly over the next half century. On the consumption side, the proportion of energy used in various end uses has been changing only slowly with industries' share decreasing slightly and the commercial/residential share increasing. Electricity production, which now accounts for about 25 percent of total U.S. energy consumption, is projected to grow to as much as 50 percent of total energy consumption between now and the end of the century. A slightly different breakdown of end uses of energy is shown in figure 12. Space heating and cooling in buildings account for 21 percent of total consumption. Direct heat and process steam account for about 27 percent. As much energy goes into water heating as is consumed in air conditioning. One important consumer of electricity is not highlighted in

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End Uses of Energy in the U.S., 1970

Transportation	25%
Space heating	18
Process steam	16
Direct heat	11
Electric drive	8
Raw materials	6
Water heating	4
Air conditioning	3
Refrigeration	2
Cooking	1
Other	6

Figure 12

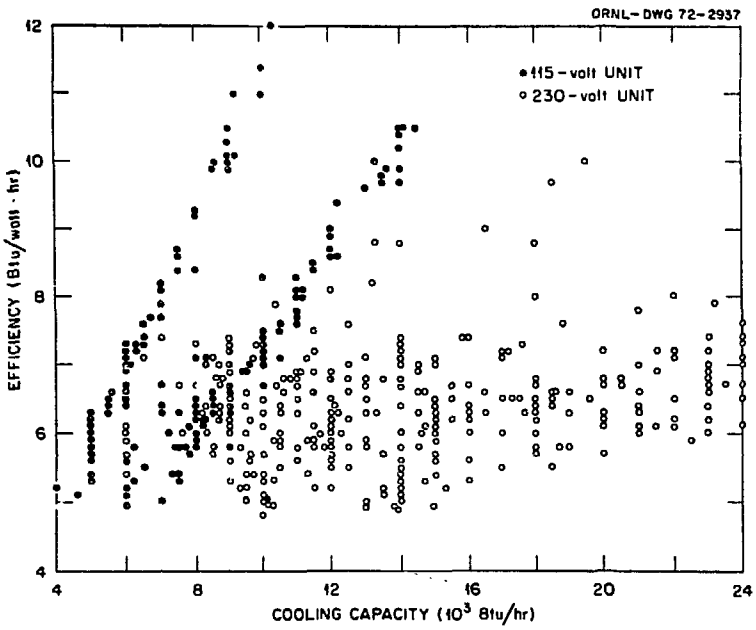
figure 12; lighting accounts for about 20 percent of our entire electricity consumption.

If we wish to understand energy consumption clearly enough to accurately project what will happen over the next decade or two we must look at the consumption patterns of electricity very carefully. One of the first things to note is that the growth in electrical consumption over the past two decades has been five to ten times population growth rates. There are two main reasons for this high growth. First electricity is "clean", high in intrinsic quality, and versatile. Therefore a lot of the demand growth is derived from people switching over from other energy sources (e.g. coal furnaces in individual homes). The second factor is that growth of per capita income has been absorbed by a wealth of energy intensive appliances (e.g. tele-

vision, air conditioners, dishwashers) which fueled demand growth. It is equally interesting to note that the surge in the sales and variety of these kinds of new energy consuming appliances since 1950 has slowed down. Sales have slowed because the market is now becoming nearly saturated for many of the appliances (with a notable exception of air conditioning). New kinds of major energy-consuming appliances are not appearing very often.

Unfortunately many appliances have been constructed with the goal of minimum purchase cost and have very poor electrical efficiency, sacrificed in order to cut manufacturing cost. Air conditioners can be found on the market that have electrical efficiencies ranging over a factor of 3! In figure 13 we show the range of electrical efficiency available for various commercial room air conditioners as a function of their size. High efficiency units generally have slightly higher manufacturing costs but it is interesting to note that market price is not strongly correlated with efficiency.

Prior to the new energy price shift the only motivation to the manufacturer to make a highly efficient unit was to penetrate the market of higher capacity air conditioners while keeping power requirements within limits of standard household wiring. The consumer had essentially no information at the point of purchase about the electrical efficiency of competing air conditioners or about his "best buy" in terms of his minimum total cost to own and operate. In the absence of that information most purchase decisions were based on minimum first cost; this usually meant that the consumer paid more for the aminity of air conditioning than needed and that electrical demand grew unproductively. It seems not only sensible but imperative that consumers be provided with information about efficiency so that they can make more enlightened purchase decisions. It seems defensible to insist that air conditioners sold in interstate trade equal or exceed some minimum efficiency. The same argument holds for heating systems. Electrical resistance heat is half as efficient as heat



Efficiency of Room Air Conditioners as a Function of Unit Size.

Figure 13

derived from an electric heat pump but its lower capital cost attracts the speculative builder since it lowers the "first cost" of a house. Central electric resistance heating, the so-called electric furnace, should be banned except as a back-up to a more efficient system such as a heat pump.

Energy consumption in the commercial sector is mostly lighting, heating and cooling. Here again we face the problem of capital versus operating costs. The financial market is such that the building owner is inclined to minimize capital investment and pass on operating costs to the tenants. As a consequence commercial buildings tend to be very energy inefficient. Buildings are generally overlit, under-insulated, over-cooled in summer, and over-heated in winter. Waste heat from lighting can account for 60% of the air conditioning load in some commercial buildings.

It is now becoming clear that it is economical to redesign new structures for much greater energy efficiency. Utility costs can be cut by 60 percent or more by careful architectural design and engineering. Such gains are not likely by retro-fitting existing structures but retrofit can economically reduce energy requirements by 30 to 40 percent (e.g. through increased insulation and weather stripping, slight thermostat adjustments, lessened humidity control, more sophisticated operation and maintenance of the heating and cooling system, and decreased illumination levels).

In the transportation sector we find major opportunities for productive increases in energy efficiency. This is particularly important since transportation accounts for approximately 60% of our oil consumption. Private automobiles account for 55% of all of our transportation energy. Energy efficiency has been shifting rather rapidly over the past twenty years in certain sectors of our transportation system. In figure 14 we see that energy consumption per passenger mile has dramatically decreased in rail transportation (due to replacement of the steam locomotive)

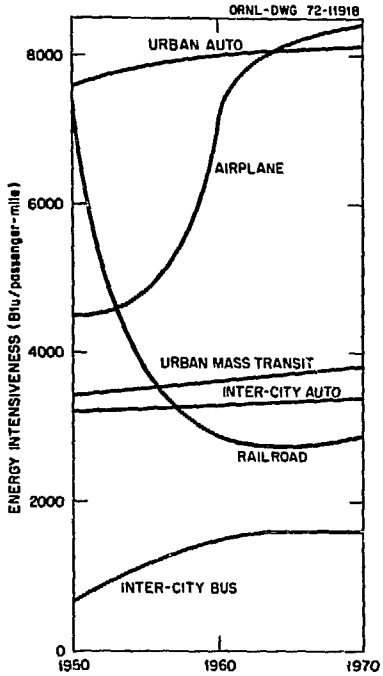


Figure 14

but sharply increased in the case of the airplane (mostly due to the higher speed jets). At the same time that airplanes have been the fastest growing sector in passenger transportation the rails have steadily lost passengers. Clearly we have been trading time for energy.

While we might think of energy efficiency as a major source of the increased use of energy in transportation over the past twenty years this turns out not to be the case. In figure 15 we show that per capita travel has accounted for almost half of the entire increase in energy consumption in the transportation sector over the past twenty years! Quite clearly population growth and energy efficiency have played important roles but the major factor has been the fact that we have used our increased affluence to travel more.

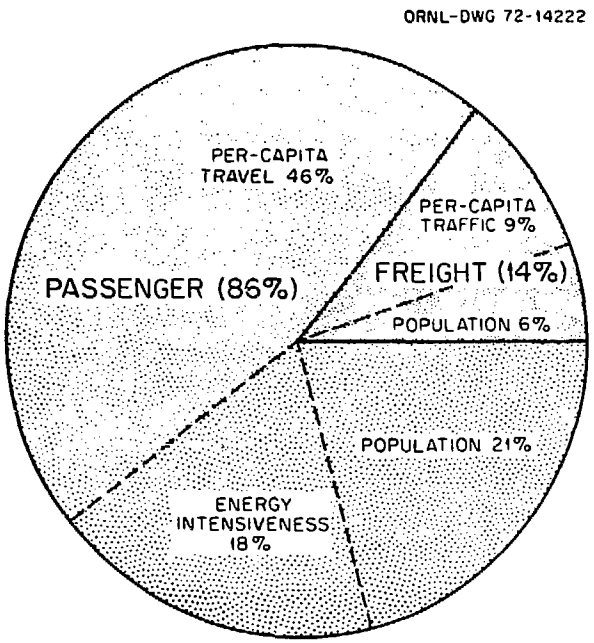


Figure 15
Sources of Transportation Energy Increase
1950–1970

We must also remember that there are both direct and indirect energy investments in maintaining our lifestyle (see figure 16). In the case of the automobile the indirect energy investment required to produce and maintain the vehicle and highway are a very important fraction of the total energy consumption of the automobile over its lifetime (about 6000 out of 16,000 BTUs per mile). It is now quite evident that the new price of energy and the uncertainty of its availability is causing the American automobile buyer to shift rapidly toward more efficient cars. The average efficiency of the new American car in the 1976 model line is more than 1/3 greater than the average efficiency of new cars only two years ago. One consequence of this rapid market response is that gasoline sales, which until recently grew at over 3% per year, will probably remain level for as much as a decade.

Analyses of the many places in which energy is used in our economy indicate that in the face of the new energy price a lot of responses are not only possible but

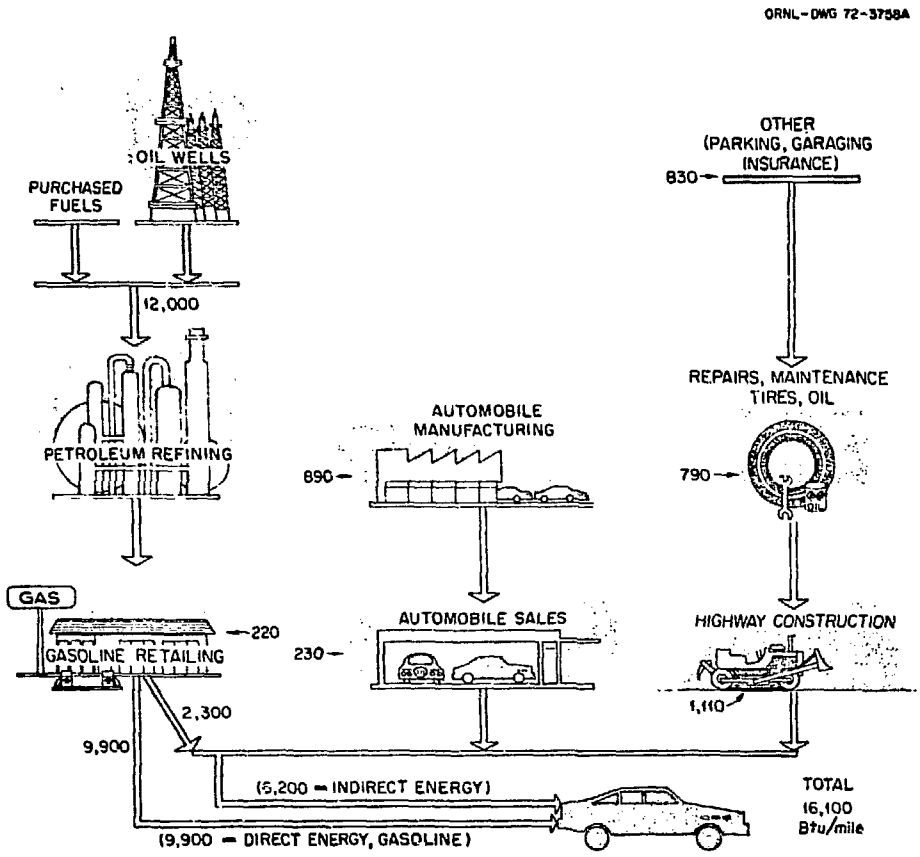


Figure 16

are probable in the long run if we assume that people make economically sensible decisions. These responses include shifts to higher efficiency, alteration of lifestyles, changes in urban growth patterns, and new industrial processes. Also the same analyses indicate that there are many relatively easy and productive short term expedients to reduce energy demand growth. Conservation, a rational economic response to price and other market factors, will not only provide us important short-run slack in our energy demand but will also provide us in the long run with an energy system that can maintain amenities with a dramatically less energy per capita.

One of the most important factors to include in projecting energy demand is that of "time lag". People will respond to relative price shifts but the time required for such a response varies from months to many years. In the electrical sector studies of price response indicate that only about 10 to 15 percent of the total response to a price change occurs during the first year and that fifteen years or more may be required for the ultimate response. Therefore it may seem that the response to a price change may be relatively inelastic but that is only in the short run. Some long run elasticities for electricity have been estimated and are given in figure 17. A value of (-1.3) implies that an increase in electricity price of 1% will ultimately result in a decrease of electricity use by 1.3%. Such a decrease would result as a

collective result of conversion to more efficient air conditioners, the addition of thermal insulation in buildings, decreased illumination levels, changes to more efficient forms of lighting, etc. When elasticities such as those given in figure 17 are used to calculate future demand growth for electricity we find that rather than a continued exponential growth the growth rate tails off rather sharply (Projection A in figure 18). Projection B in the figure was calculated on the assumption that the price of electricity and fossil fuels increases by 50% by the turn of the century, that population increases at 1% per year and per capita income increases at $2\frac{1}{2}$% per year. Projection C assumes a doubling of electricity and fossil fuels price by the year 2000, an annual population growth decreasing from 1% in 1970 to 0.5% in 2000, and per capita income increasing at $2\frac{1}{2}$% per year. These projections should not be interpreted as firm predictions. What they do show is that when we take into account price changes and shifts in our demographic and economic system there will inescapably result a greatly lowered demand growth rate for energy in the U.S. Electricity demand growth will probably continue to be higher than other sectors of our energy economy due to the shift to electricity from other fuels such as natural gas.

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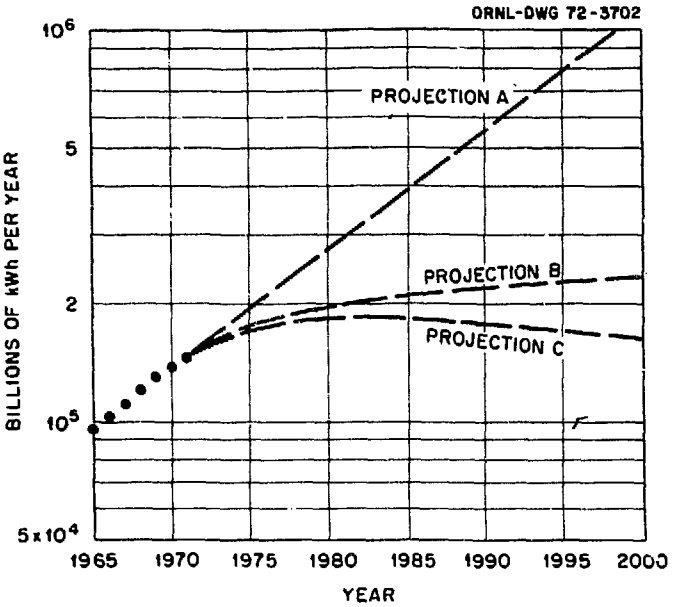
LONG-TERM ELASTICITIES
FOR ELECTRICITY

PRICE OF ELECTRICITY:		
RESIDENTIAL	-1.3	
COMMERCIAL	-1.5	
INDUSTRIAL	-1.7	
AVERAGE		-1.5
PER CAPITA INCOME		+0.6
PRICE OF FOSSIL FUELS		+0.1

Figure 17



Alternative Electricity Projections.

Figure 18

Summary

As we look to and beyond the end of the century we can speculate about the relative roles of various domestic and imported energy resources as well as that of conservation in meeting demand growth:

1. Energy consumption will taper off from the recent 4½% per year to about 2% or less. This decrease will be due to lower population growth rate, shifts to more efficient energy consumption patterns, market saturation of energy consuming equipment, and alterations of personal lifestyle.

2. Demand growth in the electricity sector will continue to exceed average energy demand growth, due to the depletion of natural gas reserves and the versatility of electricity as an energy source.

3. New technological developments in both energy production and in efficiency of energy consumption will provide important new options before the turn of the century. In the interim, however, the most promising new "source" for energy has a negative sign in front of it, namely energy conservation. If we accept the notion that it is just as good to save a barrel of oil through increased efficiency of use as it is to produce a new barrel of oil then we would make our investment decisions based on the cost of either saving an equivalent barrel of oil or producing a new barrel of oil. Since environmental, health, and other externalities still exist in the energy supply area a barrel of oil saved is worth even more than a barrel of oil earned. If it costs the equivalent of 3 to 4 dollars per barrel of oil saved through the mechanism of increased thermal insulation in buildings and if it costs about $12

per barrel to discover and develop new oil, then clearly the economic decision would be to invest in insulation rather than in new oil. We must make our decisions about capital flow into the energy problem on the basis of maximum cost-effectiveness and this means that much more attention should be given to productive ways to decrease demand growth. This is a new ways of thinking for western man, who is so accustomed to solving problems through expansionism and increased production; however, it is imperative that we not only begin to think in these ways but to act accordingly.

Most of the illustrations used in this paper were taken from the results of research conducted at the Oak Ridge National Laboratory by members of the Environmental Program sponsored by the National Science Foundation and ERDA. Further information can be obtained by contacting Ms. Miriam Guthrie, Energy Information Center, Energy Division, ORNL, Oak Ridge, Tennessee 37830.

SOLAR ENERGY RESEARCH AND UTILIZATION

by

William R. Cherry

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ABSTRACT

The gas and oil shortages of the 1970's are forewarnings of more serious energy deficiencies to come near the turn of the century. Solar energy processes are on the verge of commercial readiness to help the nation utilize this enormous, renewable clean source for many of our future energy needs. The paper describes what role solar energy will play in the heating and cooling of buildings, the production of renewable gaseous, liquid and solid fuels, and the production of electric power over the next 45 years. Potential impacts on the various energy markets and estimated costs of such systems are discussed along with illustrations of some of the processes to accomplish the goals. The conclusions of the NSF/NASA Solar Energy Panel (1972) are given along with the estimated costs to accomplish the 15 year recommended program and also the recent and near future budget appropriations and recommendations are included.

INTRODUCTION

The energy "crisis" of 1973-1974 is mostly associated with the production of useable fuels and their distribution and not because the world has run out of natural gas and crude oil. Further, since a great deal of our energy is wasted in overheated, overcooled and poorly designed structures and oversized, overpowered vehicles the demand for energy has become disproportionate to our true needs. Even with some moderation on these demands the world's energy consumption is expected to continue to increase for the foreseeable future creating major problems world wide in the extraction, refinement and distribution of our fossil fuels in the next few decades.

The shortages of the 1970's have brought into focus the necessity for man to look at renewable sources of energy which are abundantly available yet, when used, have minimal effect on the environment. One of the few energy sources that meets these criteria is Solar Energy. Numerous times in history the use of solar energy has been tried and discarded because it was not cost competitive with existing energy sources. However, the true costs of the conventional sources of energy have rarely been taken into consideration especially when the costs of destroyed land, disposal of useless or hazardous wastes and the degradation of the atmosphere, health, structures, flora and fauna are considered. Now with the cost of fossil fuels increasing substantially and the problem of future availability questionable, solar energy is finding applications which are competitive with conventional sources of energy.

Availability of Solar Energy

Solar energy arrives on the surface of the 48 contiguous states at the average rate of 4000Kcal/M^2day (1500Btu/ft^2/day), more in the southern U.S. and less in the north. Figure 1 shows the anticipated consumption (Ref. 1) of energy in the U.S. for all purposes for the years 1970,1977,1985,2000, and 2020 amounting to 16,21,29,44 and 75 x 10^{15}Kcal/yr respectively. To produce the equivalent of the total expected energy requirement for the U.S. in the year 2000 by converting solar energy arriving at the ground at 10% efficiency it would require about 4% of the U.S. 48 state land area or about 322,500Km^2 (124,000 square miles). This is slightly larger than the state of Arizona. To put it in another perspective, the major metropolitan areas of the U.S. cover1½% of the U.S., the Great Lakes occupy about 3% and U.S. farms cultivate greater than 15% of our land area to produce about 1% of our energy - food. Therefore, setting aside various regions in the U.S. as energy farms shouldn't create major problems; in fact, a lot of non-productive land would suddenly become useful.

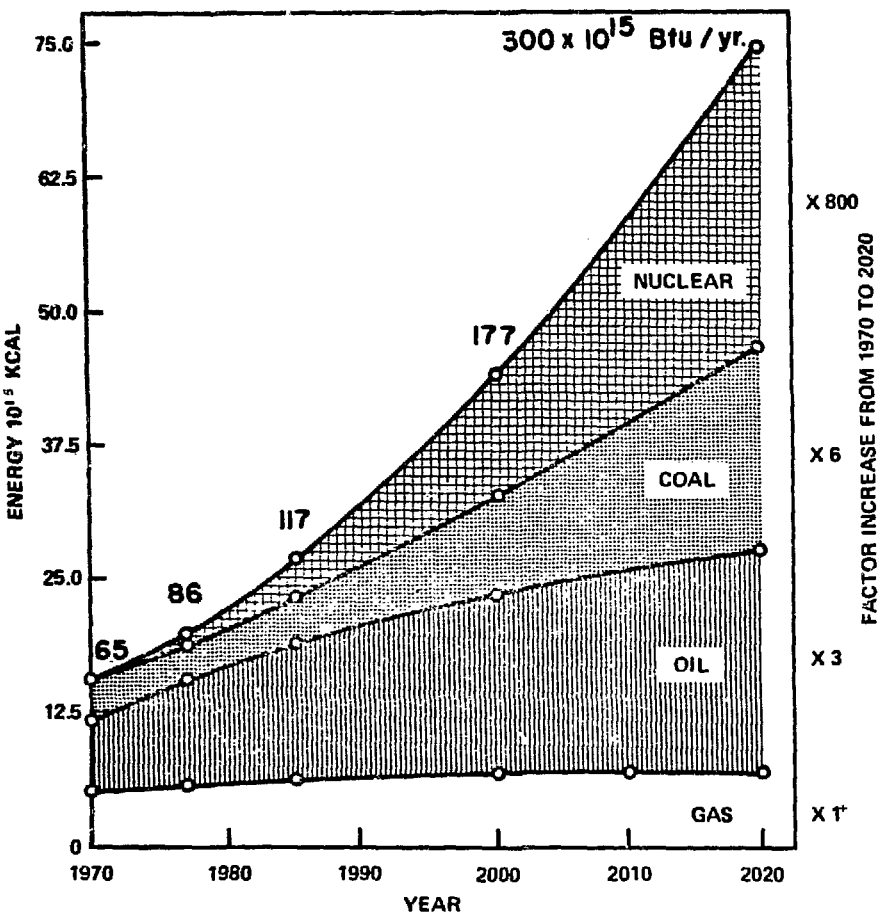


Figure 1. Projected U.S. Energy Demanded by Source

In the Solar Energy Panel's report (Ref.2) of December 1972 three applications were identified in which solar energy could have a major usage impact. These are:

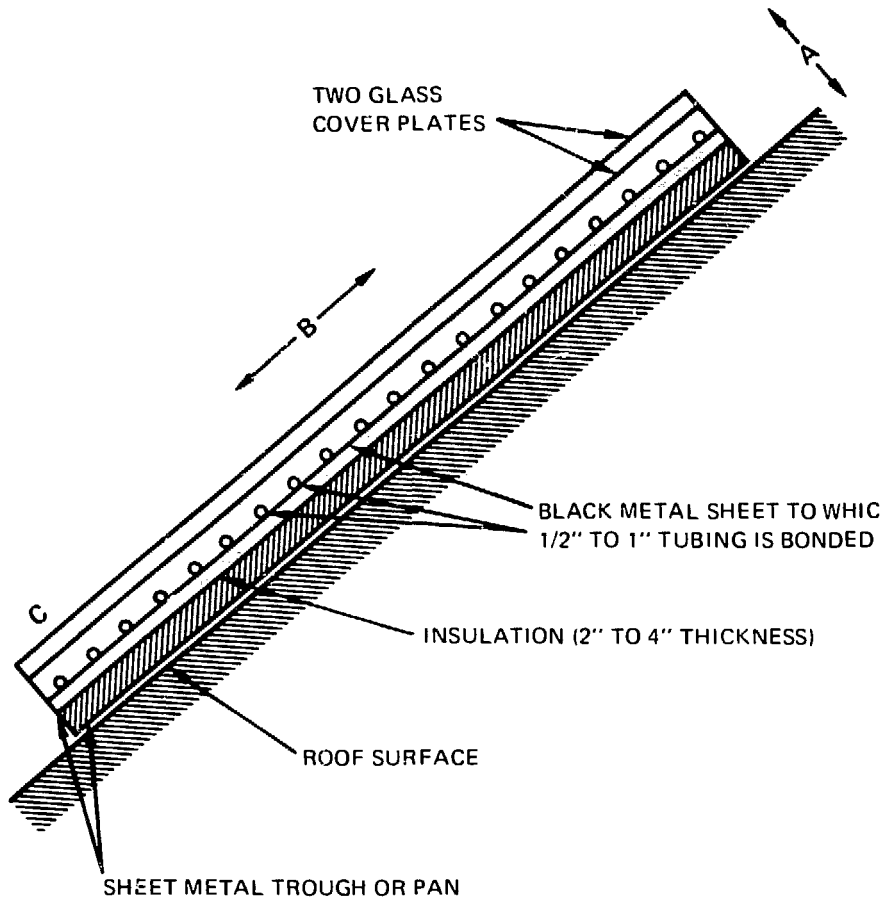
Thermal Energy for Buildings
Production of Renewable Clean Fuels
Electric Power Generation

THERMAL ENERGY FOR BUILDINGS

By the year 2000 about 5.25×10^{15} Kcal (21×10^{15} Btu) or 12% of the U.S. energy consumption will be used for heating and cooling buildings. If only 10% of this load is derived from solar energy it would represent a savings of over 0.5×10^{15} Kcal (2×10^{15}Btu) of fossil fuels which at $\$8/10^6$ Kcal($\$2/10$ Btu) would represent an annual savings of over $4 billion! Over 30 buildings in the U.S. have been equipped with solar heating systems which derived various amounts of their heating needs but none attaining 100%. The houses have been built in Massachusetts, Maryland, Florida, Delaware, New Mexico, Arizona, California, Oregon, Colorado and other areas. Only a very few structures have been built to provide a significant amount of the cooling needs of a house but great progress is now promised. The major capital investment in a solar house is the collector which must be large enough to absorb sufficient thermal energy to provide adequate instant heat and allow for storage of heat during the night or for inclement weather. The black flat plate collector covered with one or more layers of glass, illustrated in Figure 2 is typical of many systems so far developed. Some systems do use water cascading down the hot collectors rather than the closed rubes illustrated, while some systems circulate air over the collectors and store thermal energy in rock beds. Water temperatures range up to the boiling point under good sunny conditions and precautions must be taken about excessive collector temperatures if the system is shut down during the summer. In regions with favorable night sky radiation in summer, bags of water built into the roof have been used for cooling of dwellings. During the day the bags are shielded from the sun and absorb heat from within the structure. At night the shields are removed and the heat radiated to the night sky thus cooling the water mass for the next day's cooling process. In winter, the process is reversed, exposing the water bags to the sun in the daytime to absorb thermal energy, then shielded from the sky at night to prevent readiation loss and provide warmth to the dwelling.

An experimental house in Delaware is equipped with a combination of cadmium suplhide photovoltaic arrays and flat plate collectors as illustrated in Fig. 3. Air is circulated behind the solar arrays and the latent heat is stored in tubes containing fused salts which have melting points of about $10^{\circ}C$ ($50^{\circ}F$), $24^{\circ}C$ ($75^{\circ}F$) and $50^{\circ}C$ ($120^{\circ}F$). During the heating season the house air is curculated over the $50^{\circ}C$ ($120^{\circ}F$) salts while during the summer it passes by the $10^{\circ}C$ ($50^{\circ}F$) salts. A small heat pump allows the shifting of the thermal energy from one fused salt to another depending on the need. The electric power generated by the solar arrays is passed to an electrochemical storage system where it is held in reserve until needed or directly used in the house. While dwellings in the U.S. have used combinations of solar thermal collectors and wind generators to provide heating and electric power this is the first structure which has combined photovoltaics and thermal systems.

A 1970 study (Ref. 3) of costs of residential space heating showed that in a number of places in the U.S. solar energy was competitive with fossil fuels at that time. With the recent dramatic increases in natural gas and oil fuels, many more regions of the U.S. will find the use of solar energy very competitive. When solar cooling can be used in conjunction with heating then solar energy for space conditioning becomes very attractive. An industry must be started so that



NOTES: ENDS OF TUBES MANIFOLDED TOGETHER
ONE TO THREE GLASS COVERS DEPENDING
ON CONDITIONS

DIMENSIONS: THICKNESS (A DIRECTION) 3 INCHES TO 6 INCHES
LENGTH (B DIRECTION) 4 FEET TO 20 FEET
WIDTH (C DIRECTION) 10 FEET TO 50 FEET
SLOPE DEPENDENT ON LOCATION AND ON
WINTER-SUMMER LOAD COMPARISON

Figure 2. Solar Collector for Residential Heating and Cooling

the cost advantages of mass production can be brought to bear on the present high cost of collectors. These present \$64 - \$107/m^2 (\$6-\$10/ft^2) must approach \$32-\$42/m^2 (\$3-\$4/ft^2) and the public must have the benefits of a service industry before wide spread use will take place. Government funding will probably be necessary for "pump priming" of the industry and incentives given for installing capital intensive equipment which must be amortized over the life of the dwelling. Operating and maintenance costs should be low while fuel costs are zero. In regions where solar heating cannot handle the entire load, an auxiliary fossil fuel must be integrated with the solar system.

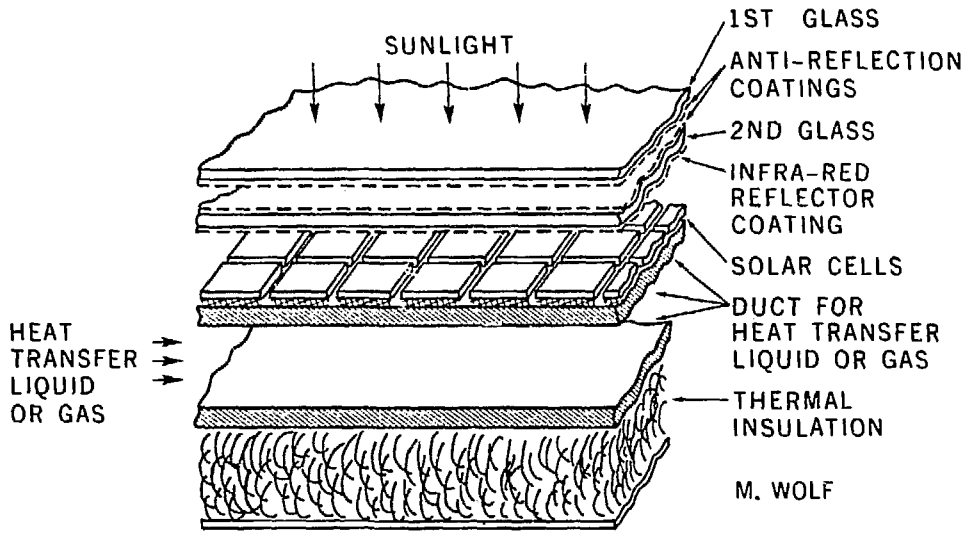


Figure 3. Structure of Combination Thermal-Photovoltaic Solar Collector

PRODUCTION OF RENEWABLE CLEAN FUELS

Over 95% of the U.S. total energy is derived from fossil fuels. Until the last few years, much of the industry and central power plants were attempting to use natural gas for firing boilers in an attempt to comply with NEPA emission standards. When natural gas became difficult to obtain, especially for new installations, oil was selected as the fuel because of cost and ease of use. This, plus the addition of millions of new vehicles to the economy each year, placed an unprecedented demand on oil refinery capacity causing short falls to appear in various locations in the U.S. Because foreign crude oil was available at costs below domestic stock, the U.S. became more and more dependent upon imports, reaching somewhere near 35% of our total demands by 1973. About half of these imports were from the middle east and when that supply became seriously reduced in late 1973 the availability of petroleum products reached a critical stage. President Nixon's late 1973 proclamation to become independent of outside sources for energy is indeed a desirable one but will require a great deal of exploitation of our natural deposits of gas, oil and coal. In addition, solar fuels which can supplement the Nation's growing demand for duel yet have a minimal impact on the environment and even help dispose of our wastes.

GASEOUS FUELS

In general about 285 m^3 ($10^4 ft^3$) of methane gas can be produced from 900kgm (one ton of dry organic material (Ref.4) which corresponds to about 2.5×10^6 Kcal (10^7Btu) of heating value. The U.S. presently uses about $0.57 \times 10^{12} m^3$ ($20 \times 10^{12} ft^3$) of natural gas per year. Under advanced growth conditions, 2% conversion efficiency, about 4.5×10^6kgm/km^2 (20 Tons/acre)of organice material can be produced per year and even more might become available through plant research. Therefore, each km^2 (acre) could produce enough organic material to yield $1.4 \times 10^6 m^3/km^2$ ($2 \times 10^5 ft^3$) of methane gas. Thus $0.57 \times 10^{12} m^3$/yr (20 x $10^{12} ft^3$/yr) divided by $1.4 \times 10^6 m^3/km^2$ ($2 \times 10^5 ft^3$/acre) yields $4 \times 10^5 km^2$ (10^8acres) of the U.S. to produce all the current natural gas consumption. This is equivalent to about 5% of the U.S. 48 state land area or less than 1/3 of the area used for farming. This crop being renewable year after year could continue to supply a large amount of the nation's gaseous fuel needs for years to come. Costs of natural gas during 1971 ranged from about $1.00 to $4.00 per million Kcal compared with estimated costs of $2.00 to $8.00 per million Kcal for solar produced methane.

LIQUID FUELS

The pyrolysis or organic materials under an atmosphere devoid of oxygen at temperatures greater than 500°C will produce both combustible gases and a good quality oil suitable for use in power plants. (Ref.5) Research on 17,600kgm (4 Ton) per day plant showed that about 2 barrels of oil can be derived from a 900 kgm (ton) of dry organic material. Enough gas was also produced to provide the fuel to heat the reactor to produce the oil. If the $4 \times 10^5 km^2$ (10^8 acres) mentioned in the previous paragraph were devoted to oil production at 4.5×10^6 kgm/km^2 (20 tons per acre) per year about 4×10^9 barrels of oil could be produced each year from this land. This is equivalent to about 2/3 of the present total U.S. petroleum consumption. Major developments in farming and harvesting enormous crops at low cost must be achieved before such a system will compete with natural crude oil prices but the recent upswing in costs and the eventual nonavailability of natural crude oil will make the pyrolysis process more attractive. Natural crude ranged from about $2.00 to $4.00 per million Kcal in 1971 compared to estimated costs of $3.00 to $6.00 per million Kcal by the solar /pyrolysis process. Already this process is being used for the disposal of urban wastes and because there is a credit earned for the cost to dispose of garbage this helps to make the liquid fuels produced by these plants competitive with natural fuels. If the total U.S. solid urban waste of about 4.5×10^{10}kgm/yr (5×10^7 tons/yr) were subjected to pyrolysis about 10^8 barrels of oil could be obtained. This is about 1½% of our annual petroleum consumption.

SOLID FUELS

With the drive to convert the gas and oil burning boilers of industry and the electric utilities to coal perhaps some could be converted to wood burning. Until about 1971 more energy in the U.S. was derived from wood burning than controlled nuclear fission. A recent study (Ref.6) showed that in certain regions of the U.S. conditions exist which would permit the production of clean, renewable wood fuels at a competitive price with fuel oil. Assuming a 1% solar energy capture efficiency and an average annual insolation 4000Kcal/m^2/day (1500Btu/ft^2/day) an aera of about 1000km^2 (400 square miles) would produce enough wood on a continuous basis to power a 1000 MW steam electric plant operating at 35% efficiency with a load factor of 75%. This energy plantation would have the power plant located near its center and would emit a minimum of pollutants because of complete combustion nutrients in the plantation soil from which the fuel is derived. Improved photosynthetic processes could reduce the land area needs. Also, they would be attractive and useful for recreation and

ecological purposes. Modern growing, harvesting chipping and drying processes would have to be utilized and developed. Estimates of the price of fuel derived from pulpwood and chips ranged from about $4.60 to $5.40 per million Kcal in 1971. Coal and oil costs ranged from about $2.00 to $4.00 at that time.

ELECTRIC POWER GENERATION

In 1970 about 22% of our total energy consumption was devoted to the generation of electric power including the use of gas, oil, coal and nuclear energy. Only electric power produced from hydroelectric plants, amounting to about 3% of our total energy demand, did not consume some unrenewable resource for its production. Unfortunately most of the choice sites for hydro power plants in the U.S. have been built up and it appears that it is unlikely to ever double the production of electricity by this method on the U.S. mainland. Projections (Ref.1) indicate that more and more of our increasing total energy consumption will be used to produce electric power amounting to 27% in 1977, 32% in 1985, 43% in 2000 and greater than 50% by 2020.

Nuclear energy has been the bright hope of the future to pick up the electric power generation load from the fossil fuels. With the many problems the world is facing in harnessing the atom ranging from sociological, ecological to technological it is clear that alternate methods for producing electricity should be explored now so that they will be ready for wide scale application in the next 15 to 30 years. Following are some indications of the potential of solar energy related methods which could provide significant quantities of electric power to the U.S.

WIND POWER

Kung's (Ref.7) studies indicate that between 1% and 1½% of the 1 kw/m^2 of energy reaching the earth's surface in the U.S. is converted into the kinetic energy of the atmosphere thus amounting to some 10 to 15 watts/m^2. Certain regions of the U.S. have reliably continuous winds particularly along the New England and Middle Atlantic East Coasts, along the Great Lakes, through the Great Plains, along the Gulf Coast, through the Rockies and Cascades and along the Aleutian Chain of islands. It is estimated (Ref.2) that there is over 10" kilowattts of generating capacity in the winds over these regions. If only 0.1 of 1% of this energy were converted to electric power it would be equivalent to one quarter of the total electric generating capacity of the U.S. today. Due to friction and deflection by buildings and natural features of the terrain the aeroturbines should be placed from 30 to 350 meters (100 to 1000 feet) above the ground and in those locations where winds persist at 4.5 to 6.5 m/sec (10 to 15 mph) or greater. A comprehensive study (Ref.8) shows how the total electric power requirements for all of New England could be derived from floating wind stations located off shore. Hydrogen can be produced as a clean fuel from such an installation, stored in underwater pressure vessels and shipped to the mainland as a clean fuel in place of the diminishing natural gas. Table 1 indicates the electric power generation possible by the year 2000 if steps are taken now to mass produce this significant energy source. Costs of plant installations are expected to range from about $300 to $600 per kilowatt and electric power costs ranging from 16 to 21 mills per kWh. One of the largest aeroturbines built in the U.S. was located at Grandpa's Knob near Rutland, Vermont. In a 9m/sec (20 mph) wind this unit developed 1.25 mw from the 53 meter (175 ft) tip to tip blades. An ice storm during the early 1940's caused a blade fracture and the whole system fell into disuse when low cost electric power was strung through New England by the Rural Electrification Administration shortly after World War II.

Table 1

Electrical Energy Production from Wind Power by 2000 AD

	Annual Power Production	Possible by Year
Offshore, New England	318×10^9 kWh	2000
Offshore, Eastern Seaboard, along the 100 meter contour, Ambrose shipping channel south to Charleston, S.C.	283×10^9 kWh	2000
Along the E-W Axis, Lake Superior (320 m)	35×10^9 kWh	2000
Along the N-S Axis, Lake Michigan (220 m)	29×10^9 kWh	2000
Along the N-S Axis, Lake Huron (160 m)	23×10^9 kWh	2000
Along the W-E Axis, Lake Erie (200 m)	23×10^9 kWh	2000
Along the W-E Axis, Lake Ontario (160 m)	23×10^9 kWh	2000
Through the Great Plains from Dallas, Texas, North in a path 300 miles wide W-E, and 1300 miles long, S to N. Wind Stations to be clustered in groups of 165, at least 60 miles between groups (sparse coverage).	210×10^9 kWh	2000
Offshore the Texas Gulf Coast, along a length of 400 miles from the Mexican border, eastward, along the 100 meter contour.	190×10^9 kWh	2000
Along the Aleutian Chain, 1260 miles, on transects in each 35 miles long, spaced at 60-mile inervals, between 100 meter contours. Hydrogen is to be liquified and transported to California by tanker.	402×10^9 kWh	2000

Estimated Total Production Possible: 1.536×10^{12}kWh by year 2000

Enormous amounts of solar energy is absorbed by the tropical oceans increasing their surface waters to temperatures above 27°C (80°F). The melting of polar ice caps and glaciers causes a large source of cold dense water at about 4°C (40°F) to flow along the ocean bottoms toward the equator eventually warming and rising to the surface and then heading North in the Northern hemisphere. In regions where the warm and cold water overlay each other, such as in the Gulf Stream, the potential exists for the conversion of this energy into electricity using Carnot cycle engines. Figure 4 illustrates a possible floating station (Ref.9) with dimensions of 120 meters (360 ft) long by 100 meters (300 ft) deep located in the Gulf Stream and drawing warm water from the surface and the cooling water from depths of 600 to 900 meters (2000 to 3000 feet). Assuming a 3% efficient system, a power plant of 100 mw would require the passage of about 1.8 million m^3 (64 million cubic feet) of warm water per hour for the boiler. With a 1.5 x 100 meter (5 foot high by 300 foot long) intake it would need to capture water at the rate of 3.5m/sec (8 miles per hour), just about the speed of the Gulf Stream. Cooling water for the condensers would be drawn through a pipe about 10.5 meters (35 feet) in

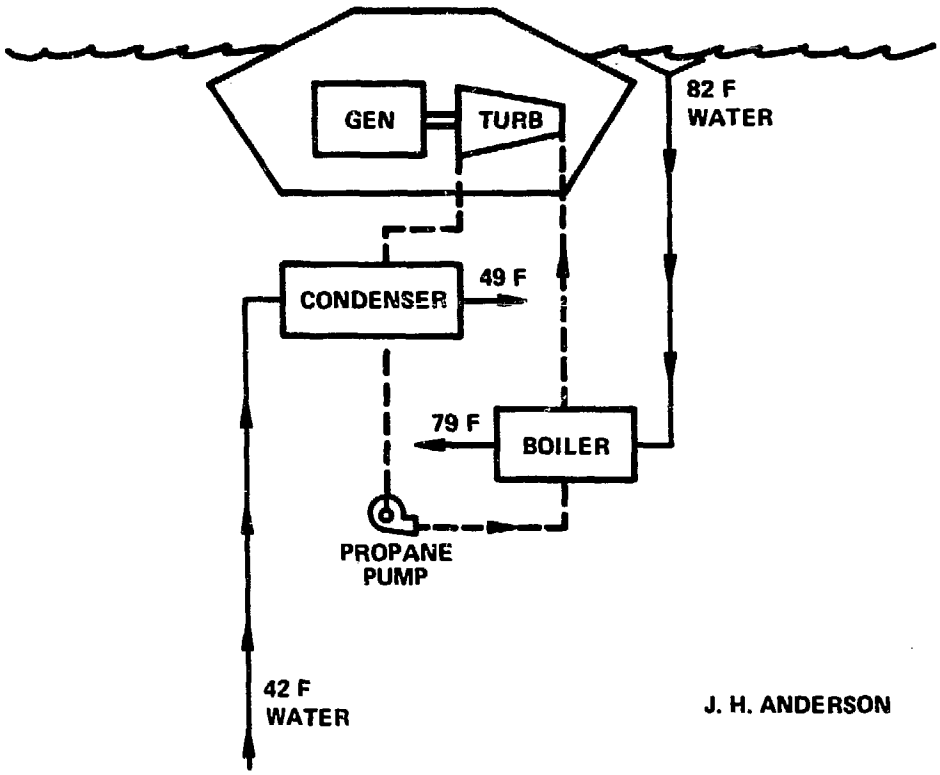


Figure 4. Sea Solar Power Plant

diameter from near the bottom of the ocean. The propane would be contained in a closed system and is the medium which powers the turbogenerator producing the electricity.

Since ocean thermal power plants are closely allied to the ship building idustry some reasonable estimates can be derived for the power station costs. Installation costs are estimated to be between $300 to $500 per kw and because of very favorable load factors of 90% the cost of power is expected to range from 5 to 10 mills per kWh. Ocean thermal power stations obviously require the special conditions of warm surface waters and cool underlying currents. This occurs only on the Gulf and lower Atlantic coasts of the U.S. but could be developed as a major electric power source for those regions of the U.S.

CONCENTRATED SOLAR THERMAL ELECTRIC POWER PLANT

Vast regions in the SW portion of the U.S are endowed with direct sunshine between 80% and 90% of the possible sunlight time. By focussing the solar radiation on tubular collectors under a concentration factor of about 10, temperatures of 425°C (800°F) or more can be obtained. The general scheme of such a system is shown in Figure 5. Several studies (Ref.10) are underway to better identify the problems of large scale solar thermal systems and components. If systems of 20% efficiency evolve which are economically competitive with conventional electric power generation methods, then a 1 million Kilowatt power station would occupy about 26 sq. km (10 sq. mi.) of desert in the U.S. SW. Much new technology and materials developed for the space program will be brought to bear on the solar thermal collection, transmisison, storage and conversion problems to see how such systems fit into the Nations' future. Plant installation cost estimates range from about $900 to $2000 per installed kilowatt. This is considerably more than fossil fuel plants but nuclear installation costs are now rising above $500 per kilowatt. When fuel and siposal costs for the life of these plants are considered there could be come major trade-offs by the 1990's.

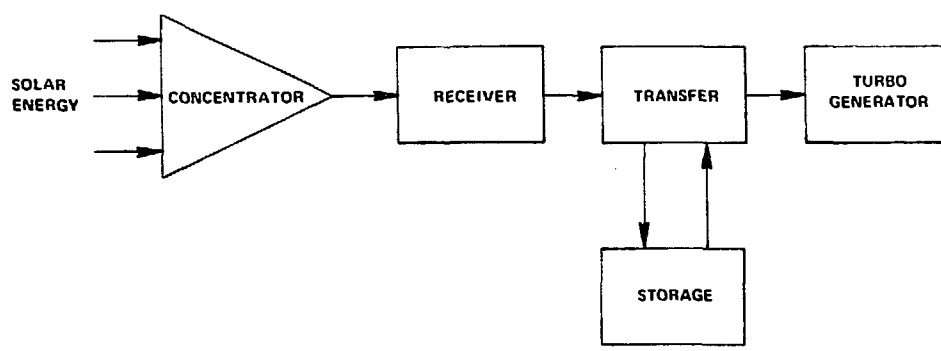


Figure 5. Thermal Conversion Concept

PHOTOVOLTAIC ELECTRIC POWER GENERATION

Photovoltaic type phenomena have been known since first reported by E. Becquerel in 1839. It wasn't until 1954 when the Bell Telephone Laboratories announced the silicon solar cell that practical conversion efficiencies approach-

Table 2

Solar Cell Efficiencies

Material	Air Mass Zero (Space)	Air Mass One (Ground)
Silicon	11-12%	13-14%
Gallium Arsenide	10-11%	12-13%
Cadmium Sulphide	3-4%	5-7%

ing 10% became available. Since that time, about a dozen substance have been researched for their potential as practical photovoltaic materials. Silicon solar cells have been used almost exclusively for powering long life satellites since the launching of Vanguard 1 March 17, 1958. Gallium arsenide was developed to a space flight quality but didn't replace silicon because of its significantly higher cost. Thin film cadmium sulphide cells in 7½ x 7½ cm (3 x 3 inch) sizes have not as yet proven themselves suitable for space flight but are striving for acceptance in terrestrial applications. The greatest problem in adopting photovoltaics for ground applications is their cost, primarily caused by the very limited production needed in the space program and the rather sophisticated materials and processes required in their production. Typical performance characteristics of the three main solar cell materials are shown in Table 2.

Some recent developments (Ref.11) in the silicon solar cell fabrication methods are showing individual cells with air mass zero efficiencies greater than 14% and ground performance approaching 18% with the expectations of attaining 20% in the next year or two. While space quality silicon solar arrays cost anywhere from $300 per watt to over $1000 per watt, terrestrial systems are now selling for around $50 a peak watt in small orders and as low as $20 a peak watt in kilowatt quantities. Improved manufacturing processes and an expanding market for remote and unattended navigation aids and data relay stations should reduce these costs to something around $10 per peak watt. A peak watt is defined as the maximum power output of an array at normal incidence to the sun in the zenith at sea level on a clear day(approximately 100mw/cm^2).

Before extensive use of photovoltaic arrays will come about, such as wide application on buildings, auxiliary power plants and massive central station installations, large scale automated methods of producing long life arrays at costs in the tens of cents per peak watt will have to be developed. Steps in this direction are being made in the research of single crystal silicon dendritic growth (Ref.12) and the Edge Defined, Film-Fed Growth (EFG) process (Ref.13) which will permit the continuous growth of ribbons suitable for making solar arrays. Cadmium sulphide lends itself particularly well to mass productions since the base material is deposited upon thin substracts by a vapor deposition process. (Ref. 14) Other investigations (Ref.15) are underway in methods of depositing silicon films by chemical vapor deposition (CVD) so as to reduce array fabrication costs and reduce the amount of semiconductor needed in an array. The ultimate method will probably closely resemble the process and technology used in the manufacture of photographic film which is produced in millions of square meters per year at costs less than $10.00 per square meter. This concept is illustrated in Figure 6 which represents a continuous operation with efficient use of manpower, materials, and energy.

When low cost photovoltaic arrays become available in large quantities one

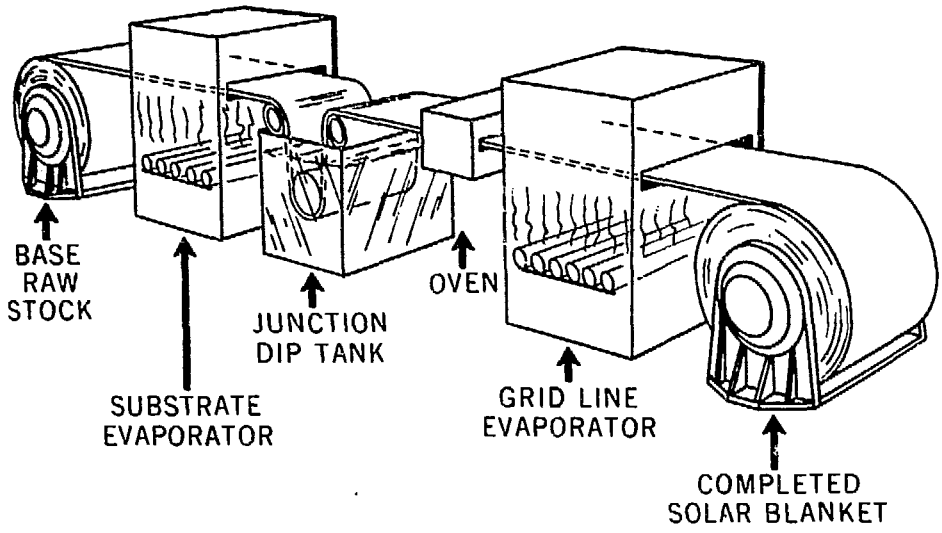


Figure 6. Solar Array Manufacturing

of the early applications will be for providing electric power on buildings and at remote sites. Experiments using solar arrays in conjunction with flat plate thermal collectors were studied at the University of Pennsylvania and now being done at the University of Delaware's "Solar One" house where cadmium sulphide is employed. Figure 3 illustrates the general principle showing the collection of sunlight on the solar array where electricity is produced and the cooling of the array being done by the passage of a fluid behind the cells. The thermal energy is then stored in either rocks, a liquid or in fused salts until needed for space conditioning.

As very large amounts of solar array become available then considerations will be made for their use in terrestrial central power stations.(Ref.17) This is illustrated in Figure 7 showing the conversion of underutilized land into productive regions. For such stations to become self-sufficient for around the clock service, inexpensive high capacity electic storage systems will have to be developed to work in conjuction with them. These are in research now. Another concept (Ref.18) explores the potential of floating power stations on huge helium filled mattresses at elevations in excess of 50,000 feet to get above the weather. A "mattress" 2.6 sq. km (1 sq. mile) and 30 meters (100 feet) thick could support over 9.1×10^6 kgm (10,000 Tons) at 0.1 atmosphere elevation, sufficient to provide 250,000 KW of electric generating capacity.

The ultimate method for collecting solar energy is described in a concept of a synchronous space station (Ref. 19) converting the sun's rays to electricity by solar arrays, inverting to microwaves which are beamed to a terrestrial station which then converts the energy back to 60 hertz current. All of these schemes would require considerable research and development of components

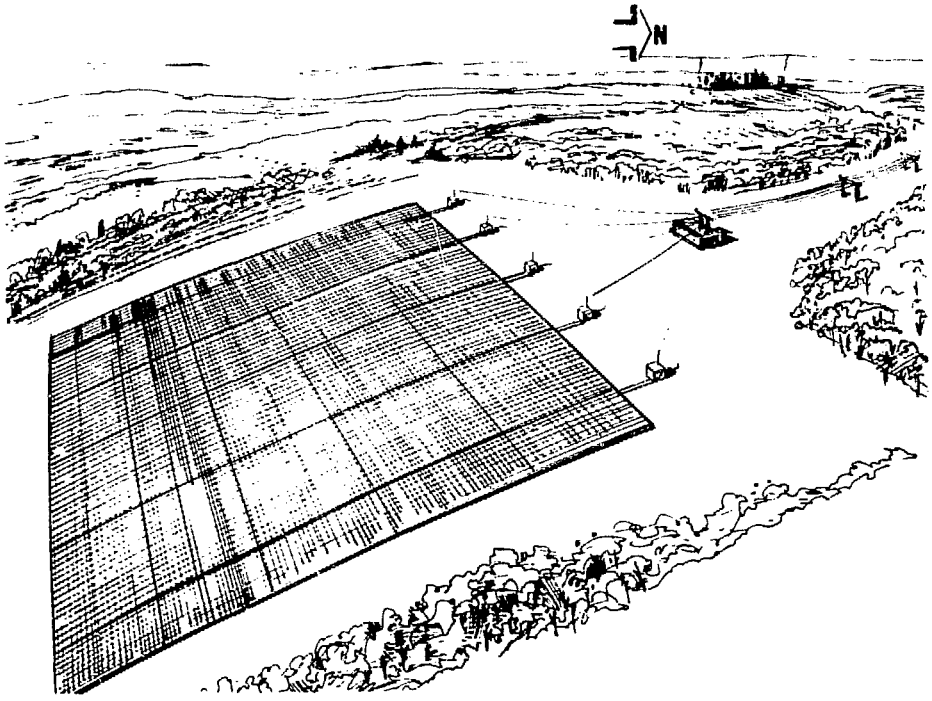


Figure 7. One Square Mile Terrestrial Solar Power Plant

and systems which are not yet available and especially the development of very low cost solar arrays.

ELECTRIC POWER PLANT COSTS

The comparative costs for the construction for various types of electric power plants are shown in Figure 8. The costs for gas, oil and coal plants are well known; however, due to nonavailability of fuel no new gas and oil fired plants are being built in the U.S. Some oil plants are being converted to coal and there are about 50 new nuclear plants in planning or under construction which will add to the 37 or so now on line. Costs for all these plants are increasing dramatically as are the fuels they consume. The construction costs of breeder plants are projected to range from $500 to $1000 per installed kilowatt but the first full scale plant is not expected "on line" until the early or mid 1980's. Since no commercial power plants using solar derived energy or fuels have been built, the construction cost varies widely depending upon the

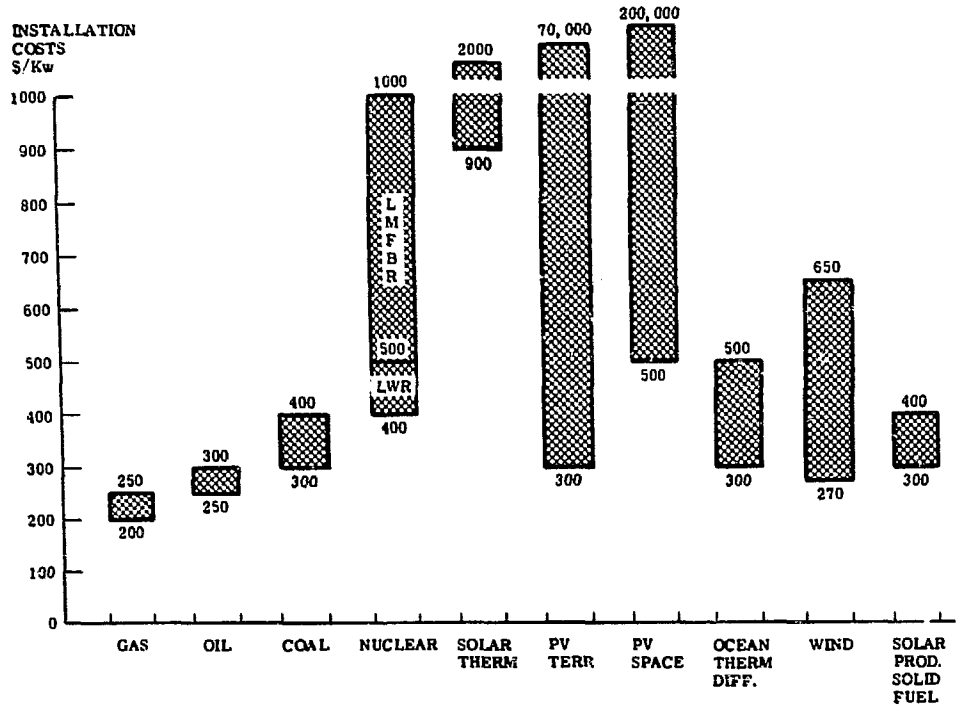


Figure 8. Estimated Installation Costs for Electric Generating Plants

source. Best estimates seem to fall near the $1000 per kw price which is high in the 1970 market but will be competitive in the near future. Obviously, no operating experience has been gained for solar plants, thus these costs can only be estimated but are thought to be modest. Fuel costs are zero. Wood burning plants would be similar to coal fired plants since the only difference in their operation would be the fuel.

STATUS OF SOLAR ENERGY RESEARCH

Table 2 shows the general state of the art in the various solar energy application areas mentioned in this paper. Only solar hot water heaters are in a commercial readiness status at this time. Building heating systems are expected to be available in mass quantities during 1974 or 1975 as should large scale pyrolysis systems especially for the disposal of urban solid wastes. While many small power plants have burned wood in the past no planned energy plantation type of system has been developed.

Table 3

Status of Solar Utilization Techniques

Application	Research	Development	Systems Test	Full Scale Demonstration	Model Plant	Commercial Ready
Thermal Energy for Buildings:						
Water Heating	X	X	X	X	X	X
Building Heating	X	X	X	X	X	
Building Cooling	X	X	X			
Combined H/C Systems	X	X	X			
Production of Fuels:						
Gaseous Fuels	X	X	X	X		
Liquid Fuels	X	X	X	X	X	
Solid Fuels	X	X	X	X		
Electric Power Generation:						
Wind Power	X	X	X	X		
Ocean Thermal Power	X	X	X			
Solar Thermal Power	X	X				
Photovoltaic Power	X	X				

RECOMMENDED PROGRAM AND BUDGET

The NSF/NASA Solar Energy Panel (Ref.2) recommended a research and development program spanning a period of 15 years for the total expenditures shown in Table 4. The actual funded program for Fiscal years 1973 and 1974 along with the funding recommended by the Chairman of the AEC on December 1, 1973 in response to the President's request for an energy R&D program is shown in Table 5. Some adjustments in the AEC's recommendations are expected during the second session of the 93rd Congress meeting during 1974 which should place even more emphasis on accelerating the application of solar energy to our National energy needs.

SOLAR ENERGY IMPACTS & CONCLUSIONS

With funding support from both Government and private sources at the levels recommended by the NSF/NASA Solar Energy Panel the impact on the Nation's energy demands can be expected as shown in Table 6. As can be seen from the table the savings in fossil fuel consumption in one year at the turn of the century would more than pay for the R&D expenditures to develop solar energy applications.

In conclusion, it is expected that at least 20% of the U.S. total energy requirements by 2020 will be derived from solar energy. This is nearly equivalent to the total energy consumed by the U.S. in 1970. From this harnessed

Table 4

NSF/NASA Solar Energy Panel Recommended 15 Year Program

Application	Funding in $Millions
Thermal Energy for Buildings	$100
Production of Fuels	$370
Electric Power Generation:	
Wind Power	$610
Ocean Thermal Power	$530
Solar Thermal Power	$1,130
Photovoltaic Power	$780
Total	$3,520

Table 5

U.S. Terrestrial Solar Energy R&D Program
(in millions of dollars)

Application	Actual		Proposed	
	FY73	FY74	FY75	FY75-79 Total
Thermal Energy for Buildings	0.9	5.6	12.8	50.0
Production of Fuels	0.7	1.1	2.4	20.4
Electric Power Generation:				
Wind Power	0.1	0.2	6.2	31.7
Ocean Thermal Power	0.2	0.8	1.9	26.6
Solar Thermal Power	1.4	2.7	5.0	35.5
Photovoltaic Power	0.9	2.8	4.2	35.8
Totals	4.2	13.2	32.5	200.0

solar energy, at least 35% of the building heating and cooling requirement at least 30% of the Nation's gaseous fuel requirement, (more if wanted) 10% of the liquid fuel requirement (more if wanted) and at least 20% of the Nation's electrical power demand can be obtained. All this may be accomplished with a minimal impact on the environment, producing little atmospheric thermal or particulate pollutants, no unusable solid residues and no harmful conditions or wastes.

Table 6

Impact of Solar Energy Applications on the Nation's Energy Demand

System	Year	Annual consumption[2] (10^{15} BTU)	Percent of total energy consumption in USA	Estimated percent of market captured	$10^6 Annual savings in fossil fuel @$1.00/$10^6$ BTU	Significance[6] on impact on reference energy system by 2020
Thermal energy for buildings	1985	[3]17	15	<1		Major on building industry
	2000	[3]21	12	10	2,100	Minor on total energy
	2020	[3]30	10	35	10,500	consumption
Conversion of organic materials to fuels or energy						
Combustion of organic matter	1985	37	32			Major on electric utility
	2000	76	43	1	760	Modest on total energy
	2020	160	53	10	16,000	consumption
Bioconversion to methane	1985	[4]27	23	1	270	Major on gas consumption
	2000	[4]31	18	10	3,100	Minor on total energy
	2020	[4]91	14	30	12,300	consumption
Pyrolysis to liquid fuels	1985	[5]50	44			Major on oil consumption
	2000	[5]63	36	1	630	Minor on total energy
	2020	[5]80	27	10	8,000	consumption
Chemical reduction to liquid fuels	1985	[5]50	43			Major on oil consumption
	2000	[5]63	36	1	630	Minor on total energy
	2020	[5]80	27	10	8,000	consumption
Electric power generation						
Thermal conversion	1985	37	32			Modest on electric utility
	2000	76	43	1	760	industry
	2020	160	52	5	8,000	Modest on total energy consumption
Photovoltaic						
Systems on buildings	1985	[3]9	9			Major on building industry
	2000	[3]15	9	5	750	Minor on total energy
	2020	[3]21	6	50	10,500	consumption
Ground stations	1985	37	32			Major on electric utility
	2000	76	43	1		industry
	2020	160	52	10	16,000	Modest on total energy consumption
Space stations	1985	37	32			Major on electric utility
	2000	76	43	1	760	industry
	2020	160	52	10	16,000	Modest on total energy consumption
Wind energy conversion	1985	37	32			Major on electric utility
	2000	76	43	1	760	industry
	2020	160	52	10	16,000	Modest on total energy consumption
Ocean thermal difference	1985	37	32			Major on electric utility
	2000	76	43	1	760	industry
	2020	160	52	10	16,000	Modest on total energy consumption

Notes: (1) Each of the above impact estimates assumes the successful development of practical economically competitive systems. However in each case a judgement has been made resulting in estimates that are less than the maximum possible. The estimates are not necessarily additive since not all systems will be carried to commercial readiness.

(2) Nonrenewable fuel consumed to generate the electric power as projected in the energy reference systems and resource data report, AET-8, Associated Universities, Inc., April 1972 [1].

(3) Nonrenewable fuel consumed to generate the projected electric power requirements for buildings, AET-8 [1].

(4) Methane consumed to meet projected energy needs, AET-8 [1].

(5) Oil consumed to meet projected energy needs, AET-8 [1].

(6) Minor, 0.5%; Modest, 5-10%; Major, >10%.

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ECONOMICS OF SOLAR-ELECTRIC POWER

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The advantages of solar energy as a long-term solution to the energy crisis are frequently cited. Solar energy is free, largely non-polluting, and its extensive use would not disturb local or global heat balances which are thermodynamically inevitable for energy derived from fuels. These very real and important advantages have frequently been made the basis for proposals calling for massive federal support for research and development on solar energy systems. The argument is frequently advanced that both U.S. and European research and development support for breeder reactors is excessive and misplaced in view of the dangers and hazards of this mode of energy production. It is said that a comparable investment in solar energy research and development might solve our energy needs without a long-term reliance on breeder reactors.

Over and above scientific or technical solutions for solar energy components such as heliostats, efficient absorbers, photocells, and the like, an overriding objective of solar energy research and development must be cost reduction. It is the purpose of this study to define the cost constraints on any system for electric power generation from solar energy in as simple and general a way as possible. When this has been accomplished, cost targets which must be met by particular systems for solar-electric power generation can be defined and the prospects for meeting such targets evaluated.

Solar Insolation

Any system for electric power generation from solar energy will be dependent on the total energy received by the system from the sun. This in turn is governed by the climatic characteristics of the site on which the system is constructed. These site characteristics will be defined on two quantities: the peak solar power density, P, and the average annual solar insolation per unit area, J. The peak power is used to match the solar system to a predetermined installed electrical capacity, E, by adjusting the area, A, of solar collectors so as to provide the full generating capacity when the peak solar power is realized. With the area determined in this way, the annual yield of solar energy from the system can be determined when J is known.

The maximum solar power density on a clear day at noon depends on the latitude of the site and the angular elevation of the sun at noon. In the Southwestern deserts of the United States, its maximum value in the summer is about 320 BTU/ft.^{2}hr. and this value will be used here.

One of the sunniest spots in the United States is the Sonora Desert of Arizona. On this location, a test station has been operated for many years by the Desert Sunshine Exposure Tests, Inc. (DSET) on a site 40 miles north of Phoenix. Measurements of J made by DSET at this site over a 20-year period from 1955-1974, as reported on their data sheet of January 1, 1975, are:

	J (BTU/ft.^{2})	Hours of Sunshine
Minimum 1966	628,000	3,805
Maximum 1956	734,000	4,160
20 year average	696,000	3,843

As an average value for a most favorable solar site, we will use 700,000 BTU/ft.^{2} per year for J with 3800 hours of sunshine corresponding to 317 days per year for electrical generation with solar energy. For less favorable sites in the Midwest and South, J would have a lower value of about 500,000 BTU/ft.^{2} per year with only 230 days for electrical generation with solar energy.

By way of summary of this section, we define the characteristics of the site on which a solar electric power plant is to be built by two characteristics of its solar insolation as follows:

P = Peak solar power density at mid-day on a clear day, in BTU/ft.^{2} · hr.

J = Total average yearly solar insolation per unit area of site, in BTU/ft.^{2} · yr.

An important derived quantity is J/P, the number of hours at peak power to produce the annual solar insolation. For the Arizona site, this is 2,200 hours; for less favorable sites, 1,600-1,800 hours.

Characteristics of Solar-Electric Systems

For particular solar-electric systems constructed on a site defined by J and P, four characteristic parameters are required for this analysis:

A = Area of solar collectors, in ft.^{2}

f = Fraction of solar energy falling on collectors which the system makes available for electric generation

E = Installed electrical generating capacity, in KWe

H = Heat Rate for system in BTU/kwh

For the analysis to be carried out here, all systems considered will be taken to have an installed electrical generating capacity of 100 MWe so that $E = 10^5$ for each reference system.

General Cost Characteristics

For the economic analyses, the following typical values will be used:

Value of electrical energy at point of generation is R mills/kwh. In the examples given here, R is taken to be 50, but expressions valid for other values of R are given.

The percentage of gross annual income required to cover profit, taxes, insurance, and depreciation is taken to be 12 percent.

The initial capital investment in the system is amortized over 25 years at 8 percent interest resulting in a present value of 10.67 times the annual capital cost.

Method of Cost Analysis

We first match the area of solar collectors to the installed generating capacity so as to use this capacity fully when the peak solar power is being received. The maximum rate of delivery of solar energy from the solar collectors is fPA BTU/hr and this thermal power will convert to electric power at the rate of (1/H)kw per BTU/hr. Thus,

$$E = fPA/H \tag{1}$$

From this expression, the area of solar collectors required to match the installed electric generating capacity at peak solar insolation is:

$$A = EH/fP \tag{2}$$

This expression for the area of solar collectors required to achieve a peak generating capacity E will be used in analyzing five typical solar electric plants of widely different operating characteristics. For them, the values of f will vary between 0.1 and 0.9 and of H between 3,400 and 25,000 with a corresponding wide variation in the area A required. All of them will, however, provide the same annual output of electrical energy Q_e as may be seen from:

$$Q_e = fJA/H = EJ/P \tag{3}$$

where A has been substituted from Equation 2.

Since we have chosen E to be 10^5 for the reference solar-electric system to be considered here and, as has been seen, J/P = 2,200 hours for the most favorable solar sites in the Southwestern deserts, the annual electrical output of all reference solar systems is:

$$Q_e = 2.2 \times 10^8 \text{ kwh/yr.}$$

This output corresponds to an average annual power level of 25 MWe or an average power of 58 MWe during the 3,800 hours of daylight at this site.

For the analyses which follow, we need to determine the initial capital investment C in the solar plant which this annual production of electrical energy will sustain. At R mills/kwh, the gross annual income from Q_e is 0.22R million dollars. Setting aside 12 percent of this income for profit, taxes, insurance, and depreciation and deducting from the remainder the annual budget for operation and maintenance, O & M in millions of dollars, leaves an annual income of 0.19R - O&M million dollars for capital amortization. At our assumed amortization rate of 8 percent over 25 years, this gives a rule of thumb allowable capital investment of :

$$C = 2R\text{-}10(O\&M) \text{ million dollars} \tag{4}$$

This expression is quite general for any system which converts solar energy into electricity. As examples of its use, five quite different solar-electric systems will be analyzed. For this purpose, R will be chosen at 50 mills/kwh which is high by present standards but seems likely to be true of both fossil and nuclear plants by 1985 when commercial solar-electric systems might become available. The annual budget for operations and maintenance is arbitrarily taken to be $500,000 although this figure would probably vary considerably among the five systems chosen for analysis. These choices result in a maximum capital investment of $95 million for any solar-electric plant with an installed generating capacity of 100 MWe matched to the peak solar power at its site. This result can now be applied to a capital cost analysis of a variety of possible solar-electric systems.

1. Point Focus System

The system for solar-electric power generation on which research and development is most advanced consists of a central tower supporting a solar receiver-boiler generating high-pressure steam surrounded by a circular field of heliostats of radius about twice the height of the central tower. The heliostats are equipped with large light-weight mirrors with two-axis drives controlled by a central computer responsive to the position of the sun which maintains an image of the sun from each heliostat on the solar receiver. Development problems for this system include accurate control of the angular orientation of the heliostats to within a few minutes of arc, maintenance of high mirror reflectivity over long periods, and protection against wind-borne sand damage and damage from infrequent severe storms and tornadoes. Another problem is that of minimizing radiative and convective heat loss from the central receiver.

For this system, the fraction f consists of three components: 1) the percentage of the total solar radiation which is direct from the sun and reflectable by the mirrors; 2) the mirror reflectivity; and, 3) the fraction of the energy falling on the receiver which is not lost by convection or radiation but absorbed in the working fluid. For the first fraction, the measured value at the DSET site over a nine-month period in 1973 and 1974 was 80 percent, and the Project Independence Solar Energy Report on page A-1-13 also gives 80 percent for Yuma, El Paso, Phoenix, and Albuquerque. The mirror reflectivity with effective maintenance, either manual or automatic, can perhaps be maintained at 80 percent. A possibly attainable design goal for minimizing radiative and convective losses from the receiver would be to hold them within 20 percent of the energy falling on it so that the fraction absorbed may be taken as 80 percent. Thus, an optimistic but possible value of f for this system is 0.5. A reasonable value of the heat rate, H, for this system is 10,000 BTU/kwh. Using these values in Equation 2 with E=100 MWe, the area of solar collectors required is:

$$A = 10^5 \times 10^4/0.5 \times 320 = 6.25 \times 10^6 \ \text{ft}^2.$$

If each heliostat mirror is a square five feet on a side, the area of each is 25 ft^2 and the number required for this system is 250,000.

Assume that the central power plant (consisting of central tower, boiler, steam lines, turbines, generator, and cooling tower) can be built for $250/KWe, or $25 million. This leaves $70 million to cover the cost of the heliostats and allows a maximum investment of $280 in each heliostat. With half the land area covered by heliostats, this solar farm would cover 290 acres.

2. Line Focus System

Another approach to solar-electric power is based on fixed trough mirrors of parabolic cross-section which concentrate solar radiation on a tube or pipe whose position is adjustable so as to coincide with the line focus of the mirror. The receiver is coated so as to maximize absorption of radiation falling on it and minimize reradiation from it. It is encased in a glass tube with the intervening space evacuated so as to eliminate convective losses. The chief problem with such a system is the harvesting of the energy collected from a large number of such units over the large area of a solar farm. For the purpose of a comparative cost analysis with other solar-electric systems, one method of accomplishing such a harvest is sufficient. This is the EVA-ADAM chemical heat pipe being developed at the Kernforschungsanlage Julich for use with a high-temperature, gas-cooled reactor. The system has been described in a paper in Science, "Energy Choices that Europe Faces," by Wolfe Häfele, Vol. 184, pp. 360-369, April 19, 1974.

Assume each solar unit to consist of a parabolic mirror 10 ft long and 4 ft wide equipped with a one-inch ID, vacuum-jacketed pipe adjusted to the focus of the mirror. Each pipe is packed with a catalyst consisting of nickel in a porous alumina matrix. At a temperature of 1400-1500°F, maintained by the solar line image on the tube, a mixture of methane and steam is admitted at one end of the pipe at a pressure of up to 10 atmospheres. At this temperature, in the presence of the nickel catalyst, the reaction

$$CH_4 + H_2O + 195 \text{ BTU} \rightarrow 3H_2 + CO$$

takes place. The hydrogen-carbon monoxide gas is collected from all units after exchanging heat with the incoming methane-steam gas and piped to the central power station where it gives up its heat in the reverse reaction, also in the presence of a nickel catalyst, at a temperature of 800-1000°F. This heat is used in place of fuel for the generation of power and the product gas returned and redistributed to the solar units.

As in the case of the heliostats, the fraction of direct solar radiation which can be focused by the mirrors is taken to be 80 percent and the mirror reflectivity also 80 percent. Because of the high temperature, the radiation loss from the pipes is estimated to be 30 percent. The fraction $\bar{f}$ is, therefore, taken to be for this system $0.8 \times 0.8 \times 0.70 = 0.45$. With this value, and the same heat rate as before, the area of solar collectors required is from Equation 2,

$$A = 6.9 \times 10^6 \text{ ft.}^2 .$$

Since each mirror unit is 40 ft.^{2} in the collecting area, the solar farm would require 170,000 mirror units, each equipped with adjustable, vacuum-jacketed, coated pipes charged with nickel catalyst and a heat exchanger between the incoming and outgoing gas. If, again, \$250/KWe is allowed for the central methanation unit and power plant, the allowable investment in the mirror units and associated equipment is \$70 million or \$410 per unit. It seems doubtful whether alternatives to the EVA-ADAM system for harvesting the energy from the solar farm would appreciably improve this cost limitation. At 50% coverage, this solar farm would require 320 acres.

3. Photosynthetic Hydrogen

Some interest has been shown in the development of a photosynthetic system which would dissociate water into hydrogen and oxygen. A detailed account of research problems in the development of such a system has been given in the proceedings of a workshop on such systems held in 1973 at Indiana University. The enzyme hydrogenase in certain organisms diverts the photosynthetic process from the usual production of ATP to the production of hydrogen. This workshop describes the research which would need to be done to achieve a practical system of this type. Such a system might consist of a layer of free chloroplasts encapsulated with enzymes and with membranes separating oxygen production on one side of the layer from hydrogen production on the other. A formidable research program would be required for the achievement of such a system. Major difficulties to be overcome would be the achievement of stable cell-free chloroplast-enzyme systems, the achievement of mutant forms of bacterial hydrogenase not deactivated by small amounts of oxygen, and overcoming blockage of photosynthesis by higher light intensities. If such a program were successful, 10% of the total solar insolation could theoretically be available for splitting water. A solar farm could then be developed with a large number of photosynthesis cells generating hydrogen and oxygen in separate channels. The gases would be collected from them and pumped to a central power station where the hydrogen would be burned with the oxygen to produce high-pressure steam directly in a turbine.

Assuming the maximum value $f = 0.1$ for such a system, and a heat rate for the hydrogen power plant of 9,000 BTU/kwh, the required area of photosynthesis cells is, from Equation 2, 28×10^6 ft.^{2} As in the previous examples, \$70 million could be invested in them if \$25 million is still reserved for the central power plant. This would allow \$2.50 per square foot for the manufacture of photosynthesis cells.

4. Flat Plate Solar System

At the present time, the most promising application of solar energy is in the heating and cooling of buildings, both residential and commercial. Such systems use flat plate collectors without mirrors or other means of concentrating solar radiation. The present major emphasis being given to the commercial development of low-cost reliable systems for this purpose may be expected to result in the quantity production of efficient flat plate solar collectors at a reasonable price. It is, therefore, worthwhile to consider the possibility of utilizing such collectors for electric power generation.

A possible system of this type might consist of a large, low-lying hexagonal structure, open around the sides for heat dissipation, the roof of which consists of solar panels. The working fluid would consist of an organic vapor such as isobutane. The vapor would enter the solar panel roof along two opposite sides of the hexagon, be heated and expanded as it flows through the roof to a plenum along the central diagonal parallel to these two edges. The heated vapor would be collected at the center of the hexagon and fed into a compressor-turbine generator unit mounted immediately below. Output vapor from the turbine would be returned to the inlet edges of the hexagon through heat exchanger tubes in a sealed pool of water at the base of the structure for heat removal. At night, air would be passed through a separate heat exchanger in the pool and discharged at the center of the structure near the turbogenerator for removal of the heat absorbed in the pool during daytime operations.

The sealed water pool used as a heat sink is an attractive feature of this system. The central station facilities of the previous examples would require centralized heat disposal by either evaporative or dry cooling towers. The dispersed electrical generation in this system opens up the possibility of a very large area for heat dissipation as well as that of employing a heat sink during day-time operation followed by heat removal from the sink during the night.

For a flat solar panel, the achievable absorption of solar energy is easily 90 percent or more. The temperature of the heated vapor is, however, low (around 300°F in average operation) so the thermal efficiency is low. If the heat rate is taken as 25,000 BTU/kwh, the area of flat plate collectors required is, from Equation 2, $10^5 \times 25{,}000/0.9 \times 320 = 8{,}7000{,}000$ ft^2. If the installed generating capacity in each hexagonal unit is 50 KWe, 2,000 units would be required for a 100 MWe facility. The area of each hexagonal structure would be 4,350 ft^2, and the hexagons 41 feet on a side. Since each unit is complete, the entire $95 million is available for them, and the maximum allowable cost per unit is $47,500. If the water pool beneath each hexagonal unit were 3,600 ft^2 and 2.5 ft. deep, the rise in temperature of the water during an average day's operation would be 13°F.

These hexagonal units could be constructed over 80 percent of desert land area with 20 percent available for access roads between them. A solar farm of the reference capacity would require only 250 acres which is somewhat less than any of the central power station solar farms. If the solar panel roofs could be manufactured for $2 per square foot and the water pool and support columns for the roof for $4,000, this would leave $35,000 for the compressor-turbine generator units. These cost limits do seem achievable with presently known technology assuming large-scale production of identical units.

5. Photovoltaic Systems

In the space program, electrical power generation from solar energy using silicon photocells has been realized for some time. In this case, cost has, of course, not been a consideration, and on a per kilowatt basis, the cost has been orders of magnitude higher than alternative systems for commercial electric power. However, major improvements in the manufacture of silicon photocells are foreseen, and the full range of possibilities in the present advanced stage of solid-state physics is such that the achievement of relatively inexpensive but durable phtovoltaic cells seems promising. Recently, the Bell Laboratories have fabricated such cells consisting of a cadmium sulfide film on a single-crystal substrate of either indium phosphide or copper indium diselenide. They have an efficiency of 12 percent, but their long-term durability has not been established. With the vigorous level of R&D now being mounted, there is a reasonable expectation that a practical system will be developed over the next decade.

Since phtovoltaic cells directly convert solar energy into electrical energy, the heat rate, H, for this system is simply the BTU equivalent of one kilowatt hour of energy or H=3,410 BTU/kwh. Assuming 12 percent conversion efficiency, the area of photocells required for 100 MWe peak power is, from Equation 2, 9×10^6 ft^2. The entire capital investment of $100 million for this system can be used for photocells since no other facilities in addition to solar collectors are required for it, and the annual cost of operation and maintenance should be very small if the photocells have long-term durability. Thus a cost

of about $11 per square foot could be allowed for photocell fabrication. This is very much less than the cost of presently available photocells, but the prospect for achieving it through a vigorous solid state research and development program is not unreasonably small. Success in achieving a photovoltaic cell of long-term stability which could be manufactured in quantity at or below this cost would have incalculable importance. The achievement would rank in importance with success in the controlled thermonuclear project in meeting the long-range energy needs of mankind.

GEOTHERMAL ENERGY

by

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In the following discussions we will cover six areas of geothermal resource utilization: (1) concept and potential of the resource; (2) natural geothermal systems; (3) artifically stimulated, dry hot rock geothermal systems; (4) energy utilization alternatives; (5) power cycle thermodynamics; and (6) power cycle economics. The geothermal program in the United States has grown considerably in the past 2 years. The National Science Foundation (NSF), the U. S. Geological Survey (USGS), and the Energy Research and Development Administration (ERDA) are currently sponsoring numerous efforts scattered throughout the country in its national laboratories, universities, and many private research and development organizations. For example, Lawrence Berkeley Laboratory, Lawrence Livermore Laboratory, Battelle Northwest Laboratories, Sandia Laboratories, Oak Ridge National Laboratory and Los Alamos Scientific Laboratory are exploring geothermal possibilities. Furthermore, private industry itself is undertaking a very active effort in exploiting geothermal resources. Because the summary presented here covers only the salient features of current research in geothermal energy, References 1-11 should be consulted for further information.

1. Concept and Potential of the Resource

With a volume of 10^{12} km^3 of mostly molten or near molten rock, the earth represents a potentially inexhaustable source of energy. Typical surface manifestations of geothermal energy are evident in the form of hot springs, geysers, and fumaroles, and of course active volcanoes.[1] Unfortunately its inaccessibility, except in a relatively few areas of the world, has severely limited the exploitation of geothermal energy. The removal of geothermal energy from the earth's crust is basically an engineering problem in which the comparative economics with more conventional energy resources play a critical role.

As stated, the geothermal resource is vast. By using the Q* as a measure of its magnitude, the energy released by a 40 cubic mile volume of granite when cooled from 250°C to 50°C is equivalent to the total energy consumption of the U. S. in 1972, 0.07 Q.

*Q = 10^{21} J = 10^{18} BTU = 4 x 10^{10} tons of coal = 1.7 x 10^{10} bbl of oil = 3 x 10^{14} kWh.

Currently, conventional drilling techniques are used to reach natural underground reservoirs (aquifers) that contain hot water and/or steam. These geothermal fluids are carried to the surface where they are either used directly for space or process heating purposes or to produce electricity from a vapor turbine cycle.

2. Natural Geothermal Systems

Natural geothermal systems can be divided into four categories: (1) vapor-dominated (dry steam), (2) liquid-dominated (superheated water), (3) geopressurized reservoirs, and (4) lavas and magmas.[1]

Although dry steam fields are relatively rare, the Italian fields at Larderello and Mt. Amiata and the U. S. field at The Geysers in California, are producing over 600 MW(e) of electricity. Vapor-dominated fluids are advantageous for power production because they are usually available at relatively high temperature and high pressure (180°C, 7.8 bars, 114 psia, at The Geysers)[1] and the superheated steam can be used directly to drive turbines.

The more commonly occurring liquid-dominated systems present a complex utilization problem in that a reasonably high-pressure vapor phase must be created for power conversion in a conventional turbogenerator unit. Fluid can be partially vaporized by flashing it to a lower pressure, with the vapor then injected into a suitable turbine to produce power.[1] Or it can exchange heat to another (secondary) fluid vaporizing at a lower temperature (e.g., isobutane or a halogenated hydrocarbon, Freon) which in turn, is injected into a turbine, condensed, and pumped in a continuous closed cycle.[8,11] A disadvantage of direct steam flashing is that multiple flashing steps are required to attain high conversion efficiencies. Only a small fraction of steam is produced with a single flashing stage (about 10% for a 150°C source). Successive flashing improves efficiency but requires complex turbine design. Furthermore, the relatively high specific volume of steam at these lower temperatures results in large, expensive turbine exhaust areas. Both systems have to reinject or discard all or part of the geothermal fluid. Steam flashing, however, does require less surface equipment (such as heat exchangers and pumps) for power conversion than do secondary or alternate fluid cycles. Except for a few small systems (Kamchatka, USSR),[1] flashing plants are the only systems presently developed for liquid-dominated resources.

Liquid-dominated systems vary widely in terms of the available temperatures and pressures of geothermal fluids. For power production, temperatures of at least 100°C are desirable when coupled to sink (heat rejection) temperatures of approximately 25°C. Fluid temperatures as high as 300°C have been observed in the Imperial Valley of California and presently comprise an upper limit.

Geopressurized reservoirs such as those of the Gulf Coast, from Mexico to Mississippi, contain moderately hot water (150 to 180°C) under extremely high pressures (270 to 400 bars).[1] However, utilization of this resource has been limited by engineering problems associated with drilling into such formations and extracting useful amounts of energy. Lavas and molten magmas are another potentially useful energy source; but controlled energy extraction is only in the formative research stages at this point.

3. Artificially Stimulated, Dry Hot Rock Geothermal Systems

One concept under development by the Los Alamos Scientific Laboratory consists of creating a geothermal reservoir in rock hot enough to be a suitable energy source for either direct use or for generating electricity (Refs. 5, 6, 7, and 10). One hole would be drilled into a hot impermeable region and a large surface-area reservoir created by hydraulic fractur-

ing, similar to the techniques used for oil and gas stimulation. A circulation loop would be formed by drilling a second hole until it intersected the fractured region. Cold water kept under pressure would flow down one hole and circulate through the fractured zone to remove heat with the buoyant forces helping to pump the fluid up the second hole. Energy removal on the surface may utilize direct steam flashing or a binary-fluid cycle for power production.

The primary objective of the LASL program is to examine the engineering and economic feasibility of creating geothermal energy reservoirs in dry hot rock. The current efforts involve a rather extensive field program of drilling into hot granite, fracturing it to create surface area, and demonstrating the viability of the resource by extracting energy as heat over an extended period of time. The field program is complemented by research in geochemistry, geophysics, seismology, environmental effects, rock mechanics, fluid dynamics, and heat transfer.[5,10]

LASL's field experiments are situated on the western rim of the Valles Caldera, an extinct volcanic crater, which is located on the Jemez Plateau of north central New Mexico. Two holes have been completed, GT-1 to 2575 ft and GT-2 to 9619 ft. A third hole, EE-1, is currently being drilled and will be one leg of a two-hole circulation loop with GT-2. The equilibrium bottomhole temperature of GT-2 is approximately 200°C with a geothermal gradient of 50°C/km. Fracturing experiments have been conducted in both GT-1 and GT-2, and techniques are being developed toward determining fracture orientation and size. These measurements are critical to engineering the geothermal system because with our current concept intersection of the fractured region is required to establish a circulation loop. Microseismic, electric resistivity, magnetic, and hydrologic flow experiments will be used in establishing fracture geometry.

Another important factor in the design of geothermal power plants for both artificially stimulated and natural resources is the chemical composition of the fluid. Frequently large quantities of dissolved minerals, particularly silica (SiO_2) and calcium carbonate ($CaCO_3$) are present and they create scaling, corrosion, and erosion problems for heat exchangers, turbines, and related surface equipment. These problems vary in magnitude from those created by geothermal water containing less than 100 ppm total dissolved solids to those from Imperial Valley water with more than 300,000 ppm.[1,3]

Estimating reservoir lifetime in terms of geothermal fluid production rates and fluid quality is very difficult but is extremely critical to optimal economic design of a power plant. Furthermore, the reinjection of spent fluid to alleviate surface disposal problems, to control subsidence, and help in sustaining reservoir lifetime is far from a proven technique. Communication between a production and reinjection well is not at all certain in the case of natural reservoirs. For this reason, maximum use should be made of such wells; the difference between the geothermal fluids' wellhead and reinjection temperature should be maximized to the limit governed by available ambient conditions. For artificially stimulated resources, communication will be established prior to production but reinjection should occur at the lowest practical temperatures to favor thermal stress cracking.

Thermal stresses will develop as circulating cold water continues to cool the rock in the fractured region. The volume contraction resulting from this cooling process might cause thermal stress cracking which potentially could increase the effective heat transfer area and allow penetration of water deeper into the formation where temperatures are higher. Computer models have been developed for predicting the thermal power-time history of a dry hot rock reservoir.[4,10] The fluid dynamics

and heat transfer processes are examined for cases with and without thermal stress cracking. Because the energy extraction capacity of the fracture system is very quickly limited by the low thermal conductivity of the rock, large fractures are required to insure a steady supply of geothermal heat for long time periods (~20 years).

4. Energy Utilization Alternatives

Using geothermal energy to produce electricity is far from a new concept to the world. The Larderello dry steam fields in Italy began production in 1904. As seen by Table I, their capacity has grown to 390 MW(e) with plans to increase to 430 MW(e) by 1980. The United States began producing electrical power from geothermal steam at The Geysers field in California in about 1960, with a 12.5 MW(e) capacity. This has increased to 396 MW(e) in 1974 with plans to have a 1180 MW(e) capacity by 1980.

TABLE I

WORLD PRODUCTION OF GEOTHERMAL POWER

	Megawatts Electric MW(e)	
Country	1974	1980 (Est.)
El Salvador	--	60
Iceland	3	82
Italy	390	430
Japan	53	147
Mexico	75	150
New Zealand	170	?
Philippines	--	200
USSR	6	38
USA	396	1180 (Geysers)

For countries such as Iceland, New Zealand, and Russia, the numbers given in Table I represent only electrical production and are by no means representative of their total utilization of geothermal energy. They all have extensive space heating or direct industrial applications in addition to producing electricity. The Geysers area, the Italian Larderello and Mt. Amiata fields, and the Matsukawa fields in Japan are all vapor-dominated or dry steam systems and utilize the geothermal fluid directly in low-pressure steam turbines. The more commonly found systems consist of liquid-dominated or superheated water. The Cerro Prieto area in Mexico, the Wairakei fields in New Zealand, and the resources of Iceland and Russia are liquid-dominated and generate electric power by flashing the geothermal fluid to a lower pressure to produce steam which in turn is used to drive low-pressure turbines.

5. Power Cycle Thermodynamics

The second law of thermodynamics imposes real limitations to the production of electricity from a low-temperature geothermal heat source. Since the geothermal fluid temperature of a liquid-dominated system does not remain constant as one extracts useful work, a somewhat specialized ideal process must be constructed for calculating the maximum amount of work that can be produced. In one scheme, an infinite number of infini-

tesimally small reversible Carnot heat engines would be required. The maximum amount of work would then result from taking the geothermal fluid at wellhead conditions (temperature T_{gf} and pressure P_{gf}) and allowing heat to be removed through these Carnot engines to produce work and reject an amount of heat to the environment at temperature T_o. This process would be continued until the geofluid reached the so-called dead state or ambient condition (T_o, P_o). The total maximum work can then be expressed by a quantity called the availability ΔB which is given by

$$W_{max} = \Delta B = \Delta H - T_o \Delta S \Big]_{T_o,P_o}^{T_{gf},P_{gf}} ;$$

where ΔH = enthalpy difference between State (T_{gf},P_{gf}) and State (T_o,P_o);

ΔS = entropy difference between State (T_{gf},P_{gf}) and State (T_o,P_o).

This maximum work quantity can then be compared to the actual amount of work produced by any real power conversion process.

Comparisons of this type are usually achieved by defining a cycle efficiency (η_{cycle}) which represents the net useful work obtained from the system divided by the amount of heat transferred from the geothermal reservoir. As the cycle efficiency decreases the amount of heat rejected to the environment increases. For an ultimate sink of 25°C with a geothermal heat source at 50°C cycle efficiencies would be less than 5%. As the temperature increases to 100°C the efficiency would be ∿8%, at 150°C ∿12.5%, and at 200°C ∿17.5%.

An alternative approach to using cycle efficiency would be to compare directly the real work to the maximum possible work ΔB by defining a utilization efficiency η_u as,

$$\eta_u = \frac{W}{\Delta B} \quad .$$

η_u will then be a measure of the effectiveness of the utilization of the geothermal resource. Ideally, we would like to keep η_u as high as possible; but there are limitations in the efficiency of work-producing machinery (turbines and pumps) as well as in the heat transfer systems associated with generating power.

Because the maximum availability of the geofluid (ΔB) increases as the resource temperature (T_{gf}) increases and as the sink temperature (T_o) decreases, high T_{gf}'s and low T_o's should be maintained. Due to the relatively low geothermal gradients that prevail in the eastern United States, there are some economic limitations to maintaining a high T_{gf}. But many areas have favorable conditions for heat rejection, particularly where large quantities of water exist. This situation should be contrasted with prevailing conditions in the western United States, where because of the lack of water it is necessary to use dry cooling towers or air-cooled condensers. There are further limitations to these minimum and maximum temperatures. For example, any heat transfer step will require reasonable temperature differences to keep the equipment sizes at practical levels. Temperature differences are very important in the tradeoff between fluid utilization and the economics associated with producing power.

Several power conversion schemes applicable to liquid-dominated systems are summarized in Fig. 1. Although in each case a production and reinjection well system is shown, reinjection might not be required in many applications. Direct steam flashing systems are currently used through-

out the world for producing power while binary-fluid cycles employing organic working fluids are just beginning to be developed. Binary-fluid cycles are usually saturated, superheated, or supercritical Rankine-type cycles. They involve a primary heat exchange step where the heat from the geothermal resouce is transferred to one or more higher vapor pressure compounds to generate a vapor, which expands through a turbogenerator to produce electricity and then passes to a condenser/desuperheater for heat rejection to the environment. The cycle is completed by pumping the fluid up to the operating pressure with a feed pump. Compounds considered for these applications are lower molecular weight hydrocarbons (e.g., isobutane, propane), their halogenated derivatives (e. g., Freons, CH_2F_2, $CHCl_2F$) and ammonia (NH_3). Properties of these alternate working fluids, particularly their low-temperature vapor density, make them attractive for turbine applications. In addition, they potentially should have higher utilization efficiencies than even two-stage flashing systems. This would reduce the capital investment in the geothermal wells. Flashing systems are, of course, simpler in that they do not require a primary heat exchange step.

Topping/bottoming and dual cycles represent combinations of two binary-fluid cycles. In the topping/bottoming type cycle, the entire fraction of the geofluid's heat is transferred to a topping fluid which rejects heat

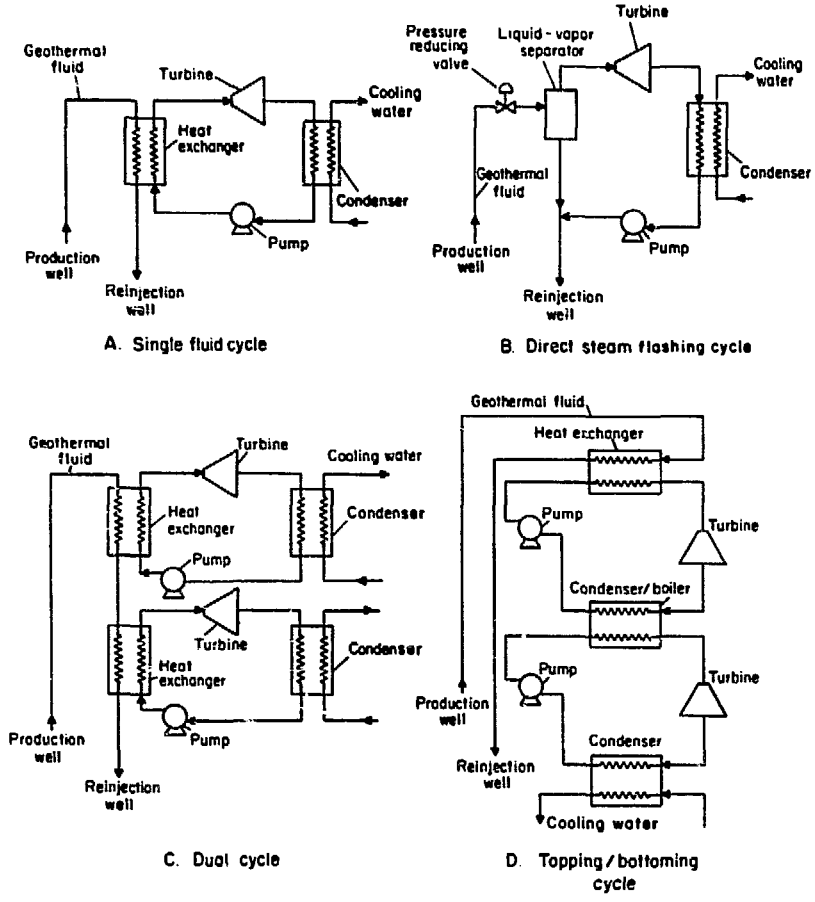

Fig. 1. Schematic of electric power conversion cycles for liquid-dominated geothermal resources.

in its condenser/desuperheater to a bottoming fluid which is vaporized and in turn finally rejects heat to the environment. In the dual cycle only part of the geofluid's heat is transferred to one cycle while the remaining fraction is transferred to a second cycle operating at a lower temperature. The characteristics of the geothermal fluid, particularly its temperature, will determine whether one or two cycles are optimal.

In the discussion that follows a summary of the preliminary results from a joint study between Oak Ridge National Laboratory and Los Alamos Scientific Laboratory will be presented.[11] Our major effort has been directed toward developing thermodynamic and economic design criteria applicable to geothermal electric power systems.

When evaluating the potential of binary-fluid cycles or direct steam flashing systems, accurate data on the thermodynamic properties (heat capacity, density, vapor pressure, pressure-volume-temperature (PVT) relationships) and transport properties (viscosity, thermal conductivity) are required to calculate performance. For example, a revised form of the Martin-Hou equation of state with 21 empirical parameters was used for calculating PVT properties.[11] The properties of water are very well understood as are the limitations of low-pressure steam turbomachinery. This is not the case for alternate working fluids and consequently we have concentrated our work in characterizing binary-fluid cycles.

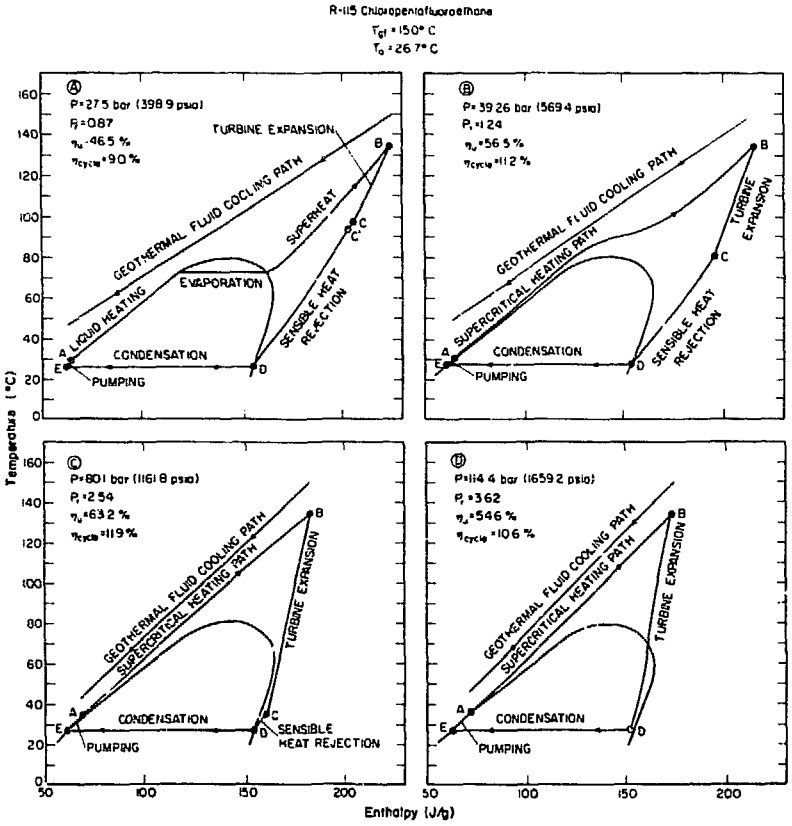

Fig. 2. Approach to the thermodynamically optimized Rankine cycle for R-115 (C_2ClF_5) with a 150°C liquid geothermal resource and heat rejection at 26.7°C (80°F). Temperature-enthalpy diagrams shown at four different reduced cycle pressures.

A specific example is included here for a 150°C liquid-dominated resource with a heat rejection temperature of 26.7°C. Monochloropentafluoroethane (R-115) was selected as the working fluid. Temperature-enthalpy diagrams for four different operating pressures are presented in Fig. 2 to illustrate the dramatic effect that pressure has on cycle performance. In going from a subcritical cycle at 27.5 bars (Case A, P_r = 0.87) to a supercritical cycle at 80.1 bars (Case C, P_r = 2.54), the utilization efficiency increases from 46.5 to 63.2%. This improvement is due primarily to a more uniform heat capacity at the higher pressure and a reduction in the amount of sensible heat rejection (desuperheat). At supercritical pressures there is no phase change and the working fluid heating path can be maintained almost parallel to the geothermal fluid cooling path. As the pressure is increased to 114.4 bars (Case D) cycle performance declines to an η_u of 54.6%. This is caused by the less than ideal efficiencies of the turbine and pump components (85 and 80%, respectively) and the larger component work requirements associated with higher pressure operation.

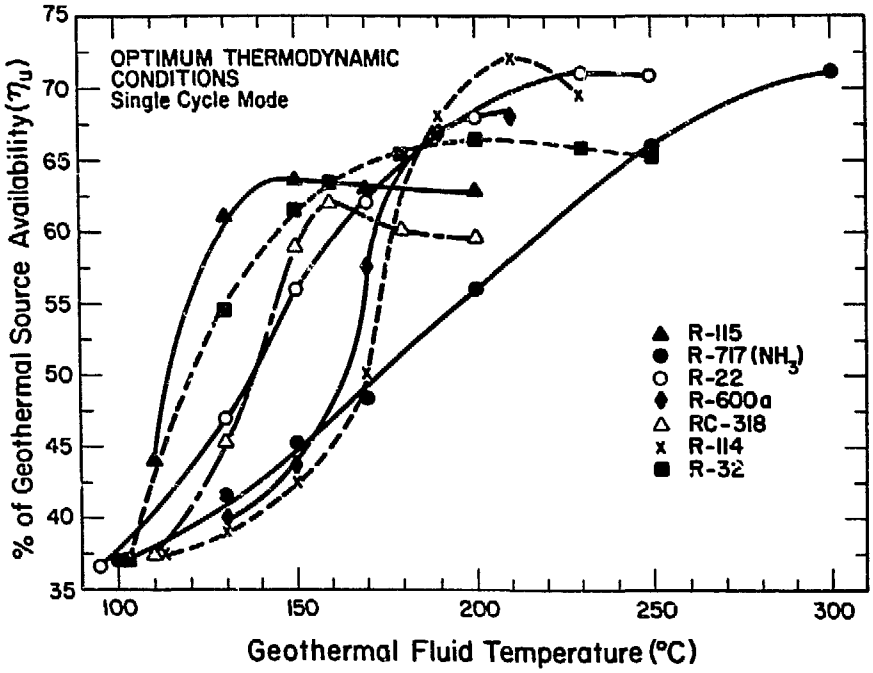

Fig. 3. Geothermal well utilization efficiency η_u as a function of geothermal fluid temperature for optimum thermodynamic operating conditions.

For any given working fluid there is an optimum set of operating conditions yielding a maximum η_u for particular geothermal fluid and heat rejection temperatures. In screening potential fluids, some knowledge of the magnitude of η_u and how it changes as the resource temperature changes would be particularly useful. Figure 3 shows how η_u varies for six additional fluids, besides R-115, for geothermal fluid temperatures ranging from 100 to 300°C. The fluids examined were (1) R-717 (ammonia, NH_3), (2) R-115 (C_2ClF_5), (3) R-22 ($CHClF_2$), (4) R-600a (isobutane, i-C_4H_{10}), (5) RC-318 (C_4F_8), (6) R-114 (C_2HClF_4), and (7) R-32 (CH_2F_2). These fluids represent a wide range of properties including molecular weight, vapor pressure, heat capacity, and specific volume. A distinct curve with a maximum η_u exists for each fluid and gives an indication of a range of

temperatures where optimum performance would be expected. It is important to emphasize the differences in the shape of the curves as well as the maximum value that is achieved.

Thermodynamic optimum conditions (maximum η_u) were determined for each fluid by varying the cycle operating pressure at each geothermal fluid temperature. This required considerable computer computational time. In the initial screening process it would be helpful to have a less involved procedure for evaluating fluids. Figure 4 was obtained by plotting the difference between the temperature of optimum performance (T*) from Fig. 3 and the fluid's critical temperature (T_c) as a function of reduced, ideal gas state heat capacity (C_p^*/R). C_p^*/R can also be expressed using the heat capacity ratio ($\gamma = C_p/C_v$) as $\frac{\gamma}{\gamma-1}$. Data for the seven fluids correlated well with the reciprocal C_p^*/R relationship given on the figure. In a qualitative way this behavior can be explained by changes in properties associated with changes in molecular weight. Lower molecular weight compounds like R-22 (MW = 86) and ammonia/R-717 (MW = 17) reach their optimum performance at much higher values of superheat above the critical point. As the molecular weight increases the amount of superheat decreases. This type of procedure might be valuable in the preliminary assessment of a potential working fluid since γ and T_c are commonly known properties for a great many compounds.

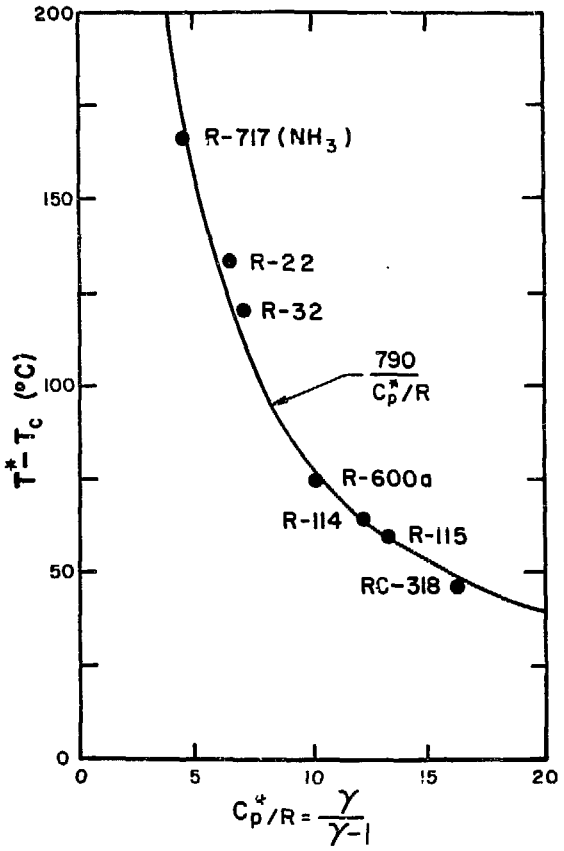

Fig. 4. Generalized correlation for the degree of superheat above the critical temperature for optimum well utilization as a function of ideal gas reduced heat capacity.

6. Power Cycle Economics

The entire picture of geothermal power production isn't revealed until the economics are considered. In the time remaining, it would be difficult to present details; but I will at least try to give the basic concepts. In comparing direct steam flashing with binary-fluid cycles, differences between the primary components including wells, heat exchangers, condensers/desuperheaters, turbines, and pumps are important. Well drilling and casing costs typically comprise between 40 to 80% of the total capital investment in the power plant. This percentage is strongly dependent on the depth and diameter of the well and the type of formation it is drilled in. Binary-fluid systems will have large investments in heat exchangers and condenser/desuperheater components; and a much smaller amount invested in the turbogenerator and pump units. Flashing system equipment investment is largely centered around the low-pressure, large-diameter steam turbines and heat rejection systems employed, e. g. cooling towers. Single- and two-stage flashing systems have η_{ts} values from 40 to 50% which are below those for good binary-fluid systems (>60%). Consequently for a given size power plant, flashing cycles will require more wells than binary-fluid cycles. One uncertainty that should be mentioned is that flashing systems are in use today and binary-fluid cycles are just being developed. For example, scaling problems associated with the primary heat exchanger might be important.[3,9]

In evaluating potential working fluids, turbine size requirements are important to the economics. Using a similarity analysis, the efficiency of converting thermal energy into rotating mechanical work is governed by two dimensionless numbers involving four parameters: (1) turbine blade diameter; (2) turbine rotational speed; (3) stage enthalpy drop; and (4) volumetric gas flow rate. In the cases we considered, turbine efficiency was maximized; thus the relationship among the parameters was specified. Therefore turbine sizes and operating conditions and consequently costs could be estimated. Generalized figures of merit ξ, involving the fluid's molecular weight M, critical pressure P_c, and reduced vapor energy density $h_{fg})_r/v_g)_r^{sat}$ evaluated at the heat rejection temperature T_o for several potential working fluids are presented in Table II. For a given power output, ξ decreases with turbine size.

TABLE II

TURBINE SIZE FIGURE OF MERIT

Heat Rejection Temperature T_o = 26.7°C (80°F)

$$\xi = \frac{\sqrt{M}}{P_c}\left[\frac{v_g)_r^{sat}}{h_{fg})_r}\right]_{T_o}$$

Compound	Formula	
R-717	NH_3	0.177
R-32	CH_2F_2	0.223
R-22	$CHClF_2$	0.411
R-115	C_2ClF_5	0.649
R-600a	C_4H_{10}	0.881
RC-318	C_4F_8	1.628
R-114	$C_2Cl_2F_4$	2.246
Water	H_2O	30.71

Because of the numerous variables that need to be specified before costs can be estimated, several specific cases were examined. A 100 MW(e) capacity was selected. A 150°C liquid-dominated resource with a two-stage flashing and R-32 (CH_2F_2) binary-fluid cycle and a 250°C dry hot rock resource with ammonia as the working fluid were considered initially. In each case, well flow rate and depth were specified and reinjection well costs included. Economic optima were determined by varying the operating pressure of the binary-fluid cycle for fixed heat exchange conditions. Flashing system optima were calculated by varying the flashing stage pressure or temperature. Figure 5 presents the results.

Cost estimates of this type are not only very site specific in the sense that they depend on well flow rate, geothermal fluid temperature, and geothermal temperature gradient, but they also depend heavily on the assumptions made concerning the process equipment and well drilling costs. We have tried to be conservative in our estimates, particularly with respect to well costs, and consequently total capital investments are high. For the 150°C liquid-dominated resource, costs range between

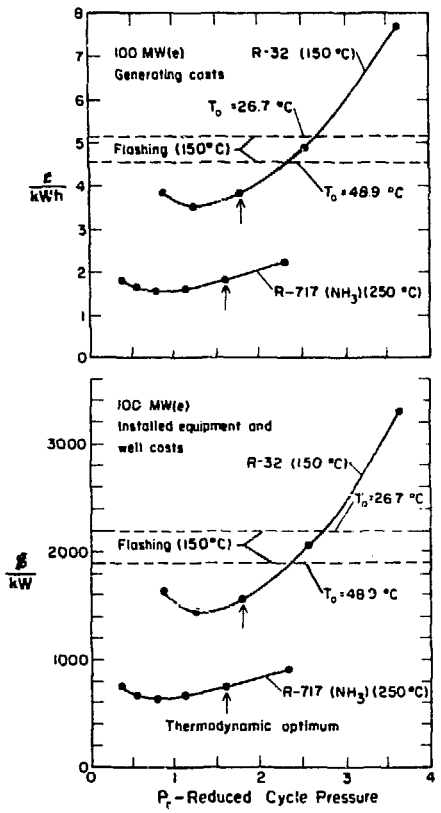

Fig. 5. Approach to economic optimum cycle conditions. Cost per kWh and cost per installed kW as a function of reduced cycle pressure P_r. NH_3 for a 250°C dry hot rock geothermal source and R-32 for a 150°C liquid-dominated geothermal source.

$1400/kW to $2200/kW with between 45 to 80% of that figure invested in the wells depending on cycle choice. This case was for a geothermal gradient of 50°C/km which is far from the anamolously high gradients of 200°C/km found in certain regions of the world. Using a 50°C/km gradient but drilling to obtain 250°C fluids in a dry hot rock system with a well flow rate three times higher, costs drop to $600/kW.

At this point, the controlling effects that well flow rates, fluid temperatures, and geothermal gradients have on the economics should be evident. The effect of resource temperature on generating costs was determined by optimizing an R-32 cycle at several geothermal fluid temperatures between 130 and 250°C assuming a constant geothermal gradient of 50°C/km and a fixed well flow rate (see Fig. 6). There was a distinct minimum in the cost curve at a particular temperature. In other words, for a given set of resource and power plant conditions there is an optimum depth for drilling.

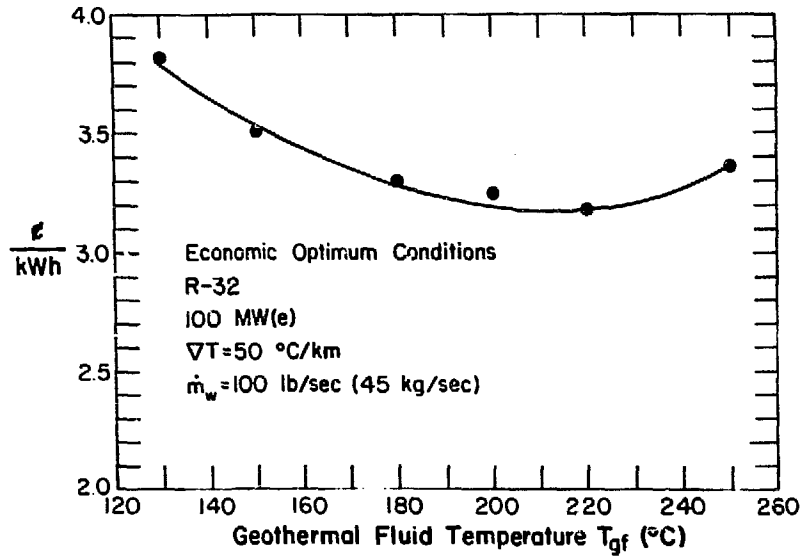

Fig. 6. Generating costs versus geothermal fluid temperature for an R-32 binary-fluid cycle. Well depths correspond to a geothermal gradient of 50°C/km with heat rejection at 26.7°C.

These results were expanded into a generalized cost model for preliminary estimating purposes. In this model, installed generating cost is expressed parametrically as a function of well flow rate (45 to 225 kg/sec), geothermal fluid temperature (100 to 300°C), and geothermal gradient (20 to 200°C/km) using a binary-fluid cycle for power production. Figure 7 illustrates the parametric dependence at 113 kg/sec.

Given our conservative economic approach, geothermal generating costs still appear competitive (Table III) with the present escalated fossil-fuel and nuclear generating costs, and should be given serious consideration as one alternate energy source.

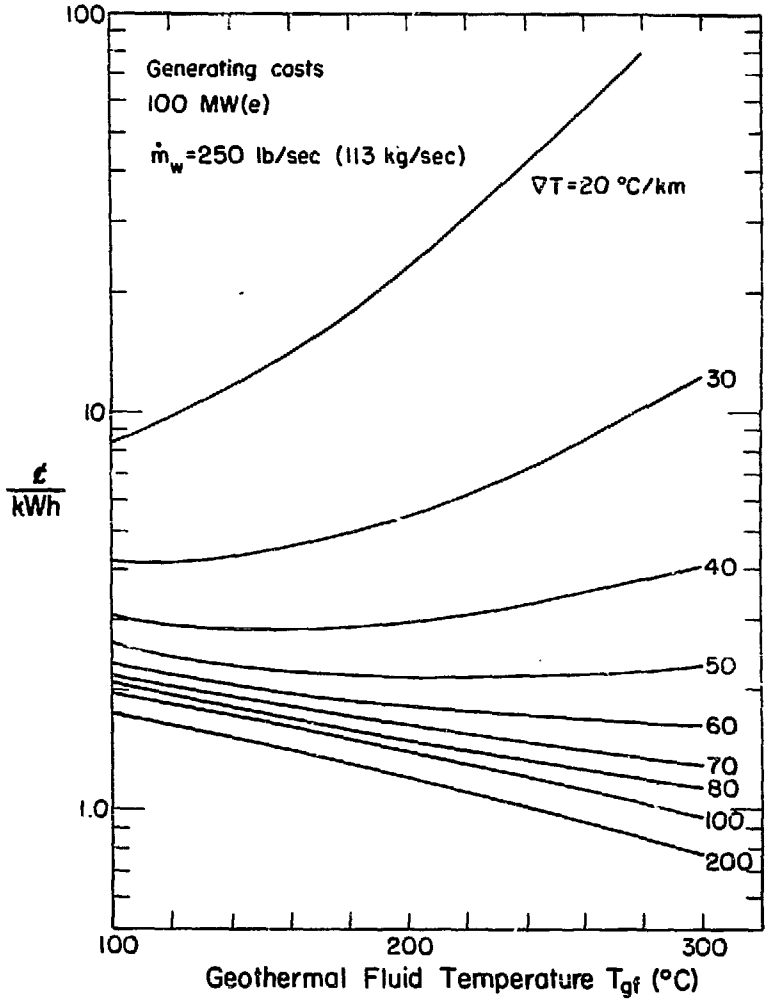

Fig. 7. Generalized cost model for geothermal systems. Generating costs expressed as a function of geothermal gradient ∇T and geothermal fluid temperature T_{gf} for a well flow rate $\dot{m}_w$ = 113 kg/sec (250 lb/sec).

TABLE III

COMPARISON OF FOSSIL-FUEL, NUCLEAR, AND GEOTHERMAL GENERATING COST ESTIMATES

Resource Type	Installed Equipment Costs ($/kW)	Equipment Cost as (¢/kWh)[a]	Operating and Maintenance as (¢/kWh)	Well or Fuel Cost (¢/kWh)	Total Generating Cost (¢/kWh)
Direct flashing[b]	300-600	0.68-1.37	0.13	0.80-2.80	1.61-4.30
Binary-fluid cycles[b]	400-700	0.90-1.60	0.13	0.53-2.45	1.56-4.18
Nuclear	≥800	≥1.83	0.13	0.30	≥2.26
Fossil fuel--oil	300-500[c]	0.68-1.14	0.13	2.0	2.81-3.27
Fossil fuel--coal	300-500[c]	0.68-1.14	0.13	1.0	1.81-2.27

[a] 17% annual fixed charge rate.
85% (7446 h/yr) load factor.

[b] 150-200°C resources.
$\dot{m}_w$ = 100-300 lb/sec well flow rate.

[c] Higher costs correspond to stringent environmental control systems.

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COAL MINING AND THE ENVIRONMENT: SEEKING A BALANCE IN APPALACHIA

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INTRODUCTION

Coal has been called the curse of Appalachia. For many years, we sold much more than coal -- we sold the beauty of our land, the purity of our streams, and the health and economic well-being of our people. On the other hand, few people outside of the coal mining industry realize how precarious that industry's position became in the 1950's when everyone, including the coal people, believed the claims of the Atomic Energy Commission that nuclear power would soon replace coal. The industry situation certainly has changed. While many segments of our nation's economy are declining, the coal business is booming as never before and can well afford the cost of environmental and human protection and rehabilitation. An observer who is familiar with coal mining practices of only a few years ago can easily see the current major improvements in land reclamation, which is in sharp contrast to the poor or non-existent reclamation of the past; still, we have a long way to go.

This review will touch briefly upon the past and present situations particularly in Kentucky, but will put the greatest emphasis on future actions toward achieving a balance between coal extraction and environmental quality. While we should expect and insist on responsible action by the operators of coal mines, this must be matched by responsible and realistic demands by legislators through the statutes they write and by the regulators who write and enforce regulations under those statutes.

BACKGROUND

In 1973, Kentucky led the nation in coal production. The nearly 128 million tons were mined about equally in 703 surface mines and 795 underground mines.(1)

Kentucky's coal lies in two separate coal fields having very different characteristics. Most of the coal from the comparatively steep slopes of Eastern Kentucky, part of the Appalachian coal field, has a low sulfur content. In contrast, the Western Kentucky coal field, an extension of the Illinois Basin deposits, has a more gently rolling terrain and yields a high sulfur coal. The estimated identified remaining coal resource in Kentucky is nearly 65 billion tons: adding hypothetical resources of coal in unmapped areas, the total may be as large as 117 billion tons of bituminous coal.(2)

HISTORICAL DEVELOPMENT

Except for relatively primitive mining from obvious outcrops, the first mechanical surface extraction of coal in Eastern Kentucky was done in 1905 when a steam shovel began operating at Lily, in Laurel County. The first commercial surface mine in Western Kentucky was opened in 1919

a few miles west of Madisonville. By 1937, Kentucky was producing about 180,000 tons of surface-mined coal annually, principally in the western part of the state.

World War II gave a significant boost to surface mining in both Eastern and Western Kentucky, with defense industries demanding every ton of coal that could be extracted, no matter how difficult the operation. By 1947, Kentucky's production of surface-mined coal had increased to 10.5 million tons a year.

The increased demand for coal, as well as an improving road system for haulage from mobile mining sites, resulted in renewed surface mining activity in Eastern Kentucky beginning in the 1940's. Despite rapid expansion, surface mining still accounted for only 5% of Eastern Kentucky's coal production by 1957, much less than the 67% in Western Kentucky.

After the coal recession of the 1950's, however, the production of surface-mined coal picked up remarkably. By 1966, 39% of Kentucky's coal production, or 36.4 million tons, was coming from surface mines, with 25% of this surface-mined coal coming from Eastern Kentucky. By 1970, surface and underground mining each produced about 50% of Kentucky's 125.3 million tons. Figures of 1973 indicate that 51% of Kentucky's surface mined coal came from the Eastern part of the state.

Among the coal states, Kentucky was slow to enact laws regulating surface mines. West Virginia in 1939 became the first to pass surface-mine legislation. Indiana passed its first surface mining legislation in 1941, Illinois in 1943, Pennsylvania in 1945, and Ohio and Maryland in 1947.

Two bills to regulate the industry were introduced into Kentucky's 1948 Legislature, but both failed of passage. After attempts at regulation failed in the 1950 and 1952 Legislatures, the 1954 Legislature passed a law which established a Commission of Strip Mining and Reclamation, called for the issuance of permits, and indicated that reclamation should be done "where practicable." The Commission was abolished in 1956, but re-established in 1960. Effectiveness of the regulatory efforts may be assessed in light of the discovery in 1960 that only nine of some 160 surface mine operators in Eastern Kentucky had obtained the required permits.

The 1964 Legislature passed Kentucky's first effective surface mine legislation, however, there were a number of deficiencies in the law. Finally, the 1966 Legislature, after lengthy discussions, passed a surface mine law which was quickly hailed by conservationists and damned by industry representatives as strictest surface mining legislation in the United States. The legislation also authorized Kentucky's becoming the first member of the Interstate Mining Compact.

The contrast between the situations before and after 1966 are so great that it is common practice to refer to lands that were strip mined before 1966 as "pre-law" lands. This is further emphasized by the observation that of about 130,000 acres disturbed in Kentucky by surface mining of coal before 1966, there remains approximately 80,000 acres of abandoned mined lands which are inadequately revegetated. These areas are referred to as orphan mined lands.

PRESENT STATUS

In Kentucky we have about 80,000 acres of orphan mined land remaining from past mining, we are currently disturbing about 25,000 new acres each year and have a coal resource of approximately 500,000 acres potentially mineable by surface methods. These actual and potential problems are dissimilar in nature and require distinct approaches.

Orphan Mined Lands Program

Nearly 130,000 acres of land were strip-mined in Kentucky for their coal deposits and most of this area was abandoned before the first effective reclamation laws were passed in 1966. No accurate data are available for the state as a whole, but estimates of the amount of inadequately revegetated land remaining range from 70,000 acres[3] to 93,000 acres.[4] The latter figure includes other surface mining activities such as stone, clay, sand and gravel in addition to coal. Much if not most, of the revegetated pre-law land has been reclaimed by natural, adventitious growth. The usual criterion is to consider a vegetation coverage of 70% or more to be adequate. In my estimation, the 80,000 acre figure is probably accurate to about ±20%.

In 1972, the Kentucky General Assembly established a revolving fund recommended by Governor Ford to reclaim orphaned strip mine land. The Legislature appropriated $500,000 to implement the program during the following two years, and added $1,000,000 in 1974 to continue the effort. The Kentucky Department for Natural Resources and Environmental Protection administers the orphaned mined lands rehabilitation program.

The goal is to purchase the land and rehabilitate it as rapidly as possible. Two areas have been obtained, both in the Western Kentucky coal field. One area comprising about 225 acres in Muhlenberg County has been designated as a Federal Job Corps Training Camp where approximately 100 men are receiving on-the-job training as heavy equipment operators while they are reclaiming the land. This cooperative effort between the U. S. Department of Labor and the Kentucky Department for Natural Resources and Environmental Protection has progressed to the point that dormitories, maintenance shops, and other buildings have been finished and reclamation of the first 75 acre block should be completed by May or June, 1975. The reclamation plan envisions about 15 acres being set aside for the Job Corps Training Center and the remainder to become permanent pasture.

The 400 acres of the Hopkins County site lies along one side of a state highway connecting two growing communities: one, the county seat, has a population or about 16,000 and the other 2,500. Because of its location and accessibility, it is planned that the restored land will be used for residential, industrial, and recreational purposes. The entire 400 acres is expected to be rehabilitated under contract within calendar year 1975.

Lands restored under this program can be transferred to other state agencies, sold at cost of acquisition and restoration to political subdivisions of the state, or publicly sold to the highest bidder. But in any case, sale of the land is under the condition that no strip mining can ever again be carried out on the land.

Surface Effects of Current Mining

The surface mining law currently in effect in Kentucky affects area mining, contour mining and auger mining operations. These mining methods depend primarily upon the nature of the terrain. On the steeper slopes of Eastern Kentucky, contour mining is the usual practice, while on the more gently rolling terrain of Western Kentucky, coal is mined by area stripping.

Contour strip mining (figure 1) is commonly practiced where mineral deposits occur along contours in mountainous terrain. Basically, this method consists of removing the overburden above the bed by starting at the outcrop and proceeding along the hillside. After the deposit is exposed and removed by this first cut, additional cuts are often made in a similar manner until the ratio of overburden to product brings the operation to a halt. This type of mining creates a shelf or "bench" on the hillside, while on the inside, it is bordered by a highwall, which may range from a few to perhaps more than 100 feet in height. On the outer portion of the operation is located the "outslope", which consists of the spoil material cast down the hillside during the mining activities. Unless controlled, or stabilized, this spoil material can cause severe erosion and landslides.(5) New regulations authorized by the 1974 Legislature to be effective in July, 1975, will permit no more than 40% of the first cut spoil to be pushed over the outslope, and no overburden due to second and subsequent cuts can be placed on the outslope or on the outer one-third of the bench. At present, slopes

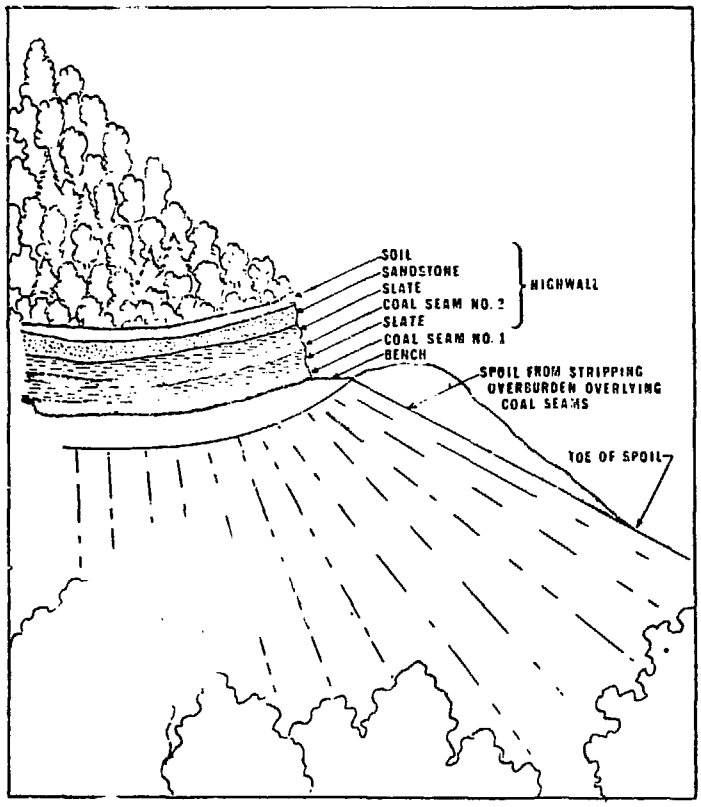

Figure 1
Coal Seams Mined at Outcrop on Mountainside

in excess of 27° can be mined only by augering or by a haulback method where no overburden is allowed over the outslope.

Area stripping, (figure 2) is usually practiced on relatively flat terrain. A trench or "box cut" is made through the overburden to expose a portion of the deposit which is then removed. The first cut may be extended, parallel, to the limits of the property or the deposit. As each succeeding parallel cut is made, the spoil, (overburden) is deposited in the cut just previously excavated.[6] The coal operator is required to cover the final mining pit and grade to the approximate original contour and revegetate the area which has been mined.

In all cases, toxic material and exposed auger holes must be covered by a minimum of four feet of dirt. Surface run-off water must be impounded and treated to control sediment and acid if necessary, and drained in such a way as to reduce erosion and stream pollution. Any acid water breakthrough must be sealed off. After final contouring and grading, the land must be revegetated according to an approved plan. Time limits are set for grading, backfilling and revegetation after coal removal.

The 1974 Legislature also directed the Department for Natural Resources and Environmental Protection to regulate the surface effects of underground mines. Regulations have been written and are being promulgated to require permitting and reclamation of haul roads, cut for entry, parking areas, waste disposal areas and other surface disturbances associated with underground mines.

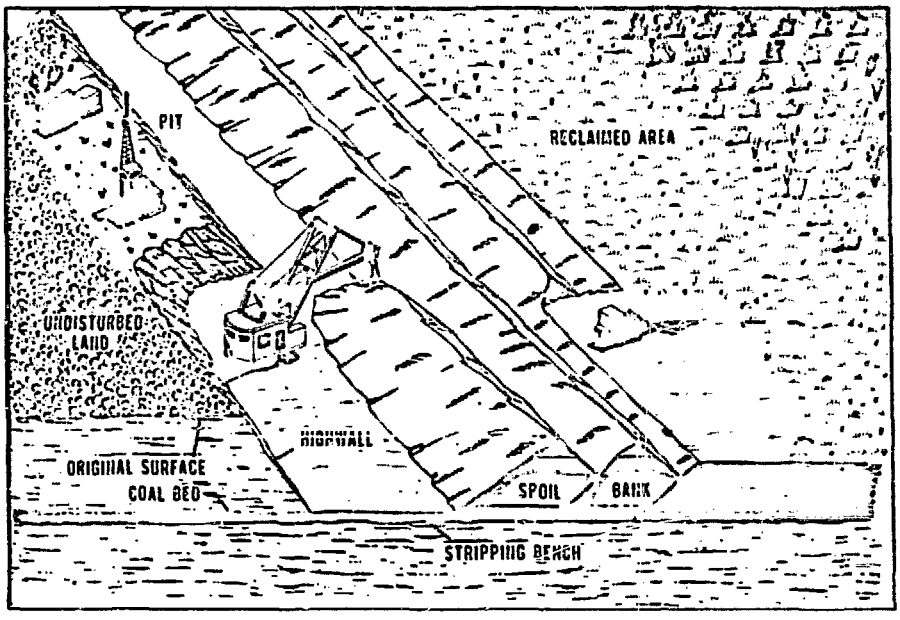

Figure 2
Area Strip Mining with Concurrent Reclamation

COAL AND OUR FUTURE ENVIRONMENT

There is no doubt that the United States has a vast coal resource. Depending upon the assumptions used, various persons have estimated that coal can supply our country's energy needs for many, possibly hundreds, of years. Without entering into an argument over the feasibility or the desirability of doubling or tripling the output of coal, it is clear that coal will be a major fuel for the remainder of this century. In anticipation of the likely expansion in surface and underground coal mining, the Commonwealth of Kentucky has intensified its efforts to reduce the adverse effects on the environment associated with the extraction and the utilization of coal.

Coal Utilization Research

The 1972 General Assembly appropriated $400,000 to support coal utilization research at the University of Kentucky's Institute for Mining and Minerals Research. During the first two years of the program the main emphasis was on the availability and detailed characteristics of Kentucky coal, on process evaluation and site selection for coal liquifaction and gassification plants, and on the establishment of a nucleus of people with expertise in the broad area of coal utilization.(7)

In 1974 the General Assembly approved Governor Ford's request for authorization of $57.7 million to mount a major expansion of Kentucky's energy resource utilization program. The authorization provides: $50 million over a six-year period to provide seed money for pilot and demonstration plants to produce synthetic fuels from coal; $4 million for a new specialized research and analysis facility near Lexington in central Kentucky; and $3.7 million for expansion of the research efforts through the University of Kentucky's Institute for Mining and Minerals Research.

The research program includes projects in the five following areas: Evaluation of Reserves; Mining; Reclamation; Coal Utilization; and Environmental Effects. Of these five areas, the major one is that of Coal Utilization, which includes research and experimental projects involving liquifaction of coal, chemical reactions of coal with hydrogen at various pressures and temperatures, physical and chemical desulfurization of coal, and production of methanol from coal. All five areas of research are being addressed in terms of short range practical application to immediate problems with a view toward longer range developments.

All of these research areas have a direct bearing on environmental quality, especially the work on coal utilization. While some of the interest in synthetic fuels from coal stems from the convenience of using liquid or gaseous fuels, it should be kept in mind that the removal or abatement of impurities, principally ash and sulfur, is a major underlying factor motivating much of the current research efforts to develop clean fuels from coal.

Reclamation Research

A number of general comments can be made concerning the major environmental problems associated with disturbing the surface of the earth to extract coal in Kentucky. Sediment is the number one problem, especially in the mountainous eastern part of the state. The number two problem in Eastern Kentucky is the failure of an outslope, resulting in obvious slides. Such slope failure often results in blocking stream beds and occasionally blocks a road or encroaches upon private property. The

problem of vegetation failure is most prevalent in the Western Kentucky coal field where the coal and overburden have a high sulfur content sometimes producing acid terminal soils. In addition, seasonal variations in rainfall may lead to revegetation failure. These failures are also found in isolated areas of Eastern Kentucky, primarily because of improper reclamation techniques, difficulty in seeding steep outslopes, and occasionally, because of toxic or predominately rock-type overburden. Chemical water pollution problems occur mainly in the Western Kentucky coal field, primarily because of the same factors producing revegetation failures. Some chemical water pollution problems do occur in Eastern Kentucky, most of which can be attributed to old abandoned underground mine workings and some old, unreclaimed orphan surface mined areas.

The Kentucky Department for Natural Resources and Environmental Protection, in cooperation with various state and federal agencies, has initiated a number of reclamation research projects directed toward overcoming the major barriers to successful reclamation. Some of the recently completed and ongoing research and demonstration activities are summarized in the following paragraphs.

1. Slope Failure Research

Next to sedimentation, slope failure is the biggest problem associated with surface mining in Eastern Kentucky. Slope failure occurs as a result of many factors, but mainly because of the placement of too much overburden material on the natural outslope and the presence of water. Slides have been known to occur in areas of Eastern Kentucky as many as thirteen years after mining operations have ceased. Slope failures are not only an eye sore, they drastically increase our sediment problems.

A program of Slope Stability Research, funded jointly by Kentucky and the Appalachian Regional Commission, has been directed toward identifying factors responsible for the residual chronic slides in steep slope terrain, and toward preparation of guidelines to methods of detecting slide movements and practical methods of arresting their progression. Eight representative surface mines throughout Eastern Kentucky have been selected for instrumentation and monitoring. (Reference 8)

2. Revegetation Research

The establishment of new vegetation on surface mines is a problem in certain areas of Eastern Kentucky. As part of an Appalachian Regional Commission grant program, the Department entered into an agreement with the United States Forest Service Experiment Station in Berea, Kentucky to conduct a study entitled, Revegetation Research for Eastern Kentucky. Noticeable beneficial results have been observed on many of the project test plots as compared to the poor to mediocre results of the usual revegetation practices performed by coal operators on problem spoils.

The objectives of the Revegetation Project are:

a. To identify problem areas and classify them by physical and chemical conditions;

b. To carry out soil and rock strata studies;

c. To evaluate present mining and revegetation requirements and recommend alternative means to overcome problems;

d. To conduct tests on research plots and monitor through two full growing seasons; and

e. To develop a manual to be used by surface mine operators and reclamation inspectors to establish guidelines for effective revegetation.

Establishment of quick cover crops has been emphasized. With minimum seed bed preparation, the addition of fertilizer and mulches, the establishment of quick cover crops such as pearl millet, has been successfully demonstrated. However, some problems have been encountered. In some cases, it was found that the quick and abundant growth actually smothered the more desirable perennial grasses, such as Kentucky 31 fescue, which were planted along with the quick cover crops.

The Forest Service group recommended that the Division of Reclamation require a chemical and physical evaluation of the overburden strata before issuing a surface mine permit in areas considered highly sensitive to environmental damage, and on coal seams known to have produced acid spoils in the past or are suspected of being acid producers. In cases when the overburden analyses indicate that the proportion of the acid overburden is so great that it cannot feasibly be buried, then consideration should be given to prohibiting mining, rather than attempting the very difficult task of correcting the acid problem.

The final report, in the form of a revegetation design manual has been issued. (Reference 9)

3. Design of Surface Mining Systems

Because of the obvious problems involved in continuing, possibly expanding, the surface mining industry, we in Kentucky felt that we needed to identify new approaches toward surface mining, and at the same time take a look at present methods by which our Department administers the surface mine law and regulations. Because of this need, a study was undertaken entitled, Design of Surface Mining Systems, in conjunction with MATHEMATICA, Inc., and the engineering company Ford, Bacon and Davis. The study, conducted as part of an Appalachian Regional Commission-Kentucky project for "Improved Surface Mining Techniques in Eastern Kentucky", was divided into two parts. Part "A" of the project was aimed at identifying alternative approaches to surface mining, using varying combinations of existing equipment, which appear to be feasible based on different resource objectives such as maximizing recovery of the resources, minimizing the adverse environmental impact, and reclaiming land for multi-purpose use on a large scale. In addition, the contractor was asked to recommend desirable changes in the general administration of our reclamation enforcement program. Part "B" of the study was directed toward identifying feasible modifications of mining systems which might improve surface performance, and toward the design of new equipment, procedures, and systems which would improve the mining operation, both for increased resource recovery and lessening the adverse environmental impact.

From the investigations conducted under this program, two new modified mining methods were proposed. One is the modified block-cut method, which is presently proposed for implementation through an Environmental Protection Agency demonstration grant.

Another potential method which appears feasible is a modified mountain-top removal mining technique. (Figures 3, 4, 5, 6, and 7). This mining operation is conducted similar to the conventional mountain top removal method, but like the buried highwall technique, it substantially reduces the need to deposit overburden material on the outslopes typical of mining in Eastern Kentucky. Work under this project has been completed and three project report volumes have been issued. (Reference 5)

4. Chemical Water Quality Research (Eastern Kentucky)

While chemical stream pollution, particularly acid mine drainage, is not as big a problem in Eastern Kentucky as it is in the Western Kentucky coal field, nevertheless, many streams in the Eastern part of the state are affected to some degree by mine drainage pollution, and the overburden associated with a few coal seams are known to be acid producers.

In cooperation with the Appalachian Regional Commission, Kentucky began a chemical water pollution project to determine the characteristics which would allow for pre-mining identification of areas in Eastern Kentucky having a high potential for developing chemical pollution, and to propose alternative waste material handling methods for such areas.

The method employed during this study was to select surface mining sites which were associated with different coal seam groupings, to monitor the stream quality, and to obtain and analyze stratigraphic samples of coal seams found in each grouping. On the basis of this work, coal seams in Eastern Kentucky that have the highest potential for acid production have been identified, and appropriate methods of overburden handling have been outlined. (Reference 10)

5. Chemical Water Pollution (Western Kentucky)

Many of the area-type surface mines in Western Kentucky operate with the pit floor well below the local water table. Consequently, both ground and surface water accumulates in the pits where the chemical reactions

Sketches of
Cross Section of Mountaintop Mining Modification A –Mining Parallel to Ridges

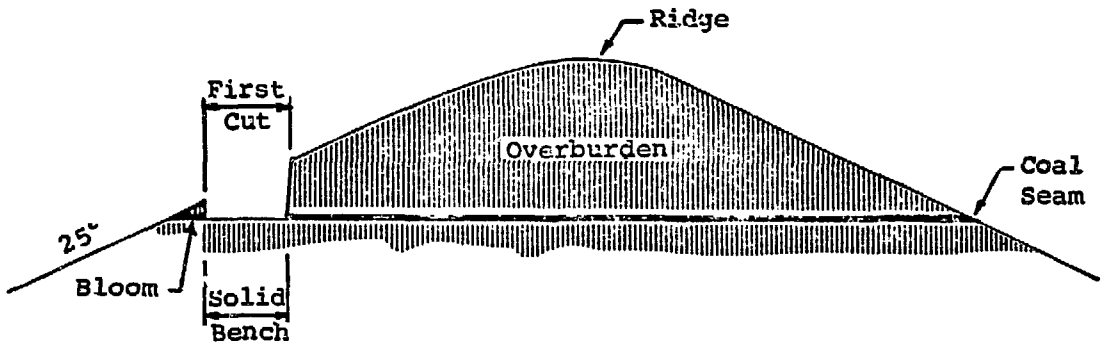

Figure 3
First Cut (Block Cut)

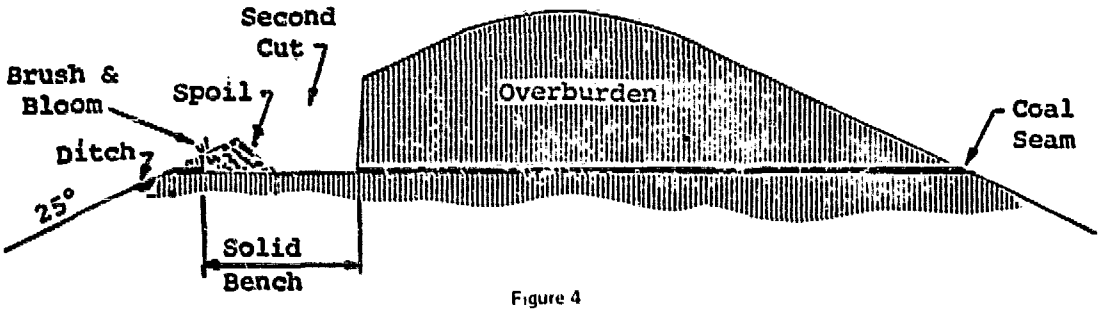

Figure 4
Second Cut

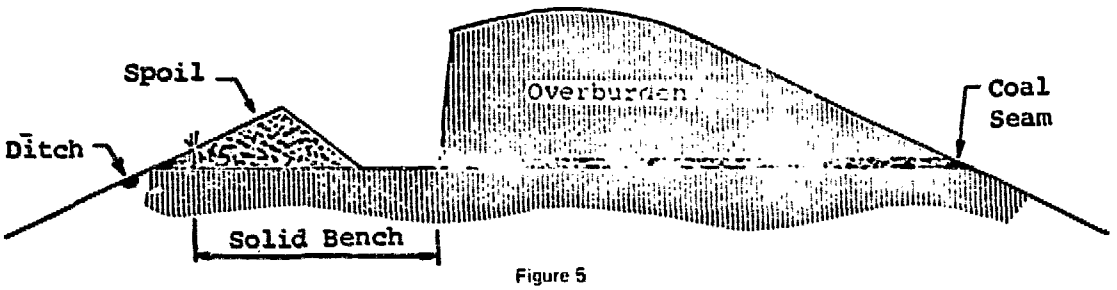

Figure 5
Third Cut

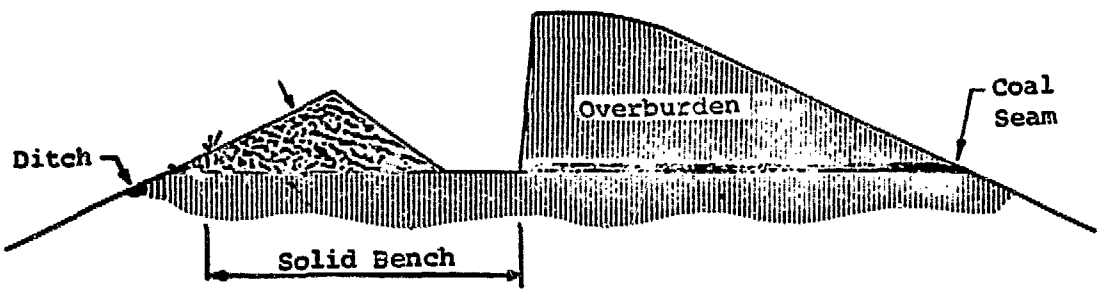

Figure 6
Fourth Cut

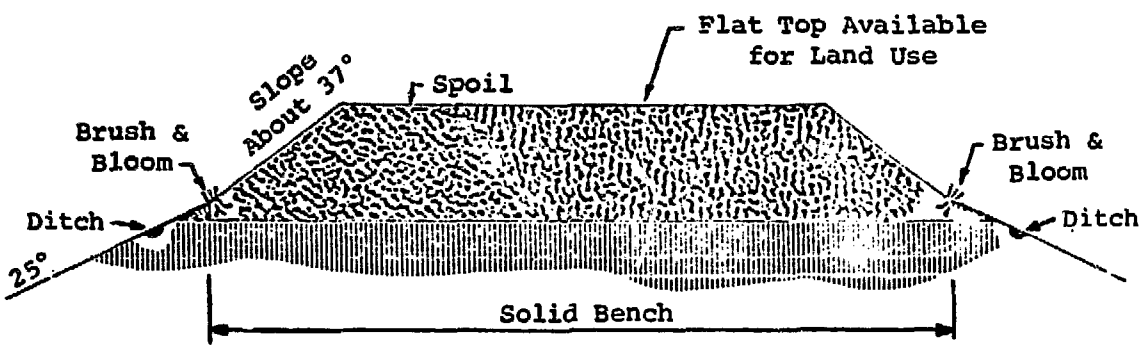

Figure 7
Cross Section of Mountaintop After Mining

leading to acid formation take place. In the past, drainage water which accumulated in the surface mine pit was discharged untreated directly into a stream. However, since the adoption of Kentucky Water Quality Standards for Surface Mining, this method of discharging water is no longer permitted. Water which has accumulated in a pit must now meet stringent standards before being discharged. Concurrent with an oversupply of acid water, during some seasons of the year revegetation efforts sometimes fail in Western Kentucky because of insufficient moisture in the soil.

In order to attack both of these problem concurrently, Kentucky, in cooperation with the Environmental Protection Agency and the Peabody Coal Company began a project entitled "Revegetation Augmentation by Reuse of Treated Active Surface Mine Drainage." The objective of this ongoing project is to demonstrate the technique of using neutralized acid mine drainage from a full scale, active surface mine to irrigate new vegetative cover on re-graded spoil banks, and to eliminate pollution from the surface water.

As shown in the process flow and instrumentation diagram (figure 8) the acid water will be pumped out of the pit to a mixing tank. In the mixing tank, the acid water will be treated with pulverized limestone. From the mixing tank the water will flow to a pond, where an aerator will provide oxygen to speed up the neutralization process. From the aeration pond, the neutralized water will go to a settling lagoon where the limestone sludge and heavy metals will settle out. From the settling lagoon, the water will be pumped as needed to the spoil irrigation system and sprayed at predetermined rates on the seeded spoil, or will be drained directly into the receiving stream.

Both the neutralization and irrigation units will be engineered and constructed for semi-portability, so as to be compatible with the transient

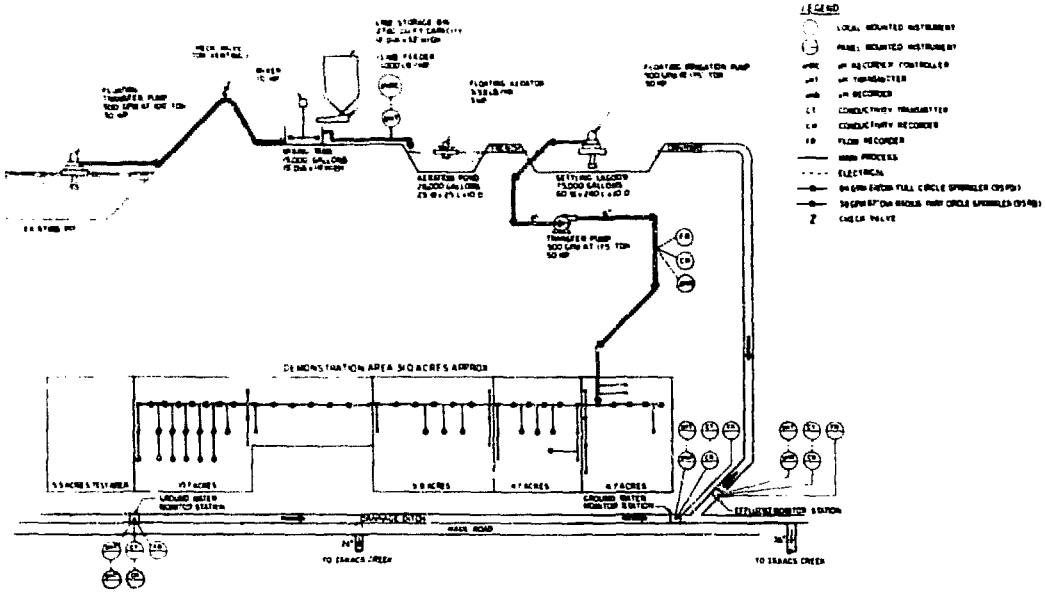

Figure 8
Vogue Mine—Process Flow and Instrumentation Diag am

nature of the surface mine operation. Continuous monitoring of discharges, receiving streams, and runoff quality will be carried out during the entire project. Costs and effectiveness of the project will also be documented.

6. Demonstration of Debris Basins for Control of Sedimentation in Steep Slope Terrain

Under present regulations, the surface mine operator in Kentucky is required to build approved sediment control structures in the hollows below the mining site. These control structures are designed to retain the water coming off the strip mined area long enough for the suspended solids to settle out. While debris basins are the best practical means of controlling sediment from strip mining, still there are many limitations and problems with using this sediment control method.

Under a grant from the Environmental Protection Agency, Kentucky has undertaken the task for developing the needed research and documentation on the current practice of using debris basins for sediment control. In this study, which is now getting underway, we and our contractor, the L. Robert Kimball Consulting Engineers, will evaluate and document data related to the design, construction, operation, maintenance, costs and the quality of discharge water coming from control structures presently used in Eastern Kentucky. Subsequently, based on data obtained from our study, we will outline alternative design and construction methods applicable to producing the desired water quality and which will insure the safety of people living downstream.

7. Demonstration of On-Site Control of Surface Mine Sedimentation

In view of the problems and limitations of controlling sediment by the use of debris basins, the Environmental Protection Agency has approved

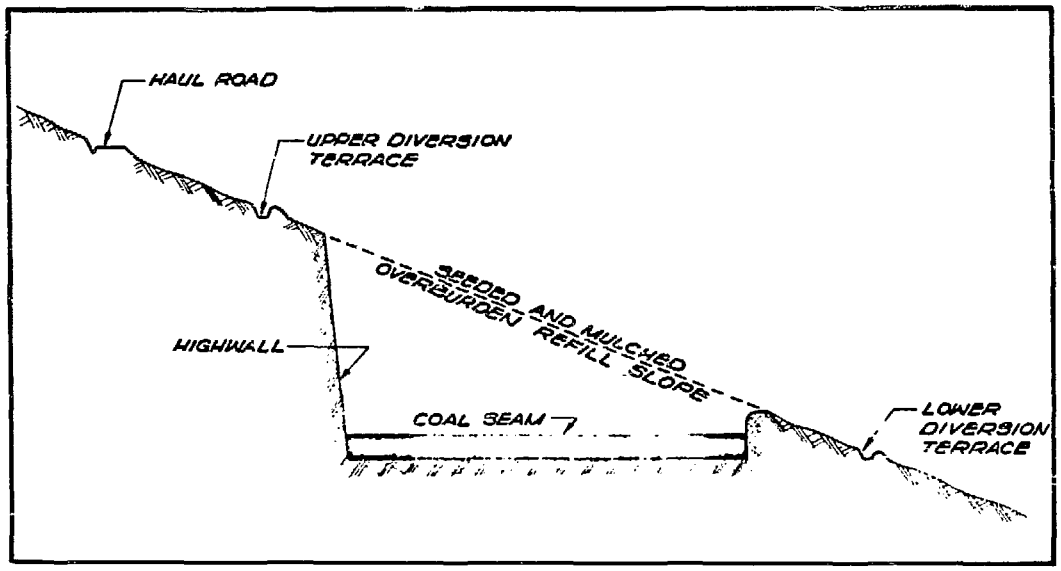

Figure 9
Typical Cross Section Showing Haul Roads, Terraces, Mined Contour, and Final Contour

a grant for a project which will demonstrate the cost and effectiveness of using non-structural conservation practices at the source of the sediment in connection with the modified block cut method of contour mining. These conservation practices will present no flood hazards, and hopefully will prevent the sediment from reaching the stream channel. Thus attacking the problem at its source, not after it is already in the stream.

Water diversion terraces will be located above and below the disturbed area (figure 9). These diversion terraces will be constructed and vegetated prior to the beginning of any mining activity. The outlets of the diversion terraces will be broad, vegetated "fan" areas (figure 10). The "fan" areas will also be constructed and vegetated prior to mining, and will serve as the final filtering device before the water reaches the stream channel.

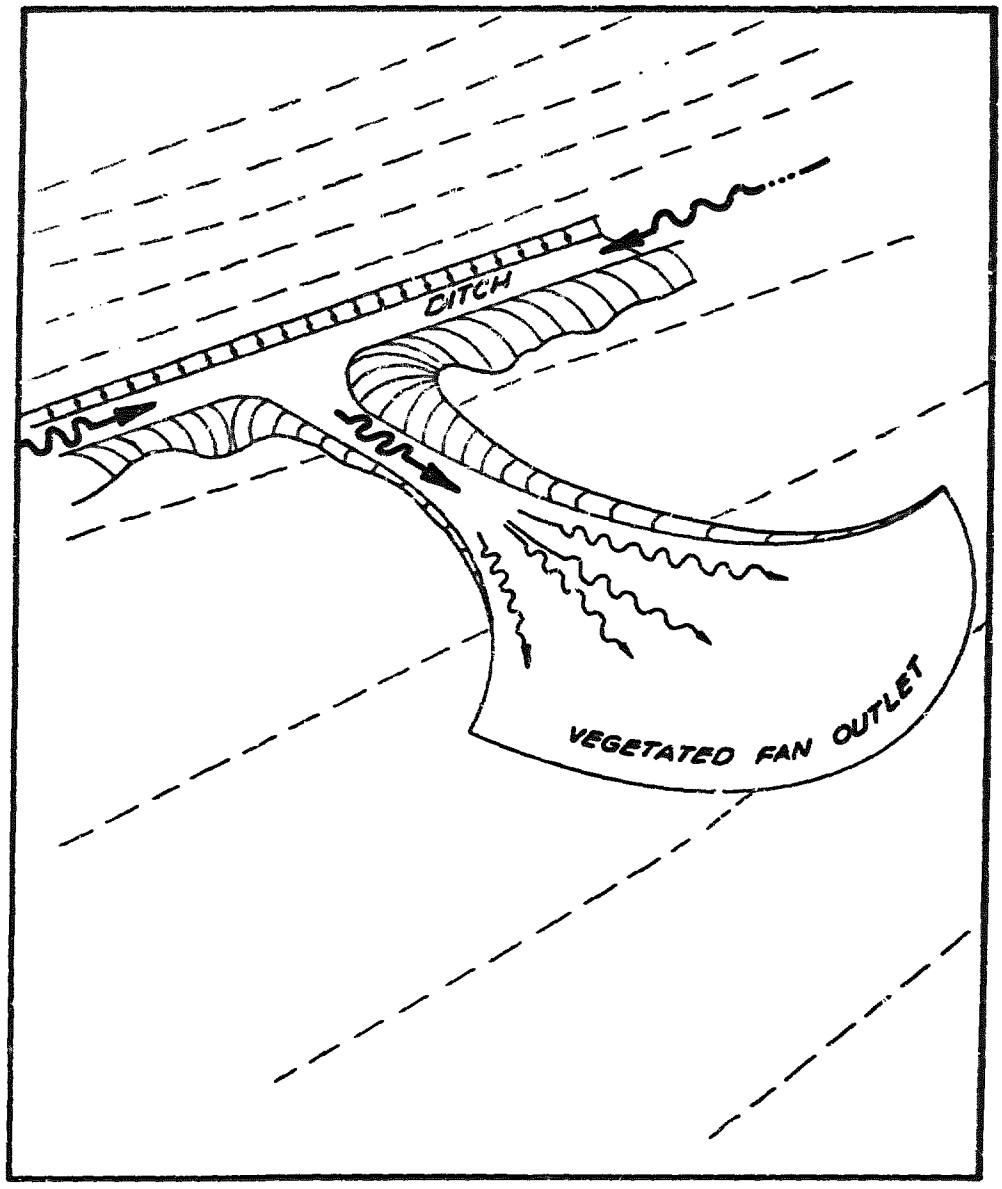

Figure 10
Typical Schematic of Vegetated Sediment Control Fan Outlet

After the vegetation is established in the diversion terraces, and "fan" areas, haul roads will be built to each area prior to the removal of the overburden. In figure 11, the haul road is shown as being located above the highwall with ramp roads leading to each section. Other possible locations of the haul roads will also be considered.

After the coal and overburden from the first mined area is removed, the overburden from the second block to be mined will be placed in the vacated area, returning the ground it its approximate original contour. The spoil will then be mulched and seeded immediately (figure 12). The slope length of the replaced spoil will be reduced by specially designed terraces.

This method, if demonstrated satisfactorily, will not only minimize the disturbed area and reduce the volume of sediment leaving the operation, but will also eliminate the highwall and the cutslope disturbance -- thereby returning the area nearly to its original state and reducing the potential for slides.

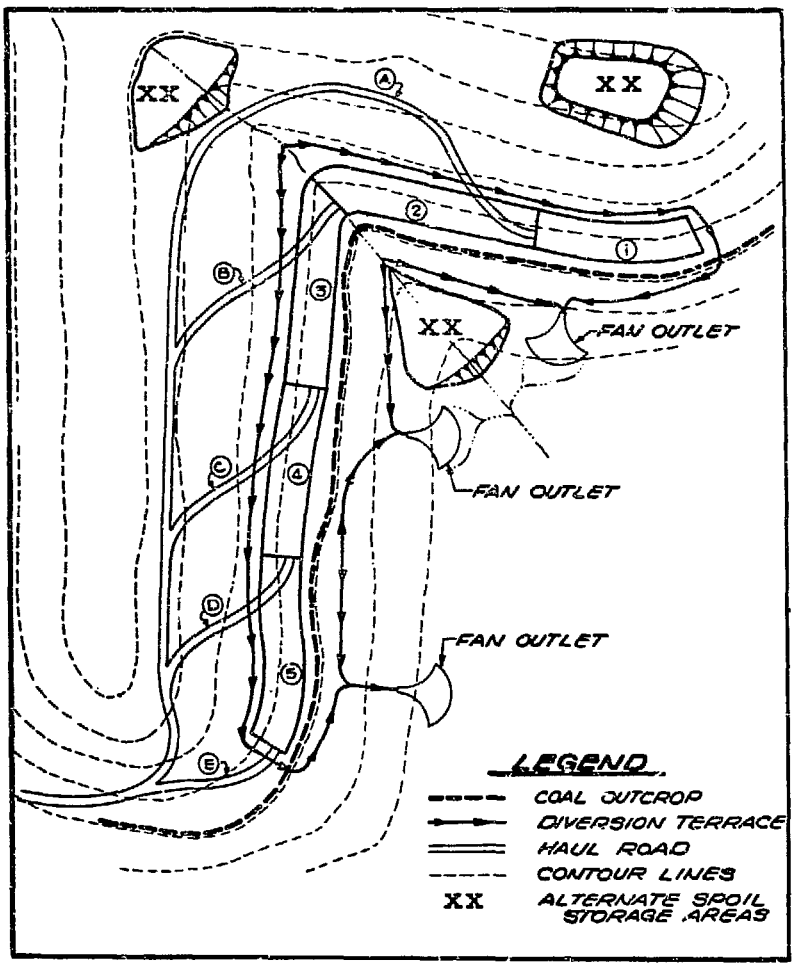

Figure 11
Typical Proposed Plan of Strip Mining

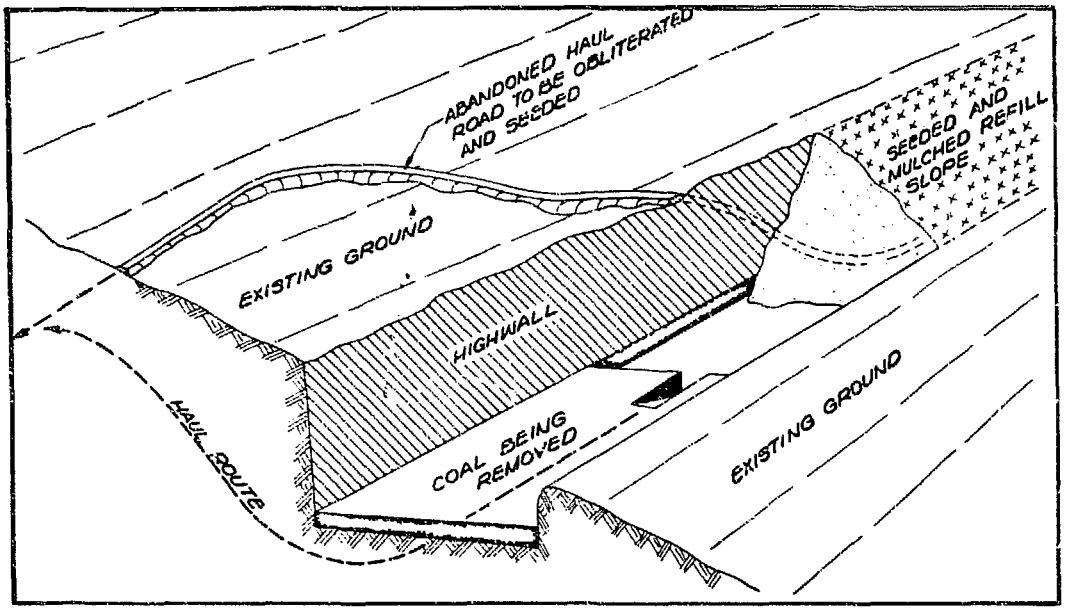

Figure 12
Typical Schematic of Proposed Mining and Reclamation Sequence

8. Demonstration of Coal Mine Haul Road Sediment Control Techniques

The design, construction, and maintenance of haul roads have not been of very much concern to many coal mine operators since their main interest is in the extraction of the mineral itself. Consequently, many haul roads have been poorly designed and grossly neglected. However, in terms of the environmental impact, the haul road is a principal contributor to stream pollution. Some studies indicate that as much as half of the sediment coming from a surface mining operation can be attributed to the haul road.

Although generally guidelines concerning haul roads have been issued by various regulatory authorities, they have not been definitive, nor have any innovative techniques been introduced. In order for Kentucky to be better equipped to provide definitive criteria for the control of sediment from the haul roads, we have begun along with the Environmental Protection Agency a project entitled "Demonstration of Coal Mine Haul Road Sediment Control Techniques."

The haul road under study will be divided into various test sections which will be approximately one-fourth mile in length, and separated by natural drainage divides (figure 13). Various control techniques to be introduced into the test sections include such things as: diversion ditches above the road's highwall, slope reduction of the highwall, low cost drainage control structures, grassed or lined ditches and soil cements.

The results of these control methods will be monitored for each section, by on line monitoring equipment and periodic grab samples.

9. Surface Mine Pollution Abatement and Land Use Impact Investigation

The reclamation research effort has concentrated attention on specific problems, limited areas, or at most, the entire mine. In contrast, a new program sponsored by the Kentucky Department for Natural Resources and Environmental Protection, and the Appalachian Regional Commission is entitled "The Surface Mine Pollution Abatement and Land Use Impact Investigation" and is aimed toward three main goals -- identifying pollution problems resulting from surface mining on a large watershed, recommending alternative abatement schemes, and analyzing the impact of surface mining on surrounding land use patterns. The investigation is being carried out on a selected model area in the Eastern Kentucky coal field. It is anticipated that knowledge obtained from this project will be applicable throughout the Central Appalachian Region.

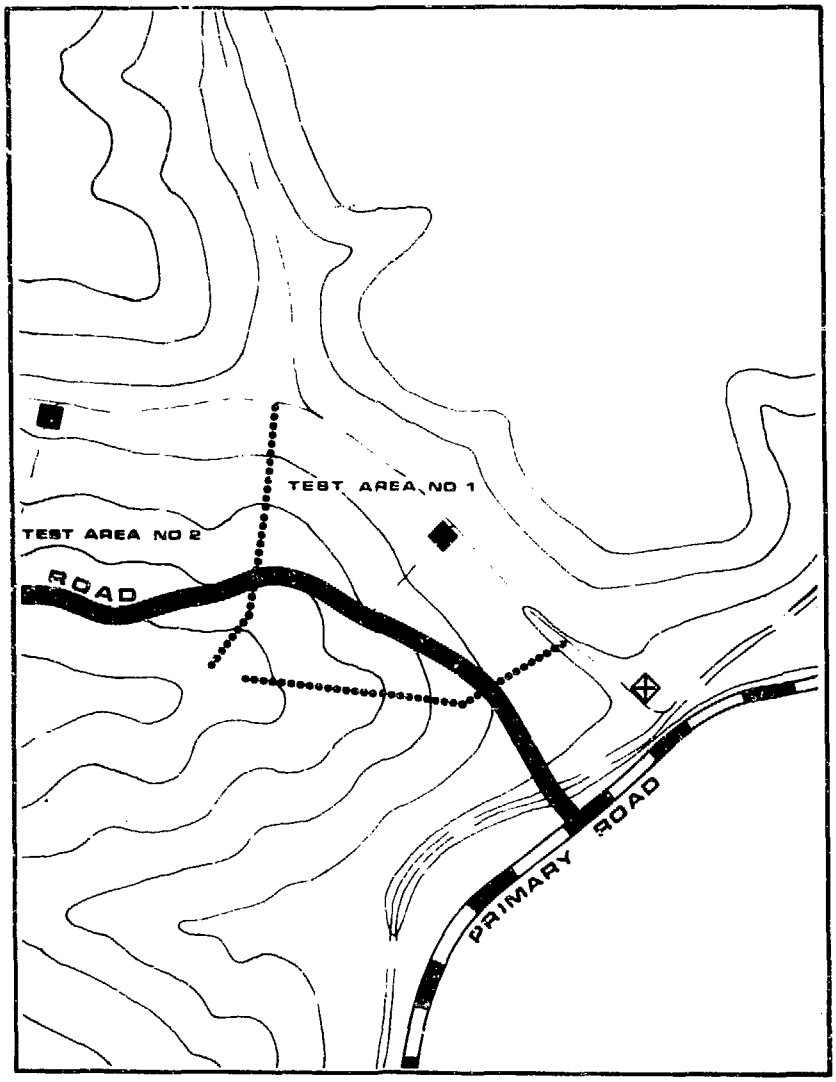

Figure 13

During the project an inventory of orphan (pre-law), active, and inactive surface mines will be undertaken. Both high and medium altitude aerial photographs will be employed as the primary inventory tool, with periodic spot checks on the ground. This inventory will provide information leading to the identification of land and water problems associated with surface mining and enable a model area to be selected for more thorough investigations.

After the selection of the model area (probably a manageable subtributary of a water basin), problems will be classified by type, degree, and extent. Surface mining impacts upon existing land use and population centers will be evaluated in terms of environment, social, and economic values.

Within the model area, the potential impact of surface mining upon future land use, especially in areas of potential growth, will be projected and evaluated and potential areas of critical environmental concern will be identified. For those problems determined to be significant, alternative abatement programs and costs will be determined.

10. Other Cooperative and Future Studies

A number of studies are being done in cooperation with the University of Kentucky, the Tennessee Valley Authority, the U. S. Bureau of Mines, and the U. S. Soil Conservation Service. These involve assistance by the Kentucky Department for Natural Resources and Environmental Protection by supplying data related to orphan mined lands, information on specific watershed, and general surface mine reclamation statistics.

The National Aeronautics and Space Administration has approved funding for a program which was initiated in February, 1975, to analyze the feasibility of using satellite and other remote sensing data to monitor and inspect surface mining operations in Western Kentucky.

Several studies have been proposed and are pending. These include a demonstration project to rehabilitate an orphan mined area in Eastern Kentucky, the investigation of 34 watersheds and a demonstration of revised mountaintop mining systems.

SUMMARY

Extraction of coal in past years both from underground and surface mines has done great damage to our environment, and in many cases, has left us with massive scars on our beautiful land. From our experience in the field and on the basis of research, we can categorically deny that our living environment must be destroyed in order to extract coal. While there does appear to be isolated areas where successful reclamation of a surface mine may not be possible, hence should not be permitted, still, in the majority of cases the land can be restored to equal or higher quality than before mining.

Certainly it is the duty of all citizens to do everything in their power to help our country to become less dependent upon insecure sources of vital fuels. An increased rate of extracting coal is a key factor that very likely will be with us through the next two or three decades. Thus, if we are to have both our fuel and a decent world to live in, it is imperative that the regulatory agencies be firmly supported by statutes that

require mining, reclamation and enforcement to be done using the best current methods, but to be effective those statutes must include adequate funding and recognize the critical need to obtain qualified personnel to provide them with continuing education in the broad and rapidly changing field of environmental protection.

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REVIEW OF CENTRAL POWER MAGNETOHYDRODYNAMICS AT THE UNIVERSITY OF TENNESSEE SPACE INSTITUTE AND ITS RELATION TO THE WORLD EFFORT IN MHD

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Introduction

Central power magnetohydrodynamics has grown to the point where it can be applied producing in the first generation of electrical plants 50 to 55 percent thermal efficiency and in later versions of these plants efficiencies up to 75 percent, in contrast with overall efficiencies of 40 percent or less, available in present coal-fired central power plants, considerably less than that in nuclear plants. Magnetohydrodynamic power generation can do all of this, at the same time providing low levels of pollution in the power plant effluent.

It also has the advantage of being a relatively low-cost technology when compared to other central power technologies being presently developed. This technology promises to do all of these things along with a cost savings of $120 to $274 billion in the country's power bill by the end of the century. Current status and future plans in the United States will be reviewed as well as the technical status in the Soviet Union.

The principle of Magnetohydrodynamic (MHD) Power Generation was invented by Faraday in 1831 during the same time that the rotating generator principles were first uncovered. Mechanically, MHD power generation is very simple because there are no moving mechanical parts other than the electrically conducting flowing fluid itself. In the United States, coal is the only interesting fuel since it is the only fuel which will be available in sufficient quantities to be meaningful by the time MHD is developed.[1,2]

There are three different types of MHD energy conversion. The open-cycle system utilizes fossil fuel as its heat source, the resulting combustion gas being the working fluid. The closed-cycle generator usually refers to the closed-cycle plasma generator which requires an external heating source to heat a noble gas as the working fluid. Finally, there is the liquid-metal generator which is also closed-cycle, but utilizes a two-phase mixture. The open-cycle system is by far the most promising and most advanced. Emphasis will be placed on this system here.

Open-Cycle Generators

The group at the University of Tennessee Space Institute has focused its attention on the study of directly coal-fired MHD generators and has succeeded in demonstrating that such generators can be operated successfully on coal.[3,4] As a matter of fact, this demonstration includes the fact that the slag formed from the coal ash coats the walls of the generator in such a way as to protect it from corrosion. Major damage in MHD generators is not caused by heat transfer from hot gas, but by micro-arcs that form in the cold boundary layer as current passes from the hot conducting plasma core into the electrodes. Such damage may also occur when voltage breakdown between electrodes occurs.

The first successful generator tested was a segmented Faraday generator.[5] The difficulties of maintaining ceramic or water cooled blocks that form the insulating walls within the generator indicate that this is not a good design. We saw the need of developing the diagonal conducting wall generator[6] which was analyzed from a theoretical standpoint, originated by de Montardy,[7] as a series connected generator. The diagonal conducting wall generator is made of metal window frames which form the electrodes and sidewalls. Figure 1 shows such a generator which is essentially a copper pipe made by utilizing window-frame-like copper elements with thin insulators separating them. Construction is simple and inexpensive and has turned out to be very rugged in use. Such generators have been operated by us for two years without disassembling during which time hundreds of short runs as well as continuous operation of up to one hour have taken place in a wide variety of experimental conditions for a total of approximately 10 hours operating time.

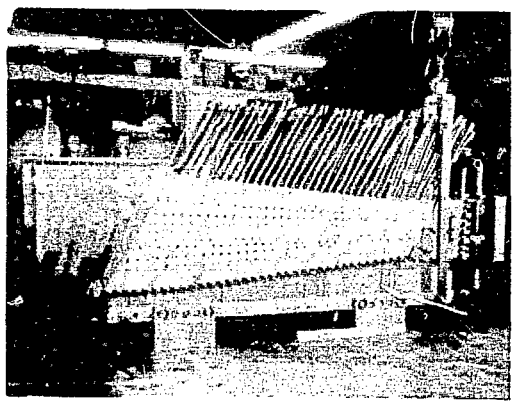


Figure 1
Water-Cooled 60° Diagonal Conducting Wall Generator

The coal slag coating of the interior of the generator during operation protects the entire structure from electrical corrosion[8] and covers the entire inside of the generator as shown in the photograph of Figure 2 without resulting deterioration of performance. In fact it was long realized that no electrode material could survive the corrosive environment of the open-cycle MHD generator using clean fuels. Replenishment of electrodes must be employed.[9]

This scheme is expensive and troublesome. With the use of combustion gas of coal carrying at least a portion of the slag, the electrodes (as well as sidewalls) are virtually the self-renewable coal slag. Examination of a cross section of this deposit under the microscope, as shown in Figure 3, indicated that a solid part of the deposit approximately 0.001 in. thick appears to be formed during operation of the generator.

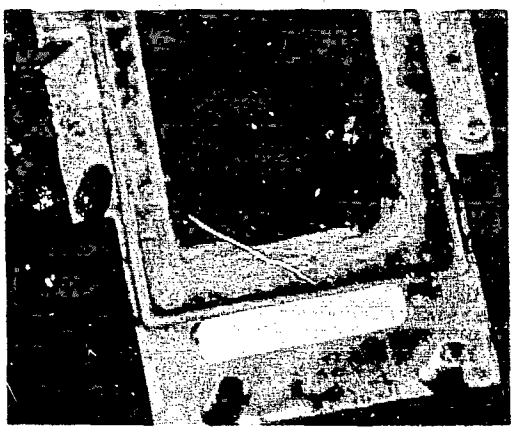


Figure 2
Interior of Generator Channel Coated with Coal Slag

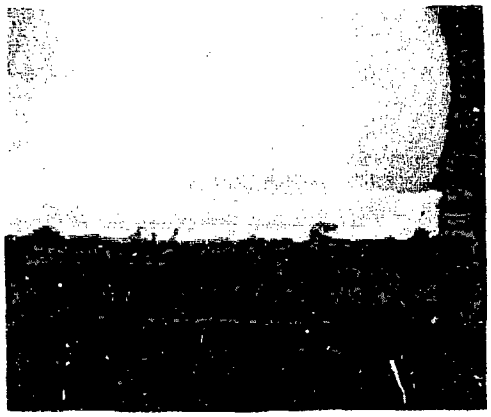
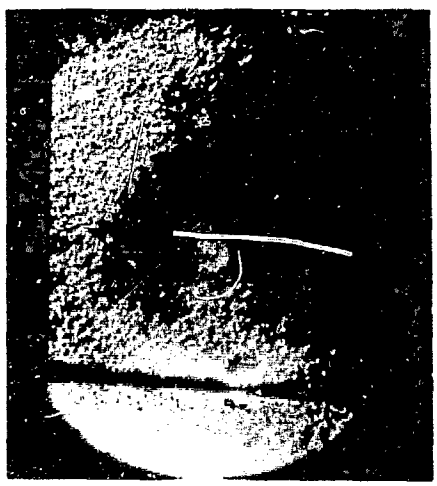


Figure 3
Cross Section of Deposit 0.03 in. Thick Formed During Operation of the Generator. The Side to the Left Toward the Copper and Side to the Right Toward Flow

On top of this is another layer of deposit which as apparently been liquid at one point in its history and has deposited in a glass-like layer probably after the generator was turned off. When the slag layer was carefully removed, the generator electrode was subjected to investigation by the microscope, and as shown in Figure 4, there is absolutely no change in the electrode surface from this original surface characteristic when it was put into the experiment.

Figure 4
Copper Electrode Surface after One Hour Operation of Coal. This Photograph Shows Part of the Cathode Edge and its Reflection in a Mirror at the Bottom of the Picture



By contrast, prior to the coal experiment, we conducted a series of experiments on electrode deterioration in the presence of clean fuel. The fuel used was benzene whose chemical composition is similar to that of coal, but of course, contains no ash. In order to conduct a careful experiment, we first ran the generator on coal to deposit a layer of slag within the generator. Then the generator was disassembled and the electrodes examined in a way similar to that examination conducted on the one hour coal run. The result is shown in Figure 5. Arcs in the generator have cut through the coal slag deposit and down into the copper, especially on the edges of the electrode where higher concentrations occur due to the interaction of electric and magnetic fields.

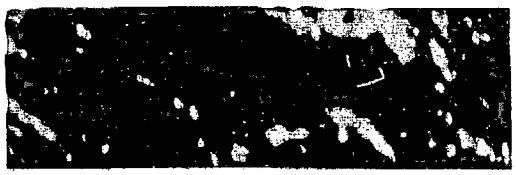


Figure 5
Coal Slag Eroded from Electrode Surface at 0.6 Amp/Cm^2 Average Current. No Copper Erosion is Observed. Currents Are Typical of Central Power Generators

Presently cermets are being investigated as a possibly superior method for channel construction when sprayed on the inside and bonded to the copper. These cermets promote a more rapid growth of the slag layer over a variety of coal materials. Beyond that, other more sophisticated materials experiments are being conducted in hopes of further improving on what seems to be a first solution of the problem of generator wear.

A direct coal fired MHD plant has tremendous advantages over any other schemes of utilizing coal in a power plant. If the coal must go through a gasifying process first, the efficiency of such a gasifying process will be, at most, on the order of 75 percent. Present efficiencies are quite low, around 60 or 65 percent. In this case even if a MHD power plant turbine plant is 55 percent efficient, one must multiply this 55 percent by the 75 percent efficiency of the gasification process to arrive back at an overall efficiency of 41 percent, no better than that of present coal burning plants. Gas turbines are particularly affected by such calculations because particles down to one micron size have to be removed from the flow. Thus the temperature of a fixed bed gasification process must be reduced for such particle removal in a bag house and then reheated for the turbines.

On the other hand, the direct coal fired MHD plant not only has an efficiency of 55 percent but depends on the seed removal process and on holding time in a radiant boiler to completely eliminate sulfur from the power plant effluent and drastically reduce the NO_x concentration.[10-13] A diagram of the MHD section of an ideal power plant utilizing direct fired coal is shown in Figure 6. It is possible that the preheaters might be separately fired in the first plants of this type which means that fuels of a purity of that required for gas turbines or clean fuel MHD generators might be used to fire the preheaters. The requirement for such fuel is only 30 percent of that required for runn-

ing a whole plant so the attendant penalties mentioned in the previous discussion are reduced by two-thirds, resulting in an overall efficiency of 50 percent for the early plants. The high temperature preheater problem may be eliminated even in early plants because calculations show that enriched air containing 40 percent oxygen and 60 percent nitrogen can be produced for a cost of 4 dollars per ton of oxygen and used in the MHD power plant in place of high temperature preheaters.

Experiments on downstream equipment shown in Figure 6 are proceeding in our laboratory. A preliminary uncooled slag separator operating at 1200°C separated as much as 95 percent of the slag from the flow. This is desirable to keep such slag out of the preheater section and sections downstream of this. Presently experiments are being run with two larger water cooled cyclones and a radiant boiler section. This radiant boiler must operate at temperatures of approximately 2000°K. This is much above

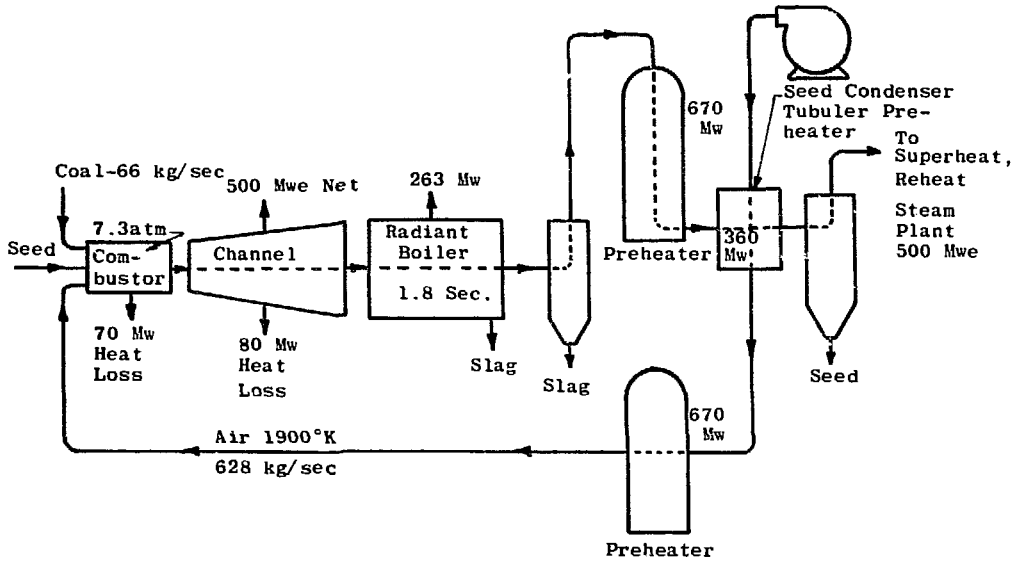


Figure 6
MHD Section of an Ideal Power Plant Utilizing Direct Fired Coal

the temperature of ordinary boilers. The construction of such boilers must be within acceptable cost limits in the full scale plant so that inexpensive materials must be used. The experimental boiler section is behaving well in preliminary runs. In general, the technique is to promote growth of slag in this device in order to protect the boiler tubes and reduce heat transfer. The radiant boiler is shown in Figure 7 and the slag separators are shown in Figure 8.

Because of higher efficiency, hence better fuel utilization, the operating cost will be reduced. At the same time, higher overall thermal efficiency implies a reduction of thermal pollution. These advantages have prompted wide attention to using the MHD generator bottomed with a conventional steam plant as a base load central power station. However, MHD competes well

Figure 7
Radiant Boiler Transition Section Operating at 2000°K

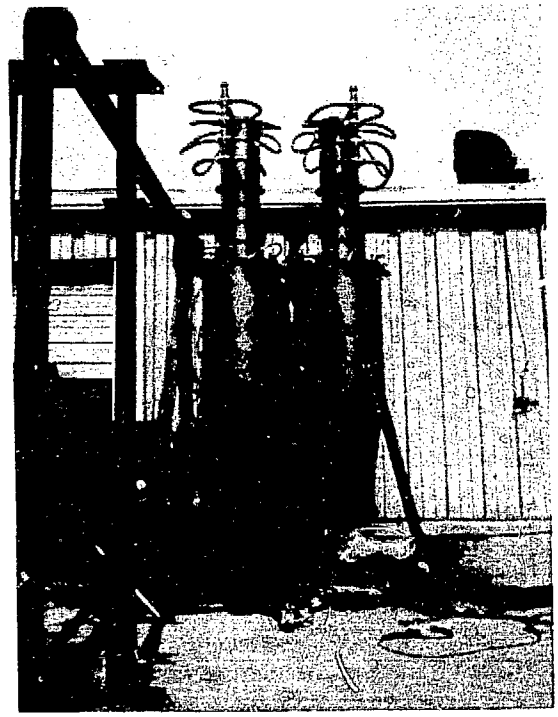


Figure 8
Slag and Seed Separating Cyclones Removing Slag Potassium and Sulfur from the Affluent. Previous Models Have Taken Out Up to 95 Percent of the Slag Particles

also in the areas that can be best suited by MHD power. High power short duration requirements to power wind tunnels and other experiments is a prime example.

In 1973, the MHD community had drawn up a national program[14] for MHD central power generation which will lead MHD to be available for commercial service by 1985. This is the recommended date by the utility industry.[15] The overall cost of this program is projected to be $410 million (1973 dollars). Figure 9 gives an overview of the proposed program. Adoption of this plan and its successful execution would make possible significant amounts of electrical power generation using the MHD fuel consumption and environmental benefits.

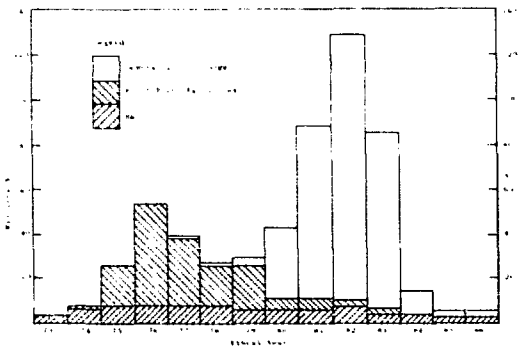


Figure 9
MHD Development Cost Plan

Recently the Electric Power Research Institute (EPRI) has made a new projection of a much more elaborate plan for MHD development with a somewhat extended time schedule. The just issued, "A National Plan for Energy Research, Development and Demonstration" from Energy Research and Development Administration (ERDA) mentions MHD, but does not yet give a development plan. The Congress has, however, issued several statements to encourage MHD development and have appropriated money directly for MHD projects. In the next fiscal year they indicate an appropriation somewhere between $30 and 50 million.

Closed Cycle Generators

Closed cycle generators are sometimes called non-equilibrium generators since they take advantage of the non-equilibrium effect of the plasma. Hence, the process enables the generator working fluid to be at much lower temperature as compared to the open cycle system yet still have sufficient electrical conductivity due to the elevated electron temperatures. Good technical progress has been made in this area. However, due to the lack of suitable nuclear reactor to heat the noble gas to the required temperature (of the order of 2000°K), the closed cycle generator has been greatly curtailed. Recently, a fossil fuel heat source has been proposed and study is going on at General Electric.

The USSR MHD Program

Recently a very complete study was made by Rudins[16] comparing the United States and Soviet Union MHD program. The Soviet Union has a number of installations for all three different types of generators. But, as in the United States, open cycle work has dominated the MHD effort. The most important facility is the U-25 at the Institute of High Temperatures which was reported before by the present author.[17] This installation is a complete pilot plant with the MHD portion generating 25 megawatts while the steam bottom plant delivers 50 megawatts. The decision to proceed with this project was made in 1966 and the MHD generator was first run in 1971. At present the MHD generator delivers about 13 megawatts and it is expected that this device will produce 20 megawatts by the end of the year

For long duration experiments a new channel called the R-channel was designed. The sidewalls were constructed according to the electrical design developed at the University of Tennessee where diagonal conducting walls carry a relative large percentage of the generator current. This channel was designed for 3 megawatts, but in operation yielded 4 megawatts (a considerable improvement over the projected performance). This improvement is due to the conducting sidewalls, improved uniformity and reduced losses connected with currents entering the electrodes. The channel was operated for 100 hours without apparent difficulty in which time the relatively trivial event of a water hose coming loose caused premature shutdown.

The U-25 has made data from this channel operation available to us and it confirms on a much larger scale many of the smaller scale experiments that we have conducted in our laboratory in this design. It is a very useful product of the cooperative program with the Soviet Union to have this data available a number of years in advance of achieving it in the United States. We know now that our designs and results on a smaller scale can be extrapolated to the 12 megawatt level. This is, of course, highly useful in any sort of development program. In addition, this Soviet plant also is producing vital experience on air preheater, seed recovery systems, inverters and downstream steam plants. Because of the different conditions in the Soviet Union as regards to mineral resources, natural gas will be available for a longer time than it will in the United States and, thus, their MHD program is directed towards natural gas conversion.

The U-25 plant's exterior air preheaters consist presently of aluminum oxide, and are heated by natural gas and then used to heat the incoming air. Such heaters are periodically cycled to provide a continuous flow of air at 1200°C. Such preheat is necessary in the MHD cycle in order to make the combustion products conducting. In the U-25 additional temperature is gained through the addition of a small amount of pure oxygen preheated at 1200°C to the air. The preheaters have been in operation for some time, though it is not completely clear for how long they have been operated. Others at the High Temperature Institute have been cycled for 8000 hours. Their seed-recovery process is quite successful, as the Moscow group claims 99.9 percent seed recovery. Other technical triumphs in the program include successful operation of boiler tubes for long periods of time in a potassium-seed combustion gas. We believe that the project itself is skillfully and intelligently organized so that the Soviet Union will acquire the necessary technology for

central power in a short periof of time at an optimum cost. Questions of endurance and electrical efficiency will be solved in good time, and the High Temperature Institute should be congratulated on its ability to put such a plant in operation so soon. In the U. S., because of cost limitation, we are at least five years away from a plant of this type.

The Soviet Union now projects the construction of a 1000 megawatt MHD topping plant to begin within the next 5 year period. This development is moving more rapidly there than it is in the United States.

Concluding Remarks

Because of its simplicity, MHD power generation is less expensive than ordinary coal or nuclear plants. It also is more economical, for because of its higher temperature, it can raise the 40 percent efficiency of present base-load power stations to 60 percent or more. That would mean that we will get 50 percent more energy for a pound of coal burned in an MHD plant than can be obtained from a conventional coal-fired plant.

A few years ago, we calculated that the cost savings to the United States through the development of MHD power generation would amount to from $40 to $130 billion by the end of the century. Now with the drastic increase in the cost of coal, these savings would be tripled so that at a minimum would be $120 billion and might go as high as $274 billion. Further fuel cost increases result in making MHD even more important.

As part of the MHD power generation system, the sulfur dioxide pollution in high sulfur coals is reduced by 120 times, nitrogen oxides by many times, particulate matter by 10 times and finally, thermal pollution is reduced by more than 50 percent even without the use of cooling towers. All of this can be done at the relatively low cost of $410 million in 10 years.

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NUCLEAR ENERGY: BENEFITS VERSUS RISKS

by

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Just a few years ago almost everyone looked forward to the coming age of nuclear energy as a boon to mankind. Of course the coal interests have always been less than enthusiastic, but that was to be expected. Recently, however, many persons have undertaken the role of professional critics, joined by some conservationists.

I feel particularly betrayed in this instance, for I have long considered myself a conservationist. Certainly one of my strongest motives in promoting nuclear energy has always been the conserving of our valuable and irreplaceable fossil fuels, coal, oil and gas. Because this can be accomplished and, at the same time, the pollution of our atmosphere reduced, I felt a sense of righteousness in promoting nuclear energy. But these critics say that all these fine benefits just are not worth the risk. I strongly disagree. I believe that more lives have already been saved by the advent of nuclear energy than will be lost as a consequence of it in the next hundred years.

A swarm of controversy over the growing nuclear technology appears to be developing. If it were just an occasional book or article, I would be inclined to hold my peace. Unfortunately, it is deeper than that. Part of the federal licensing procedure for a nuclear-power plant, though not for any other kind, stipulates that a public hearing be held at which individuals may intervene. In some cases these hearings have been so drawn out that the power company has withdrawn its application rather than face the continued publicity. A power plant planned for construction at Bodega Bay, California, has been abandoned. The opposition was concerned mainly with the natural beauty of the proposed site, but the issue of earthquake damage was the deciding factor. New York State Electric & Gas Co. has decided to postpone indefinitely the project to build a nuclear-power plant at Ithaca. In this instance the intervenors protested the possible thermal pollution to Cayuga Lake.

Electrical power, polluted air

First, let me summarize some of the benefits. I do this quickly because there really is not much argument about this part. The real reason that power reactors are being installed in so many places in the U. S. (some 80 nuclear-power plants have been ordered; 15 are in operation) is to save money. Although construction costs of a nuclear plant are higher than those for a fossil-fueled plant, the operating costs are much less. As a consequence the cost of electricity will be less than it would have been with fossil-fuel plants.

The demand for electricity has almost doubled within the past ten years, and another doubling is projected for the next decade. Part of this rise is caused by the population increase, but for the most part it reflects a higher standard of living. When I came to Oak Ridge National Laboratory some 20 years ago, air conditioning was a rarity. Now the summer demand for electricity in some regions exceeds the winter demand. Although nuclear energy is beginning to supply some of the ever increasing demand for power, the fossil fuels (coal, oil and gas) are being burned at an ever increasing rate. Moreover our reserves are very limited. Whether the commercial supply of them will be exhausted in 50 years or 200 years is not certain--but the time is short compared with the already brief span of man's existence on this planet, or with the hundreds of millions of years that it took to form those deposits of coal and oil. Our limited reserves are fast going up in smoke.

And smoke there is! From a single large, coal-fired power plant, such as Bull Run near Oak Ridge, hundreds of tons of noxious sulfur oxides are emitted every day. In addition to the sulfur, thousands of tons of carbon dioxide are emitted by Bull Run per day. (It has been observed that the carbon-dioxide concentration in the atmosphere is increasing at about 2% per decade, a change that may have implications for long-term effects on climate.) No longer is the air clean and pure in the Tennessee Valley--or in New York, or in Los Angeles, or indeed in most of the U. S. Our eyes may burn, and pine trees drop their needles.

Unfavorable atmospheric conditions can be so bad that many people sicken and die as they did in Donora, Pa., in 1948 (43% of the population became ill, 20 deaths attributed to smog), or in London, England, in December 1952, when the excess fatalities were estimated at 3500.[1] (There was a time in English history, around 1300, when King Edward I decided to take steps toward reducing pollution. He made it a crime punishable by death to burn coal.)

It is imperative that we take steps to reduce this outpouring of noxious gases either by removing them from the smokestacks, thereby increasing the cost of electricity, or by installing nuclear-power plants. Coal-fired power plants are not the only contributors to the air pollution of the country: Automobiles and trucks also represent a major source, as does the heating of homes and buildings. To reduce this pollution caused by combustion, a general conversion to electricity will have to ensue. Homes must be heated electrically and automobiles and trains driven electrically, which will triple the demand for electricity, a challenge that can only be met economically with nuclear-power plants.

Nuclear power offers a virtually inexhaustible supply of cheap electricity. Moreover, it offers a chance to clean up the atmosphere. But there is, in addition, a third major benefit--the myriad uses of radioisotopes. These isotopes, produced so copiously in every nuclear-power plant (and indeed representing the chief danger in their operation), have already proven to be a great boon to mankind. Although production reactors have been the chief source of the fission-product radioisotopes, such as Sr^{90} and Cs^{137}, power reactors will undoubtedly become the major producers in the future. Research reactors and cyclotrons supply most of the medical isotopes. Estimates of the benefits of these isotopes to industry are of the order of a $1000 million a year. Many major industries use radioisotopes to gauge the thickness of sheet steel in a rolling mill; the level of a liquid in a tank or the flow of oil through a pipeline is measured with radioisotopes. Isotopes are also used for well logging in the exploration for oil. A slow leak in a water main or a gas line can be found with an isotopic tracer. The gamma rays from Co^{60} are used for "x raying" welds and are used in a chemical plant to produce new plastics. The dramatic uses of radioisotopes in agriculture, biology and medicine have caught everyone's attention.

Daily hazards

I could easily lecture for many hours about the benefits of nuclear energy. However, there are also risks. Those radioactive isotopes that are so useful when properly prepared also represent a major hazard. The possibility, no matter how remote, of spreading millions of curies of radioactivity over the countryside is not a pleasant one to contemplate. The critics present a gloomy picture. How likely is such an accident? Before discussing that question, let us recall some risks that we all encounter in everyday life[2,3] (see Table 1).

Table 1. Risks in Daily Life*

Type of Risk	Death rate per 10^6 hrs of exposure
Riding in a private car (U. S.)	0.95
Riding on railroads and busses	0.08
Flying on a scheduled airline	2.4
Riding a motorcycle	6.6
Death due to disease, old age	1.0
Smoking cigarettes	1.2
Rock climbing	40.0
Radiation at a rate of 5 rem/yr (extrapolated linearly from experiments at high-dose rate)	0.05

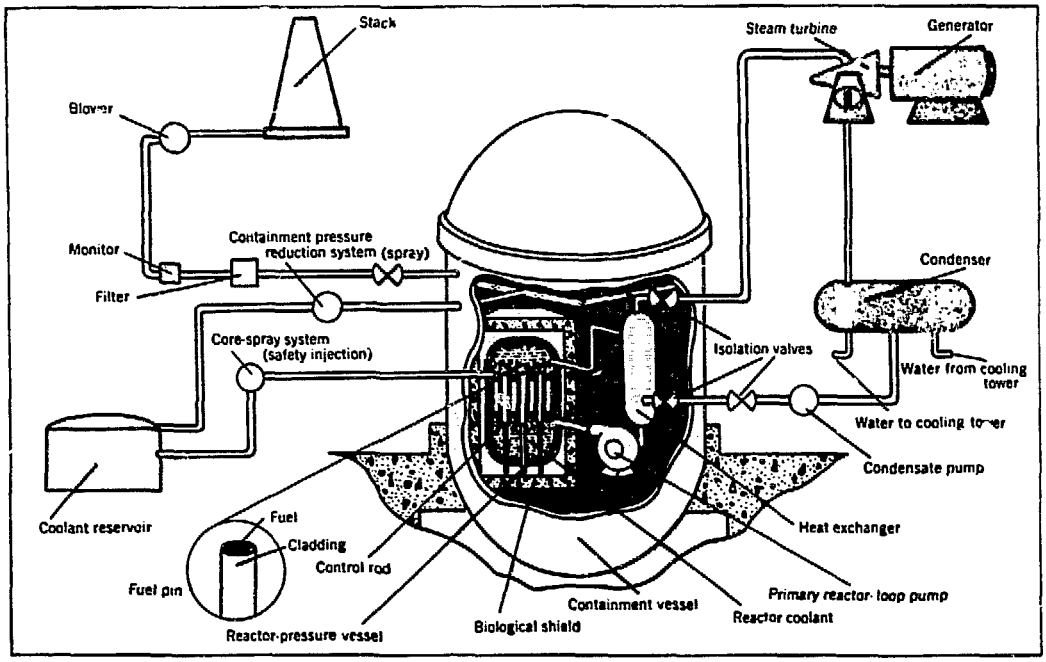
*Data from reference 3.

To get a feeling for the numbers involved, consider the probability that an average member of the population will die during the next hour due to disease, such as heart failure and cancer. The figure is about one in a million, or probability $P = 10^{-6}$ hour^{-1}.

It appears that people are willing to accept a risk of about that same magnitude provided it is voluntary and the benefits are personal and real. For example, the risk of being killed while riding in a car is about 10^{-6} per hour of exposure, about one-tenth of what it was a generation ago. There have indeed been significant advances in automobile safety. The risk of riding in a commercial airplane is now about 10^{-6} per hour, which means that air travel is some ten times safer than auto travel on a mileage basis because planes travel so much farther in an hour. Air travel in private planes is a much more dangerous undertaking; fatalities in these flights are some 20×10^{-6} per hour of exposure, 20 times more risky than commercial air travel. And yet many people willingly take the risk of their own free will. No one imposes the risk upon them.

On the other hand, if the risk is imposed upon a person (such as an airplane falling on a busy street, or the explosion of gas mains in a city), he will insist that the probability of death be much less than the normal disease death rate. He will live below a dam, if he is convinced that the chance of the dam collapsing is very remote (perhaps 10^{-8} per hour of exposure) and that there is good reason (benefit) for him to live with the exposure to a small, but not zero, hazard. He may protest if a chemical plant or a nuclear-power station is built near his home--suggesting that it be built in another location--but if he is convinced that the risk is small, he will not move. A small risk is, as we have assumed, something less than 10^{-8} per hour of exposure or 10^{-4} per year. In other words, if he is convinced that a major catastrophe will happen only about once in every 10,000 years, he will feel that the risk is acceptably small. Will

Los Angeles and San Francisco be spared a major earthquake for that long? Less than 50 years ago 150,000 people were killed in Japan as a result of an earthquake.



SAFEGUARDS IN A NUCLEAR-POWER REACTOR. The fuel cladding, the reactor vessel and the containment vessel are the three major barriers that prevent the escape of fission products.

Above figure is used courtesy of Physics Today, May, 1970.

Nuclear risks. . .

Only by experience can we demonstrate that the risk of living near a nuclear plant is small. The situation is indeed remarkably similar to the budding electric-power industry in the latter part of the last century. There was a great deal of opposition to the introduction of electricity into the home. The critics pointed out that electricity was dangerous, that people would be electrocuted, that innocent children would stick their fingers into electric sockets and die a horrible death and that wires would become overheated and burn down the homes. Of course they were right. A thousand people in the U. S. are accidentally electrocuted every year. Moreover, it has been estimated that 16% of the fires are electrical in origin and 1200 Americans lost their lives last year in these fires. However, there are 200 million people in the U. S., so the individual's chance of being killed is small, about 10^{-9} per hour of exposure. This is well below the "acceptable" risk of 10^{-8}, and the benefits of electricity are so apparent to everyone that no one wants to turn back the clock.

Let us now turn to the risks of operating nuclear-power plants. These can currently be classified as:

Thermal pollution of the rivers and lakes, also known as thermal effects.

Low-level release of radioactivity into the air and ground waters caused by the normal operation of nuclear-power and reprocessing plants.

The accidental release of large amounts of radioactivity.

To my mind this last item is the risk causing the most concern, but the critics (Chauncey Starr calls them "nuclear hypochondriacs") have been equally vociferous about the first two items.

Thermal pollution is not a new phenomenon, nor is it confined to nuclear-power plants. Many industrial plants generate a large amount of heat, and it is much less expensive to dump the waste heat into a river than to release it to the atmosphere. The rivers that flow through Pittsburgh, for example, are raised in temperature by 20 or 30 deg. This has had an adverse effect on the fish and has in general upset the ecology. Federal standards are needed, and enforcement by the states is most desirable. Such legislation is now pending in Congress. These regulations should apply to any plant, be it nuclear, fossil-fueled or chemical. Nuclear plants should conform no more or no less than any other type. It is true that a nuclear electric plant dumps more heat into a stream than a fossil-fueled plant of corresponding electric-power output. But it does not make sense to raise a storm of protest over a nuclear plant of 500 MW electric capacity while a 1000 MW electric fossil-fueled plant escapes almost unnoticed. New York State has passed legislation requiring nuclear plants to make an environmental-evaluation report, which is not required for conventional plants.

It is not surprising that a nuclear-power plant that generates millions of curies of radioactivity may discharge a very small amount of radioactivity into the atmosphere or waste stream. The whole argument has to do with defining a "small amount" of radioactivity. The nuclear critics insist that it should be zero for a nuclear plant, whereas they recognize that a coal plant does emit some radioactivity from the small amount of uranium and its daughter products in the coal.

Merril Eisenbud and Henry G. Petrow[4] have noted that although the amount of radioactivity from a large coal-burning power plant is less than 1 curie per year of Ra^{226} and Ra^{228}, this release is the equivalent of considerably greater amounts of I^{131} and Kr^{85}, which are the principal atmospheric effluents from a nuclear-power plant. In either case the radiation dose to the nearby population is very small compared to the natural background of radioactivity.

. . .from radiation effects

Actually we know much more about the effects of radiation on the human body than we do about the effects of various chemical pollutants that occur in ever increasing amounts in the air we breathe and the water we drink. Hundreds of millions of dollars have been spent by the Atomic Energy Commission in biological research aimed at establishing not only the effects of radiation on man but also on the environment, so we can be certain that the ecological effects will be minimal. This concern is almost without precedent. Certainly the automobile industry has not expended much money on the effects of smog on the population, or the tobacco industry on lung cancer or the chemical industry on the effects of DDT on the ecological cycle. One of the nuclear critics' favorite expressions is that there is enough radioactivity in a reactor to irradiate everyone in the U. S. with a lethal dose. There is also enough insecticide manufactured to poison every U. S. citizen; moreover, the insecticides are meant to be widely distributed, yet the radioactivity is carefully confined.

As a result of the tremendous research effort on the effects of radiation, the Federal Radiation Council has developed a set of radiation-protection guides. The levels that have been set, even for workers in the nuclear industry, are meant to be at least an order of magnitude below that where physical effects on the individual would be observed. (This is in contrast to the ozone level in Los Angeles, which is set just barely below the level where eye irritation will be noticed.)

If workers in the nuclear industry were to get the maximal level of 5 rem per year, there probably would be a small increase in the observed number of deaths caused by leukemia after a number of years. But the additional risk of death by leukemia to each person so exposed would be less than 10^{-8} per hour of exposure, less than the normal occupational hazards.[5] Actually, it is rare for anyone to get 5 rem during a year, and most of us get much less. Although 5 rem is considered to be a conservative figure (much less, for example, than radiologists used to take) it is thought that an additional factor of 30 reduction should be made when considering the dosage levels to the population at large. Hence the protection guides limit the amount of activity to such a low level that the general population will receive no more than a fraction of a rem per year. Everyone receives something like a tenth of a rem per year of radiation because of cosmic rays and natural radioactivity in the earth and air--everyone, that is, but those who live in certain high-level radiation areas, like India, where they receive eight times as much.

When one adds to this the radiation from medical x rays (estimated to be another 0.1 rem to the average member of the population), it is apparent that the amount contributed by nuclear power is small in comparison. I do not hesitate to take several rem of x rays when it is needed for diagnosis or treatment of disease. Here is a very real example--the benefits far outweighing the risks. On the other hand, I am opposed to taking even medical x rays needlessly. Some of the older machines for dental x rays sprayed the whole body; the use of a filter and cone can produce better pictures with less radiation. X-ray machines in hospitals have also been greatly improved; good, clear, lung radiograms can be obtained with a dose of one-tenth to one-hundredth of a rem rather than with the several rems required with poor equipment and procedures.

Recent measurements by the Bureau of Radiological Health, Department of Health, Education and Welfare, have shown that the Dresden Nuclear Power Station, Ill., has contributed a negligible amount of radioactivity to its environs, something less than 1% of the natural radioactive background and orders of magnitude below permissible limits. But despite the conservatism in setting the federal radiation-protection guides, the Minnesota Pollution Control Agency, responsible for water purity, has recently protested the granting of a license to operate a reactor, unless the operator guarantees to maintain a level of activity release that is a factor of 100 below the values recommended by the Federal Radiation Council. If the utility is not granted a license to construct a nuclear-power station, power demands will have to be met by adding fossil-fuel stations with all the stack effluents. All in the name of "safety." I believe it is demonstrable that the hazard from the presently regulated amount of radioactivity released in normal operation of a nuclear-power station is much less than that from the pollutants emitted by the operation of a fossil-fueled station.

Safeguards

However, the risk of releasing a large amount of activity inadvertently is quite another matter. The hypothetical consequences of such an accident were the subject of a much publicized Brookhaven National Laboratory report some ten years ago. The authors assumed the worst possible combination of circumstances. They gave no credit for containment in estimating that half of the fission products would become airborne; they assumed that the accident would occur during an atmospheric inversion and low-wind velocity; and thus the fission products would be carried straight toward a population center with very little dilution or mixing. Under these catastrophic, but unlikely, circumstances up to 3000 people could be killed, assuming evacuation was not possible. The possibility that such a major catastrophe will occur is, I believe, exceedingly remote. However, the occurrence of several smaller events is certainly within the realm of possibility; there surely is some risk. Nevertheless, it is the stated mis-

sion of the nuclear industry and the regulating agency to make the possibility of such an accident exceedingly remote. How do we go about it?

First, the fission products are contained in fuel elements that would melt only if cooling were to fail. Second, the fuel elements are contained within a primary coolant circuit that undergoes the most thorough series of tests and inspections that any pressure vessel has ever been subjected to. Then the whole works is contained within a large steel or concrete containment vessel. Finally, there is an exclusion area surrounding the power plant and a low-population zone outside of that. This should result in considerable dilution of the radioactive fission products before they reach the population center, as well as introduce a delay so that evacuation can begin.

For the radioactive fission products to escape, the fuel elements must melt, the primary vessel must burst and the containment vessel must fail. Even if all these failures occurred, it appears that probably no more than 5% of the fission products would become airborne--rather than the 50% assumed in the Brookhaven report. Even so, the release of 5% of the radioactive products under unfavorable atmospheric conditions would be serious. And we can see ways that it might happen. However, bear in mind that, when a mechanism for an event can be postulated, the design can be modified to make that particular mode of occurrence most unlikely. It is true that fate has a way of figuring out another path to an incident that was not foreseen. But the designers and builders of nuclear-power plants have exercised sophisticated ingenuity and have spent large sums of money to make the plants as safe as they know how.

There have been accidents and releases from experimental reactors.[6] The releases have been small by comparison with the hypothetical Brookhaven incident, and no member of the public has been injured. The graphite moderator of a large reactor in Windscale, England, caught fire, causing some fuel elements to melt and burn. A considerable amount of radioiodine was spread over the countryside, thereby contaminating milk supplies and crops. That reactor was not in a containment vessel (all nuclear-electric stations in the U. S. are contained), so perhaps 2% of the fission products did escape. No power reactor in the U. S. has been similarly involved. There were some fuel elements melted in the Fermi reactor, but neither the primary nor the secondary containment was violated.

A small experimental army reactor (SL-1) released a considerable amount of radioactivity to the building where it was operated, but only a relatively small amount of activity, an estimated 80 curies of I^{131}, escaped from the building and precipitated on the desert. The prophets of doom have heavily dramatized these reactor incidents, pointing out that it can happen despite our best efforts. It all depends on your point of view. To me it demonstrates that a fairly major release of radioactivity from the core can occur, as at Windscale or SL-1, and yet no one outside the reactor building received a tolerance dose of radiation.

The important question still remains. Have we succeeded in reducing the risk to a tolerable level, that is, something less than one chance in ten thousand that a reactor will have a serious accident in any year? When we have one hundred nuclear-power stations in operation, which is not too far in the future, an accident once every hundred years might be expected. And if a hundred people were to be killed, such as now happens in a major airline disaster, it is a lower calculable risk than that taken by many facets of U. S. industry today, and a small price to pay for the benefits.

Have we succeeded in reducing the hazards to such a low level? There is no way to prove it. We have accumulated, so far, some 100 reactor years of accident-free operation of commercial nuclear electric power stations in the U. S. That is a long way from 10,000, so it does not tell us much.

The only way we will know what the odds really are is by continuing to accumulate experience in operating reactors. There is some risk, but it is surely worth it. I am impatient with those who cry "wolf" when there is so much to be achieved. On the other hand, it is a mistake to use the head-in-the-sand approach and say it can never happen to us. Scientists and the public should be prepared to face the possibility of a nuclear incident just as we expect major earthquakes that will exact a large toll in property and lives. Only a few people advocate abandoning the West Coast. I hope only a few advocate abandoning nuclear power, which promises so much for mankind.

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Public Concern for Nuclear Power

by

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There is general recognition in the United States today that we do have an energy problem and that we have a long way to go in developing an effective solution. The types of problems which we face are a function of the time frame being considered and the solutions differ significantly.

There are three major principles of energy development that our nation must follow if we are to maintain our way of life.

First, we must conserve energy--whenever and wherever we can. This will require sacrifice in the short run and technological innovation in the long run.

Second, we must use today's energy fuels more efficiently--by such means as substituting more plentiful fuels for those that are scarce, and by developing to commercial fruition technologies that will enable us to make better use of our two most readily abundant fuels, coal and uranium.

Third, we must move ahead to develop more advanced energy technologies for the time when conventional sources of oil and gas will provide a far smaller proportion of our fuel requirements than the nearly three-fourths of our energy they supply today. Synthetic fuels made from coal and oil shale, advanced fission reactors, fusion, and solar and geothermal sources all suggest the range of energy concepts that must be explored.

The Energy Reorganization Act of 1974, which established the Nuclear Regulatory Commission (NRC) and the Energy Research and Development Administration (ERDA) and abolished the Atomic Energy Commission, has provided much of the Government's organizational basis for solving our long-range energy problems. The Nuclear Regulatory Commission has the responsibility for regulation and licensing to assure the safety of commercial nuclear facilities. The Energy Research and Development Administration brings together Federal activities in energy research and development to assure coordinated and effective development of all energy sources. ERDA officially began this task on January 19, 1975.

ERDA's capability for carrying out broad based programs is based on R & D programs and personnel transferred from other Federal agencies. These include: from the Department of the Interior, fossil fuel energy research and development programs such as those conducted by the Bureau of Mines energy centers, and including off-shore drilling technology, oil shale production techniques,

oil and gas secondary and tertiary recovery, and conservation; also the Office of Coal Research programs, including coal liquefaction and gasification, and research on underground electric power transmission. From the National Science Foundation, solar, including wind and ocean thermal, and geothermal energy efforts. From AEC, nuclear fission and fusion R & D, nuclear weapons activities, uranium enrichment, physical, biomedical and environmental research, including waste management, and AEC programs in geothermal and solar energy, electrical transmission and storage, and underground coal gasification. From the Environmental Protection Agency, new automotive power systems, and alternate fuels. .

The Government's commitment is reflected in the request for funds that ERDA is asking Congress to appropriate. Compared to operating costs in the current fiscal year, the percentage increases for fiscal year 1976 would amount to: (1) solar, geothermal and advanced systems--211%, (2) conservation--93%, (3) fossil--60%, (4) fusion--41%, (5) other nuclear--23%, (6) environment and safety--20%. Obviously, achieving energy self-sufficiency is an enormous undertaking. However, money invested in energy development today should pay significant dividends in future years.

In the near term, nuclear power must play a significant role if our nation is to satisfy her growing energy needs. A review of the development of the United States' nuclear power program serves to outline the key steps in the concerted development of nuclear power technology to an advanced state, enabling the U. S. to place heavy reliance on nuclear power at this time.

History of the United States' Nuclear Power Program

During the late 1940's, the Atomic Energy Commission began its experimental power reactor program. This program was aimed, first, at obtaining the basic scientific and engineering data needed for proof of technical feasibility and safety of the more promising approaches to nuclear power generation, and, second, at demonstrating the actual or potential economic feasibility of such approaches. One outgrowth of this program was the Experimental Breeder Reactor-1 at the National Reactor Testing Station in Idaho, which produced the world's first useful electricity from nuclear energy in 1951.

In 1953, the AEC embarked on a five-year "experimental" program to develop reactors giving promise for civilian power applications. A number of power reactor experiments were built and operated in the 1950's. These early experimental plants were undertaken largely by AEC laboratories and contractor installations.

The revision of the Atomic Energy Act in 1954, which encouraged industrial cooperation, ushered in the next stage of the industrial development of nuclear power. Although it had been hoped that under the 1954 Act nuclear power development would be largely privately financed, it was found necessary for continued Government support. The AEC power demonstration reactor program, begun in 1955, invited industry to join with the AEC to develop power reactors. There have been several stages in this program, and over the years it has reflected the coordinated efforts of the AEC, the electric utilities, and the reactor manufacturers in constructing and operating demonstration plants on actual utility systems.

The year 1957 was significant because it marked the initial operation of a 60,000 kw prototype nuclear power plant, the pressurized water reactor. This AEC-owned reactor facility, at Shippingport, Pennsylvania, built under a cooperative agreement with the Duquesne Power Company, was the nation's first large-scale civilian nuclear power reactor.

The years 1957-1963 saw the initial operation of several demonstration nuclear power units with power outputs up to about 200,000 kw. Some of these were built as part of the joint demonstration program and some were privately financed. The Yankee-Rowe reactor in Massachusetts, the Dresden-1 reactor in Illinois, and the Indian Point-1 reactor in New York were typical examples of such units.

The general arrangements in the AEC demonstration program were modified in 1962 specifically to encourage support of power reactors in larger sizes--above 400,000 kw. This phase of the program included the Connecticut-Yankee and the San Onofre plants which went into operation in early 1968. It was this scale-up in size, and the competition between the two big nuclear equipment companies, which enabled nuclear power plants to move into competition with fossil fueled (coal and oil) plants in the 1963-1968 period.

In 1963, the results of all of these various reactor programs were embodied in commitments by private utilities to build the Oyster Creek plant in New Jersey and the Niagara-Mohawk plant in New York with favorable projected economics and without Government assistance. These plants were in the 500,000 to 600,000 kw range.

The first large wave of nuclear power plant orders began in 1965, when 7 nuclear power plants were purchased; 20 more nuclear plants were ordered in 1966 and 30 plants in 1967. The orders dropped to 14 plants in 1968 and to 7 in 1969 due to a number of factors, including the traditional cyclic buying patterns of U. S. utilities. But the orders then picked up again to 14 plants in 1970, 20 plants in 1971, 36 plants in 1972, 38 plants in 1973, and 36 plants in 1974. By the end of 1974, 221 civilian nuclear power plant units with a total capacity of about 215 million kw had been ordered.

Experience with the development of nuclear power has clearly shown that taking a new energy concept from the research and development stage, to the experimental stage, then to the demonstration plant stage and finally to large-scale commercial utilization is a difficult and expensive undertaking--particularly toward the end of the developmental process. In developing the light-water reactor for civilian power production, the AEC spent about $1.5 billion over approximately a 25-year period; in addition, another $2 billion was spent on naval light-water reactor development which has been of major benefit to the civilian power program. The nuclear industry has also expended a considerable sum in the development of nuclear power.

The Nuclear Energy Option

Nuclear energy serves as a viable option for meeting our electric power requirements. The other options are: (a) nonnuclear energy sources, (b) more efficient means of converting energy resources to useful forms, and (c) more conservative means of using the available energy. Obviously a combination of the various options within these categories will be necessary to meet the nation's future energy needs.

In the nuclear category, energy can be extracted either through the fissioning of heavy metals, notably uranium, plutonium and a thorium derivative, U-233; or by the fusion of light elements, particularly deuterium and tritium. Of the two nuclear options, the fission processes are the more advanced in development. A substantial light-water reactor (LWR) industry is already well established, as I have just indicated. A comparable high-temperature gas-cooled reactor (HTGR) industry is in the process of becoming established with the placement of multiple orders by utilities for large HTGR power plants. Both of these systems depend, however, upon uranium-235 as their primary fuel. The

relative scarcity of uranium-235 in relation to its much more plentiful fertile counterpart, uranium-238, severely limits the utilization of uranium resources by the LWR and HTGR.

Because of this limitation of existing nuclear power reactors, we have been conducting research and development for many years on the concept of the "breeder" reactors, which can produce more nuclear fuel than they consume and hence utilize the nation's nuclear fuel resources to their maximum potential. The "fast breeder" reactor can convert the abundant nonfissionable form of uranium (U-238) to the nuclear fuel, plutonium (Pu-239), resulting in utilization of 60 percent or more of the total energy from uranium thereby assuring the availability of useful uranium reserves for many hundreds of years.

In 1967, after considering the ongoing reactor programs and the results of research up to that time, the AEC selected the Liquid Metal Fast Breeder Reactor (LMFBR) as the basis for its highest priority breeder reactor development program. The LMFBR was chosen over the other breeder reactor concepts principally because of predicted performance, industrial support, a broad base of technological experience and proven basic feasibility.

The objective of the U. S. LMFBR program is to develop a broad technological and engineering base with extensive utility and reactor industry involvement which will lead to the establishment of a strong and competitive commercial breeder industry in the mid-1980's. Prior to commercial utilization of the LMFBR by the electric utilities, the technology and economics of this reactor system must be demonstrated in a utility environment.

The Clinch River Breeder Reactor Plant (CRBR), a 350,000 kw demonstration liquid metal fast breeder reactor power plant, will be built near Oak Ridge, Tennessee, under a cooperative arrangement between ERDA and representatives of the nation's electric utilities. The demonstration plant will provide experience for industry and utilities in LMFBR plant design, construction and operation. This project will be jointly funded by the Federal Government, electric utilities throughout the United States, and segments of the nuclear equipment industry. It should be noted that more than 370 electric systems have pledged more than $245 million toward the project.

Other fission options are less well developed, and these include: the light-water breeder reactor which has the potential for operating on a self-sustaining uranium-thorium fuel cycle; the molten salt breeder reactor which also operates on the uranium-thorium fuel cycle and uses liquid fuel with continuous on-line fuel processing to achieve modest breeding; and the gas-cooled fast reactor which operates on the same fuel cycle as the LMFBR but has the potential for higher breeding ratios because of its more energetic neutron spectrum. However, none of these concepts has been fully developed.

The remaining nuclear option is the controlled thermonuclear reactor system which has yet to be demonstrated scientifically feasible.

Fusion is the process of joining atoms to produce energy, as happens in the sun and the stars. It is the opposite of nuclear fission--the splitting of an atom.

The quest for economic fusion power has been called one of the most challenging engineering and scientific endeavors of all time. In order for fusion reactions to occur, the reactants must be heated to about 100 million degrees Centigrade and for magnetic confinement systems, held at this temperature for about one-half a second. The deuterium-tritium reaction is considered the most attractive for first generation fusion power reactors. Deuterium is present in sea water and may be extracted at low fuel cost by means of proven

processes. It is, thus, virtually an unlimited fuel resource. Tritium, on the other hand, does not occur naturally and must be bred by means of neutron absorption in lithium. Hence, the supply of lithium determines the capacity to utilize tritium in fusion reactors. Known litnium reserves are large, however, and the potential for expanding lithium resources is excellent.

Later, when the technology has been developed to permit the commercial use of deuterium-deuterium reactions, requirements for lithium will be alleviated and the CTR industry could eventually be based upon the virtually inexhaustible deuterium resource.

It is estimated that even with success with a vigorous research and development effort the CTR option cannot contribute significantly to the energy supply until well after the start of the next century. However, the extent of the energy resources this option can exploit, coupled with the avoidance of many of the environmental problems associated with conventional power systems, fully justifies the major research effort under way to develop this system to its full potential.

Problems--Past, Present and Future

As could be expected, significant problems are being encountered with the large-scale introduction of the new and relatively advanced nuclear power technology into the economy. Utility and manufacturer organizations are finding that building nuclear plants which will perform reliably poses a number of difficulties and problems. Meeting the rigorous engineering standards required in constructing nuclear plants has involved some delays. Other factors associated with introducing new technology involving licensing, management, labor and component delivery have also caused delays. It is important to note that fossil fuel plants of large size and advanced design are encountering similar difficulties.

A further development which has become an important factor in the U. S. nuclear power program over the past several years is the increased concern about the safety and environmental impact of modern technologies.

Radioactive Discharges

Several years ago, the adequacy of the radiation protection standards was challenged on the grounds that the routine discharge of low levels of radioactivity from nuclear plants would result in a large increase in cancer incidence or infant mortality. Those who made these charges were particularly concerned about the increase in radioactivity in the environment which they believed would occur as more and more nuclear power plants went into operation.

Radiation standards established by the Federal Radiation Council are based on criteria set by the National Council on Radiation Protection and Measurements and the International Commission on Radiological Protection. In 1970, the functions of the FRC were transferred to the Environmental Protection Agency. All Federal agencies including the ERDA and NRC are required to adhere to these standards. The underlying philosophy of radiation protection has always been and continues to be the general principle that radiation exposure should be kept "as low as practicable." This policy governs the licensing and regulating activities of the Nuclear Regulatory Commission and has resulted in radiation levels at the boundary of nuclear power stations being only a very small fraction of the ratural background radiation to which we are all normally exposed.

In spite of the extensive research program which has been under way for more than 30 years, we are unable to demonstrate any biological effect at these

radiation levels even with the sophisticated techniques known. This really shouldn't be surprising since the levels of radiation from commercial nuclear power plants are less than the variation in natural background radiation we all encounter as we move around the country. The low level releases from nuclear power plants are carefully monitored by the utility as required by NRC. Independently, NRC, the Environmental Protection Agency and the States conduct monitoring programs to check on the utilities. This entire effort is designed to assure that radioactivity released by the plant does not result in "buildup" in the environment.

It should be remembered that radiation standards were set before population exposures from nuclear power plants occurred and thus are quite different from public health standards for other potential hazards which only came after measurable effects were noticed in the population.

Reactor Safety

Concern has also focussed on the safety aspects of nuclear power plants.

The nuclear industry has been and is one of the safest industries in the nation. This has, in large part, been due to the fact that unlike most other industries, the nuclear industry has not waited for serious accidents before adopting rigid safety controls. Safety has been the watchword from the beginning.

To assure that nuclear power plants are built and operated safely and that reactor accidents are prevented, a "defense in-depth" technical concept is used. Briefly stated, it consists of three basic aspects as follows:

(1) achievement of superior quality and design, construction and operation of nuclear power plants;

(2) accident prevention safety features which prevent any unlikely malfunction from growing into more serious problems; and

(3) finally, consequence limiting safety features, such as the large containment shells, which are now becoming more commonplace on the landscape of the country.

Primary assurance of safety in a nuclear power plant is provided by correctly designing, constructing and operating the reactor. Extensive and systematic quality assurance procedures are required and are applied at every step to provide the needed verification of plant safety.

A rigorous licensing process has been established to review and assure the safety of nuclear power plants. These reviews take into account the possibility that deviations from normal reactor operations can occur, and because of this fact, additional protective systems and backup safety features are provided.

The combination of the defense in-depth concept, technical review and inspection activities, supplementing a careful and safety conscious design and quality assurance effort, provides a high degree of assurance that the public, as well as the nuclear plants themselves, are adequately protected and that the safety record which has been achieved by the nuclear industry to date will be continued.

In August of 1974 the results of a two-year study directed by Dr. Norman C. Rasmussen of MIT were released. This study made a quantitative assessment of the potential risks involved in nuclear power plant accidents and compared these

risks with nonnuclear risks to which our society and its individuals are already exposed. The basic conclusion of the study is "that the risks to the public from potential accidents in nuclear plants are very small."

The study found that the likelihood of a person living in the general vicinity of a reactor being injured in any one year in a reactor accident is one chance in 150,000,000. An individual's chance of being injured in an automobile accident in that same year is one in 130. On a broader societal viewpoint, if there were 100 reactors operating in the U. S., one individual of the 15,000,000 people living in the vicinity of these reactors might be killed and two individuals might be injured every 25 years. For comparison there were approximately 1.5 million injuries and 55,000 fatalities last year due to automobile accidents.

High-Level Wastes

Significant concern has been expressed over the disposal of the high-level radioactive wastes which remain after the reprocessing of nuclear fuel elements.

The problems involved in safely containing the solidified waste away from man and the environment are technically feasible and straightforward and are based on chemical and physical principles which have been known and used routinely for years.

It should be made very clear that there is a significant difference between the way wastes generated as a result of wartime needs were handled and the way that commercial reactor wastes will be handled. These differences make possible a completely different technical approach.

The AEC-ERDA high-level radioactive wastes consist of very large volumes of mixtures of solids and liquids in many large steel tanks located just beneath the surface of the ground. This waste, from production of material for defense, has been accumulating since 1945. It should be understood, also, that this waste will have to be monitored and handled even if there had never been a kilowatt of nuclear generated electricity in this country.

In the commercial sector, used fuel from a nuclear power plant is shipped in special containers, called casks, by truck or rail to a reprocessing facility. The high-level liquid wastes extracted by the reprocessing facility are then stored at the reprocessing site. Within five years this liquid waste must be converted to a solid and within 10 years shipped to a Federal repository. The responsibility for the isolation and ultimate disposal of high-level wastes rests solely with the Federal Government. The cost of this Government storage must be borne by the utility that operates the nuclear power plant.

At present no commercial reprocessing plants are operating in the United States; however, it is expected that those currently under construction will begin operation in the late 1970's. Thus, it will be the 1980's before any solidified high-level waste will be delivered to a Federal repository. The Energy Research and Development Administration is currently considering three sites for the construction of a Federal repository for interim storage of high-level waste. The sites being considered are the Federal Government's Nevada Test Site, Idaho Reactor Test Site, and the Hanford Reservation in Washington State. A Federal repository will be designed for interim storage of up to 100 years to allow for the orderly development of permanent storage facilities in geologic formations such as salt.

The volume of waste is small. At present it is only a fraction of one percent of the total defense generated wastes in this country. Through the

year 2000, all the commercial high-level wastes in this country can be handled in a facility which, including a buffer zone, handling, receiving and storage facilities, would take a land area of no greater than 1500 acres, depending upon the storage concept chosen. In other words, to handle commercial high-level wastes in this manner requires only a relatively small area of land be dedicated to this use.

Shipment of Radioactive Materials

In regulating the shipment of radioactive materials it is assumed that accidents will occur and that there will be no way of predicting which shipment will be involved in an accident. Therefore, these shipping casks must be capable of withstanding, without leakage, all of the normal conditions of transportation as well as a series of accident tests which produce damage conditions comparable to the actual damage a package might encounter in a hypothetical severe transportation accident. Prior to certification by NRC and the Department of Transportation, tests on these casks include dropping from a height of 30 feet onto an unyielding surface, exposure for at least 30 minutes to a fire having a temperature in excess of 1475°F, immersion in water for at least 8 hours, and dropping onto a 6-inch diameter pin from a height of 40 inches.

Based on the design and testing of the shipping casks and train and truck accident statistics, ERDA estimates that an accident resulting in the release of radioactivity will occur once in 10,000,000,000,000 vehicle miles or approximately once in 5,000 years. Even in such a remote accident possibility, highly hazardous levels of radioactivity would be confined to a radius of 100 feet of the damaged cask and would then only be dangerous if someone remained in the vicinity for a very long time. It should be remembered that even though there have been serious accidents which have resulted in damage to the outside of the massive shipping cask, no radioactivity has ever been released.

Only about one percent of all radioactive shipments involve highly radioactive material such as shipments of used fuel rods from a nuclear power plant to a nuclear fuel reprocessing plant. About 95% of all radioactive shipments involve very small amounts of material or very little hazard material on its way to hospitals, clinics, or laboratories. Most of these shipments would offer little public hazard even if the package were completely crushed and the material released.

The need to prevent the theft of material which could be used to make an atomic bomb is one of the most important responsibilities the Federal Government has. At ERDA facilities we employ extensive techniques to safeguard all nuclear materials which have a potential for clandestine uses while inside our facilities as well as in transit. During transportation these ERDA materials are guarded by armed Federal employees.

An overall security plan for every commercial power reactor and fuel handling facility must be approved by the Nuclear Regulatory Commission as part of the licensing requirements. As indicated previously, there are no commercial reprocessing plants in operation today, thus there is little movement of spent fuel or plutonium in the commercial sector at present. However, the NRC is requiring stringent security requirements which must be adhered to by the commercial industry to assure continuing public safety as the number of spent fuel shipments and shipments from reprocessing plants increases.

Conclusion

In the years ahead, the United States will need to use in the most efficient manner possible all of the practical energy sources available to us if future energy demands are to be met. Nuclear energy has an important role to play in this regard.

In a real sense, public acceptance of nuclear power will depend on whether these plants, after a reasonable maturing period, deliver the reliable, economic and safe power which has been promised for them. As with other technologies, the public will sooner or later judge nuclear power by the straightforward tests of success or failure. This is as it should be.

RADIOACTIVE WASTES: SOURCES, TREATMENT AND DISPOSAL*

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INTRODUCTION

Of all the problems associated with nuclear energy, probably none is so chronic and its solution so elusive and controversial as that of "permanent" disposal of the radioactive wastes produced by fission and transmutation reactions. The technical problems arise from the effectively infinite radioactive lifetime of some of the wastes, and from the fact that an appreciable fraction of the earth's air, crust and water would be required to dilute the wastes to concentrations considered to be acceptable. Together these factors impose a requirement either of disposing of wastes in a manner permitting and ensuring indefinitely long surveillance and attention to ensure their confinement or of disposing of them in a place so free from natural disturbance or remote from man that such attention is not required. A few moments' reflection on the nature of man and on his history strongly suggests the second course of action, which, if it is possible, relieves mankind of long-term responsibility. Another alternative method of permanent waste disposal is simply to destroy the very long-lived radioactive isotopes. While all attempts to accelerate significantly the process of radioactive decay have failed so far, there is a way which may be practical to destroy a very significant part of the radioactive wastes. This will be discussed later on.

A final way to circumvent the problem of permanent waste disposal is simply to forego nuclear energy. It is not the purpose of this essay to discuss the pros and cons of various energy sources. It is assumed that there will be significant amounts of radioactive wastes; this is a discussion of them and of the options for disposing of them.

It is generally accepted that the primary hazard presented to people by radioactive wastes devolves from their radioactivity. Thus, it is worthwhile to consider for a moment what the general nature of that hazard is. Most radioactive materials decay with the emission of α or β particles or of γ rays. Some have alternate decay modes and emit two or all three types of radiation. In general, a given number of curies (defined as 3.7×10^{10} disintegrations per second) of an α particle emitter in the body is more hazardous than the same number of curies of a gamma ray emitter inside the body. This results from the fact that all the energy of the α particle is deposited in the body in the immediate vicinity of its emitting isotope; the γ ray, on the other hand, penetrates tissue easily, and some of the rays may leave the body unattenuated. Conversely, an α particle emitter outside the body is less hazardous than a γ ray emitter outside the body because shielding from α particles, which hardly penetrate the skin, is much easier than shielding from the much more penetrating γ

rays. Beta particle emitters are, in general, intermediate between α and γ emitters in their hazardousness.

Because many radioisotopes emit more than one type of radiation during decay, the above generalizations are an oversimplification. Further, some plants and animals eaten by man preferentially take up certain elements, and for those radioactive materials which get inside a person, either by ingestion or respiration, there is the important consideration of preferential uptake or concentration in specific organs such as the thyroid gland, the bones or the liver. Some radioelements or their compounds are taken up in a highly specific manner by the body. This biological concentration can lead to serious damage because of the resultant high local dose, when that amount of radioactive material dispersed uniformly over the body might be relatively harmless.

From the above it is apparent that the hazard posed by radioactive wastes must be considered from a number of points of view: type of radiation emitted; ecological pathways followed to arrive in food and ultimately in man; biological concentration; sensitivity of organs to the radiation; amounts of various types of radioactive materials and their sources; and the location of unconfined wastes. In addition to the above may be added lifetime (more correctly, half-life) of the radioisotope and the method of its disposal.

SOURCES

Man lives in a "sea" of radiation, both outside and within his body. Typically, man is subjected to 120 to 140 millirems per year from naturally occurring radioactivity in and around him. A millirem is a relatively very small amount of radiation. For comparison it may be noted that about 450 rems absorbed by a man over a relatively short time would have about a 50-50 probability of killing him.

Natural

Radiation commonly around and in man comes from such varied sources as ^{40}K, ^{14}C, ^{3}H, $^{219,220,222}Rn$ and cosmic rays. There are, of course, significant amounts of ^{238}U, ^{235}U and ^{232}Th, and of the radioactive elements in their decay chains, also present in the earth's crust and water, but these are mostly fixed in minerals, such that with the exception of the Rn isotopes they are not commonly in the biota of which man is a part. Since Rn is a gas, it is motile, and if it is inhaled by a man before it decays to its solid daughters, the subsequent decay chain is likely to run its course in that man. The relatively short half-lives of ^{14}C ($\sim$ 5600 yrs) and ^{3}H ($\sim$ 12.3 yrs) preclude the possibility that they persist from their creation in the primordial past. They are made continuously through nuclear reactions induced by cosmic rays.[1] The amount of ^{14}C, though relatively small ($\sim 2.8 \times 10^{8}$ curies worldwide in steady state, about 97% of which is deep in the oceans), is adequate to make practical the technique of "carbon dating" used successfully by archeologists, historians, and others to determine the ages of carbonaceous things a few tens of thousands of years old. The amount of ^{3}H is still less ($\sim 2.8 \times 10^{7}$ curies worldwide in steady state, about 90% of which is in water, 10% in the stratosphere, and 0.1% in the troposphere). The very long half-life of ^{40}K ($\sim 1.3 \times 10^{9}$ yrs) suggests that it could have been around at the generally accepted time the earth was formed (4-6 billion years ago) and still be there at 5 to 10 percent of its original amount. The amount of ^{40}K may be calculated to be about 4×10^{23} curies in a layer of the earth about 10 miles thick.

The average man contains about 0.02 gram of ^{40}K, or about 0.14 microcuries.

In the context of radioactive wastes, tritium, ^{14}C radium and radon isotopes are the radioisotopes of greatest interest from among those mentioned.. Actually, only the radium and radon isotopes are truly important "natural" wastes. The tritium and ^{14}C are only of consequence as they are produced artifically in concentrations.

Mills

The nuclear fuel cycle starts at the mines and nearby mills where uranium (or thorium) ores are taken from the ground, and a first separation of the desired element from the unwanted waste dirt is carried out. And it is here that the first significant radioactive waste problem arises. Typical "good" uranium ore contains only about 0.2% U_3O_8; thus, it is apparent that a great deal of the material present in the ore is left at the uranium mill after the uranium has been removed. The volume of such wastes that will be generated per year in the year 2000 has been estimated[2] to be about 880 million cubic feet. The total volume accumulated by the year 2000 is estimated to be 14 billion cubic feet! This estimate, based on a recent AEC Office of Planning and Analysis forecast[3], gives an idea of the potential magnitude of the problem. The present practice is to dispose of this waste material or "tailings" as it is called, by simply dumping it into "monumental" tailings piles at the mills. Radon is continuously emitted from such piles, and radium is also a potential source of harmful radiation if it escapes by seepage into ground or surface water. Methods have been suggested for limiting the amount of radon evolved from tailings piles; these methods are based on putting layers of dirt or spreading asphalt membranes on the piles to inhibit diffusion of the radon long enough for it to decay substantially to its non-volatile daughters. Figure 1 presents an idea of the size and disposition of the piles now in existence in the western states. Guides for disposing of uranium milling wastes have been published[4], and continuing attention is being given to this waste disposal problem.

Fabrication Plants

After mining and milling, the uranium concentrates typically are refined (a process which further purifies the concentrate suitable for the uranium enrichment plant), enriched in the isotope ^{235}U at a gaseous diffusion plant, and the enriched uranium is fabricated into fuel. Uranium enrichment produces two streams of material: enriched UF_6 product, and depleted UF_6 "tails." The tails are far and away the larger of the streams, and could be considered a radioactive waste. However, it appears likely that the LMFBR, which uses depleted uranium in its blanket to breed plutonium, will put this material to good use.

Reactor fuel fabrication plants, by their nature, produce wastes which are mainly alpha-contaminated. Light water reactor (LWR) fuel fabrication involves uranium of low enrichment (typically, about 3% ^{235}U), and may involve plutonium as well. The decision on whether to recycle plutonium back to light water reactors will probably be made in the coming months.

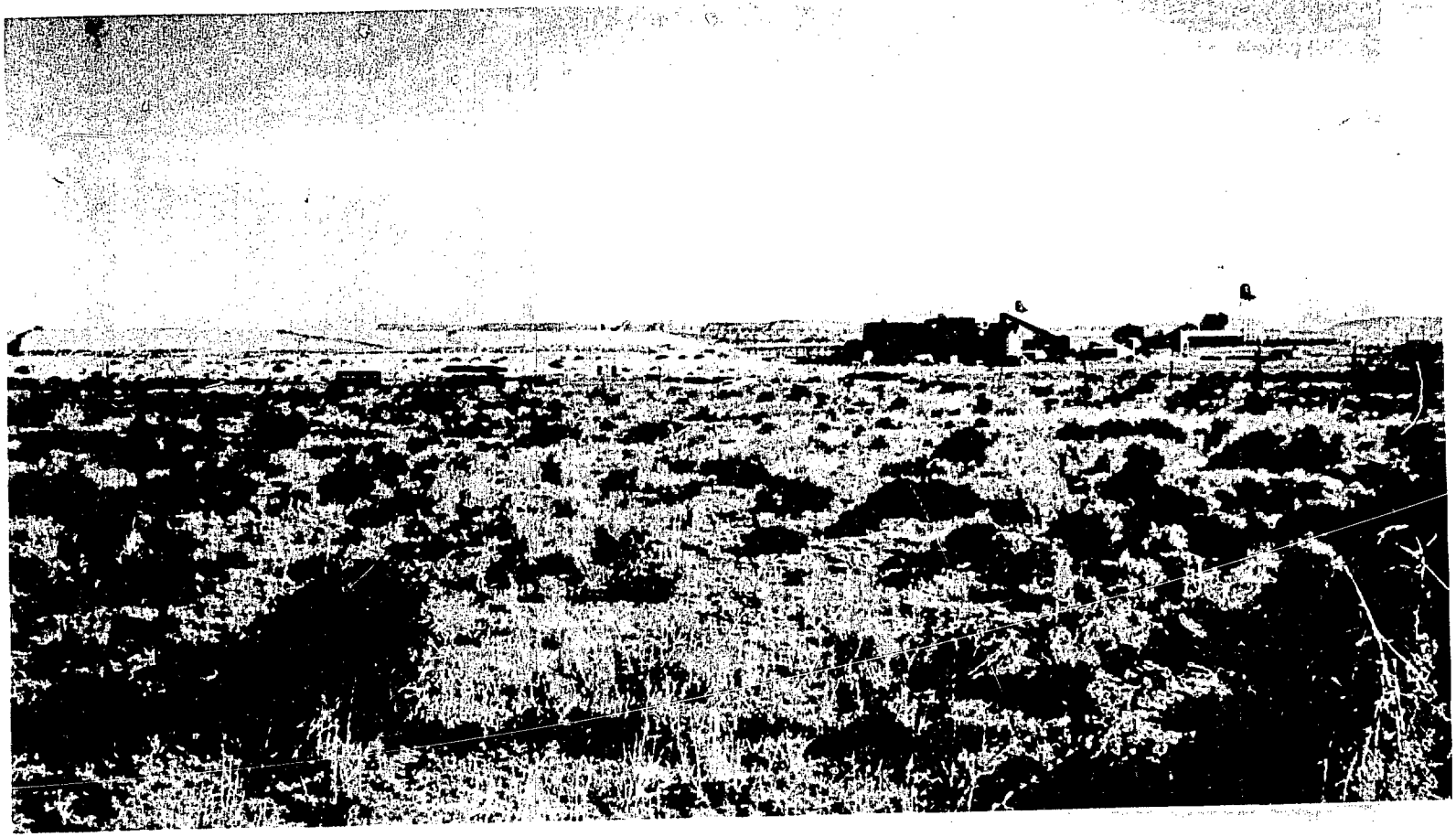

Figure 1
Tailings Pile at the Kerr-McGee Mill near Grants, New Mexico

High temperature gas-cooled reactor (HTGR) fuel fabrication involves highly enriched uranium (about 93% ^{235}U) and thorium. Thorium decay produces ^{220}Rn, which has been mentioned previously in connection with natural radiation, and with uranium milling wastes. As mentioned earlier, delaying the emission of ^{220}Rn, whose half-life is just under one minute, permits it to decay to its solid daughters, which may be disposed of as moderately radioactive wastes. In the steady state, HTGRs must be fueled partly with ^{233}U produced by nuclear reactions from the ^{232}Th. The disposal problem becomes more acute when fuel is fabricated from ^{233}U. This is true partly because of the presence of ^{232}U in the ^{233}U. ^{220}Rn is produced in the decay chain of ^{232}U, in amounts dependent on the ^{232}U content. It is also true partly because ^{233}U is itself more toxic than ^{238}U or ^{235}U.

Liquid metal fast breeder reactor (LMFBR) fuel fabrication involves uranium and plutonium. The toxicity of plutonium has already been noted. Fuel fabrication plant wastes include all manner of solids and sludges that arise from decontamination operations, liquid waste stream treatment, and off-gas cleanup. Uncompacted wastes may vary in density from 2 to 200 lbs/ft^3, with uranium, plutonium and thorium contents of from trace amounts to several grams per cubic foot. About 1/2 to 2/3 of the waste volume is combustible, and volume and weight reductions of 50 and 20, respectively, may be obtained with these fractions. It has been estimated[2] that about 20,000 ft^3 of alpha waste will be generated per tonne of plutonium or ^{233}U fabricated, and that these wastes will contain about 0.5% of the plutonium or ^{233}U.

Reactors

The really major problems of radioactive waste disposal are born in the reactor, where uranium or plutonium fissions occur, and where transplutonium elements (i.e., elements higher in atomic number than plutonium) are produced. Although it is in the reactor cores that far and away most of the radioactive materials to be disposed of are produced, in a more precise sense, reactors do not actually produce the most radioactive wastes. They produce spent fuel elements, which in the present concepts of waste management are not radioactive wastes. Although "poisoned" with fission products and laden with relatively non-fissile transplutonium isotopes, these spent fuel elements also contain enriched uranium and fissile plutonium. Thus, they are not truly wastes. The other radioactive materials produced at reactors contain far less radioactive wastes than the fuel element, and are much less of a disposal problem.

The next step in the fuel cycle, i.e. fuel reprocessing, separates the uranium and plutonium from the fission products and transplutonium elements, and it is at this step that "the (waste disposal) buck stops." That is not to say, however, that reactors do not produce radioactive wastes--they do. Further, each of the various reactor types produces its own types of wastes, though there is a general similarity among them. A great deal has been written about reactor wastes, both in general[5,6] and about specific reactors.

There are liquid, gaseous and solid reactor wastes to be disposed of. The liquid wastes are mostly aqueous, and are treated at the reactor to remove the radioactive components as sludges or solids so the decontaminated water may be disposed of in environmental water (streams, rivers, lakes or oceans). This type of treatment must perforce produce a solid waste.

Gaseous wastes vary markedly from one reactor type to another. For the light-water reactors prevalent in the U. S., fission product krypton is the most important. Tritium may also be present, but in relatively small amounts. Some radioactive particulates are produced which are filtered from the gas (ventilation air is the chief source) leaving the reactor. These too become, finally, solid wastes. Radioactive krypton (primarily ^{85}Kr) may be removed from reactor gaseous effluents by several processes with varying degrees of effectiveness.

The two principal power reactor types in the United States are the boiling water reactor (BWR) and the pressurized water reactor (PWR). Both are light-water-moderated and cooled, i.e., their cores are immersed in ordinary (light as opposed to heavy) water which circulates and removes the heat of fissioning from the fuel elements. Radioactive wastes are produced at quite a few different places in the power plants. In general, these are treated to produce solid wastes, as shown in figures 2 and 3. A comparison[6] of BWRs and PWRs indicates that BWRs generate a larger volume of solid radioactive waste per thermal megawatt-hour than PWRs, but that the number of curies shipped from the plants per thermal-megawatt-hour is essentially the same, about 3×10^{-5}. In general, since 1970 the curie content per unit volume of PWR waste has exceeded that of BWR wastes by factors of 2 to 8, and is about 0.1 to 1 curie per cubic foot.

Incorporation into an inert matrix of wastes from the filtration, ion exchange and evaporation processes used to produce solid wastes is commonly used to produce a solid safe for shipping and disposal. Incorporation in cement is routinely used, although other matrices such as plastics and asphalts are used. Although the volume of waste to be disposed of is approximately doubled by putting it in cement, cement provides radiation shielding, mechanical strength, and affords some protection against the inadvertent leaching of radioactivity from the solid.

Solidified wastes from reactors have been shipped to "burial grounds" for disposal. Several commercial organizations* exist which dispose of these wastes. The wastes are generally low level,** and as mentioned above are either incorporated in a stable matrix, e.g., cement or plastic, or are baled to produce compact, dry solids. The high-level wastes produced at the fuel reprocessing plants cannot be stored at these commerical burial grounds.

Non-radioactive gases present with the fission product krypton are important in determining how the gaseous wastes are treated. Off-gas treatment systems for BWRs have recently been reviewed.[8] Radioactive gaseous waste streams arise mainly from the condenser off-gas stream. Hydrogen and oxygen in the amounts of 110 and 55 standard cubic feet per minute, respectively, from radiolytic decomposition of water in the core will be present, as

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*Examples of organizations offering this service are Nuclear Engineering Co., Inc., ATCOR, and Pickard, Lowe and Associates.

**The disposal of radioactive wastes at commerical burial grounds may be limited to those having a specific activity of no more than about 10^{-8} curies of alpha activity per gram of total solid. Reactor wastes sent to burial grounds will average about one curie per cubic foot, due mainly to induced radioisotopes in reactor and fuel structural components.

well as air in the amount of about 18 1/2 standard cubic feet per minute from in-leakage. Over a year's time the noble gas content of the nearly 10 million cubic feet of air in-leakage will be about 10 standard cubic feet. The annual total amount of radioactive noble gas produced by the 1000 megawatt (electrical) plant will be about 40 cubic inches. Treatment methods of these wastes from a 1000 megawatt-electrical energy plant may be compared on the basis of radioactive noble gases (krypton plus xenon) present after 30 minutes delay before treatment. (The delay is obtained by passing the gases through a long pipe. During this delay a 25-fold reduction in the curies of Kr plus X3 is obtained. In 10 hours the reduction is 114-fold.)

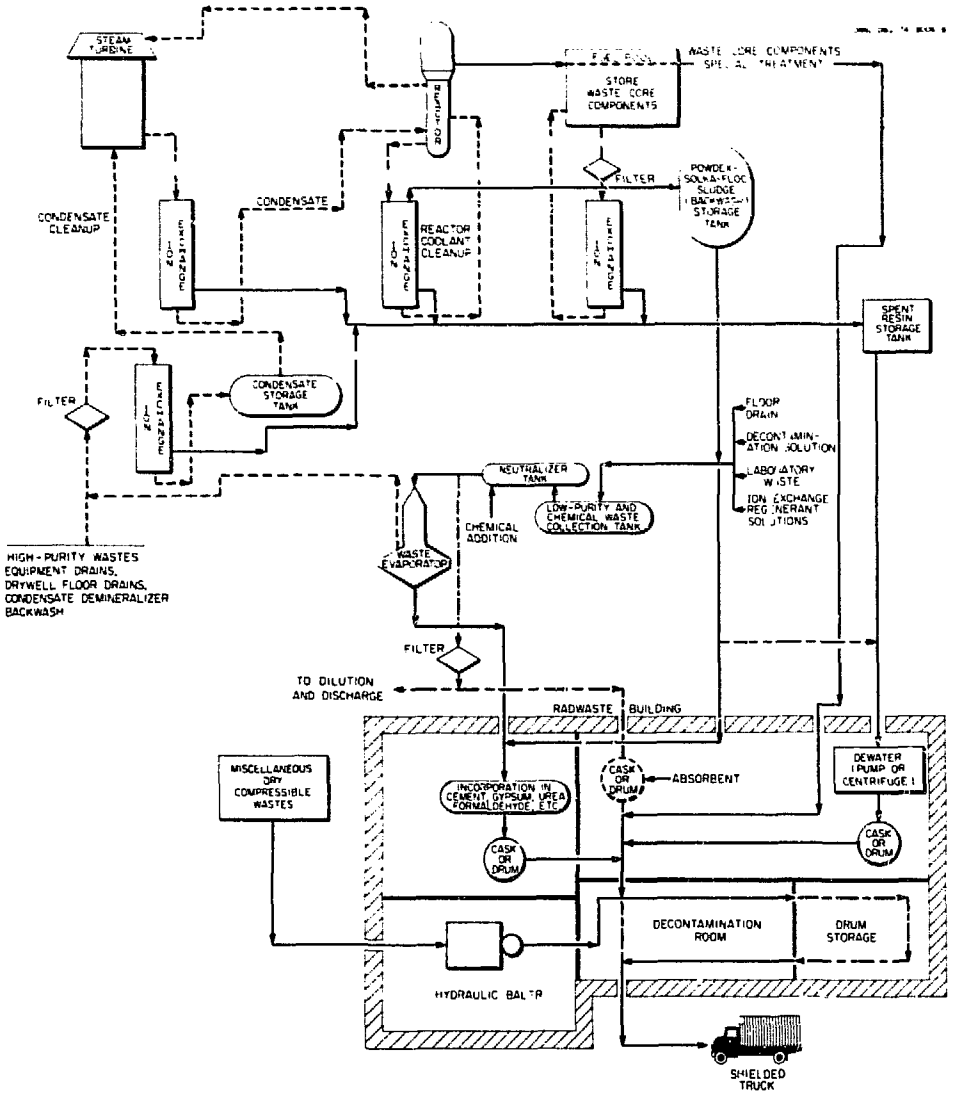

Figure 2
Typical System for Treatment of Solid Radioactive Wastes at a Boiling Water Reactor

After the 30-minute delay and recombination of hydrogen and oxygen in a recombiner to form water, the non-condensible gases may be handled in several ways to decontaminate them. Basically these involve either one of several versions of selective absorption on charcoal, or cryogenic distillation, or selective fluorocarbon absorption. In each case, after their selective concentration the noble gases may be transferred from the concentration system to metal cylinders for storage. It should be noted that fluorocarbon absorption, although promising, its quite new; further, potentially dangerous problems of ozone buildup may exist with cryogenic charcoal absorption and cryogenic distillation unless care is taken to prevent it.

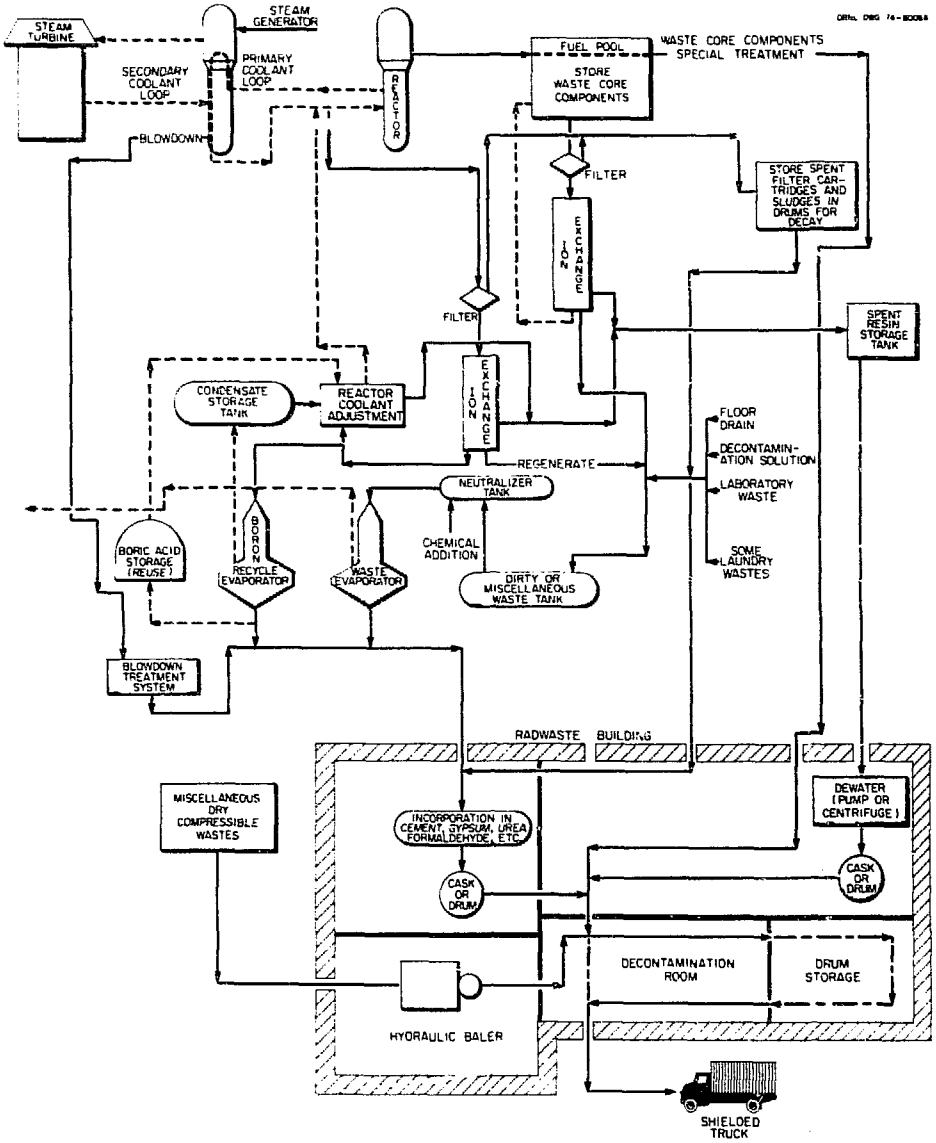

Figure 3
Typical System for Treatment of Solid Radioactive Wastes at a Pressurized Water Reactor

A third type of reactor, the high-temperature gas-cooled reactor (HTGR), shows promise of becoming important in the U.S. in the next 10 to 15 years. In this reactor the coolant is helium and the moderator is the graphite present in the fuel itself. Very preliminary information[6] on its waste disposal problems suggests that they will be similar to those of LWRs. Figure 4 shows schematically what the 330 megawatt HTGR, Fort Saint Vrain Nuclear Generating Station, helium purification system is like.[9,10]

A final word is in order about the reactors themselves as a radioactive waste disposal problem. If, as has been projected,[2] there are about 1,200,000 megawatts of installed nuclear electricl power by the year 2000, there may be ∿1000 reactors whose useful lives will be over in th 10 to 30 years following the year 2000. These must be disposed of, or "decommissioned." According to the recent trend there will be 2, 3 or more of these reactors on a single site, so there will be well under 1000 sites to be decommissioned. Nonetheless, since these reactors will be highly radioactive from induced radioactivity in the containment vessels and other materials of construction, as well as from fission produces from accidental release,* there will exist a substantial disposal problem. There appear to be two approaches to the problem. One is to cut the reactors up into pieces

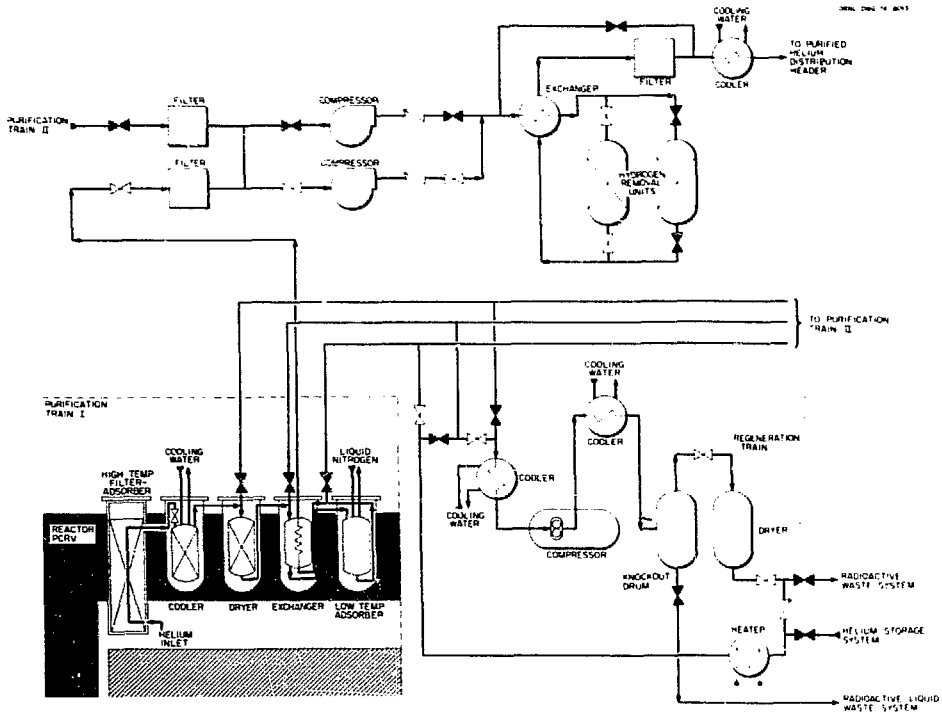

Figure 4
Helium Purification System for 330 Megawatt-Electrical Fort Saint Vrain Nuclear Generating Station HTGR
(Taken from Reference 9)

*The recently released study Reactor Safety Study, An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants, WASH-1400 (August 1974) estimates 1 reactor core melt accident in 17,000 reactor-years. Thus, 1000 x 30/1700 = 1.7 core melt accidents.

that can be hauled away to a disposal area, thus reducing the number of radioactive sites from many reactor sites to a few disposal sites; the other is to decontaminate the reactor thoroughly, and then entomb it in concrete and cover it with dirt. Although this latter approach does not restore the site to general use, and necessitates a sort of "perpetual care" philosophy, it should be remembered that the radioactivity, which is largely induced, is fixed in the predominantly metal reactor parts themselves, and will be released slowly, if at all.

Reprocessing Plants

The basic, large problems in radioactive waste disposal raise from operation of the spent fuel reprocessing plants. The status of spent fuel reprocessing has recently been reviewed.[11] In general, the spent fuel is chopped (LWR and LMFBR fuel) or burned (HTGR fuel) to make the fissile and fertile materials available for dissolving in acid. The resulting acidic solutions are treated by solvent extraction to extract uranium and plutonium (and in the case of HTGRs, thorium), leaving the fission products in an aqueous waste stream. It is this waste stream that poses the outstanding waste disposal problem of the nuclear power industry. Just as in the case of reactors, fuel reprocessing plants have many sources of radioactive wastes.

The aqueous waste stream mentioned above is certainly the most important, but gaseous wastes such as krypton, xenon, tritium, or tritiated water vapor, and volatilized iodine and solid wastes are also important reprocessing wastes requiring disposal. An especially important solid waste is the chopped up pieces of fuel cladding left after the fuel has been dissolved. These may be contaminated with difficult-to-remove plutonium. Table 1 summarizes estimated annual fuel reprocessing wastes generation rates and total accumulations for various waste types in the U. S. in the year 2000. This table was based on the assumption that an economically competitive mixture of LWRs, HTGRs and LMFBRs would exist in the year 2000 in the U. S. Since each of these reactor types leads to somewhat different types of wastes, flowsheets for reprocessing fuel from each type were assumed and wastes expected from each were calculated and compiled to produce Table 1.

TABLE 1

Fuel Reprocessing Wastes Annual Generation Rate and Total Accumulation in the U. S. in 2000 A. D. (Taken from reference 2)

Type	Annual Generation Rate		Total Accumulation	
	Megacuries	Cubic Meters	Megacuries	Cubic Meters
High-level solids	54,400	1,300	150,000	13,300
Alpha-beta-gamma				
cladding	370	1,930	1,150	15,200
ther	5.8	17,300	26	131,000
Alpha solids	54	57,200	260	349,000
Beta-gamma				
solids containing ^{3}H	14	130	96	1,290
noble gases	230	62 (at 150 atmos.)	1,630	660
iodine	.001	2.2	.01	22
other solids	1.1	1,740,000	4.5	11,100,000

The various important kinds of wastes generated during fuel reprocessing are given in Table 2 for LWR, HTGR and LMFBR fuels. These wastes are defined as high-level wastes, and federal regulations call for them to be solidified within 5 years of their generation, and for the resultant stable solids to be shipped to a federal repository within 10 years of their generation.*

In the case of HTGRs, fuel reprocessing may lead to the release of significant quantities of ^{14}C. The HTGR fuel is largely graphite, which will be burned to release the fuel values for dissolution and recovery. During the burning operations, carbon dioxide gas will be generated. After cleanup to remove iodine, tritium and krypton the carbon dioxide may be released to the atmosphere. The carbon dioxide will contain ^{14}C. The HTGR fuel is largely graphite, which will be burned to release the fuel values for dissolution and recovery. During the burning operations, carbon dioxide gas will be generated. After cleanup to remove iodine, tritium and krypton the carbon dioxide may be released to the atmosphere. The carbon dioxide will contain ^{14}C produced mainly by neutron reactions with nitrogen present in the fuel, but also by neutron absorption by the naturally-occurring ^{13}C. The amount of carbon dioxide produced will be trivial as an atmospheric pollutant no matter what the projected number of HTGRs whose fuel is reprocessed by burning.

TABLE 2.

Calculated Curies in Spent Fuel per Tonne of Heavy Metal Charged to the Reactor

(Taken from Reference 2)

Source of Radioactivity	Curies Present at Indicated Days after Discharge					
	0 day	30 days	90 days	160 days	365 days	3653 days
			LWR[a]			
Cladding	1.42×10^5	8.03×10^4	4.52×10^4	2.62×10^4	1×10^4	2.4×10^3
Fission Products	1.38×10^8	1.08×10^7	6.19×10^6	4.19×10^6	2.22×10^6	3.18×10^5
Actinides	3.91×10^7	1.83×10^5	1.33×10^5	1.26×10^5	1.14×10^5	7.2×10^4
			HTGR[b]			
Light Elements	6.52×10^3	3.55×10^3	3.49×10^3	3.4×10^3	3.26×10^3	1.76×10^3
Fission Products	2.96×10^8	2.32×10^7	1.32×10^7	9.1×10^6	4.55×10^6	1.01×10^6
Actinides	1.04×10^8	2.18×10^7	4.77×10^6	1.0×10^6	3.81×10^4	2.80×10^4
			LMFBR[c]			
Cladding	1.34×10^6	6.06×10^5	3.99×10^5	2.8×10^5	1.32×10^5	5.98×10^3
Fission Products	1.96×10^8	1.68×10^7	9.56×10^6	6.7×10^6	3.31×10^6	3.15×10^5
Actinides	8.05×10^7	7.16×10^5	6.79×10^5	6.6×10^5	6.21×10^5	4.10×10^5

[a]Burnup: 33,000 megawatt-days/tonne; power: 30 megawatts; flux: 2.92×10^{13} neutrons/cm^2-sec.

[b]Burnup: 94,271 megawatt-days/tonne; power: 64.57 megawatts; flux: 8.04×10^{13} neutrons/cm^2-sec.

[c]Burnup: 37,118 megawatt-days/tonne; power: 49.28 megawatts; flux: 2.49×10^{15} neutrons/cm^2-sec.

These regulations are given in "Siting of Fuel Reprocessing Plants and Related Waste Management Facilities," Federal Register 35, No. 222, 17530 (Nov. 14, 1970). There is at present no federal repository, so there is something of a dichotomy implicit in the regulations.

However, if the fuel contains 20 to 30 parts of nitrogen per million parts of graphite, the ^{14}C liberated by a 1.5 tonne per day (of uranium plus thorium) reprocessing plant may not be negligible. LWRs, whose fuels contain nitrogen as an impurity, may generate comparable amounts of ^{14}C, but since the carbon dioxide content of LWR fuel reprocessing effluents is so small, retention of the carbon dioxide by conversion to a solid (e.g. $CaCO_3$) appears much simpler and more economical than for HTGR fuel reprocessing effluents.

It is important to note that at present there is no commerical reprocessing plant for reactor fuels operating in the United States. The USAEC maintains reprocessing capability at the Savannah River Plant near Aiken, South Carolina and at the Idaho Chemical Processing Plant near Idaho Falls, Idaho, but these plants are devoted to fuels from AEC and U.S. Navy reactors. The earliest expected commerical fuel reprocessing capability will probably be at the Allied-General Nuclear Services plant at Barnwell, South Carolina, which may be in operation starting in 1976-77. This plant is designed for operation with LWR fuel of about 33,000 megawatt-days burnup and 160 days decay ("cooling") before reprocessing. It will have a nominal capacity of 5 tonnes of uranium per day, or about 1500 tonnes per year. Projections[2] indicate that this capacity will be inadequate to meet the PWR fuel reprocessing load almost as soon as the plant becomes available. Table 3 gives the magnitude of the reprocessing problem, and so, indirectly, of the waste disposal problem.

TABLE 3.

Tonnes of Fuel Requiring Reprocessing from 1974 to 2000

(Taken from Reference 2)

Year	LWR	HTGR	LMFBR
1974	100		
5	400		
6	1100		
7	1700		
8	2032		
9	1955	3.9	
1980	2395	6.6	
1	3030	7.7	
2	3509	36.8	
3	4051	66.3	
4	4195	97.8	
5	4752	169.3	
6	5229	239.2	
7	5689	321.1	5
8	6355	406.3	7.1
9	6999	492.1	77.1
1990	7650	589.6	175.4
1	8158	683.4	306.4
2	9000	764.0	492.1
3	9536	858.1	709.8
4	10,092	954.6	1038
5	10,478	1040	1470
6	10,871	1116	2073
7	11,194	1193	2689
8	10,837	1261	3450
9	11,180	1333	4270
2000	11,041	1415	5123

Just as in the case of reactors, there is the problem of "decommissioning" the fuel reprocessing plants when they reach the end of useful life. However, it is not so clear that the option exists to cut up the contaminated parts of the reprocessing plants and remove them to a central waste storage facility. Whereas the bulk of the activity of the reactors is induced in relatively stable metal components, the activity of the reprocessing plant is, by the nature of the operations, in a variety of chemical and physical forms as it passes through the plant and the process equipment. Thus, extensive "loose" contamination will be present in the plants, and this will pose a major obstacle to its complete removal from the plant site. For this reason it is likely that the "perpetual care" approach to disposal after decommissioning will be the one chosen for spent fuel reprocessing plants. Of course, there will be fewer spent fuel reprocessing plants to decommission than there will be reactors. Seven or eight 5 tonnes per day plants should be adequate to handle the LWR spent fuel reprocessing load in the year 2000. About three 1.5 tonnes per day HTGR spent fuel reprocessing plants may be needed, in addition to about four 5 tonnes per day LMFBR fuel reprocessing plants. Thus, there may well be 15 or more spent fuel reprocessing plants present in the U. S. in the year 2000 that will need to be "disposed of" as radioactive wastes sometime between 2000 and 2030 AD. (The useful life of a reprocessing plant may be about 30 years.) Of course, part of these plants will have been built before 2000 AD, and others may be built after that year.

Miscellaneous

There are numerous sources of radioactive wastes which are outside the nuclear fuel cycle. These include wastes from hospitals where radium and its daughters have been used for decades, and where now a wide range of radioisotopes is used for a variety of diagnostic and therapeutic purposes; from universities, where research is carried out in the physical and life sciences with almost every radioelement available; from radio-pharmaceutical plants where radiophosphorous, radiosulfur, radiocarbon, tritium and other radioelements are incorporated in various drugs; from oil logging sources made of neutron emitters; and from dozens of research reactors around the country.

Future sources of wastes may include tritium and neutron-activated components of fusion reactors, or spent heat sources for powering heart pacers (made with ^{238}Pu) or remote power stations, or many other radioisotopes. Regardless of the source, these wastes will be treated by the methods developed to handle the more common or abundant sources of radioactive wastes.

TREATMENT

Radioactive wastes are treated prior to their disposal to put them in chemical and physical forms suitable for the intended method of disposal. As has been discussed, there are liquid, gaseous and solid wastes, and these contain alpha, beta and gamma emitters. The waste treatment method chosen depends on all of these factors. Thus, as mentioned in the section on Reactors, low activity level aqueous wastes are treated by ion exchange[12] and evaporation,[13] so that the decontaminated water may be disposed of in environmental water. The radioactivity is concentrated in a sludge or other solid, e.g., ion exchange resin. These solid wastes are treated to make them more compact, if possible, and they are commonly incorporated in a solid matrix whose function is to prevent their subsequent release in a dispersible form.

Gaseous wastes are composed largely of non-radioactive gases such as air, helium, carbon dioxide or nitrogen contaminated with relatively small

amounts of radioactive gases such as ^{85}Kr, xenon isotopes, and tritium, or vapors such as tritiated water vapor, and the iodine isotopes ^{131}I and ^{129}I. Such wastes are usually treated by preferential sorption of the radioisotopes onto materials such as charcoal (for Kr and I), silica gel (for tritiated water), molecular sieves (for tritiated water) and silver-impregnated high-specific-surface-area solids (for I_2). The gaseous radioactive wastes are thus put into the form of solid wastes, or in the case of krypton, are put in metal cylinders as compressed gas, and the decontaminated gaseous wastes may be disposed of in the earth's atmosphere.

Because of the special hazard presented by ingested or inhaled alpha emitters, and the highly specific uptake of iodine in the thyroid gland these materials require special attention. Alpha emitters are largely actinide elements, and when half-lives are taken into account, the elements uranium, neptunium, plutonium, americium and curium emerge as the elements of principal concern. Highly specialized methods for their treatment are being studied. Iodine, primarily the isotope ^{129}I when the wastes are allowed to decay a year or more before treatment (^{131}I, while the predominant fission product iodine isotope, has a half-life of only 8.05 days), is a special problem because its many chemical valence states, its proclivity to add to organic compounds and the volatility of many of its common forms give it a troublesome ubiquity. Both ^{129}I and ^{131}I are beta emitters.

Decay

There is a form of preliminary waste "treatment" which is widely used that is highly effective in reducing waste disposal problems. The treatment is simply to wait for the wastes to decay before final treatment prior to disposal. A simple example of this has already been mentioned in the Reactors section of Sources of radioactive wastes. In this example, a 30-minute delay before treating the condenser off-gas resulted in a 25-fold reduction in the curies of krypton plus xenon to be handled in the off-gas treatment system. There is a similar advantage to be gained by waiting before fuel reprocessing. However, the period of waiting required is about 10^4 times longer, or about 0.5 to 1 year. The principal radioisotope providing incentive for extended waiting, or "decay" periods is ^{131}I. Table 4 shows how the amounts of ^{131}I and ^{129}I change with time. Clearly there is no incentive to wait more than a year from the point of view of radioiodine decay because the very long half-life isotope ^{129}I (the half life is 1.6×10^7 years!) dominates after about 200 days.

TABLE 4.

Amounts of Radioiodine from One Tonne of Irradiated Heavy Metal from an LWR
(Basis: 33,000 megawatt-days/tonne; 2.92×10^{13} neutrons/cm^2·sec)

Isotope	Curies Present at Indicated Days after Discharge					
	0 day	30 days	90 days	160 days	365 days	3653 days
^{131}I	8.61×10^5	6.71×10^4	3.83×10^2	9.23×10^{-1}	1.99×10^{-8}	0
^{129}I	3.71×10^{-2}	3.73×10^{-2}	3.74×10^{-2}	3.74×10^{-2}	3.74×10^{-2}	3.74×10^{-2}
TOTAL	8.61×10^5	6.71×10^4	3.83×10^2	9.60×10^{-1}	3.74×10^{-2}	3.74×10^{-2}

Radioactive decay heat is another important problem in waste treatment which is ameliorated by delay. Although only a few percent of the energy released by fission is not released virtually instantly as kinetic energy of the fission products during the fission process, the few percent released more slowly by radioactive decay of the fission products is not negligible. For example, the fission product decay heat production rates for the fission products (exclusive of Kr, Xe, ^{3}H and I) present in 1 tonne of heavy metal charged to an LWR and irradiated to a level of 33,000 megawatt-days/tonne are 1.92×10^{4} watts 0.438 years after discharge from the reactor, 2.93×10^{3} watts 3.44 years after discharge, 1.05×10^{2} watts 100.5 years after discharge. Since the weight of the fission products being considered is about 28.8 kilograms, the specific heat generation rates range from 0.67 watts per gram 160 days after discharge to 0.035 watts per gram 10.42 years after discharge, and 1.05×10^{2} watts 100.5 years after discharge. Since the weight of the fission products being considered is about 28.8 kilograms, the specific heat generation rates range from 0.67 watts per gram 150 days after discharge to 0.035 watts per gram 10.42 years after discharge. The factor of nearly 20 decrease in specific power gained by a 10 year delay makes a very significant difference in how the wastes may be treated.

Typically, after fuel reprocessing the liquid fission product wastes are stored in underground, shielded tanks as a method of interim disposal. Figure 8 is a cross section drawing of a representative modern waste storage tank. Storage of liquids in such tanks is now limited to 5 years or less.

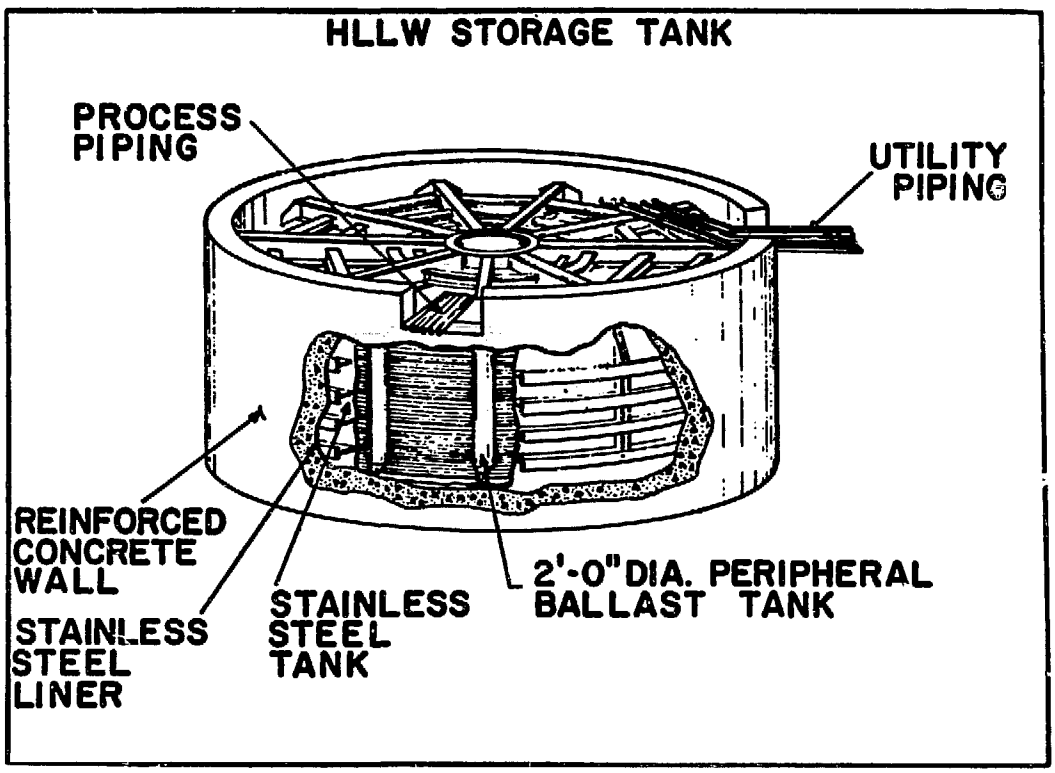

Figure 8
Liquid Waste Storage Tank
(Courtesy of the Barnwell Nuclear Fuel Plant,
Separations Facility, Allied-Gulf Nuclear Services, Barnwell, South Carolina.)

Solidification

As has been discussed, regardless of the form of the wastes initially, they are finally treated to incorporate or contain them in solids for disposal, or they are reduced to such low levels of activity that they may be released to the environment. Treatments of reactor wastes have been discussed earlier. Fuel reprocessing plant wastes are primarily very highly radioactive fission product wastes which arise from the process steps discussed in the section on Reprocessing Plants. Tables 5, 6 and 7 summarize the projected characteristics of solidified aqueous reprocessing wastes for three kinds of reactor fuels.

Table 5

Projected Characteristics of Solidified LWR Aqueous Reprocessing Wastes and Cladding
(Taken from Reference 2)
(Based on a tonne of heavy metal reprocessed)

Characteristic	Individual Waste Streams Characteristics (1) F.P. Waste	(2) Alpha Waste	(3) Solvent Cleanup Waste	(4) Caustic Scrubber Waste	(5) Cladding	Possible Combined Waste Streams Characteristics (1)+(2)+(3)	(1)+(2)+(4)	(1)+(2)+(3)+(4)
Composition, kg/tonne								
U_3O_8	1.17	0.001	0.348	--	1.1[a]	1.52	1.17	1.52
PuO_2	0.011	0.011	0.001	--	0.01[a]	0.023	.022	0.023
$Na_2B_4O_7$	--	--	79.3	31.6	--	79.3	31.6	111
Fe_2O_3	1.07	0.016	--	--	--	1.09	1.09	1.09
Cr_2O_3	0.15	0.002	--	--	--	0.15	0.15	0.15
NiO	0.13	0.001	--	--	--	0.13	0.13	0.13
P_2O_5	0.09	--	Trace	--	--	0.09	0.09	0.09
F.P. oxides	31.5	Trace	Trace	--	0.02[a]	31.5	31.5	31.5
Actinide oxides	6.28	Trace	Trace	--	--	6.28	6.28	6.28
Zircaloy-4, Inconel	--	--	--	--	270	--	--	--
Total weight, kg/tonne	40.4	0.031	79.6	31.6	271	120	72.0	152
Volume, ft^3/tonne	0.74[b]	0.001[b]	1.18[c]	0.47[c]	2.12[d]	1.41[c]	0.69[c]	1.88[c]
Thermal conductivity, BTU hr^{-1} ft^{-1} $°F^{-1}$ at 500°C	0.26	0.26	0.55	0.55	3.6[e]	1.02	1.48	0.96
Density, g/cc	1.92[b]	2.07[b]	2.37[c]	2.37[c]	4.5[d]	3.01[c]	3.67[c]	2.86[c]

[a] Assumes 0.1% Pu and U, and 0.05% of the fission products (F.P.s) are lost to the cladding.
[b] Product is assumed to be 70% voids.
[c] Product is assumed to be a void-free dispersion of solids in $Na_2B_4O_7$.
[d] Cladding is compressed to 70% of theoretical density.
[e] Conductivity at 100°C.

TABLE 6

Projected Characteristics of Solidified HTGR Aqueous Reprocessing Wastes and SiC Fuel Particle Coatings. (Taken from Reference 2. Based on a tonne of heavy metal reprocessed.)

Characteristic	Individual Waste Streams Characteristics (1) ^{235}U Recycle Particle Waste	(2) Clarifier Wastes	(3) Combined Thorex & TBP Fission Product Wastes	(4) Combined Thorex & TBP Alpha Wastes	(5) Solvent Cleanup Wastes	Possible Combined Waste Streams Characteristics (3)+(4)+(5)	(1)+(2)+(3)+(4)+(5)
Composition, kg/tonne							
C	15	2.3	--	--	--	--	17.3
SiC	18	27.3	--	--	--	--	45.3
$Na_2B_4O_7$	--	--	113[a]	--	51.4[b]	155[c]	240[d]
Na_2SO_4	--	--	--	34.3[e]	--	34.3	34.3
Na_3PO_4	--	--	--	3.90	--	3.90	3.90
Li_2SO_4	--	--	1.21	--	--	1.21	1.21
AlF_3	--	--	2.73	--	--	2.73	2.73
Al_2O_3	--	--	10.4	--	--	10.4	10.4
Fe_2O_3	--	--	2.16	--	--	2.16	2.16
NiO	--	--	0.53	--	--	0.53	0.53
Cr_2O_3	--	--	0.39	--	--	0.39	0.39
SiO_2	--	--	0.40	--	--	0.40	0.40
MoO_3	--	--	0.06	--	--	0.06	0.06
CuO	--	--	0.05	--	--	0.05	0.05
UO_2	8.52	--	--	--	--	--	8.52
U_3O_8	--	0.047	0.045	0.258	0.096	0.398	0.446
ThO_2	--	0.569	0.991	0.964	2.06	3.99	4.56
PuO_2	0.567	0.002	1.20	0.112	0.002	1.31	1.88
F. P. Oxides	4.80	7.2	91.30	Trace	Trace	91.30	103.3
Actinide Oxides	0.794	Trace	1.633	Trace	Trace	1.633	2.427
Total weight, kg/tonne	47.7	37.4	226	39.5	53.5	309	480
Volume, ft^3/tonne	1.14[f]	0.79[f]	2.41[g]	0.51[h]	0.77[g]	3.56[g]	5.79[g]
Thermal conductivity, BTU hr^{-1} ft^{-1} $°F^{-1}$	0.41	0.41	1.42	1.5	0.60	1.13	1.39
Density, g/cc	1.48	1.68	3.30	2.73	2.44	3.07	2.93

[a] 1.05 kg of sodium added per tonne to balance the boron chemically. 108 kg of $Na_2B_4O_7$ added per tonne to give 50 wt % waste solids in the $Na_2B_4O_7$.
[b] 35.5 kg of B_2O_3 added per tonne to balance the sodium chemically.
[c] 10.7 kg of B_2O_3 added per tonne to balance the sodium chemically. 135 kg of $Na_2B_4O_7$ added per tonne to give 50 wt % waste solids in the $Na_2B_4O_7$.
[d] 10.7 kg of B_2O_3 added per tonne to balance the sodium chemically. 220 kg of $Na_2B_4O_7$ added per tonne to give 50 wt % waste solids in the $Na_2B_4O_7$.
[e] 5.50 kg of sodium added per tonne to balance the sulfate chemically. 1.64 kg of sodium added per tonne to balance the phosphate chemically.
[f] Product is assumed to be 50% voids.
[g] Product is assumed to be a void-free dispersion of solids in $Na_2B_4O_7$.
[h] Product is assumed to be a void-free dispersion of solids in Na_2SO_4 + Na_3PO_4.

TABLE 7

Projected Characteristics of Solidified LMFBR Aqueous Reprocessing Wastes and Cladding

(Taken from ref. 2. Based on a tonne of heavy metal Reprocessed.)

	Fission Product Wastes								Cladding		Possible Combined Waste Streams Characteristics			
	Without Boron		With Boron											
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)				
Characteristic	1% of Cladding Dissolved	10% of Cladding Dissolved	1% of Cladding Dissolved	10% of Cladding Dissolved	With $Fe(NO_3)_2$ Reductant	With U^{4+} Reductant	Solvent Clean-up Wastes	Caustic Scrubber Wastes	Alpha-Contaminated	Induced Activity Only	(1)+(5)+(7)+(8)	(2)+(5)+(7)+(8)	(3)+(5)+(7)+(8)	(4)+(5)+(7)+(8)
Composition, kg/tonne														
Fe_2O_3	3.75	37.5	3.75	37.5	8.52	--	--	--		--	12.27	46.02	12.27	46.02
Cr_2O_3	1.01	10.1	1.01	10.1	--	--	--	--		--	1.01	10.1	1.01	10.1
NiO	.42	4.17	0.42	4.17	--	--	--	--		--	0.42	4.17	0.42	4.17
PuO_2	0.11	0.11	0.11	0.11	0.02	0.02	0.02	--	0.03[a]	--	0.15	0.15	0.15	0.15
U_3O_8	1.02	1.02	1.02	1.02	--	0.02	0.10	--	0.3[a]	--	1.12	1.12	1.12	1.12
$Na_2B_4O_7$	--	--	86.5	86.5	--	--	67.9	95.8	--	--	164	164	164	164
F.P. oxides	34.2	34.2	34.2	34.2	Trace	Trace	Trace	Trace	0.02[a]	--	34.2	34.2	34.2	34.2
Actinide oxides	0.91	0.91	0.91	0.91	Trace	Trace	Trace	Trace	--	--	0.91	0.91	0.91	0.91
Stainless Steel	--	--	--	--	--	--	--	--	650	700	--	--	--	--
Total weight, kg/tonne	41.4	88.0	128	175	8.54	0.04	68	95.8	650	700	214	260	214	260
Volume, ft^3/tonne	0.81[b]	1.84[b]	1.53[c]	1.84[c]	0.19[b]	0.0003[b]	1.01[c]	1.43[c]	4.17[d]	4.50[d]	2.74[c]	3.05[c]	2.74[c]	3.05[c]
Thermal conductivity, BTU hr^{-1} ft^{-1} $°F^{-1}$ at 500°C	1.26	0.26	1.02	1.41	0.26	0.26	0.55	0.55	9.0[e]	9.0[e]	0.9	1.13	0.9	1.13
Density, g/cc	1.81[b]	1.69[b]	2.95[c]	3.35[c]	1.56[b]	2.90[b]	2.37[c]	2.37[c]	5.50[d]	5.50[d]	2.75[c]	3.02[c]	2.75[c]	3.02[c]

[a] Assumes 0.3% Pu and U, and 0.05% of the fission products (F.P.s) are lost to the cladding.

[b] Product is assumed to be 70% voids.

[c] Product is assumed to be a void-free dispersion of solids in $Na_2B_4O_7$.

[d] Cladding is compressed to 70% of theoretical density.

[e] Conductivity at 100°C.

Solidification of high level wastes from reprocessing plants is a very important process step, since it bears directly on the disposal step which follows. For this reason methods of solidification have received a great deal of attention. Methods range from incorporation in glasses made from calcined wastes with appropriate additives, to calcination in fluidized beds to produce a granular powder which is stored in steel containers.

Partitioning

The special problem posed by long-lived alpha wastes deserves separate discussion. As was mentioned earlier, the elements of greatest concern are uranium, neptunium, plutonium, americium and curium. If these actinide elements could be removed from the wastes (primarily from the fission product wastes from fuel reprocessing plants, but also from fuel fabrication and refabrication plants), the period of significant radioactive hazard at the disposal sites may be reduced from millions of years to less than 1000 years. However, the required degree of removal of these actinides from the fission products to achieve this extraordinary change in the nature of the waste disposal problem is such that only about one part in 10^4 of the actinides may remain with the fission products. Further, once separated from the fission products and the inert, confining solid matrix containing the fission products, the actinides are more hazardous than before because now they are much more concentrated, and any release is correspondingly more toxic. So the problem has two major facets: (1) partitioning the actinides away from the fission products or other radioactive wastes with an unprecedented (and in a practical sense, perhaps unattainable) degree of separation, and (2) completely and positively removing the actinides from the biota essentially

forever. The second part of the problem, while seemingly impossible of attainment, may not be impossible as will be discussed later under "Transmutation" in the section on DISPOSAL.

The first part of the problem is being studied conceptually and experimentally.[14] Figure 9 is a schematic representation of a conceptual processing sequence to remove the actinides. This part of the problem is extremely difficult because of the very high degree of separation required, and because additional contaminated materials are produced in the course of carrying out the partitioning. Thus, the very real danger exists that the solution to the problem does not "converge." The actinides may be more dispersed at the end of the process than at the beginning, or the volume of wastes containing the fission products may be unacceptably large -- or both. Also, it should be noted in the figure that during interim waste storage, radioactive decay leads to the buildup of additional plutonium which must be removed in an additional step.

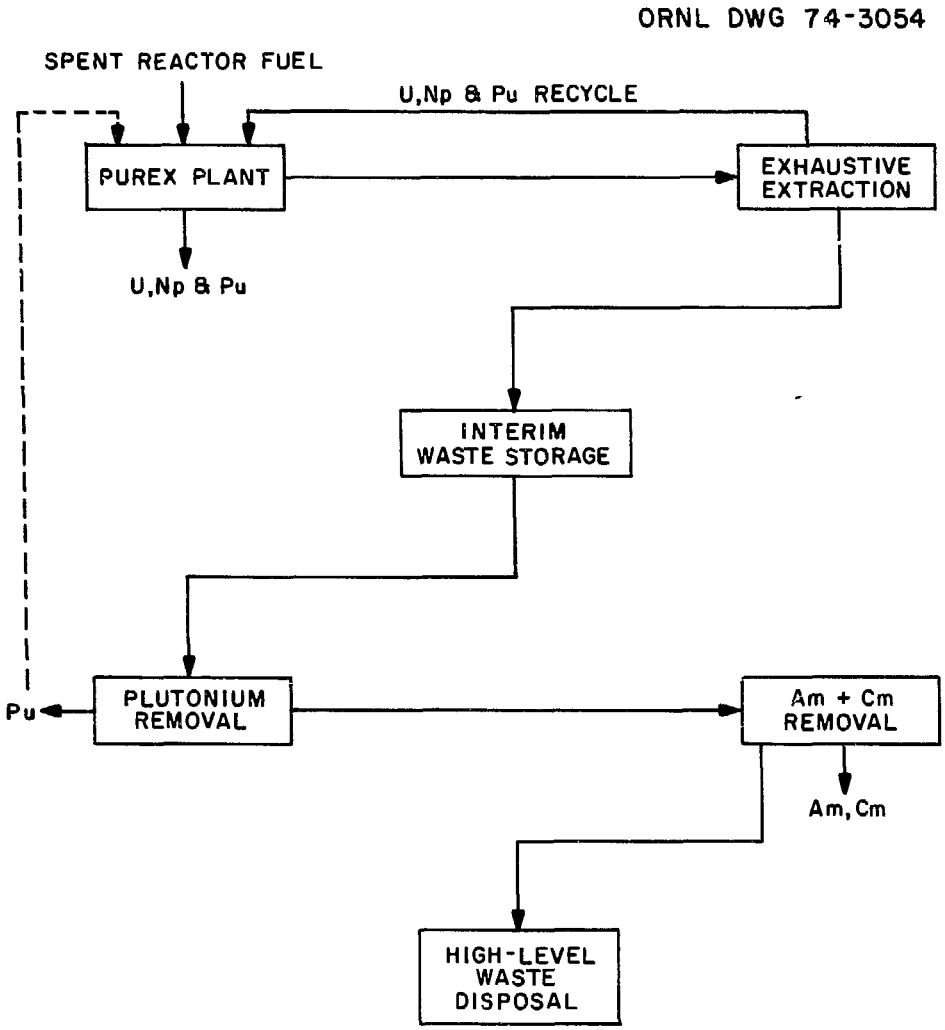

Figure 9
Conceptual Processing Sequence for the Removal of Actinides

DISPOSAL

At the outset it must be stated that there is no such thing as perfectly safe "ultimate disposal" of high level radioactive wastes. However, certain types of wastes may be safely disposed of by dispersion in the environment, and safe disposal of others in stable geological formations may be possible. As was mentioned in the TREATMENT section, there is a chance that the critically important, alpha-emitting, long-lived actinides may be removed by partitioning them from fission products.

In the short term, it appears that some sort of interim storage of high level wastes in accessible containers may be used to retain the option of treating them later in any way found suitable, e.g., by partitioning. A comprehensive study of methods for long-term management of high-level wastes has been made,[15] and a summary of this report was prepared.[16]

Dispersion

To the present time tritium, krypton and xenon have been disposed of by release into the atmosphere. The amounts of these materials have been so small as to make no significant change in the natural background radiation.

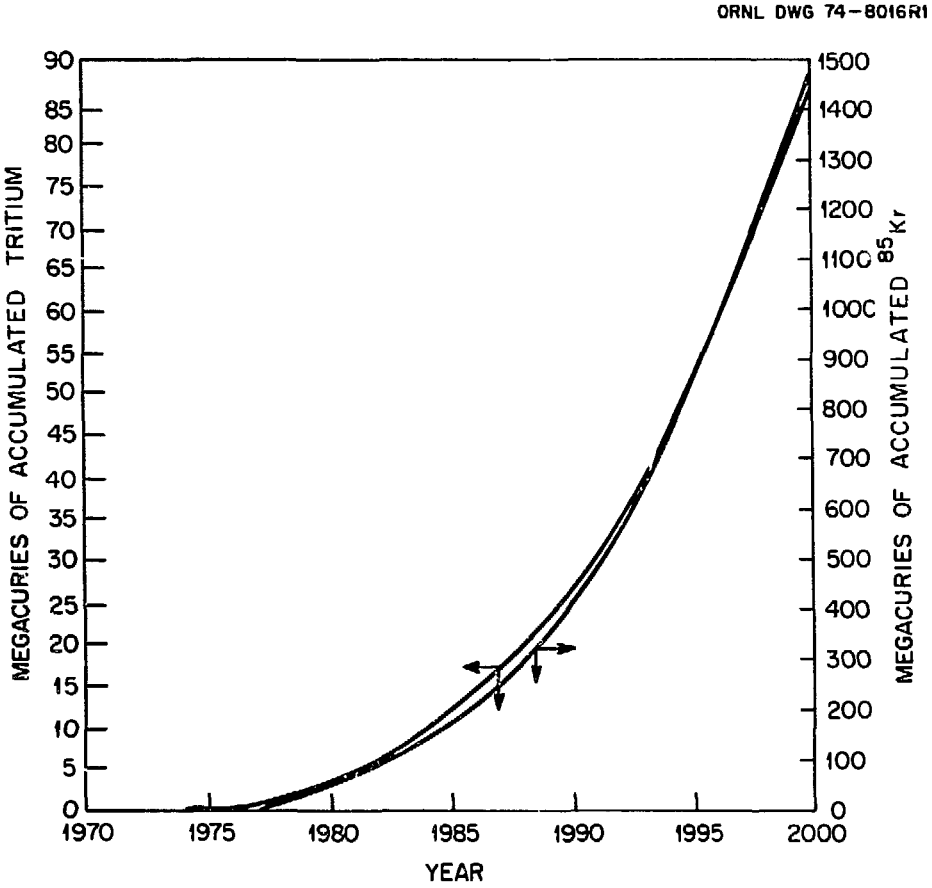

Figure 10
Projected Buildup of ^{85}Kr and Tritium from Reactors and Reprocessing Plants to the Year 2000
(Data Taken from Reference 2)

Figure 10 shows the projected build up of ^{85}Kr and tritium in the world to the year 2000. Present plans call for removal of the bulk of ^{85}Kr from reactor effluents, and especially from fuel reprocessing plant effluents. There are also plans for tritium removal, but it is not so obvious that tritium poses a health threat. Removal of $^{14}CO_2$ from fuel reprocessing plant effluents, for both LWR and HTGR fuels, may be necessary because its projected buildup in the biota may exceed acceptable limits. This question remains to be answered. Dispersion of a broad spectrum of non-gaseous radioisotopes is permitted in very low concentrations in both the atmosphere and environmental waters.[17] However, the air and water of the entire world are inadequate to provide for safe dispersal of the high level wastes to be produced by projected fuel reprocessing plants.

Geologic

Of the so-called "ultimate disposal" methods being considered, the concepts based upon use of geologically stable features of the earth, e.g., abandoned salt mines, appear most promising. Other methods, such as disposal at sea in high-integrity containers, or extraterrestrial disposal using rockets appear more fanciful. In any case, removal of the actinides prior to disposal makes all long-term, high-level waste disposal proposals more attractive, provided the actinides can themselves be safely disposed of or destroyed.

Figure 11 provides an instructive presentation of the various options for high-level waste management and disposal. In this presentation, options shown for disposal of the actinides are (1) recycle to a transmutation step which destroys them, (2) fixation in a solid for disposal on the earth, or (3) extraterrestrial disposal, e.g. by shooting them into the sun or into space on a rocket. As has been mentioned, there appears to be little to recommend separating the actinides from fission products only to store them in a much more concentrated and thus potentially more dangerous

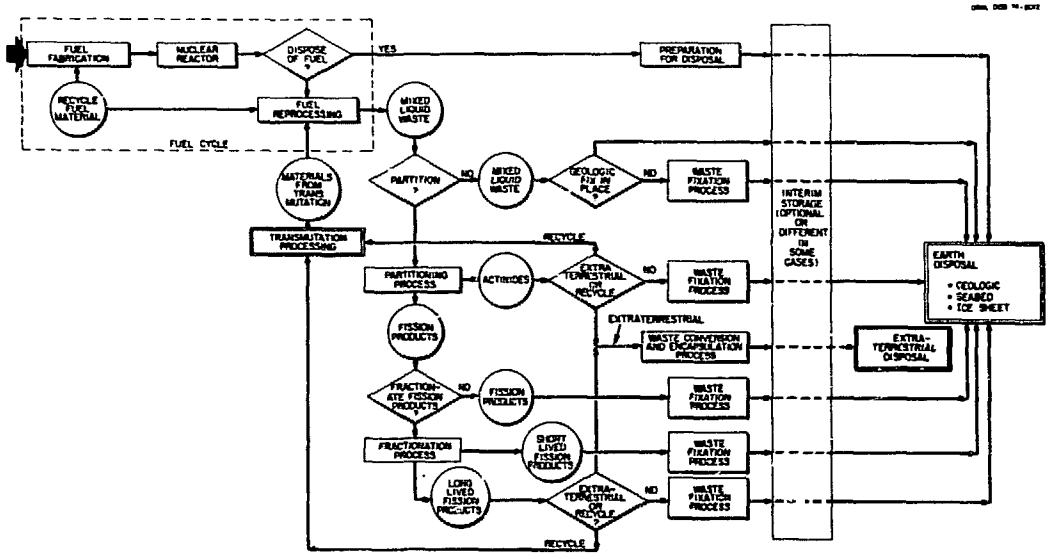

Figure 11
High-Level Radioactive Waste Management and Disposal Option Diagram
(Taken from WASH-1297)

form. Also, until rocketry becomes cheaper and more fool-proof, there is not likely to be much waste disposed of in space. This leaves transmutation as the most promising of the proposed actinide disposal methods.

Transmutation

Transmutation has been discussed,[18] and in principle appears feasible. As has already been mentioned, the process improvements necessary in existing fuel reprocessing operations, as well as the required development of new processes to carry them out, promise to be extraordinarily difficult.

An idea of the decrease in waste hazard which may be obtained through removal of actinides from high-level wastes, as well as of the way the hazard associated with these wastes changes with time, both with and without actinide removal, is presented in figure 12. This figure applies to LWR wastes, and relates the hazards of wastes stored with and without actinide removal to the hazards associated with the naturally occurring mineral pitchblende, and with typical uranium ore. The lower curves were calculated assuming uranium, neptunium, plutonium, americium, curium and ^{129}I removals of about 99.9%, 95%, 99.99%, 99.9% and 99.9%, respectively, i.e., to an extent where their cumulative contribution to the hazard index of the waste after 1000 years is about the same as that due to the fission products remaining after 1000 years. The upper curve

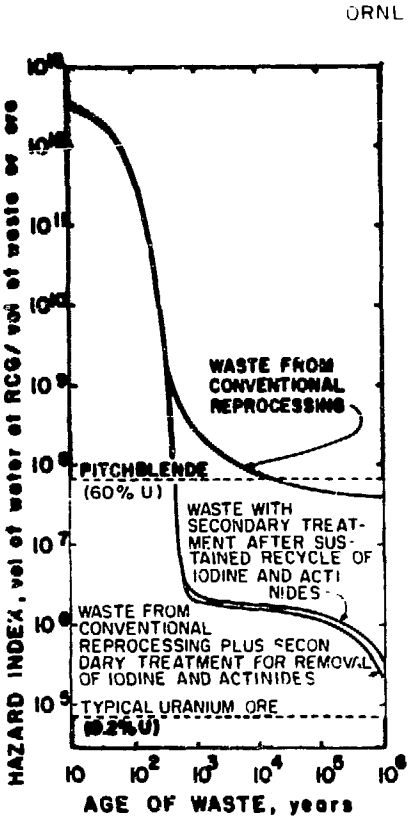

Figure 12
Effect of Age and Method of Treatment
on the Hazard Index of High-Level Wastes from LWR's

was calculated assuming conventional fuel reprocessing, which removes no more than about 99.5% of the uranium and plutonium, and 90-95% of the neptunium. Removals of americium and curium are not carried out at present.

After appropriate treatment, the solidified high-level wastes could be stored in metal containers in an underground repository with a high degree of assurance of containment. A great deal of study has gone into the question of what is the most suitable type of repository,[15] and for a variety of reasons (not the least of which is that their very existence bespeaks great temporal stability) salt deposits appear to be the optimum choice. Figure 13 shows where some of the major salt deposits are in the U. S. Those in the southwest,

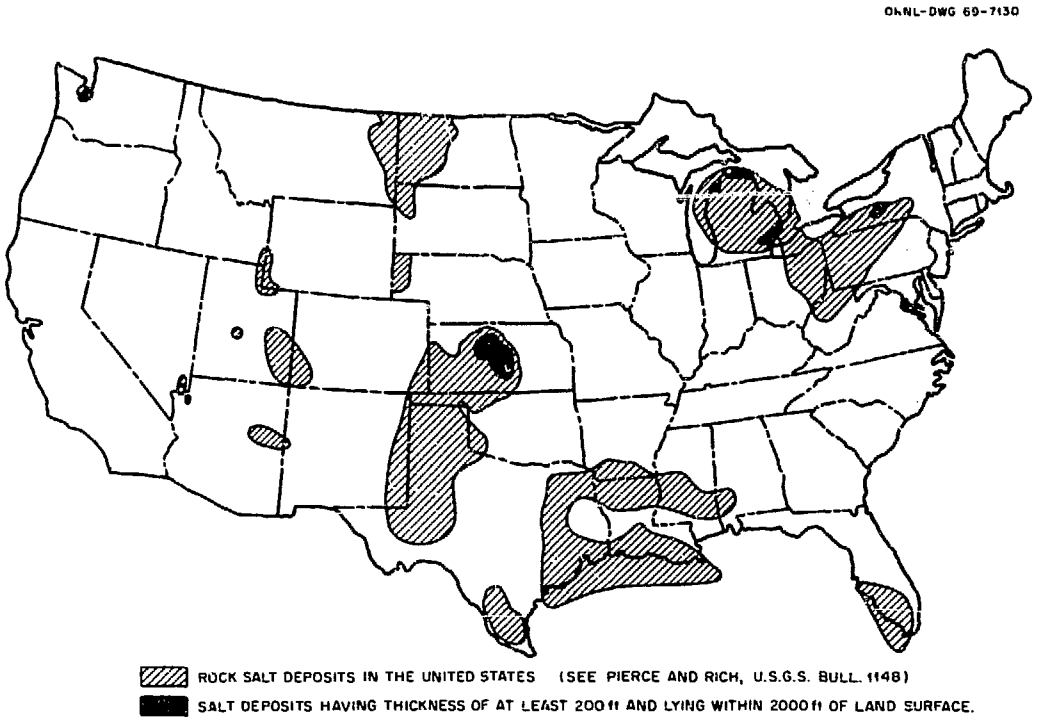

Figure 13
Rock Salt Deposits in the United States

particularly in New Mexico, appear most promising. Figure 14 is a picture of the inside of a salt mine, and gives an idea of how the area looks in which high-level wastes may well be stored.

Wastes continue to accumulate. Storage of high-level wastes in a way which should be acceptable for up to 100 years, and which permits their retrieval for further treatment to put them in condition for "ultimate" storage, if desirable, is being studied. Methods being considered include (1) standing waste cannisters in the desert in a restricted access area, where the climate is dry, and relying on air convection to remove decay heat, and (2) storing waste cannisters in specially-built facilities in pools of water for decay heat removal, again located in remote, restricted-access

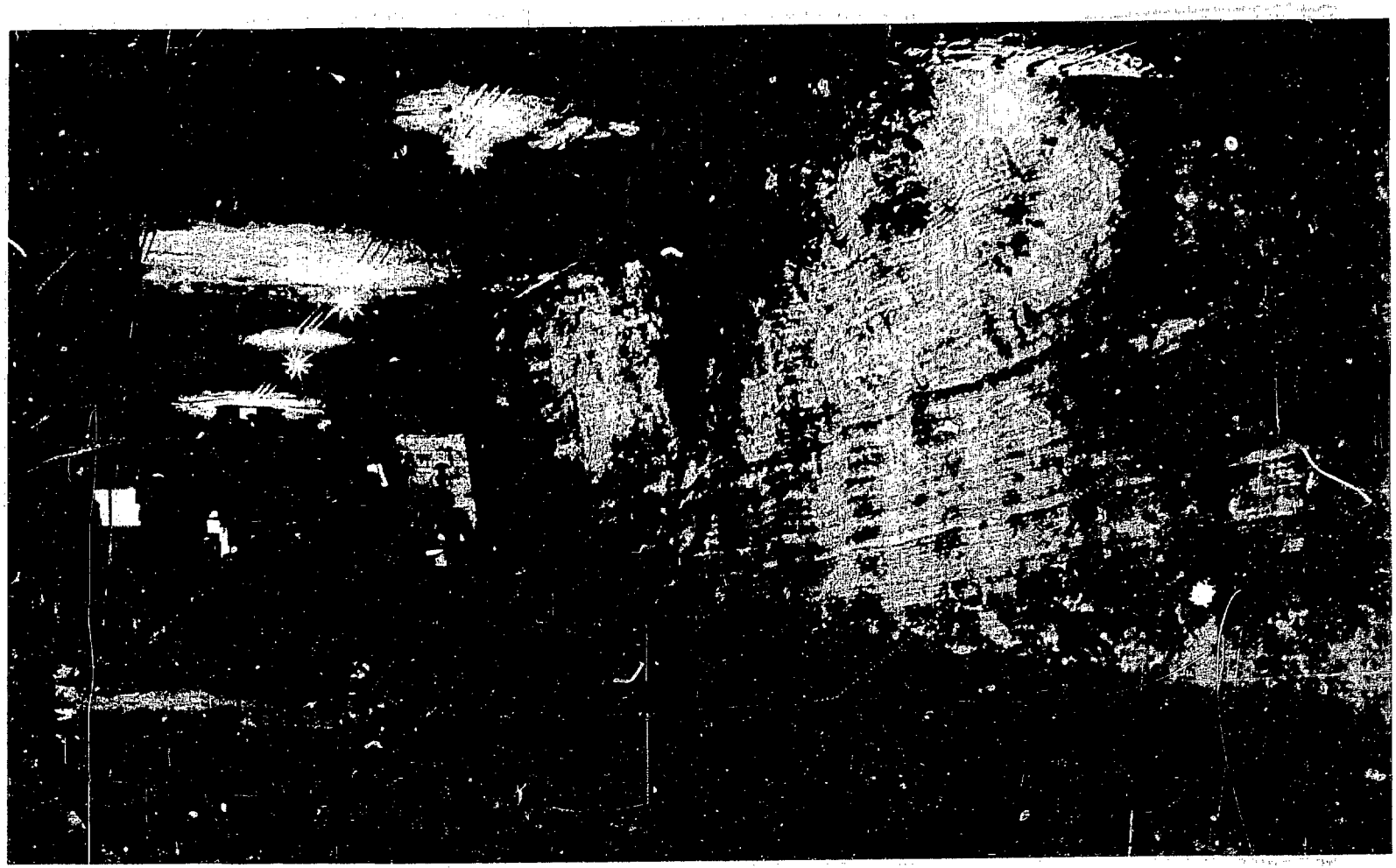

Figure 14
The Inside of a Typical Salt Mine

areas. Figure 15 is a schematic representation of a retrievable waste cannister. Figure 16 shows how cannisters might be arrayed in a desert storage area. Figure 17 is one concept of a pool storage facility.

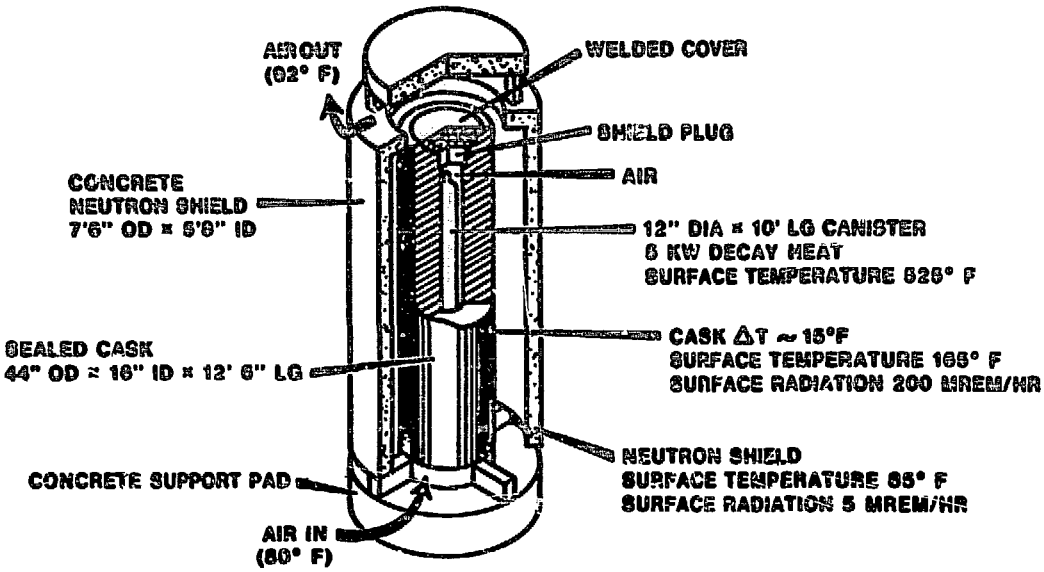

Figure 15
Retrievable Waste Surface Storage Facility Cannister
[Taken from *Waste Management Studies, Progress Report No. 8,*
ARH-2437H, April-May 1973, compiled by R. Y. Lyon, Atlantic Richfield Hanford Company (June 1973).]

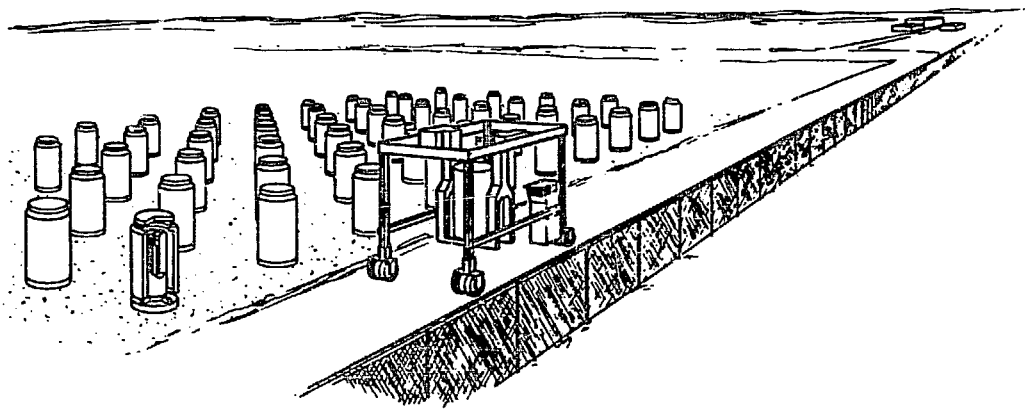

Figure 16
Proposed Retrievable Waste Surface Storage Facility Showing an Array of Cannisters
[Taken from *Waste Management Studies, Progress Report No. 8,*
ARH-2437H, April-May 1973, compiled by R. Y. Lyon, Atlantic Richfield Hanford Company (June 1973).]

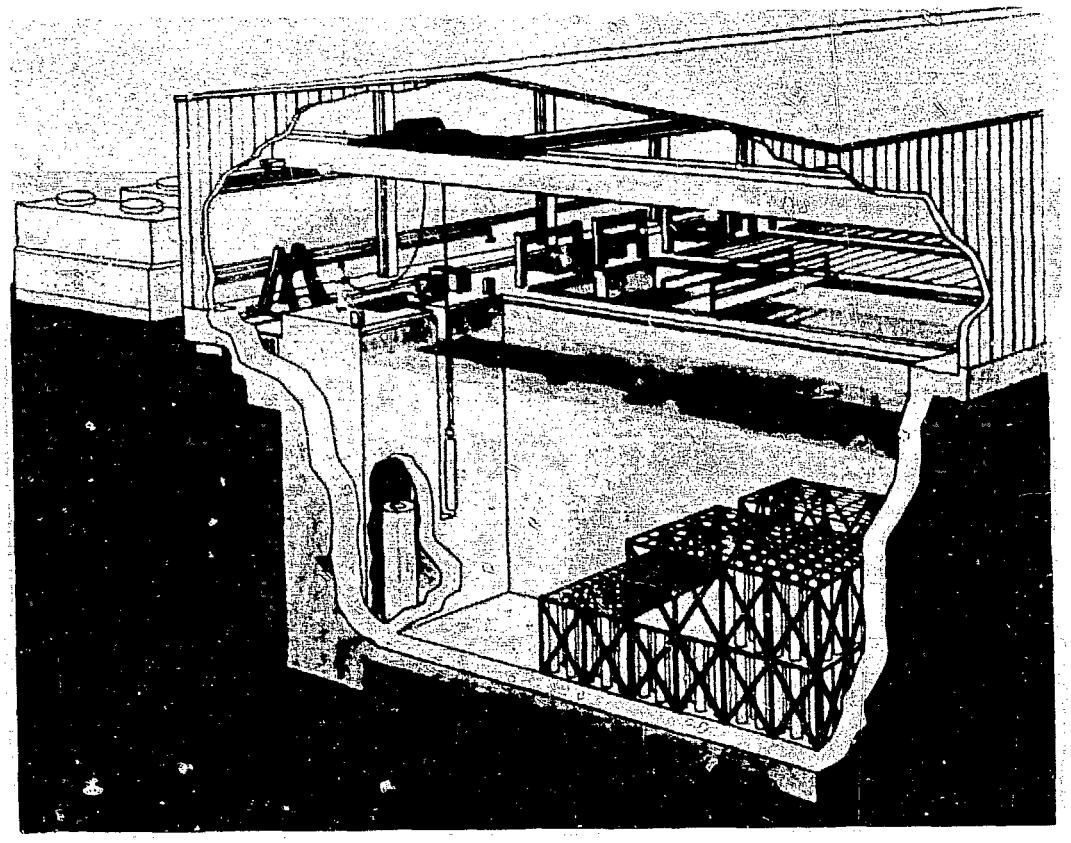

Figure 17
Proposed Retrievable Waste Surface Storage Facility: Pool Storage Concept
[Taken from *Waste Management Studies, Progress Report No. 8,*
ARH-2437H, April-May 1973, compiled by R. Y. Lyon, Atlantic Richfield Hanford Company (June 1973).]

Interim

There is at present a hiatus in the progress toward selection of a federal repository for permanent high-level waste disposal. Until this selection is made, and the myriad other problems attending "ultimate" disposal are solved, some sort of interim waste storage plan must be put into action. The projected total volumes of various wastes to be stored one way or another at a Federal Repository are shown in figure 18.[19] As can be seen, far and away the largest volume (3022 million cubic feet) is from intermediate-level wastes. However, the largest number of curies in the repository is associated with the high-level wastes (16,200 million curies). Comparison of the 1,630 million curies of solidified wastes stored in the year 2000 with the total of 151,000 million curies (see Table 1) accumulated in that year gives an idea of the amount of high-level waste in tank storage and being processed at the fuel reprocessing plants.

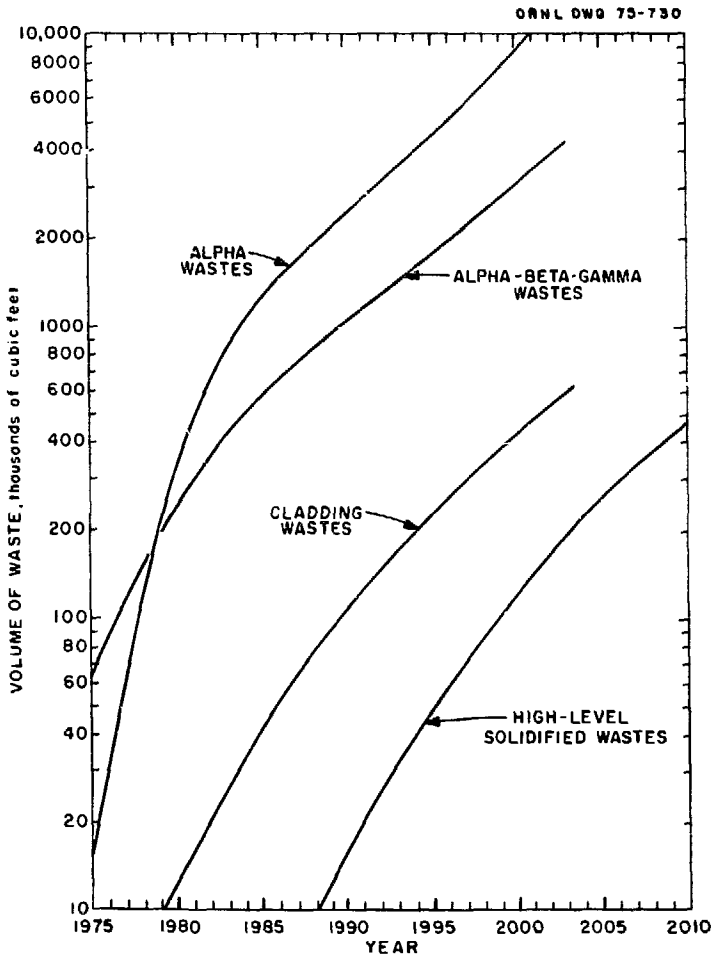

Figure 18
Projected Accumulation of Various Wastes at a Future Federal Repository
(Taken from Reference 19)

SUMMING UP
(A Subjective View)

The preceding sections have presented a picture of waste disposal for the nuclear energy industry based on reasonable projections for nuclear energy growth and on established or easily attained technology. The single exception to this statement is in regard to waste partitioning to separate the actinides from other radioactive wastes; the anticipated difficulty of reducing this concept to practice has been noted, as has the potential advantage to be derived from it. But what does it all mean? Can radioactive wastes really be coped with? Or are the problems so severe, the consequences of an accident or of failure to anticipate all the serious problems so catastrophic, as to preclude nuclear energy as a major energy source? The answers to such questions are of fundamental importance, and like so many truly important questions are not capable of unarguable answers.

It must be allowed that there is a qualitative difference between storing and caring for wastes for a thousand years, and storing them for one hundred thousand to a million years. A geologist who would guarantee stability of a salt mine--or any other "geologically stable" formation--for a million years certainly cannot be classified as conservative. On the other hand, examples of manmade structures which have endured intact for more than a thousand years are readily called to mind, e.g., the Great Pyramid of Khufu (∿4600 years), the catacombs near Rome (∿1900 years), and the Great Wall of China (∿1700 years). So there is objective evidence that man's plans for the future and his creations based on them are commensurate with plans involving waste storage times of the order of one thousand years.

But what of the problems of man unknowingly digging up a waste disposal area in the distant future, or of a natural occurrence bringing waste containers or contaminated earth to the surface where man will contact it? There is certainly precendent for man unearthing relics of his past. As a matter of fact, it is a well established profession. But what of the radioactivity? As this essay has tried to show, at storage times longer than about a thousand years there will be no radiation in excess of that found naturally on the earth, (if actinides plus a few selected fission products are removed), and there will be less radiation than large segments of the population are subjected to right now.

Lest the conclusion be drawn that no waste disposal problems exist, it should be recalled that the actinides may indeed pose a long-term problem. So may the tailings piles at the mills, though solutions to these problems appear to be attainable, at least in principle. So may the potential existence of a large number of decommissioned reactors and a smaller number of fuel reprocessing plants. In the case of these decommissioned facilities, the bothersome aspect is not so much one of a radiation hazard in the long term. (In this regard, the problem resembles that of the planned federal waste disposal sites.) The disquieting factor is more related to a potentially large number of such decommissioned facilities spread widely over the country. The questions of how many such sites to allow, and of where they should be, are important ones which deserve careful attention. These questions are, in fact, being closely studied, but their answers lie in the future.

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Environmental Impacts of Nuclear Power

by

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A. Effects of Radiation on Human Health

There is an impression in some quarters that the effects of radiation on human health are only very poorly understood, but this is definitely not the case. At least the upper limits on health effects are rather well known from various incidents in which people have received large radiation exposures. The data have been analyzed in recent reports by two prestigious groups of radiation medicine experts, the National Academy of Sciences-National Research Council Committee on Biological Effects of Ionizing Radiation (BEIR),[1] and the United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR).[2] In addition there is a continuing surveillance of the information by the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP), groups mainly concerned with setting standards for maximum permissible exposure.

The principal effects of radiation on people are (1) acute radiation sickness, (2) cancer, and (3) genetic defects. Acute radiation sickness results from exposures in excess of 100 rem and can be fatal in a matter of days. The exposure which has a 50% probability of causing death is about 400 rem without medical treatment[3] and perhaps 600 rem with treatment.[4] If death does not result, the patient recovers after several weeks and all symptoms disappear. There have been less than ten American fatalities from this malady, all of them research workers involved in experiments where something went wrong.

Cancer induction by radiation has been a much broader threat, and there is a rather substantial body of human data on it.[1] The largest single source is the Japanese atomic bomb victims--about 24,000 people were exposed to an average of about 130 rem, and there have been over a hundred excess cancer deaths as a result. There were almost 15,000 people in United Kingdom treated with heavy x-ray doses for ankylosing spondylitis, an arthritis of the spine, receiving an average whole body exposure of almost 400 rem which resulted in over a hundred excess deaths, and there have been even more deaths among 4,000 uranium miners who received average doses to the lung approaching 5000 rem from radon inhalation. There have been several situations that have caused about 50 excess deaths, including those involving 775 American women employed in painting radium numerals on watch dials between 1915 and 1935, almost 1000 German victims of ankylosing spondylitis treated with Ra^{224}, and fluorspar and metal miners exposed to radon gas; and there have been several situations studied involving ten or so excess deaths.

It has been conventional to treat these data with the "linear, no threshold" hypothesis, assuming that effects are just proportional to population exposure in man-rem. This involves a very large extrapolation; it assumes, for example, that the probability of cancer induction by 1 mrem (0.001 rem) which is typical of most exposures of interest, is 10^{-5} times the probability from 100 rem, which is the region from which most data are available. In addition, it has been conventional to assume that cancer induction is dose rate independent, no larger if all dosage is received at once, as in much of the experimental data, than if it is spread out uniformly over many years. It is well established[5] that there are mechanisms in the body for repairing radiation damage. There is direct evidence for this from animal studies, and the fact that there is less time for this repair is the reason why rapidly multiplying cells are more susceptible to radiation injury which is the basis for cancer radiation therapy. Cancer induction by radiation is known to be a multi-event process, not due to a single damaging incident to a single cell. For these reasons, all four of the prestigious groups mentioned above have acknowledged that the linear, no threshold and dose rate independent hypotheses are highly conservative, much more likely to over-estimate than to under-estimate effects of low dosage. All of them accept these hypotheses as a basis for setting exposure standards, but only the BEIR Committee condones using them for estimating risks; UNSCEAR pointedly refuses to do so,[2] and NCRP has been highly critical of it.[3]

For lack of an alternative, we will use these hypotheses, with the understanding that they give upper limits to the effects. In particular we will use the BEIR estimate of 180×10^{-6} cancer deaths per man-rem,[6] which means that for every rem of radiation a person receives to his whole body, his probability of ultimately dying of cancer is increased by 1.8 parts in ten thousand above the normal probability (16.8% for the average American). On this basis, one rem of whole body radiation reduces life expectancy by a little more than one day.[7] For perspective it may be noted that the life expectancy reduction from smoking a single cigarette is equivalent to that of 5 millirem (mrem) of radiation.[8]

For situations in which radioactive material enters the body, exposures to individual organs become more relevant than whole body exposure, and the BEIR Report[1] gives risks for these individually; in terms of cancer deaths per million man-rem, some of these are[9] for bone-6, for the thyroid-6, for lungs-39, for gastro-intestinal tract-30, etc. Studies of the survivors of the Japanese atomic bombings gave no evidence that the incidence of diseases other than cancer is affected by radiation.[10]

There is no evidence from human data for genetic defects in off-spring from radiation to parents, so all estimates are based on animal data. Averaging between the BEIR and UNSCEAR estimates gives 150×10^{-6} eventual genetic defects per man-rem exposure of the entire population.[11] These genetic defects range from such simple things as an extra finger or toe (usually removed surgically shortly after birth) to rather serious defects that make life difficult, and include diseases which develop much later in life. Such genetic effects normally occur in about 3% of all live births, about 100,000 per year in the U. S. They are generally caused by spontaneous mutations in the sex cells, and the rate at which spontaneous mutations take place is highly sensitive to the temperature of the gonads. The custom of men wearing pants increases the temperature of the gonads by over 3^{0} Centigrade,[12] so that an equivalence may be developed between radiation and wearing pants. It works out that 1 mrem of radiation to the gonads carries about the same genetic risk as 1 1/2 hours of wearing pants.[13]

The basis for the 150×10^{-6} genetic effects per man-rem estimate has been open to some question recently. Studies of the survivors of the Japanese atomic bombings[14] have yielded no evidence for additional genetic defects among off-spring, a result which assures that the above estimate is not too small; and a recent reassessment indicates that it may be an order of magnitude too large.[15]

B. Routine Emissions

We now turn to a discussion of the various ways in which members of the public can receive radiation exposure from the nuclear industry. In this section we consider exposures resulting from routine emissions of radioactivity in the course of normal operations.

Basically, a light water reactor consists simply of long, thin rods of fuel (fuel pins) enriched to about 3% in U^{235}, submerged in water. In the proper geometry, this allows a chain reaction in which a neutron striking a U^{235} nucleus induces a fission reaction, which releases neutrons, one of which induces another fission, etc. Each fission reaction releases energy (about 200 MeV) which is rapidly converted to heat, warming the surrounding water. The reactor therefore serves essentially as a gigantic water heater; as water is pumped through at a rate of thousands of gallons per second, it is heated to 600°F. The hot water may then be converted to steam either in the reactor (boiling water reactor, BWR) or in an external heat exchanger (pressurized water reactor, PWR); the steam is then used to drive a turbine which turns a generator to produce electric power.

The fuel is in the form of UO_2 ceramic pellets about 1/2 inch long by 3/8 inch in diameter. About 200 of these pellets are lined up end to end inside a zirconium alloy tube (cladding) which is then sealed by welding to make a fuel pin. The reactor fuel then consists of about 40,000 of these fuel pins, or a total of about 8 million pellets.

When a U^{235} nucleus is struck by a neutron and undergoes fission, the two pieces into which it splits are ordinarily radioactive. This is the principal source of radioactivity in the nuclear energy industry. They fly apart with considerable energy (about 80% of the 200 MeV energy release is in their kinetic energy) but they are stopped after only about 0.001 inch of travel, so nearly all of this radioactivity remains very close to the original uranium nucleus, inside the ceramic fuel pellets. The same is true for the second most important source of radioactivity, capture of neutrons by the uranium to make still heavier radioactive nuclei, known as actinides, such as plutonium, americium, and neptunium.[16] While essentially all of these radioactive nuclei remain sealed inside the ceramic pellets, a few of the fission products have a degree of mobility and wander around inside the pellets, and some small fraction of them eventually get out of the pellets, but they are still contained inside the cladding. However, during the operation of the reactor, a small fraction (typically one or two per thousand) of the fuel pins develop tiny leaks in the cladding, in which case the radioactive material that has diffused out of the pellets is released into the water.

There are chemical clean-up facilities for removing the radioactive material from the water, but these facilities do not remove the gases. Among the fission products are krypton and xenon isotopes which, of course, are gases, and in addition, iodine is a very volatile element so that, in spite of elaborate equipment for trapping it out, some fraction of one percent of the iodine comes off with the gases. These gases, including also small fractions of one percent of a few other volatile fission products, are held up for some time within the power plant to allow the short half life activities to decay away, and are eventually released into the environment. This is one source of radiation exposure to the public from the routine operation of the nuclear industry. Regulations require that no member of the general public, including those living closest to the plant, receive a radiation dose from these emissions larger than 5 mrem per year to the whole body, or 15 mrem per year to the thyroid. It is estimated that if all the electric power now used in the U. S. were produced by light water reactors, the average American would receive an average annual exposure from this Kr and Xe of about 0.05 mrem per year.[17,18] The iodine released gives exposures to human thyroids of the same order of magnitude,[19] mostly due to the concentration in

cow's milk of material settling on grass, but this does considerably less harm because of the lower effectiveness for inducing cancer noted above.

Another source of routine emissions of radioactivity is from tritium (H^3). In about one fission reaction out of 500, the uranium nucleus splits into three parts (ternary fission) rather than two, and in about 5% of these cases (once in 10,000 fissions) one of the three pieces is H^3. Other sources of H^3 in reactors are (n,t) reactions on boron (used for control purposes because of its large neutron absorption cross section), and (n,γ) reactions on the H^2 in water (this is much more important in heavy water reactors). The difficulty with H^3 is that it mixes with the ordinary hydrogen in the water and cannot be separated from it. Thus, when any water is released from the plant, it includes some H^3, this goes into a nearby river, lake, or ocean. Regulations require that no member of the general public be exposed to more than 5 mrem per year of whole body radiation from this water, and this is calculated on the assumption that a person derives all his drinking water and fish from the plant discharge canal and swims in it for an hour per day. Estimates are that if all our power were nuclear, the average American would receive less than 0.01 mrem per year from this source.[20]

When the fuel in a reactor has been burned up as much as possible consistent with proper operation, it must be removed from the reactor and replaced with fresh fuel (typically one-third of the fuel is replaced in one such operation per year). The spent fuel is stored for about six months in the power plant to allow short half-life radioactivity to decay away, and it is then shipped to a fuel reprocessing plant. There the fuel pins are cut into pieces of manageable size and dissolved in acid, and the solution is then chemically processed to remove the uranium which is useful for making fresh fuel, and the plutonium which will hopefully be used for making future fuels. Everything else is now classified as "waste;" this waste includes all of the fission products which contain the vast majority of the radioactivity, the uranium and plutonium that escaped removal in the chemical processing (this is typically 0.5% with current technology), and the other actinides produced. The eventual disposal of this waste is an important topic which we will discuss later.

When the fuel pins are dissolved, the gases once again present a problem. Xenon has no long half life isotopes so no radioactive Xe is present, but Kr^{85} has a ten year half life and in current technology, all of it is released to the atmosphere from a tall stack. The tritium is also released as water vapor in the same way. Estimates are that if all of our present electric power were nuclear, the average American would be exposed to 0.02 mrem per year from the Kr^{85} and 0.15 mrem per year from the tritium.[21] In addition, people in other countries would be exposed to 0.02 mrem per year from Kr^{85} produced in the U. S. There are now active and advanced development programs for greatly reducing the emissions of Kr^{85}, but reducing the tritium emissions is a much more difficult problem.

When these exposures are added to the 0.05 mrem per year from the power plants, we see that the exposure to the average American from routine emissions if all our power were nuclear would be about 0.23 mrem per year.

It may be of interest to compare this 0.23 mrem/year average exposure with other radiation we experience.[22] It is less than 1/500 of the exposure we get from natural radiation (U. S. average is 130 mrem per year) and about 1/300 of our radiation exposure from medical and dental x-rays. It is said that the latter could be reduced by a factor of five without compromising effectiveness if tighter regulations on equipment and procedures and more elaborate training programs were instituted.[23] Natural radiation varies widely, from an average of 250 mrem per year in Colorado and Wyoming to 100 mrem per year in Texas and Louisiana. There are areas in India and Brazil where average exposures are 1500 mrem per year from monazite sands which are rich in throium and uranium (studies of the population in these areas have revealed no unusual effects).

There are considerable variations even within a single city; e.g. the radiation level is 10 mrem per year higher[24] in Manhattan (built on granite) than in Brooklyn (built on sand). A rather important source of radiation exposure is building materials as brick and stone contain significant quantities of radioactive material. Living in a typical brick or stone house (rather than a wooden one) gives about 40 mrem per year additional exposure, so that six months of this gives more exposure than a lifetime of all nuclear power. The 0.23 mrem per year from routine emissions if all our power were nuclear is substantially exceeded even by such minor sources of radiation as[22] luminous dial watches (1 mrem per year), and airplane flights (0.7 mrem per hour at 30,000 feet), and is comparable to the dosage from television watching by children (0.3 mrem per year).

The consequences of 0.23 mrem per year of whole body radiation to the average American may be readily calculated from the numbers given in Sec. A; they are[25] 8.3 additional cancer deaths per year and 7.0 additional genetic defects. In addition to radioactivity releases from power plants and fuel reprocessing facilities, there are releases of uranium and its daughters from various other elements of the nuclear fuel cycle. These involve alpha particle emitters which do their damage to a few specific organs following inhalation, so the effects cannot be expressed in terms of whole body radiation. In terms of deaths caused if all our power were nuclear, these effects are

uranium ore mills[26]	0.16/year
conversion facilities[27]	0.09
enrichment facilities[28]	0.01
fuel fabrication plants[29]	0.03
transportation[30]	0.08

Adding these effects to the 8.3 deaths per year from power plants and fuel reprocessing gives a grand total of 8.7 deaths per year.[31] This is the first entry in Table I (Sec. J) which is a compilation of deaths per year from radiation to the public in U. S. if all the electric power we now use were derived from light water reactors.

C. Routine Emissions of Long Half-life Radionuclides

The estimates of the previous section are based on a steady production of 400×10^6 KW of electric power for a period long enough to bring effects of Kr^{85} and H^3 into equilibrium with their decay, which would be a few decades. However, there would be no such equilibrium with long half-life radionuclides like C^{14} (5600 yr), Rn^{222}, which is a grand-daughter of Th^{230} (8×10^4 yr), and I^{129} (1.6×10^7 yr), so their effects would grow linearly with time. At present and for the near future, they contribute to population exposure in a very minor way so control of their emissions has not been considered to be an urgent matter and has received little attention either from the AEC or from the critics. However, it is clear that action on these matters cannot be long delayed unless, of course, the linear, no threshold, dose rate independent theory of biological effects of radiation is abandoned.

The issue of C^{14} was first raised by Magno, Nelson and Ellett[32] in mid-1974. C^{14} is produced by (n,α) reactions on the rare oxygen isotope O^{17} and by (n,p) reactions on N^{14} impurity in the fuel and coolant. If all our power were from light water reactors, about 0.02 Megacuries per year would be produced and this would increase the C^{14} concentration in the biosphere by 0.016 p Ci of C^{14} per gram of carbon which would contribute a dose of 0.0026 mrem per year to all humans[33] for several thousand years. On the linear-no threshold theory this would eventually cause about 600 cancer deaths in the U. S. plus many times that in the rest of the world. It is clearly important to control these emissions, and since the problem was brought to light in June 1974 that problem has

been under study. It seems likely that equipment now being developed to freeze out the Kr^{85} in reprocessing plants will simultaneously remove most of the C^{14}.

The issue of nation-wide exposure from Rn^{222} emitted from uranium mill tailings was first raised in Ref. 17 published in Oct. 1973, but it was not included in the summary of that report and received little or no public notice. When uranium is separated from the ore in the mill, the residue which contains the radium and its precursor Th^{230} is accumulated in large piles typically one square kilometer in area and 5 meters deep. The radon gas emitted from the tailings piles accumulated in fueling one year of all-nuclear power (2.5 piles of the above dimensions) is estimated by the EPA authors[34] to cause 0.8 lung cancers per year in U. S. (our estimate is an order of magnitude smaller[35]) but this will continue for a very long time if nothing is done about the problem. These mill tailings have caused local problems especially when it was found that they were used for building construction in Grand Junction, Colorado,[36] and that a pile in Salt Lake City, Utah, is giving off enough radon to cause 0.2 lung cancers per year in that city alone.[37] As a result, the whole problem has been under intense investigation, and there is active planning for removing or covering the piles. A 20 ft. earth cover reduces the emissions by a factor of ten and would cost about $3.5 million per year for all U. S. power nuclear,[17] a rather modest sum. The tailings consist of two components, slimes and sands, and the former contain 75% of the radioactivity but only 25% of the mass so they could perhaps be pumped back into the mines, reducing the problem 3-fold. There are also studies of chemically separating the radon precursors during the milling operation.[34] The whole problem would, of course, be grossly reduced with breeder reactors.

The I^{129} problem has long been recognized because of the elaborate precautions needed with I^{131} as a short half life (8 days) menace. Plans for more efficient removal of I^{129} from reprocessing plant emissions are in an advanced development stage and should soon be required.

In adding up the harm done over very long time periods by long half life radioactivity, there is a negative term that is perhaps worthy of consideration. Uranium is the ultimate source of radon gas which, according to EPA estimates[34] is killing 4000 Americans per year, so by burning uranium in reactors we are saving about 4×10^{-5} lives per year;[38] if we view this as continuing for the 4.5×10^{9} year half life in uranium, each year of all-nuclear power ultimately saves 300,000 lives.

It is difficult to give a proper treatment to these long half life emissions in Table I. If nothing is done about them and their entire potential cost in human lives is realized, they would be dominant contributors to that Table, whereas if the C^{14}, Rn^{222}, and I^{129} are properly handled they will be of minor importance. The recently announced NRC policy[39] of requiring emission control devices in power plants where the cost is less than $1000 per man-rem exposure avoided, which corresponds to $6 million per life saved, gives every reason to expect the latter to be the case. Since these problems are so recently discovered, are doing little harm as yet (with only 8 percent of our power nuclear and no reprocessing plants in operation) and are being actively worked on, it does not seem reasonable to include them in Table I, but their tentative omission is noted in the caption. If no measures are taken to control these emissions within about 5 years, we would recommend their inclusion.

It is often charged that nuclear power confers benefits on our generation at the expense of future generations. However, in assessing the impacts of our present use of nuclear power on our future progeny, there are many imponderables. For example, what do we do to future generations in burning up gas, oil, and coal at a rate of billions of tons per year? They are used as feedstock for making plastics and medicines; how many lives may eventually be lost by the

scarcity or high price of these? Historically high technology saves lives in enormous quantities; life expectancy in high technology civilizations greatly exceeds that in primitive societies. Does our development of nuclear power today increase the probability that high technology will be alive in the future? To what extent do we worry about the future in our other activities? We are using up the Earth's mineral resources at a tremendous rate; our agricultural practices and lack of attention to population control are dooming millions of yet unborn children to starvation. There is an excellent chance that there will be a cure for cancer in the not too distant future; this would nullify the entire problem raised in this Section. And of course, all of these problems would instantly evaporate if the linear, no threshold theory of radiation effects were abandoned, a relatively likely situation.

D. Power Plant Accidents

In routine operation of the nuclear industry, nearly all of the radioactivity produced in reactors ends up as radioactive waste coming out of the fuel reprocessing plant which, as we shall see, is not difficult to dispose of safely. However, the danger exists that due to some sort of accident in the reactor, an appreciable fraction of this radioactivity will be released into the environment at the power plant. In such a situation, the potentiality for damage is very high.

It should be recalled that essentially all of the radioactivity produced is sealed inside the UO_2 ceramic fuel pellets, so the only way for it to be released is for these pellets to be melted. Thus, any reactor accident of large consequences must involve a "melt-down." The melting temperature of UO_2 is over $5000^{\circ}F$ whereas normal operating temperatures are near and below $1000^{\circ}F$, so such a melt-down cannot result from small abnormalities. The most obvious cause for a melt-down might seem to be a large reactivity excursion caused by withdrawing control rods too far and too fast, but there are several mitigating effects on this. In such a situation, the power level would immediately escalate rapidly, but as a result the reactor would heat up. As the temperature increases, U^{238} captures more neutrons in the "resonance region" (due to Doppler broadening of resonances) leaving fewer neutrons to be slowed down to thermal energies where they induce fission in U^{235}; moreover as the temperature increases, water becomes a poorer moderator (in a BWR more water boils into steam which is essentially an elimination of moderator). Hence, these reactors have a large "negative temperature coefficient of reactivity" which works powerfully against large reactivity excursions. In addition, the emergency insertion of control rods (called "scram") is such a simple operation that it would very rarely fail. It depends only on gravity (PWR) or on stored fluid pressure (BWR) and so does not require electric power.

On the other hand, these safety aspects are challenged rather frequently. About once a year on an average, a generator is suddenly taken off line due to some abnormal electrical occurrence, and when this happens, the turbine which drives it can no longer accept steam. The resulting back pressure causes the steam bubbles to collapse in a BWR, thereby suddenly increasing the reactivity which greatly increases the reactor power. If the emergency control rods should fail to insert, the pressure would build up dangerously (this is also true in a PWR but to a lesser extent). This accident is called ATWS, anticipated transient without scram. In many reactors the scram system is the only defense against this once-a-year challenge. There is strong pressure to include a back-up "poison-insertion system" which would inject boron solution (a stong neutron absorber), but there has been strong resistance on the basis that if such a system were to activate unnecessarily, it would keep the reactor shut down for many hours.

The prevailing opinion among safety experts seems to be that the most likely cause of a reactor fuel melt-down is not a reactivity excursion, but rather a loss of coolant accident (LOCA) resulting from a large leak in the reactor cooling water system. The water temperature in these reactors is about 600°F (higher temperatures give higher efficiencies), so to prevent or control boiling, the pressure must be very high, about 100 psi in the BWR and 2200 psi in the PWR. If there were a rupture in this high pressure system, the water would flash into steam and come out at a tremendous rate (this is called "blow-down") leaving the reactor core without coolant. Loss of the water moderator would immediately shut down the "chain reaction," but it would not, of course, shut off the radioactive decay processes. The power generated by this radioactivity in the fuel pellets immediately after the chain reaction stops is very substantial, about 6% of the full power level of the reactor, and it is easily enough to eventually melt the fuel. In fact the situation is so bad that in the PWR, if the fuel is left completely without coolant for 45 seconds (and possibly even for 30 seconds), the temperature gets so high that bringing in water may do more harm than good; at high temperatures water reacts chemically with the zirconium fuel cladding in an exothermal reaction which would raise the temperature still more. Thus, if cooling is not restored within about 45 seconds, the reactor is doomed to melt-down[40] (in a BWR, this critical time is about 3-5 minutes), releasing the radioactive material.

Complete melt-down of the fuel would take about 30 minutes, and after an hour or so the molten fuel would melt through the reactor vessel. An appreciable fraction of the radioactivity would at this point come spewing out in the form of a radioactive dust or gas.

This is clearly a potentially very dangerous situation, so a great deal of engineering effort has been expended to minimize the probability of a LOCA, to reduce the chance that a LOCA would lead to a melt-down, and to mitigate the consequences of a melt-down if it should occur. In the first place, quality standards on materials and fabrication methods match or exceed those in any other industry, and rarely is expense an issue in this regard. In the second place, a very elaborate program of inspections is maintained during the fabrication stage, including x-raying of all welds, magnetic particle inspections, and a very elaborate series of ultrasonic tests aimed at detecting imperfections that might lead to failures of materials. Once the reactor comes into operation, there are scheduled periodic shut-downs for extensive ultrasonic and visual inspections. The latter consist of removing insulation from pipes and carefully looking for imperfections or cracks; it was in these visual inspections that workers found the hair-line cracks in a few BWRs that received so much publicity in Jan.-Feb. 1975. They were, of course, expeditiously repaired by replacing sections of pipe.

Ordinarily large leaks develop from small leaks, so the third "line of defense" is in systems for detecting small leaks if they should occur. Since the water is at high temperature and under high pressure, any leak would result in steam spewing out and this would increase the humidity. There are therefore two different types of systems, based on different physical principles, for detecting increases in humidity around the high pressure system. Since there is radioactivity in the water, the steam coming out would carry radioactivity with it, so there are two different types of systems for detecting increases of airborne radioactivity. Any indication of increased humidity or increased airborne radioactivity would be interpreted as a sign of a possible leak, calling for further inspection and study. The radioactivity gives an especially sensitive leak detection capability.

If, in spite of these precautions, a LOCA should occur, the next line of defense is the emergency core cooling system (ECCS), an elaborate arrangement for injecting water back into the system to re-flood the reactor core (all pipes

enter the reactor vessel above the core so reflooding is possible unless the rupture is in the lower part of the reactor vessel itself; the latter is of very thick high quality steel so its rupture is orders of magnitude less probable than breaks in piping or external components). The ECCS is a highly redundant system so that no simple failures of pumps or valves would prevent its operation. All estimates indicate that it is more than 99 percent certain of delivering water in the event of a LOCA.

However, there has been extensive controversy over whether the ECCS will prevent a melt-down in the event of a large LOCA ("large" here refers to a break larger than 6 inch diameter). By the time the water from the ECCS fills the reactor vessel up to the bottom of the fuel pins, the latter are quite hot so the water flashes into steam. This steam exerts a back pressure which retards the rate of flooding to something not much more than one inch per second, so there is a period during which the heat transfer is principally by water droplets entrained in steam. This type of heat transfer is not well understood, and there is also considerable uncertainty about the cooling by the water-steam mixture during the initial blow-down. In order to assess these problems, the engineers conducted experiments with full length electrically heated fuel pin mock-ups, and developed empirical "theories" to explain their observations. They then used these empirical theories in computer codes to calculate the operation of the ECCS. There is no question but that this procedure is highly uncertain and inaccurate, and the engineering approach to such a situation is to apply a factor of safety. To be specific, the normal maximum operating temperature of fuel cladding is about 1000°F and the dangerous temperatures for chemical reactions between zirconium and water are above 2700°F (although there are claims that temperatures up to 3300°F would not be catastrophic); the AEC requirement on the ECCS was that the calculated temperature not exceed 2300°F. In 1971, Union of Concerned Scientists (UCS) headed by Henry Kendall studied these matters and declared that they did not consider the factor of safety adequate. In the controversy that followed, AEC organized hearings that lasted more than a year to consider the question. Several AEC safety experts came forward to support Kendall's contention that the factor of safety was inadequate. The eventual result of the hearings was that AEC lowered the maximum calculated temperature to 2200°F, required that the calculations be expanded to include buckling and cracking of the fuel pins at high temperature, and introduced other changes. As a result, some reactors were forced to reduce their power levels until smaller diameter fuel pins could be installed--the calculated temperatures are reduced as the fuel pin diameter is reduced. As a result of these actions, the AEC safety experts who had supported Kendall said they were now satisfied (according to an AEC statement) but Kendall is still far from convinced that the factor of safety is now adequate. Very elaborate tests to further develop understanding of the problems are scheduled for 1976 using a reactor especially constructed and instrumented for that purpose (LOFT, for "loss of fluid tests"). However, as we shall see, the ECCS question is not of over-riding importance in the overall accident picture.

If a LOCA should occur and the ECCS should fail to perform its function, there would be a melt-down. In order to mitigate the consequences of a melt-down the entire system is enclosed in a very powerfully built structure called the "containment." It is constructed of very thick, heavily reinforced concrete and lined with steel plate (the most common type is tested to withstand an internal pressure of 5 atmospheres). The containment is strong enough to repel a wide variety of external threats, including missiles that a tornado might hurl at it (automobiles, trees, etc.) and conventional explosives and bombs. An airplane smaller than a Boeing 707 flying into it would not break through (the largest airplanes might penetrate the containment, but the reactor is surrounded by a thick radiation shield which would give further protection). However, the function of the containment in a melt-down accident is to contain the radioactive dust for some time. Inside the containment there are systems for pumping the air through filters to remove the radioactive dust. Moreover the containment

walls are relatively cool so many of the radioactive materials would be expected to plate out on them. Thus if the containment holds for at least a few hours, most of the airborne radioactivity would be removed and the consequences of the accident to the public would not be very serious.

However the situation could be much more serious if the containment should fail shortly after the molten fuel melts through the reactor vessel. This could happen immediately as a result of a very violent (but highly improbable) explosion as the molten fuel drops into water, or at a relatively early time as a result of high steam pressure if the water sprays designed to condense the steam inside the containment should fail to function. In such situations, the airborne radioactive dust would be released into the environment. The consequences would then depend on the weather conditions. Ordinarily the radioactivity would be widely dispersed and cause little obvious damage,[41] but if there should be a strong temperature inversion the radioactive cloud would be concentrated close to the ground so that anyone it passes would be exposed externally and would inhale radioactive dust which would expose him internally. In such a situation, there could be thousands of fatalities.

There have been many studies of the probabilities and consequences of reactor accidents, but the most elaborate is the recent study financed by the AEC and directed by Norman Rasmussen, an MIT professor. This study involved 60 man-years of effort and cost $3 million; its results were published in draft form in August 1974 in a multi-volume document labelled WASH 1400. If one is willing to accept the Rasmussen study, answers are immediately available to a wide variety of questions. We will present a few of these:

There would be a melt-down about once in 17,000 reactor-years, so if all our power were nuclear (400 reactors), we might expect such an accident every 42 years on an average. The average annual consequences (1/42 times the average consequence per melt-down) would be 0.16 deaths from acute radiation sickness plus 1.2 eventual cancer deaths, and $6.4 million in damages, mostly in clean-up and evacuation costs. The frequency of accidents of various severity (as indicated by the number of fatalities) is shown in the following Table:

Severity distribution of accidents

Severity--number of fatalities	(Frequency)$^{-1}$ - years per accident: Nuclear	Other man-caused	Natural disasters
>10	500	0.2	0.7
>100	2,500	1.5	2
>1000	120,000	25	8
>10,000	---	500	50

The Table also includes non-nuclear accidents for comparison. For example, according to WASH 1400, an accident with more than 1000 fatalities would be expected once in 120,000 years if all our power were nuclear. Other man-caused disasters resulting in over 1000 fatalities might be expected in the U. S. once in 25 years; these include dam failures, airline crashes into crowded areas, fires, explosions, releases of poison gases, etc. Natural disasters causing over 1000 fatalities, such as tornadoes, hurricanes, and earthquakes are expected about once in 8 years.

It may be noted from the Table that according to WASH 1400, no nuclear accident can cause more than 10,000 fatalities, whereas other man-caused accidents of this severity are quite possible. For example, there are several dams in this country whose sudden failure could cause over 200,000 fatalities.[42]

The worst conceivable nuclear power plant accident, according to WASH 1400, would result if there were a breach of the containment shortly after the reactor vessel is melted through, and the weather conditions include a strong temperature inversion with the wind blowing toward a nearby large city. In such an accident, it is assumed that half of the radioactivity in the core is initially scattered around inside the containment, and that the material escaping the containment includes 80% of the Kr and Xe, 60% of the I and Br, 40% of the Cs, Rb, Te, Ru, Mo, Rh, and Tc, 5% of the Ba and Sr, and 0.3% of the other fission products. The consequences of such an accident are estimated to be 2300 fatalities from acute radiation sickness plus 3200 later cancer deaths. An accident of such a magnitude is predicted to occur about once in a million years in U. S. if all our power were nuclear with the present rate of usage.

The above accident would do little property damage, but there are other situations, especially in widespread heavy rainstorms, that would contaminate large areas and require extensive evacuation and clean-up. In the worst accident of this type, expected about once in a million years, these would cost $5 billion.

WASH 1400 was issued in August 1974 as a "Draft," asking for comments and criticisms to be used in developing a final version which is scheduled for issuance in late 1975. The request for criticism has been amply satisfied, with about 100 formal comments submitted. We now turn to a discussion of these criticisms.

The overall effect of accidents is essentially the product of two numbers (1) the probability of a melt-down, and (2) the consequences of a melt-down if it should occur. Under category (1), the strongest criticisms of WASH 1400 have been on the ECCS as discussed above, and on the methodology of fault tree analysis. It has been said by critics that fault tree analysis has been abandoned by the aerospace industry because of its many obvious failures, whereas defenders claim that it is a prime safety analysis tool in the aerospace industry, especially in Great Britain. Critics correctly claim that it failed to even consider a large scale electric power failure due to a fire in the wire insulation such as occurred at the Brown's Ferry nuclear plant in early 1975, while defenders correctly claim that it did predict a large scale electric power failure due to some source in some plant by this time. It is often said that WASH 1400 does not consider human failures, but this is certainly not completely true: it starts with data on all component failures or malfunctions that have occurred as a result of human errors and mechanical failures in operating plants, and obtains probability estimates from these data; it then analyzes what combinations of these component failures would lead to a melt-down, and to each such combination assigns a probability equal to the product of the probabilities for each component failure required.

The critics have never given a numerical factor by which they consider the WASH 1400 figure of one melt-down per 17,000 reactor-years to be an underestimate, but for our purposes we shall need one. According to WASH 1400, failure of the ECCS to prevent melt-down in a large LOCA, as claimed to be not-unlikely by the critics, would modify its estimate to one melt-down in 6000 reactor-years. There have been about 2000 reactor-years of experience without a melt-down (or even a significant loss of coolant accident),[43] so the critics would be hard pressed to justify a claim that the WASH 1400 estimate of one in 17,000 reactor-years is too low by much more than a factor of ten; we therefore will take a factor of ten to be representative of their claims.

On category (2), the consequences of an accident, perhaps the strongest criticism has been that WASH 1400 uses an evacuation model. They assume that people within 20 miles of a reactor can be evacuated with a two hour half life with 90% efficiency; i.e. 45% can be evacuated in the first two hours, 22.5% in the next two hours, etc. until 90% have been evacuated. This model was derived from experiences in other situations requiring large scale evacuation such as

incidents involving release of poisonous chemicals, but the largest such incidents have required evacuation of only 80,000 people whereas the population within 20 miles of a reactor is typically ten times higher. The critics have claimed that evacuation is therefore impractical.[44] According to WASH 1400, if there were no evacuation the consequences would be multiplied by a factor of 3 or 4.

A counter-point to this factor is that the principal source of radiation exposure in WASH 1400 is inhaled radioactive dust, and in calculating this no credit is given for protection from being inside buildings. It may be shown[45] that such an assumption is valid for a non-reactive gas; the amount that gets into a building from a passing cloud is proportional to the leakage rate, but the time the gas is retained in the building is inversely proportional to this leak rate, and the two effects exactly compensate. However, particulate can deposit on surfaces as it enters through tiny cracks, so that treatment is not valid. Recent measurements by this author and collaborators at University of Pittsburgh on relative concentrations indoors and out-of-doors of particulate of known outdoor origin (e.g. Pb and Br which are from automotive exhaust, and Fe and Zn which in Pittsburgh are from industrial sources) indicate that being inside a building would reduce the inhalation of radioactive dust by about a factor of four. This would essentially cancel the increase in consequences if evacuation is impractical.

Another important criticism of WASH 1400 estimates of accident consequences was developed by the American Physical Society Reactor Safety Study.[46] It was pointed out that WASH 1400 did not give proper consideration to long term effects of radioactivity, principally Cs^{137}, deposited on the ground. It is not considered practical to evacuate people whose accumulated radiation exposure from this source would be less than 10 rem; this is about equal to the extra radiation one receives in a lifetime from natural sources by living in Colorado or Wyoming. While this radiation might typically give a person only one chance in 1000 of eventual cancer death, there might be 10 million people (as far away as 500 miles downwind) thus exposed in a large accident so the death toll would be 10,000.

Principally due to this effect, the APS Study estimated 50 times as many cancers as WASH 1400. However, they used a population density of 307 people per square mile over this large area, which is highly unrealistic; more careful estimates for planned reactor sites give 78 people per square mile[47] (note that for sites in eastern U. S., most of the 500 miles downwind is over ocean).

There has been frequent criticism of WASH 1400 arising from the fact that it gives much lesser consequences for the worst accident than an earlier AEC study, WASH 740, first published in 1957 and updated in 1965. However, there are several good explanations for the discrepancy. WASH 740 assumed that half the radioactivity in the reactor would somehow be projected outside the containment--no justification for this assumption was even attempted--whereas WASH 1400 states that an elaborate search was made trying to find mechanisms for such a projection and were unsuccessful because there simply is not sufficient energy available for such an explosion. In addition, WASH 1400 includes evacuation as noted above, whereas WASH 740 assumed no protective measures. WASH 740 assumed higher population densities around reactors; those used in WASH 1400 are the actual population densities around the first 100 reactors to be completed. In general, WASH 1400 was a much more elaborate and careful study, as attested by several who participated in both studies.

Still another criticism of WASH 1400 accident consequences is that it used 100×10^{-6} cancer deaths per man-rem which is less than 180×10^{-6} derived from the BEIR Report,[48] but on the other hand it took the median lethal dose for acute radiation sickness to be 250 rem which is nearly a factor of two too low, especially if medical treatment is administered.

The most recent estimate by H. Kendall, the leading critic on safety issues, is that the WASH 1400 consequences for acute deaths, cancer, and genetic defects should be multiplied by about 12, 50, and 25 respectively.[49] The first two of these combined with the critics' assertion (discussed previously) that WASH 1400 underestimates the probability of a melt-down by a factor of 10, gives the critics' estimate to be an average of 700 deaths per year if all our power were nuclear. This figure is included in Table I. It should be noted that the vast majority of these victims would be people whose probability of cancer death has been increased by 0.1%. Since the average American has a 16.8% probability of dying from cancer,[50] these extra cancers would be undetectable.

The risk from accidents would be much greater for people living very close to a nuclear power plant. If we assume it is half of the risk of 100 total deaths in an accident, or equivalently 1/10 the risk of 10 total deaths in an accident, our Table from WASH 1400 (based on 400 plants) would give their risk as 10^{-6} per year. Our interpretation of the claims of the critics is that there might be a melt-down every 1700 years and that following such a melt-down the death risk for a person living very near to the plant is about 1/30 (including the fact that an early containment failure is not expected in more than 1/10 of these melt-downs), so his net risk is about 20×10^{-6} per year.

In addition, a person living near a reactor is subject to more routine emissions, nearly always less than 2 mrem/yr. Multiplying this by 180×10^{-6} cancer risk/rem gives 0.36×10^{-6} which is much less than the accident risk.

One sometimes hears that a reactor accident could seriously contaminate the whole earth with radioactivity, but this is certainly not correct. The radioactivity in a reactor at shut-down is 10^{10} curie, and this drops to 10^{9} curie after 10 days and 10^{7} curies after 40 years. By comparison, the natural activity of K^{40} in the oceans is 5×10^{11} curies, and the top 500 meters of the earth's crust contains 10^{13} curies of K^{40} plus 10^{13} curies of U, Th, and their daughters.

It is often said that reactors are an inviting target for terrorist saboteurs. By carefully choosing weather conditions and well planned use of large quantities of explosives, highly knowledgeable saboteurs could probably cause the worst accident, involving 2300 (WASH 1400) to 30,000 (Kendall) acute deaths--it is difficult to see how cancer deaths occurring with very low probability 15 to 45 years later would serve the purposes of terrorists. They would have to shut down the reactor and then spend some time operating inside the reactor building, so they would have little chance for escape, and they would very probably be killed by the accident. Since reactors are surrounded by guarded fences and have elaborate constraints on entry, it would not be easy to enter the plant with the large quantities of explosives needed. All in all, it would seem that saboteurs could find easier and safer ways to carrying out mass indiscriminate murder. In fact experts of terrorism have stated that they hope terrorists will be attracted to nuclear power plants as this might divert them from much more terrible things they could do much more easily.

E. Transportation Accidents

When the spent fuel is shipped from the power plant to the fuel reprocessing plant, there is a possibility of a transportation accident in which radioactivity will be released to the environment. However, there are several mitigating points that differentiate such releases from those in power plant accidents. First, only a very small fraction of the fuel in a reactor is involved in any one shipment. Second, the fuel is stored in the power plant before shipment for about six months to allow the short half life radioactivity to decay away; this reduces the potential danger by two orders of magnitude. Third, and most important, the highest temperatures that would ordinarily be encountered in a transport accident are

those of a gasoline or organic solvent fire, and these are about 1450°F, far below the 5000°F temperature required to melt the UO_2 ceramic fuel pellets. Thus nearly all the radioactivity remains trapped in these pellets, so the principal danger is only that the cladding tubes will be ruptured releasing the small fraction of the radioactivity that had migrated out of the pellets and was trapped inside these tubes. This is principally Kr^{85} which is destined to be later released from the fuel reprocessing plant anyhow, albeit under more controlled conditions. In addition, it is sometimes assumed that in some unspecified way, a very small fraction of the solid fission products are released.[51]

In order to minimize the danger of such releases; spent fuel is shipped in very elaborate casks, designed and prototype-tested to withstand without damage to the contents a 30 mile per hour crash into a solid and unyielding obstacle, envelopment in a gasoline fire for 30 minutes, submersion in water for 8 hours, and a puncture test. These casks cost about $2 million each, and details aside, it seems reasonable to expect a high degree of protection against accident damage from such an elaborate effort.

In a document[53] WASH 1238, scenarios are given for accidents that would result in substantial releases of radioactivity. These are:

(1) A "very severe accident," expected once in 250,000 years if all our power were nuclear, might result in 10% of the fuel pins being perforated. There would be extensive releases of Kr^{85} and 1% of all other fission products (especially Cs^{137}) might be dispersed. It is estimated that exposure to the public would average 400 man-rem; multiplying this by 180×10^{-6} cancer deaths per man-rem gives 0.07 deaths. It would be urgent to evacuate within a 50 foot radius, and if convenient out to 500 feet. The cost of this evacuation and the subsequent clean-up would be in the range $10,000 to $50,000.

(2) An "extremely severe accident," expected once in 2.5 million years if all our power were nuclear, would break open the cask and release the fuel elements. The radioactivity release would be ten times that in (1) above, enough to cause 0.7 deaths. In addition direct radiation from the then unshielded fuel would give a lethal dose in 5 minutes at 100 feet. Casualties would depend on how effectively people could be kept away until shielding is restored.

(3) Accidents disabling the cask cooling system would ordinarily not be serious, but under extreme conditions there could be trouble. For example, if PWR spent fuel were left without cooling for 11 hours in 130°F weather, it is expected that 50% of the fuel pins would rupture giving a typical population dose of 2000 man-rem, enough to cause 0.4 cancer deaths on an average. On the other hand, in 100°F weather, the damage would be minimal, and BWR spent fuel is much less susceptible to overheating.

From these scenarios one derives the impression that the average death toll if all our power were nuclear would be of the order of 10^{-5} per year or less. There have been other estimates of this toll,[54,55] and one of these[55] gave results as low as 10^{-2} per year. However, it was clearly highly over-conservative. For example, it applied transportation accident spill statistics for class A packaging (used for shipment of radioactive isotopes) to spent fuel transport which requires class B packaging; class A packaging is designed to withstand an 11 mile per hour crash (vs 30 miles per hour for class B), a 266°F temperature (vs 1475° for class B), and wetting of the surfaces (vs submersion in water for class B). As another example, it assumed shipment only 90 days after removal from the reactor when 8 day half-life I^{131} is the dominant radioactivity, whereas a wait of 120 days, still shorter than is used in practice, would reduce accident consequences by an order of magnitude. We therefore use the 10^{-5} deaths per year estimate in Table I. In any case, even the highly over-conservative 10^{-2} estimate would have no importance in that Table.

There would, of course, be many more deaths from the conventional aspects of transportation accidents, but if the same amount of power were derived from burning coal, a hundred times as much transport would be required resulting, presumably, in a hundred times as many fatalities.

Another problem in transport of radioactive material arises in shipping high level waste from the fuel reprocessing plant to the storage facility. No such shipments have yet taken place and complete plans for them are still not formulated, but here again the radioactivity will be incorporated into a solid material which cannot be melted by temperatures arising in gasoline or organic solvent fires. It will be encapsulated in heavy stainless steel which is much less susceptible to fracture than the very thin and fragile fuel pin cladding. Moreover, there are no radioactive gases to be released as in the case of the spent fuel, and the total radioactivity involved is considerably less because there will be several years for decay before shipment. Because of these factors it is generally believed that shipment of high level waste is much less of a danger than spent fuel shipments.

F. Hazards from Plutonium Dispersal

There has been extensive publicity about the extreme toxicity of plutonium and its consequent danger to human health. It has often been called "the most dangerous substance known to man," and there has been a widely publicized statement that "an ounce of plutonium could kill 30 million people."[56] There has been no support for such statements in the scientific literature. The only property of plutonium that makes it more harmful than other radioactive materials is that its residence time in the lung is about four times longer,[57] so it is less harmful per gram than other alpha particle emitting radioactive isotopes with half-lives more than four times shorter; e.g. Ra^{226} has a 16 times shorter half-life than Pu^{239} and hence is 4 times more dangerous per gram for inhalation. Plutonium is not very dangerous for ingestion as it hydrolizes and forms polymers which do not easily pass through the intestinc walls, so only 30×10^{-6} of soluble plutonium salts and 1×10^{-6} of insoluble salts ingested get into the blood stream; Ra^{226} for example, gets into the blood stream 500 times more efficiently.[58]

I have recently completed a study of the hazards from plutonium dispersal,[59] and some of the results will now be summarized; all figures refer to a mixture of Pu isotopes ordinarily encountered in the nuclear energy industry, a mixture 5.4 times more toxic than pure Pu^{239}. Pu causes cancers which develop 15 to 45 years after exposure whereas other poisons cause death within hours, but if this difference is ignored, Pu is more toxic for inhalation than any chemical agent; it is, however, orders of magnitude less toxic than some biological agents. For ingestion, Pu is considerably less toxic than common chemical poisons, like KCN or $HgCl_2$ and not much more toxic than caffeine.

When meteorology is taken into account, dispersal of Pu dust in a large city would probably result in about one death for each 15 grams dispersed if there is no warning. With warning, as in a blackmail situation, people can be advised to improvise inhalation filters from handkerchiefs or clothing which would reduce the above toll by a factor of ten. After the dust settles to the ground, resuspension will cause about one eventual death for each 100 grams, with nearly all of this exposure occurring within the first few months. After the Pu becomes part of the soil, which takes several years, the net effect over the tens of thousands of years before it has decayed away is about one death for each 1000 grams dispersed. The effects of plant root uptake into food are only one death per 28,000 grams. If Pu is dissolved in a city water supply there would be one death for each 2600 grams. If Pu were dispersed in a crowd such as a sports stadium, there would be two eventual deaths for each gram dispersed, and in a building ventillation system there would be about 70 deaths for each gram

dispersed, but in both these situations there are many easier and more effective ways to kill as many people.

Expected routine releases from an all-nuclear electric power industry would be less than one gram of Pu per year[60] and this would not be in cities, so the number of deaths this might be expected to cause is much less than 1/15 per year. In Table I we estimate[61] it to be about 0.01.

For those who worry about the dangers from Pu toxicity, it may be of interest to note that about 10,000 pounds of Pu have been dispersed in bomb tests, millions of times more than would be dispersed annually by a nuclear energy industry. We have already noted that natural radium is much more toxic than Pu; there is as much radium in every meter of depth of the Earth's crust as there would be Pu in the whole world if all the world's power were obtained from fast breeder reactors. Essentially all of this Pu would be carefully contained inside nuclear facilities; Pu is worth $5000 per pound and is guarded as though it were worth $5 million per pound.

G. Theft of Plutonium for Weapons Fabrication

Widespread concern has been expressed that plutonium may be stolen from the nuclear energy industry for use by terrorists or by foreign nations for fabrication of nuclear bombs. While this threat cannot be completely quantified in the same sense as the other environmental impacts of nuclear power, it clearly cannot be ignored in assessing the environmental impacts of nuclear power.

As a consensus of various informed opinions that have been expressed on the subject,[62,63] starting with about 10 kg of PuO_2, a group of about three individuals (Taylor[62] has said "possibly even a single exceptionally talented individual," but all other bomb experts seem to disagree) each exceptionally talented, and well-trained and experienced in a different technical area, could produce a device that would have perhaps a 70 percent chance of giving an explosive yield of about 100 tons of TNT. This would be enough to devastate a large building, and since there is at least one building which sometimes contains over 50,000 people (the World Trade Center in New York City), it is often stated without explanation (e.g. on the NOVA TV program, "The Plutonium Connection") that such a bomb could kill over 50,000 people. There would also be a radioactivity problem; there does not seem to have been any evaluation of it, but it clearly would not increase the death toll by any appreciable percentage. The production of this bomb would require several months of dedicated work by the group, it would require several thousand dollars worth of equipment, and there is about a 30% chance that the bomb makers would kill themselves in the process.

The principal protection against this scenario is not to allow plutonium to become available to prospective terrorists. The method for keeping track of it since the 1940s was to weigh all plutonium entering and leaving a facility, but errors in weighing leave substantial room for undetectable losses, referred to as MUF--maximum unaccounted for. In addition, there have been losses down drains, so that it is not impossible that enough plutonium has already been diverted to make many bombs. On the other hand, there is no evidence for any plutonium ever to have been stolen in as much as gram quantities.

The AEC has long conducted programs for improving security, but in 1973, T. B. Taylor, a former bomb designer, became disenchanted with the slow progress in these programs and "blew the story open" with a remarkable series of articles in New Yorker Magazine and a less publicized book[62] in which he gave a great deal of information on how to make nuclear bombs. He felt justified in doing this to attract attention to the plutonium safeguards problem, and he was certainly highly successful in that regard. On the other hand there has been a great deal of

bitterness among those working on nuclear weaponry over the fact that a great deal of information useful to potential terrorists was revealed.

In any case, as a result of the publicity, plutonium safeguards procedures were greatly tightened, and new regulations are constantly being added. For example transport of plutonium, often called the "weakest link," must now include armed guards plus an escort vehicle with armed guards with "shoot to kill" orders. They are in constant radio contact with outside monitors, and in areas where this is not possible, an additional escort vehicle is required. New transport vehicles are being developed which can instantly be made essentially immovable and impenetrable in less than 30 minutes, and which would send out alarms automatically if attacked. There are also plans for locating together all plutonium handling facilities from fuel reprocessing where it is first separated, to fuel fabrication; this would leave shipping of fresh fuel to reactors as the only transport, and in this phase it is highly diluted with uranium and incorporated into large and massive units. Problems of theft within plants are also being vigorously attacked: radiation monitoring techniques provide constant inventory checks, and are now capable of detecting sub-gram quantities of plutonium carried out by employees.

In his original writings, Taylor emphasized that adequate safeguards could be instituted without raising the cost of electricity more than 1%, and he now seems to be reasonably satisfied with the progress that is being made. However, the non-technical anti-nuclear community has taken up the issue with great fervor.

Several counter-points have been brought up. One would think that terrorists would find it much easier to steal a military bomb; these are available by the tens of thousands, would give thousands of times larger explosive yields, and would save a great deal of effort, time, and risk. They could also steal highly enriched U^{235} which is much easier to convert into a bomb. In fact it is not obvious that nuclear power is closely connected with the whole issue. There is a great deal of plutonium already in existence, much of it of far higher quality for bomb making purposes. Uranium isotope separation is another independent route to bomb material, and that technology is becoming easier and cheaper.

If terrorists want to kill all the people in a large building, there are clearly much easier ways, as for example, by introducing a poison gas into the ventilation system. It is rather easy to devise many other techniques for indiscriminately murdering several thousand people, especially in dense crowds as at football games and other entertainment events. Experts on terrorism consider the plutonium bomb publicity to be a great asset to Society in diverting attention of would-be terrorists away from easier and much more harmful pursuits.

It would by no means be trivial to assemble a team of scientists capable of producing a bomb.[64] And once assembled, it would not be trivial to keep them motivated, and to prevent the story of the activity from being leaked during the several months the project would probably require.

Aside from the terrorist threat, it is often suggested that plutonium could be stolen by foreign governments for purposes of developing nuclear weapons. In this connection it is important to note that plutonium from power reactors is very different from that used for military bombs,[65] and would hardly be suitable for such purposes. Moreover, a nation interested in obtaining bomb material could produce it in research reactors, or could obtain it through regular channels. Germany has recently agreed to supply nuclear technology to Brazil, and there is a similar arrangement between France and Iran. It is also not very clear how a small nation would benefit from a nuclear weapon capability, especially when it is based on stolen, low grade material.

H. Radioactive Waste Disposal[66]

We now consider the problem of disposing of the high level wastes that accumulate in fuel reprocessing plants as discussed in Sec. B. They are now kept in solution and stored in large tanks. There is currently 600,000 gallons of this waste from nuclear power plants, and more than 100 times that much from government operations, principally producing plutonium for weapons.

There has been considerable publicity about some of these tanks at Hanford developing leaks.[67] These are single wall tanks of World War II vintage containing military wastes. There have been a total of 16 leaks in 15 years in the 151 tanks; the largest, in June 1973, involved the loss of 115,000 gallons, including 40,000 Ci of Cs^{137}, 14,000 Ci of Sr^{90}, and 4 Ci of Pu. Leaking material has reached as far as 47 feet below the tank bottom, still 160 ft. above the water table; it has spread out laterally only a few feet. Ground water below the site moves very slowly, taking 800 years to reach the Columbia River a few miles away, but for reasons to be discussed later, the radioactivity would move orders of magnitude more slowly even if it would reach the ground water. Tanks at Savannah River and Idaho Falls, the other two government sites, as well as new tanks at Hanford, are double walled so if leaking develops, the liquid can be pumped out and the leak repaired without loss into the ground. There is also a program for solidifying the waste into a salt-cake; this will be left in the tanks and while there will be no liquid leaks possible the material will have to be watched indefinitely.

The plans for waste from civilian power are very different. It is required that it be converted to a suitable solid form (as yet unspecified) within 5 years, and delivered to a government repository within 10 years. The first such deliveries may be expected in the late 1980's (the little waste that has already been generated is exempted from this schedule by a "grandfather" clause). The plans for after that have not yet been formulated, but it is almost universally assumed that the wastes will eventually be buried in some suitably chosen geological formation, typically about 600 meters underground. Tentative plans are that they will be in the form of 1 ft. diameter, 10 ft. long glass or ceramic cylinders (0.2 m^3 volume); a typical power plant would produce about 10 of these per year.

The principal danger once this material is buried is that it might be contacted by ground water, be leached into solution, move through aquifers with the water, and eventually reach the surface and get into food and drinking water. Thus environmental impacts depend principally on ingestion hazards. The ingestion hazard in the waste generated in one year if all our present electric power were from light water reactors is plotted in Fig. 1 as a function of time after removal from the reactor. (It should be noted that 99.5% of the U and Pu is assumed to have been removed in the fuel reprocessing). The most straightforward ordinate in Fig. 1 would be curies of each isotope, but by use of Tables developed by ICRP one can calculate for each radioactive isotope the dose in rem to each important body organ per curie ingested, and the BEIR report gives the probability of cancer death per rem dose to each organ, so by combining these the ordinate is converted into cancer-causing doses of each isotope. The total number of cancer-causing doses is then obtained by adding the curves for the various isotopes. It may be seen from Fig. 1 that for the first few hundred years the ingestion hazard is dominated by Sr^{90}, for the next few thousand years the Am and Pu isotopes are dominant, and then after 20,000 years, Ra grows in and becomes the most important threat.

As an example of what these curves mean consider a point at 500 years which, as we shall see, is as soon as it is creditably possible for any appreciable quantity of the waste to reach our environment; the ordinate there is 10^7. This means that if all our power were nuclear and the wastes generated in one year were stored for 600 years and then converted to edible form and fed to people,

a total of 10^7 people would die of cancer (assuming that the number of people involved is much more than 10^7). Or as a more realistic example, if it were dissolved in a city water supply, of which one part in 2000 is ingested by people, there would be 5000 cancer deaths ($10^7/2000$).

While this makes the material seem very dangerous, it should be pointed out that it has a volume of 800 m^3 and weighs 2500 tonne (5.5×10^6 lb.), so the mean lethal dose is about a half pound. This makes it 50 times less toxic than arsenic trioxide (As_2O_3, mean lethal dose--3 grams) which is widely used in this country as a pesticide. This is an especially interesting example because we import into our country each year about 10 times as much As_2O_3 as we would produce waste if all our power were nuclear--that is, we import annually enough to kill 5×10^9 ($50\times10\times10^7$) people. Moreover, this arsenic is not buried deep underground in a carefully chosen geological formation, but rather it is scattered around the surface in areas where food is grown. It is frequently said that the nuclear wastes will be with us for a very long time, but the arsenic will be with us forever.

As another comparison, the ingestion hazard in these wastes after 60 years is only one order of magnitude larger than that due to the radioactivity released when coal is burned to produce the same amount of energy. Again the radioactive wastes from coal burning are not buried but are scattered around on the surface completely without control, and they decay very much more slowly than the wastes from nuclear energy.

There has been so much attention to the problem of burying the wastes in a manner to assure isolation from ground water that it is often assumed that if ground water does contact the waste we are in for a real tragedy. However, that is not the case, because there are many time delays before the radioactive material can reach the surface. If the material is a ceramic or a glass, only 0.01 percent per year would be leached into solution; this alone provides a large measure of protection during the first few hundred years when the material is so toxic. Once the material is in solution, it begins to move through aquifers with the water. Water at a depth of 600 meters moves through aquifers very slowly, seldom more than 30 cm/day, and it typically must travel 100 Km before reaching the surface which takes about 1000 years (although under unusual geological conditions, it could reach the surface much more rapidly); this gives a second guarantee against release during the first few hundred years. But by no means does the waste move with the velocity of the ground water; it is held up by ion exchange processes (e.g. a Sr^{90} ion changes places with a calcium ion in the rock which holds it fixed until a reverse exchange occurs) which reduces its travel speed relative to that of the ground water by factors of about 10^2 for Sr, 10^3 for Cs, and 10^4 for Am, Pu, and Ra. This gives an additional guarantee against release of the Cs and Sr before they decay into insignificance (600 years), and means that the actinides would probably not reach the surface for millions of years.

We have developed a model which allows one to calculate an upper limit on the deaths produced by this waste. We assume that the waste is buried at random locations throughout the U. S. but always at a depth of 600 meters, and we make a comparison between the effects of the waste and that of the natural uranium and its decay product daughters in the rock and soil above it. In particular we assume that the probability for an atom of waste to be ingested by a person is no more than the probability for this to happen to an atom of the uranium or its daughters. We can calculate the latter because we know how much uranium there is in the U. S. down to a depth of 600 meters, and we know how much of it gets into people. The first quantity works out to be 3×10^{13} cancer doses--if all of the uranium and its daughters in the U. S. down to a depth of 600 meters were dug out, converted to edible form, and fed to people (assuming there were enough people) we could expect 3×10^{13} cancer deaths to result. The damage actually done

by this material is easy to estimate as there is a great deal of information from autopsies on the amount of each radioactive isotope in each organ of the human body; from these data and use of BEIR Report estimates of cancer induction probability per rem of dose to each body organ, we calculate that about 12 deaths per year in the U. S. are expected from ingested uranium and its daughters. The average probability per year for an atom of these from within 600 meters of the surface to be released and ingested by a person is thus $12/(3\times10^{13})$, or 4×10^{-13} per year. If we assume an equal probability for an atom of waste, the average expected effects of the waste are obtained by multiplying the ordinate in Fig. 1 by 4×10^{-13}, which gives the scale on the right side of that figure. We see that after a few hundred years the death toll falls below 10^{-6} per year. If this curve is integrated from t=0 to 10^{7} years, the result is about 1.1 total deaths but if the initial time for the integration is taken to be more than 100-200 years in view of the time delays mentioned above, this is reduced to 0.4 total eventual deaths from each year of all nuclear power. If the integration is extended beyond 10^{6} years, this number continues to increase slowly, but in such long time periods the consumption of uranium by reactors saves far more lives than are claimed by the waste.

In Table I we use 0.4 deaths from the waste generated by one year of all-nuclear power, but even this is very much an upper limit. The uranium (plus daughters) ingested by people is principally eroded from near the surface where wind, water, freeze-thaw cycles, rivers, insects, vegetation, etc. do their work. An atom at 600 feet depth would be much less likely to be released. It might also be noted that a cure for cancer in the next hundred thousand years would reduce these effects by a large factor.

With constant population (as assumed in the above calculations) turning over every 70 years or so, the number of people who will live in this country over the next million years is $2\times10^{8} \times 10^{6}/70 \approx 3\times10^{12}$. If less than 0.4 of these will die from the waste generated by one year of all nuclear power, each individual's risk is less than one in 8 trillion.

This model was based on random burial, but one might expect that by using all the knowledge developed by science we should do better than random burial. The most widely favored scheme is burial in a salt bed, and a particular area in southeastern New Mexico is now under intensive study. Some advantages of this over random burial are[68]

(1) There has been no water in the salt bed for 230 million years, and there is no geological reason to expect this situation to change for millions of more years.

(2) Rock salt flows plastically which would seal the waste in impervious rock, unreachable without removing the salt.

(3) The most likely way for the salt to be removed would be for severe faulting to crack through the 600 meter thick formation setting up water flow between aquifers above and below the salt. This is a tectonically stable region, so such faulting is estimated to have a probability of only 4×10^{-11} per year.

(4) If these aquifers, flowing at their present rate, were so diverted, the time required to dissolve the salt enclosing one year of waste would be 10^{5} years. This is another important time delay.

(5) The New Mexico site is arid and has a lower than average population density. It is 30 Km to the closest flowing water; aquifers below the salt formation, where the radioactivity would probably go in the event of a crack, flow hundreds of kilometers before reaching the surface. An important additional advantage of salt is that it has good thermal conductivity which is important for absorbing the rather considerable heat generated by the radioactivity in the waste for the first hundred years or so. One disadvantage in salt

formation disposal relative to random burial is that the ion exchange hold-up is reduced in salt water, but this reduction is not by a large factor.

There has also been extensive investigation of release modes other than to ground water.[68,69] Nuclear weapons are no problem, and surface erosion and diapirism could not give trouble for millions of years. The largest dangers of this type are meteorite impact and volcanism, both of which have exceedingly low probabilities.

There has been a great deal of publicity over a previous plan for a waste repository near Lyons, Kansas, and its withdrawal. This would have made use of an abandoned salt mine which had been used for extensive experimental studies, and hence would have saved a great deal of time and money. However two problems were encountered: there were a number of exploratory oil drill holes in the area, and there was extensive solution mining (pumping water in to dissolve the salt) in the area coupled with unexplained loss of water presumably due to seepage through fractures. Neither of these problems was considered to be insuperable, and many believe the site should not have been abandoned, but there were also political and public relations difficulties resulting from the fact that these problems were first forcefully pointed out by environmental groups rather than by AEC personnel. The latter say that they were considering these problems,[70] but the appropriation for a permanent repository was requested before this was done. In any case, the New Mexico site does not have these problems and has every other advantage except for higher cost. It is expected that experimental work on it may begin by 1977.

There has been a great deal of publicity over the issue of the burden we place on future generations in watching our wastes. In the first place it should be noted that in our model, there was no watching; no one is watching the natural uranium to keep it out of the environment. Thus, a very long term surveillance program would only serve to reduce the toll of less than 0.4 deaths for each year of all nuclear power. (During the period when the technology is being developed, extensive surveillance would, of course, be in order.) It therefore hardly seems worthwhile, and is surely not a vital necessity.

In the second place, the job of maintaining surveillance over a sealed repository containing a thousand year's waste would be only a part time job for a single person. He would have to travel over the area (15 miles square) to check that no one is drilling for oil or mining salt (although calculations indicate that there would be no great risk from these) and he would have to collect water samples from wells and streams in the vicinity every few weeks to check for increases in radioactivity. This one-man job hardly seems like a tremendous burden on future generations, if indeed they consider it to be worth even that very small expense.

In discussing the question of burdening future generations, it would seem to be much more pertinent to consider the burden we place on them by consuming all the World's rich mineral resources at such a rapid rate. This is a truly tremendous burden, and it can only be compensated by our providing future generations with a technology that will allow them to live in reasonable comfort without these resources. The key to such a technology must be cheap and abundant energy; with it, one can find substitutes for almost anything, but without it there can be no hope. We thus owe our progeny a source of cheap and abundant energy, and the only such source we can now guarantee is nuclear power from fission.

J. Summary and Perspectives

Table I summarizes the results of previous sections of this paper on the number of radiation deaths/yr. to the U. S. public expected from all nuclear

power. There would be approximately an equal number of genetic defects. Roughly speaking, estimates based on acceptance of WASH 1400 are about 10 deaths per year if all our power were nuclear, whereas the critics would claim that this number is about 700. We now attempt to give some perspective on these, starting with the first. Since cancer is delayed by 15 to 45 years after exposure, the average loss of life expectancy per victim is 20 years. The loss of life expectancy for the average American from these 10 deaths per year is then (10×20 man-years lost/2×10^8 man-years lived) = 10^{-6} of a lifetime = 36 minutes.

Table I: Cancer (plus acute radiation sickness) deaths due to radiation to the U. S. public from various aspects of the nuclear energy industry in generating 400 million KW-year of nuclear electricity. Not included are effects from very long half life radioactivities (Sec. C), sabotage, and terrorist use of nuclear bombs. The numbers in parentheses are this author's interpretation of the worst claims by the critics.

Source	Sections	Deaths/yr.
Routine emissions	B	8.7
Reactor accidents	D	1.4 (700)
Transport	E	10^{-5}
Plutonium (routine release)	F	10^{-2}
Waste disposal	H	<0.4
Total		10 (700)

Some of us subject ourselves to many other risks that reduce our life expectancy. One of these is smoking cigarettes; one pack per day (3.6×10^5 cigarettes) reduces life expectancy by about 8 years[71] which, assuming linearity, corresponds to 12 minutes loss of life expectancy per cigarette smoked, so the risk of nuclear power is equivalent to that of smoking 3 cigarettes in one's lifetime, or one every 20 years or so.

Statistics show that life expectancy in large cities is 5 years less than in rural areas.[72] Some of this may be explained by differences in racial make-up, but a large part of it is believed to be due to the strains of city life. If linearity is assumed, the risk of nuclear power (36 minutes loss of life expectancy) is equal to the risk of spending 8 hours of one's life in a city.

Travelling in an automobile subjects us to a death risk of 2×10^{-8} per mile, or if 35 years of life are lost in an average traffic fatality, loss of life expectancy is 7×10^{-7} years per mile travelled. The risk of nuclear power is then equal to that of riding in automobiles an extra 1.5 miles per year.[73]

Riding in a small car rather than a large car doubles one's risk[74] of fatal injury, so the 36 minutes loss of life expectancy from all nuclear power is equivalent to the risk of riding the same amount as at present, but 1.5 miles per year of it in a small rather than a large car.

Another risk some of us take is being overweight. If we assume loss of life expectancy to be linear with overweight, the 36 minute loss from all-nuclear power is equivalent to the risk of being 0.01 ounces overweight.[75] However, Pauling[76] has shown that the data are better fit by a quadratic dependence, and if this is accepted the risk of all-nuclear power is equivalent to that of being 0.2 lb. overweight.[77]

All of these estimates are based on the AEC estimate of 10 deaths per year. If we instead accept the critics' estimate of 70 times as many deaths, the risk of nuclear power is equivalent to the risks of smoking 3 cigarettes per year, or of spending 25 days of one's life in a city (one day every three years), or of riding in automobiles an extra hundred miles per year, or of riding in automobiles the same amount as at present but 100 miles of it per year (one percent) in a small rather than a large car, or of being 0.7 ounces overweight on the linear hypothesis, or 1.6 lb. overweight on the quadratic hypothesis.

Additional perspective may be gained by making a comparison with deriving the same electric power from coal by present technology. The most important environmental impact of coal-fired power is air pollution which, it is estimated, would cause about 10,000 deaths per year,[78] at least an order of magnitude more than even the critics estimate would be caused by nuclear power. In addition, this air pollution would cause[78] about 25 million cases per year of chronic respiratory disease, 200 million person-days of aggravated heart-lung disease symptoms, and about $5 billion worth of property damage; there are no comparable problems from nuclear power. Mining of coal to produce this power would cause about 750 deaths[79] per year among coal miners, more than 10 times the toll from uranium mining for nuclear power,[79] and the latter would be reduced about 50-fold with breeder reactors. Transport of this coal would cause about 500 deaths per year among the public,[80] two orders of magnitude more than would be caused by nuclear industry transportation requirements.

It is important to point out that the numbers in Table I (and the perspective we have put on them) are based on annual averages. As the nuclear critics are constantly reminding us, if their estimates are correct, there might be an accident every ten years with several thousand deaths, and every 50 years with tens of thousands of deaths. It is not difficult to make this prospect seem extremely dismal. On the other hand we should not envision these accidents as producing stacks of dead bodies; the great majority of fatalities predicted are from cancer and would occur 15 to 45 years later. In nearly all cases, the affected individuals would have only about an 0.1% chance of getting cancer. (If one accepts WASH 1400, this would be the only effect on even the closest city of the worst conceivable accident, a once in a million years event if all our power were nuclear.) The average American's risk of cancer death is now 16.8%, so typically it would be increased to 16.9%; his loss of life expectancy from these radiation induced cancers would be twice that from normal cancers, so to take this into account let us call it 17.0%. There are regional variations in cancer probability from 18.4% in New England (19.0% in Rhode Island) to 14.7% in the Southeast where the age distribution is the same but these order of magnitude larger differences are seldom noticed. If an area were affected by a nuclear accident and authorities revealed that as a result the average citizen's probability of eventually dying of cancer was increased from 16.8% to 17.0%, it would hardly start a panic. We have had some experience with a similar but much more serious situation: when reports first reached the public of the risk in cigarette smoking, tens of millions of Americans were suddenly informed that they had accrued a 10% increased probability of cancer death, two orders of magnitude larger than the effects from a nuclear accident. Even that story did not stay in the headlines for long, and brought very little counter-action.

Critics often raise the point that the risks of nuclear power are not shared equally by all who benefit but are disproportionate for people who live very close to a nuclear power plant. This, of course, is true for all technology, but let us put it in perspective. In Sec. D we showed that this risk is 10^{-6} per year if we accept the WASH 1400 accident estimates, or equal to the risk of riding in an automobile an extra 50 miles per year or 250 yards per day. Thus, if moving away from a nuclear power plant increases one's commuting distances by more than 125 yards (half a block), it is safer to live next to the power plant. If one prefers the estimates we attribute to the critics (20 times

larger), it does not pay to move away if doing so increases commuting distances by more than 1 1/2 miles per day. Even with the critics' estimates, living next to a nuclear power plant reduces life expectancy by only 0.03 years,[81] which makes it 150 times safer than living in a city.

The proponents of nuclear power generally concentrate their arguments on the importance to our country of cheap and abundant energy. It is often said that its availability in the past was the key reason for the great economic success of the U. S. It is well known that there are close correlations between energy usage and gross national product, and many blame the energy shortage and price escalation for our current economic recession. If this is correct, it is interesting to point out that this recession is causing 4000 additional suicides per year in the U. S.,[82] and for every suicide there are surely dozens of premature heart attacks and hundreds of lives spent in misery.

Hopefully our economic system can adjust to lower energy usage without causing a deterioration in the quality of life. However, this adjustment will require many years of pain, and this pain would surely be lessened if the time available for the adjustment were increased; this requires more cheap and abundant energy for the next few decades. Moreover, even if total energy usage is held constant or decreases, use of electrical energy must increase to compensate for reduced availability of gas and oil.

References

1. The Effects on Populations of Exposure to Low Levels of Ionizing Radiation (BEIR Report), National Academy of Sciences-National Research Council (1972).

2. Ionizing Radiation: Levels and Effects, United Nations (New York) 1972.

3. Standard texts on Health Physics; e.g. K. Z. Morgan and J. E. Turner, Ed., "Principles of Radiation Protection," John Wiley (New York) 1967.

4. Personal communication with staff members of Medical Division, Oak Ridge Associated Universities.

5. Review of the Current State of Radiation Protection Philosophy, NCRP Report No. 43, NCRP Publications (Washington) 1975.

6. Ref. 1 states that an additional exposure of the U. S. population to 5 rem per 30 years would cause approximately 6000 cancer deaths annually. This is a dose rate of 5000/30 = 167 mrem/year, or a population dose of 33×10^6 man-rem for a 2×10^8 population. Fatalities per man-rem are then $6000/33\times10^6 = 180\times10^{-6}$ per man-rem.

7. One rem gives 180×10^{-6} probability of cancer death which, on an average, causes 20 years loss of life, so it reduces life expectancy by 3600×10^{-6} years which is 1.3 days.

8. One pack per day of cigarette smoking (about 4×10^5 cigarettes) reduces life expectancy by about 7.5 years (calculated from Surgeon-General's Report on effects of cigarette smoking--1962) or 2700 days. Assuming linearity, one cigarette then reduces life expectancy by 7×10^{-3} days. According to footnote 7, this is the effect of $(7\times10^{-3}/1.3)$ rem, or about 5 mrem of radiation.

9. For example, Ref. 1 concludes that radiation to the bone causes 0.2×10^{-6} cancer deaths per year per rem and whole body radiation causes 6×10^{-6}. Thus 1/30 of the deaths from whole body radiation are from radiation to the bone.

If only the bone is exposed, the probability of death is $(1/30)\times180\times10^{-6} = 6\times10^{-6}$ deaths per man-rem to bone.

10. Data from the Atomic Bomb Casualty Commission are tabulated in B. L. Cohen, "Nuclear Science and Society," Doubleday (New York) 1974, p. 64.

11. Ref. 1 gives 1100 to 27,000 genetic defects per year from 170 mrem/year (or 33×10^6 man-rem per year) in the U. S. which corresponds to 33 to 800×10^{-6} genetic defects per man-rem. One could use the logarithmic median of these, which is about 160×10^{-6}. However, since the range is so broad, it may be preferable to use Ref. 2 which gives a 1% increase per accumulated rad to males in the 3% of all live births which involve mutation-induced defects. Maintaining the population of the U. S. would require about 3×10^6 live births per year (close to the present rate) so we should expect about 900 genetic defects per year per rem of exposure to males prior to conception. If all Americans were exposed to an additional 100 mrem/year, a population exposure of 2×10^7 man-rem per year, the average father would have accumulated 3 rem prior to conception so there would be 2700 additional genetic defects per year. The number of genetic defects per man-rem is then $2700\div2\times10^7=135\times10^{-6}$. This is very close to the logarithmic median of the range given by the BEIR Report (160×10^{-6}), so it seems reasonable to accept a number between them such as 150×10^{-6} genetic defects per man-rem.

12. L. Ehrenberg and G. Von Ehrenstein, Nature 180, 1433 (1957).

13. From Ref. 12, wearing pants is responsible for almost half of all present mutations, so they cause about 50,000 genetic defects per year in U. S. The man-hours of pants wearing in the U. S. are 10^8 men $\times$ 5.5×10^3 hours/year = 5.5×10^{11} per year, so there are 10^{-7} genetic defects per pants-hour. From radiation there are 150×10^{-6} genetic defects per rem, or 1.5×10^{-7} per mrem, the same as 1.5 pants-hours.

14. H. Kato, et al., Am. Jour. Human Genet. 18, 339 (1966). See also Ref. 1.

15. H. B. Newcombe (Chalk River), Mutation and the Amount of Human Ill Health, Int. Congress of Radiation Research, Seattle, Wash. (1974).

16. The principal reactions are:

$U^{238}(n,\gamma)U^{239}(\beta)Np^{239}(\beta)Pu^{239}$ $\quad$ $U^{235}(n,\gamma)U^{236}$

$Pu^{239}(n,\gamma)Pu^{240}$ $\quad$ $U^{236}(n,\gamma)U^{237}(\beta)Np^{237}$

$Pu^{240}(n,\gamma)Pu^{241}(\beta)Am^{241}$ $\quad$ $Np^{237}(n,\gamma)Np^{238}(\beta)Pu^{238}$

$Am^{241}(n,\gamma)Am^{242}(\beta)Cm^{242}$

By successive neutron captures, masses up to 244 are made in significant quantities.

17. Environmental Protection Agency Report EPA 520/9-73-003.

18. From Ref. 17, Part C, pages 135 and 137, the cheapest noble gas hold-up systems that limit site boundary doses to the required 5 mrem per year are nothing for PWR giving a population dose of 89 man-rem per year for twin reactors, and charcoal adsorption for BWR giving an annual population dose of 27 man-rem. Averaging these gives 58 man-rem per year, or for the 200 required sites exposing 2×10^8 people 0.058 mrem per year to the average person. Actually, most PWR plants use physical hold-up for more than 60 days, reducing their population dose by a factor of ten.

19. From Ref. 17, Part C, pages 141 and 142, the cheapest iodine control systems that reduce site boundary doses to below the required 15 mrem per year give annual population doses to the thyroid of about 7 man-rem for elemental iodine and 13 man-rem for organic iodine; the average exposure is thus of the order of 10 man-rem × 200 sites/2×10^6 people, or about 0.01 mrem per year to the thyroid.

20. Ref. 17, Part C, page 130.

21. From Ref. 17, Part D, page 10, Kr^{85} from a 5 metric tonne per day fuel reprocessing plant gives an average dose commitment in U. S. of 520 man-rem per year. Such a plant would service about 50 reactors, so about 8 such plants would be needed, giving 4200 man-rem. Dividing this by 2×10^6 population gives an average dose of 0.02 mrem/year. For tritium, the result is larger in the ratio of 3700/520. The Kr^{85} exposure is world-wide, but the tritium exposure is largely limited to the U. S.

22. Environmental Protection Agency Report ORP/CSD 72-1.

23. K. Z. Morgan, Talk at Environmental and Ecological Forum, Silver Springs, Maryland (January 20, 1971).

24. M. Eisenbud in "Nuclear Power and the Public," Forman, Ed.

25. An average exposure of 0.23×10^{-3} rem to 2×10^8 population is 4.6×10^4 man-rem/-yr. Multiplying this by 180×10^{-6} cancer deaths per man-rem gives 8.3 deaths per year.

26. From Ref. 17, Part B, page 39, a single mill causes 0.002 deaths per year in providing fuel for 5.3 plants. To service 400 plants would require 80 such mills, causing 80×0.002=0.16 deaths/year.

27. From Ref. 17, Part B, page 88, a conversion facility servicing 28 power plants would cause 0.006 deaths per year. Since 15 such facilities would be needed, the total effect is 0.09 deaths per year.

28. From Ref. 17, Part B, page 109, an enrichment facility servicing 90 power plants would cause 0.002 deaths per year. Since 5 such facilities would be needed, the total number of deaths per year would be 5×0.002=0.01.

29. From Ref. 17, Part B, page 128, a fuel fabrication plant servicing 26 power plants would cause 0.0016 deaths per year. Since 16 such plants would be needed, the total deaths would be 16×0.0016=0.03 deaths per year.

30. From Ref. 17, Part B, page 146, transportation of radioactive materials would cause 0.0002 deaths per reactor-year from direct radiation in passage (accidents will be discussed in Sec. F below). Multiplying this by 400 reactors gives 0.08 deaths per year.

31. It is perhaps worth noting that there are several other published estimates of this number deviating widely in the detailed contributions of noble gases and tritium, but the overall result is always close to this. Some references to other treatments are:

    "Nuclear Power and the Environment," International Atomic Energy Agency (Vienna), quoting EPA estimates for the year 1971.

    EPA-520/4-73-002: Environmental Radiation Dose Commitment, An Application to the Nuclear Power Industry (1974).

    Ref. 22 cited above.

32. P. J. Magno, C. B. Nelson, and W. H. Ellett, 13th AEC Air Cleaning Conference, June 1944.

33. Ref. 32 estimates 50 Ci/yr per million KW plant. Since 400 plants would be needed, this is 2×10^4 Ci/yr. Ref. 32 gives 0.86 p Ci C^{14} per gram of carbon in the biosphere for each Megacurie of C^{14} discharged, and Ref. 2 estimates a whole body dose to humans of 0.167 mrem/year for each pCi C^{14}/gm carbon in the body. The dose is thus $2\times10^{-4} \times 10^{-6} \times 0.86 \times .167 = 0.0026$ mrem/yr. The number of cancers is obtained by multiplying this by 1.8×10^{-4} cancers/man-rem $\times$ 2×10^8 population $\times$ 10^{-3} rem/mrem.

34. Letter from W. H. Ellett (EPA) to B. L. Cohen dated July 2, 1975. This letter cites results from improvements in the meteorology of Ref. 17.

35. The meteorology in References 17 and 34 is not given in sufficient detail to be followed, but according to Ref. 17 (and other sources) a standard pile 1 Km^2 in area emits 500 pCi/m^2-sec, and 2.5 such piles per year would be accumulated if all our power were nuclear, whereas the 7×10^6 Km^2 of U. S. soil emits an average of about 1 pCi/m^2-sec. Thus, natural radon exceeds the annual increase from tailings piles by a factor of $7\times10^6/2.5\times500=6000$. Ref. 34 estimates 4000 deaths per year from natural radon in U. S. which at first seems reasonably consistent with their estimate of effects from tailings piles. However, we give here two alternative calculations of deaths from natural radon which circumvent the rather uncertain meteorology. Ref. 2 gives 0.15 rem per year as an average exposure to the tracheo-bronchial tree which, multiplied by 39 cancer deaths per man-rem from Ref. 1 and the 2×10^8 population, gives 1200 deaths per year. As another approach, one "working level" (WL) is 1.50×10^3 pCi/m and BEIR[1] gives 0.5 rem to lung per WL-"month" where one working "month" is 170 hours or 0.02 years; these combine to give $5000/150\times10^3 \times .02 = 1.6$ mrem/yr per pCi/m^3. (This is 2.5 times smaller than the value used in Ref. 17, but more significant than this discrepancy is the fact that the BEIR value was used in assessing lung cancer incidence in miners which was instrumental in determining the value 39×10^{-6} lung cancers per man-rem.) From Ref. 2, the average Rn^{222} level in U. S. is about 120 pCi/m^3 which (when multiplied by the above 1.6) gives an average dose of 190 mrem/year to the lung. Multiplying this by 39×10^{-6} cancers/man-rem and 2×10^8 population gives 1500 deaths per year from natural radon, in agreement with our above estimate of 1200. Since radon from tailings piles is 6000 times smaller, these would give 0.20-0.25 deaths per year from the latter. However, the latter radon originates in low population regions and must travel about 1500 miles to reach populous regions; during this travel, more than half of the Rn^{222} (3.6 day half life) would decay away so the average toll would be no more than 0.1 death per year from each year of all nuclear power.

36. Summary Report on Phase I - Study of Inactive Uranium Mill Sites and Tailings Piles (EPA Office of Radiation Programs, 1974); Phase II, involving remedial action, is to start in 1975.

37. Letters from W. H. Ellett (EPA) to R. Wilson, dated July 2, 1975.

38. Nuclear energy consumes about 1 gm/MW-day of fissile material so 400,000 MW-years of electricity at 33% efficiency consumes $1\times4\times10^5\times365\times3 = 4.4\times10^8$ gm. If we assume that all mined uranium and all uranium causing health effects comes from the top meters where the average concentration is 2.7 ppm, the amount of uranium involved is 10^{13} m^2 (area of U. S.) $\times$ 600 m $\times$ ($2.7\times10^{-6}\times2.5\times10^6$ gm/m^3) = 4×10^{16} gm. Thus one year of all-nuclear power consumes 10^{-8} of the uranium.

39. Nuclear News, June 1975, p. 37.

40. To get a feel for rates of temperature rise with no cooling, the mass of fuel in a 3300 MW (thermal) reactor is about 8.6×10^7 gm. After shut-down, the heat production is 6% of 3.3×10^9 watts, or about 5×10^7 calories per second. The heat capacity is 0.074 calories per gram, so the average temperature rises at a rate of $5\times10^7/0.074\times8.6\times10^7 = 7.9^\circ$C/sec or 14°F/sec. The temperature rise at the hottest point would be somewhat faster.

41. WASH 740: Theoretical Consequences of Major Accidents in Large Nuclear Power Plants, USAEC (Washington, DC) 1957.

42. P. Ayyaswamy et al., UCLA Report ENG-7423, Estimates of the Risks Associated with Dam Failure (1974).

43. F. H. Schmidt, private communication, based on letter to him from U. S. Navy. H. A. Bethe, private communication, based on telephone call from U. S. Navy.

44. UCS-Sierra Club comments on WASH 1400.

45. Meteorology and Atomic Energy, 1968, USAEC Document.

46. Report to APS by Study Group on Light Water Reactor Safety, Reviews of Mod. Phys. 47, 51 (1975).

47. I. Wall (NRC), private communication.

48. The BEIR Report derived a number equivalent to about 100×10^{-6}, but in the discussion section effectively doubled it for purposes of conservatism to 180×10^{-6}. Actually none of these numbers are given clearly in the BEIR Report and there is room left for interpretation.

49. H. Kendall, Testimony before Udall Subcommittee on Energy and the Environment, Apr. 28-May 2, 1975.

50. World Almanac.

51. There was a proposal by M. Ross, a University of Michigan physicist, that a rather large fraction of the Cs^{137} might be released in an accident (Ref. 52, p. 830). However, recent studies by Parker and Shappert (private communication, letter to USERDA, and testimony before ASLB, Docket numbers STN50-483, STN50-486) indicate that the Ross estimates were far too large. Far smaller amounts were found to migrate out of the fuel pellets, and the Cs was found to be in chemical forms which are not volatile. When these factors are included, the Cs releases are easily taken into account in the general category of solid fission product releases.

52. Proceedings of International Symposium on Packaging and Transportation of Radioactive Materials, Miami Beach (1974), USAEC Document CONF-740901.

53. Environmental Survey of Transportation of Radioactive Materials to and from Nuclear Power Plants, USAEC Document WASH 1238, Dec. 1972. See also, L. B. Shappert et al., Nuclear Safety 14, 597 (1973).

54. A. Reinking et al., Univ. of Cal. College of Engineering Report NE-72-1 gives estimates for the State of California. Scaled to all of U. S. it gives 10 deaths per year if all our power were nuclear. See also G. Yadigaroglu et al., Nuclear News, Nov. 1972, p. 71.

55. C. V. Hodge and O. C. Baldonado, Ref. 52, p. 814. The estimates given there were substantially reduced in their later work (C. V. Hodge, private communication). Environmental Impact Statement for the Liquid Metal Fast Breeder Reactor, AEC Document WASH 1535 (1975); Sec. 4.5.

56. John Gofman in BBC television film "A Small Dose of Blackmail," which has been repeated frequently in popular anti-nuclear literature.

57. ICRP Publication 19, Pergamon Press (New York).

58. ICRP Publication 2, Pergamon Press (New York).

59. B. L. Cohen, "Hazards from Plutonium Dispersal," submitted for publication to Radiation Research. Preprints available from author.

60. WASH 1535: Environmental Impact Statement for LMFBR Program page II. C-2 gives $0.27 \cdot 10^{-3}$ Ci/1000 MW-yr. For 400 plants and using 1 mm per curie, this is 0.1 mm/year released by an LMFBR-based industry.

61. Ref. 60 gives estimates that are equivalently an order of magnitude higher, but they are based on highly conservative assumptions on resuspension.

62. Articles on T. B. Taylor by J. McPhee, New Yorker Magazine, Dec. 1973; J. McPhee, The Curve of Binding Energy, Farrar, Straus, and Giroux (1974); M. Willrich and T. B. Taylor, "Nuclear Theft: Risks and Safeguards," Ballinger Pub. Co. (Cambridge, Mass.) 1974.

63. W. C. Bartels and S. C. T. Motewell, Am. Nuc. Soc. Meeting, Philadelphia (1974), and private communication. Numerous private communications.

64. Carl Bennett (Battelle-Seattle), private communication.

65. An important problem in plutonium bombs is the presence of Pu^{240} which decays partly by spontaneous fission and hence introduces neutrons which tend to cause fizzles; more efficient explosions require holding off introduction of neutrons until maximum super-criticality is approached. This problem, when initially discovered, almost shut down the plutonium project during World War II and when ways to overcome it were developed, required the Almagordo test (the U^{235} bomb dropped on Hiroshima was not tested). Plutonium used for bombs has about 7% Pu^{240} whereas that from light water reactors has typically 24% Pu^{240} plus 4% Pu^{242} which has twice as high a rate of spontaneous fission.

66. Much of the material in this Section is from B. L. Cohen, Environmental Hazards in Disposal of High Level Radioactive Waste, Physics Today (submitted). Preprints are available from the author. References contained therein are not generally repeated here.

67. Environmental Impact Statement for LMFBR, AEC Document WASH 1535, Sec. II.F.

68. H. C. Claiborne and F. Gera, ORNL-TM-4619.

69. D. Jacobs and F. Gera, ORNL-1762.

70. H. Soule (USAEC), private communication.

71. Calculation from U. S. Surgeon-General's Report on cigarette smoking, 1962.

72. E. Teller and A. L. Latter, Our Nuclear Future, Criterion Books (New York) 1958, p. 124.

73. Since 35 minutes if $7 \cdot 10^{-7}$ yrs and the driving risk is $7 \cdot 10^{-8}$/mile, the former is equivalent to 100 miles of driving per lifetime, or 1.5 miles per year.

74. Insurance Institute for Highway Safety, Vol. 10, No. 12 (July 9, 1975) gives 24.6 fatalities per 100,000 vehicle years registered for small cars, and 11.4 for large cars. These numbers are the sum of 12.6 vs 7.2 for multi-vehicle crashes, and 12.0 vs 4.1 for single car accidents. A similar conclusion would be obtained from Accident Facts--1965, National Safety Council (Chicago) 1965.

75. Being overweight by 25% about 40 lb., reduces life expectancy by about 5 years (L. I. Dublin and H. H. Marks, Mortality among Insured Overweights in Recent Years, Metropolitan Life Insurance Co. (New York) 1952.) Since 36 minutes is $7 \cdot 10^{-5}$ years, a linear hypothesis gives the risk to be that of 8 lb/yr$\cdot 7 \cdot 10^{-5}$ yr = $6 \cdot 10^{-4}$ lb = 10^{-2} ounces.

76. L. Pauling, Proc. Nat. Acad. Sci. 44, 619 (1958).

77. Ref. 72 gives LLE = $1.9 \cdot 10^{-3}$ yr/lb$^2 \cdot$(OW)^2 where LLE is loss of life expectancy and OW is pounds overweight. For LLE = $8 \cdot 10^{-5}$ yrs, this gives OW = 0.2 lb.

78. Air Quality and Stationary Source Emission Control, U. S. Senate Committee on Public Works, March 1975 gives values for an urban plant (p. 631) and a remote plant (p. 626); we use the average between these, and multiply by 400 for the number of plants. Values are for a 620 MW plant burning 3% sulfur coal, whereas to supply the electricity under discussion would require 400 plants producing 1000 MW each, but we leave this discrepancy as a factor of conservatism. A larger number of deaths is estimated by R. Wilson, Energy Symposium, Boulder, Colorado, June 1974, and by L. Hamilton, private communication to R. Wilson.

79. B. L. Cohen, Nuclear Science and Society, Doubleday-Anchor Books (New York) 1974, p. 139-140.

80. L. Sagan, Nature 250, 109 (1974).

81. From Sec. D, a power plant neighbors risk is $20 \cdot 10^{-6}$ per year, or a total of $1.4 \cdot 10^{-3}$. This is his probability of losing an average of 20 years of life expectancy, so his average loss of life expectancy is $1.4 \cdot 10^{-3} \cdot 20 = 0.03$ years.

82. Estimate of National Suicide Council, reported in Trenton, New Jersey, newspaper, Sunday, April 20, 1975.

A PERSPECTIVE ON TRANSPORTING NUCLEAR MATERIALS

by

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Introduction

Nearly every industry has a supplier and a consumer, and in general it is necessary to transport materials from one to the other. The nuclear industry is no exception. It is, in fact, not a single industry, but a conglomerate of industries, with many separate parts, each in turn being both a supplier and a consumer. And each disparate part requires transport of materials to and from it. The parts are the elements of the nuclear fuel cycle. A full discussion of transportation requirements for the nuclear industry would consider the flow of materials directly as well as indirectly related to the nuclear fuel cycle. Thus, large volumes of chemical reagents such as acids and alkalis are required at the mills and reprocessing plants; water treatment chemicals are used at the reactors; compressed gases are used in several parts of the fuel cycle, and in different amounts and kinds depending on reactor type; ion exchange resins are used throughout the fuel cycle, and so on. Less directly related, but equally important, incremental increases in the transport of coal, iron ore, manufactured items and other products of basic manufacturing and construction industries are required to build and to maintain the elements of the nuclear industry.

However, this essay has a more limited view than consideration of all aspects of transportation of materials directly and indirectly related to the production of nuclear power. It is limited to shipment of radioactive materials. (The term "nuclear materials" is used in the title to convey the idea of totality of coverage of all the transportation operations, which the alternative term "radioactive materials" does not seem to imply so fully.)

The wide variety and levels of radioactivity of the nuclear materials trnsported lead to a wide range of solutions to the problems presented. Thus, there is the low-activity-level (but relatively high-bulk) milled ore which is shipped to the conversion plant on the one hand, and the intensely-radioactive (but relatively low-bulk) high-level radioactive waste which must be shipped to a waste repository on the other. Between these extremes are solids, gases and liquids of various volumes and radioactivity levels: spent reactor fuel; natural and enriched UF_6; fabricated fuel elements; nuclear weapons; fission product gases, e.g., ^{85}Kr; and solutions of fission products and assorted machine- and reactor-produced radioisotopes for use in medical and physical research. Methods of transportation of these materials depend on volume, weight, and radioactivity levels, and include shipment by truck, rail, air and water. Packaging is similarly related to size, weight, physical form, and radiation level. These matters are discussed in this essay.

The subject of safeguards, which is intimately related to transporting nuclear materials, will not be discussed here. Safeguards has to do with the protection and accountability of fissile materials, wherever they are. Certainly one of the most important steps in the fuel cycle from the point of view of safeguards is that of transportation of the fissile materials. However, the subject of safeguards is very complex and has both subjective and objective components. Many of its problems are not even clearly defined, let alone solved. There are, in fact, potential solutions to some of the safeguards problems which might effectively remove much of the subject of radioactive materials transport from consideration. These are mentioned later in the section on the relation of transportation to siting, and involve collecting several fuel cycle operations on a single site. The implications of the safeguards problems are important enough that the subject merits special and separate discussion beyond the brief mention of them in this essay.

All the activities of man are subject to accidents, that is, to the unexpected or unanticipated adverse happening. Transportation is no exception, and in fact includes our best known, most widely publicized, examples of accidents. So some mention of accidents is in order. Since by their nature they are random events, accidents are best discussed statistically and probabilistically, and such a treatment is beyond the scope of this essay. However, the subject will be mentioned briefly later.

Important national and international shipping regulations are listed in an Appendix to this essay, and a Bibliography is provided to guide the interested reader to sources of information which are both broader and deeper than the information presented here.

THE NUCLEAR FUEL CYCLE

The term "nuclear fuel cycle" encompasses major processes and facility operations which are directly related to and necessary for power production in nuclear reactors. Included are mining and milling uranium ore to produce a uranium concentrate, refining and conversion of concentrate to produce UF_6 (or an oxide), enrichment of uranium in the isotope ^{235}U, fuel element fabrication, reactor operation, spent fuel reprocessing, recycle of plutonium (not yet a commerical practice), conversion of radioactive wastes to a form suitable for storage, and finally, storage of wastes. Material transportation connects these fuel cycle steps. Figure 1 is one of many representations of the way the nuclear fuel cycle steps are related. It pertains to the fuel cycle for light water reactors, and includes recycle of plutonium, which is an important element in the long-term commercialization of nuclear power. As intimated in the introduction and mentioned briefly later, collecting several of these steps--especially fuel reprocessing and fabrication--onto a single site would have a profound effect on the need for and nature of the transportation operations.

At present the nuclear fuel cycle in the United States is devoted virtually solely to light water reactors (LWRs). There is a small component of reactor fuel cycle work devoted to high-temperature gas-cooled reactors (HTGRs) which may become significant over the next decade. The essential differences between the LWR and HTGR fuel cycles derive from the use of thorium and highly enriched uranium (> 90% ^{235}U) in HTGRs (instead of the slightly enriched uranium (2 to 5% ^{235}U) in LWRs), and the planned recycle of ^{233}U (produced from the thorium) to augment the ^{235}U (instead of ^{239}Pu (produced from the ^{238}U) to augment the ^{235}U which is planned for LWRs). These differences manifest themselves (in the context of this essay) primarily in two ways: (1) in the transportation of uranium from the LWR fuel reprocessing plant to the enrichment plant: HTGR fuel recycle has no comparable step; and (2) in the need for heavy

shielding on unirradiated HTGR recycle fuel. In the case of HTGRs, it is planned that fuel reprocessing and refabrication be carried out in a single plant called a recycle plant.

Since large operating HTGR power stations are in the future, there is no mining and milling industry for thorium to compare with that for uranium. Further, stockpiles of thorium compounds in the U. S. and elsewhere (most notably in Canada) are adequate for the first generation of HTGRs, so development of mining and milling for thorium appears to be well into the future, though transportation of thorium from the stockpiles to the fabrication plant is obviously needed.

Finally, if nuclear power is to be a major factor in the nation's economy over a large number of years, then the breeder reactor must be developed. The essential new element introduced by the breeder is the use of plutonium rather than uranium as the primary fissile material (assuming that the breeder [illegible]

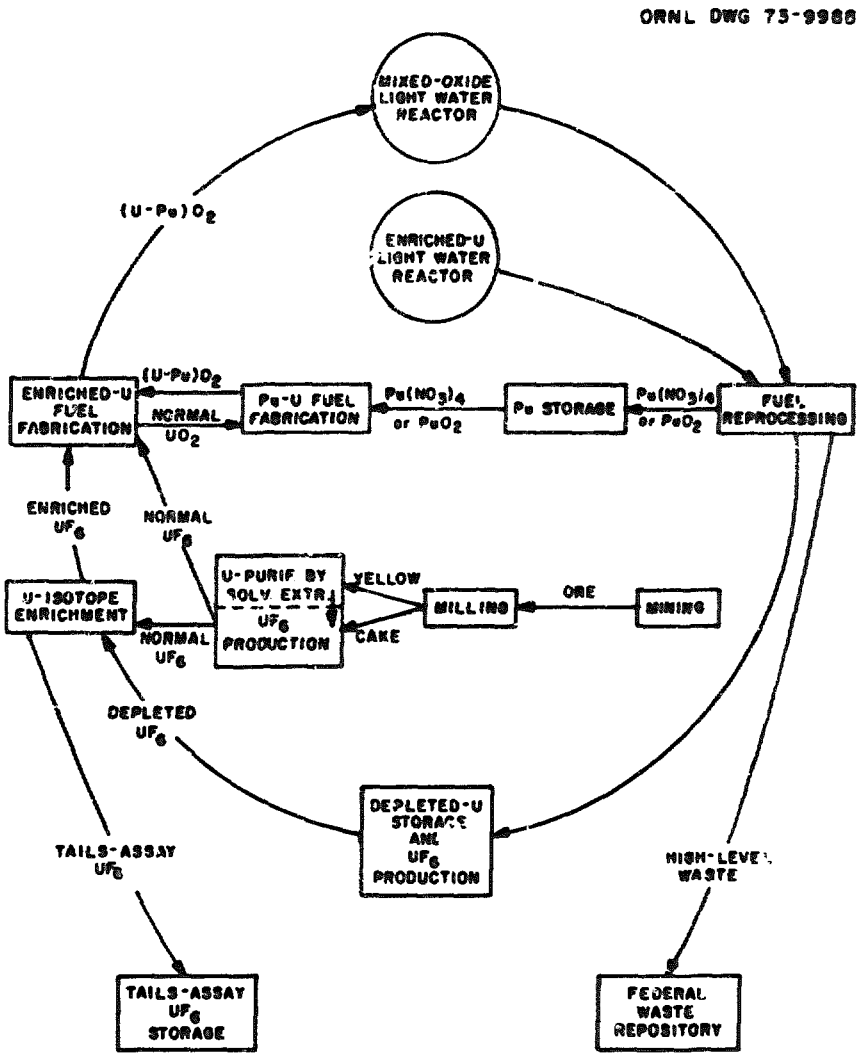

Figure 1
The LWR Nuclear Fuel Cycle Showing Plutonium Recycle

operates on the uranium-plutonium cycle). The impact of the breeder on the nuclear fuel cycle is felt in the greatly reduced amount of uranium which must be handled in mining and in the subsequent steps leading to enriched uranium production for each unit of power produced. Thus, transportation requirements in related fuel cycle steps would be proportionately lessened. Conversely, there is the increased requirement for plutonium processing and shipment. (It should be remembered that a successful long-term nuclear power industry will entail plutonium processing and transportation even with the LWR, which produces about a third as much plutonium as the ^{235}U it consumes.)

Finally, there are two important facts to consider in regard to near-term transportation in the nuclear fuel cycle: (1) While there are a number of LWR fuel fabrication plants in operation and under construction, there is no operating commercial fuel reprocessing plant in the U. S., nor will there be for one, and perhaps not for two or three years. Further, the reprocessing plant likely to come on stream first (the Allied-General Nuclear Services plant) will be too small to handle the projected LWR fuel reprocessing load virtually the day it opens it's doors for business. The implication of this fact with regard to transportation is that there are likely to be interium spent fuel storage facilities required to which the spent fuel must be shipped from the reactors when their reserve storage areas are full. (2) There is at present no available way to dispose permanently of high- and intermediate- level commercial solid radioactive wastes. Only interim tank storage of liquid wastes is possible at the present time. It appears that the solution to this problem is 5 to 10 years away. The implication of this fact with regard to transportation is that high-level solid waste shipments will likely start with a surge rather than more slowly, and more nearly in step with the growth of the nuclear industry. This appears likely becuase of the immediate necessity to relieve the constipation which will have occurred in the disposal of wastes by the time permanent disposal is possible.

SOURCES AND AMOUNTS OF MATERIALS TO BE SHIPPED

In this section the general statements made in the preceding section about the transportation of materials between steps in the nuclear fuel cycle will be elaborated upon and put in perspective. However, it must be borne in mind that all attempts at quantitative estimates of material flow are based upon projections and assumptions about the rate of growth of the nuclear industry, and of the fraction of the market captured by particular reactor types. In light of the uncertain state of development and growth of the entire power-producing industry, it would be inappropriate to suggest that such estimates are more than indicative of the way things might develop. Nonetheless, some useful purpose is served by collecting such estimates in a single essay where comparisons may be more readily made, and inferences perhaps more easily drawn.

Reactors

Since the fuel cycle is in fact a cycle, any convenient step may be selected as a starting point for a discussion of sources and amounts of materials to be shipped. In an important sense, the reactors are the central actors in the nuclear power play, and they will be discussed first. Figure 2 shows the amount of fuel projected to be required annually in the U. S. for each of the three reactor types (LWR, HTGR and LMFBR) for each year between now and the year 2000. A different way to present this information is in terms of the number of fuel assembly shipments. This approach is taken later, in Table 5 in the section on Fuel Fabrication Plants.

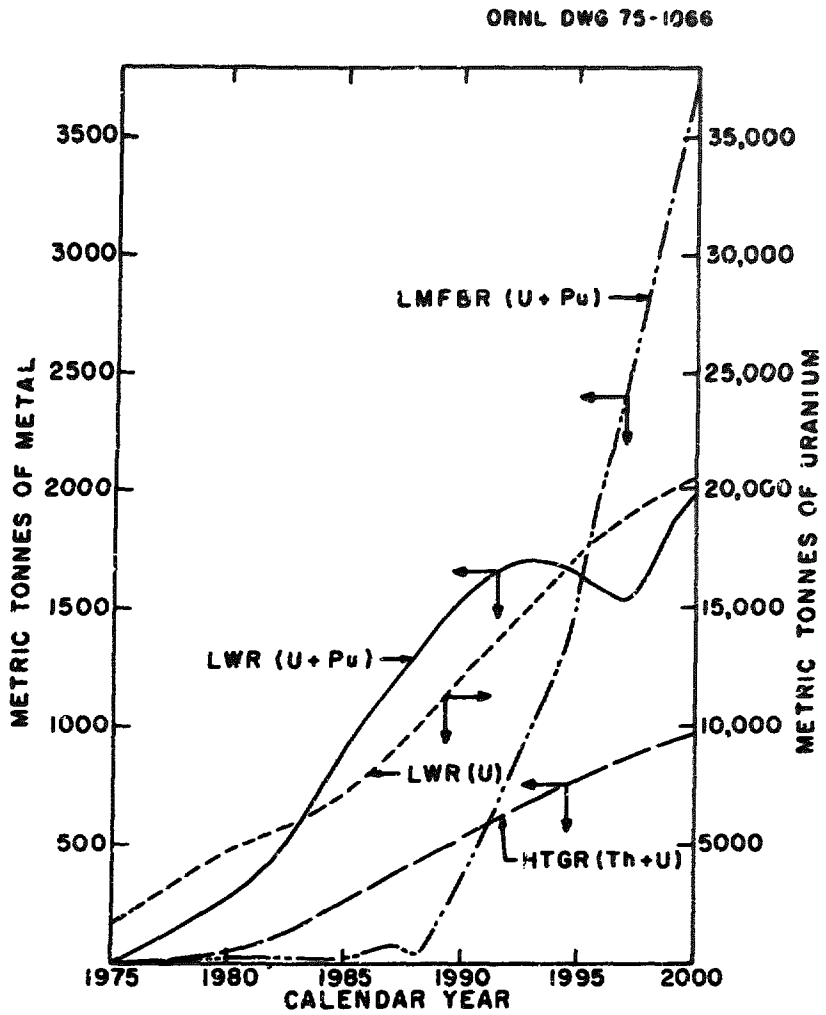

Figure 2
Projected Annual Fuel Requirements for LWRs, HTGRs and LMFBRs
(Taken from WASH-1139(74), Table 21)

All the fuel that arrives at a reactor must eventually leave it. However, for the next five years, or perhaps more, it is to be expected that a steady state between influx and efflux of LWR fuel may not be attained. This is so because spent fuel may have to be stored at reactor sites pending availability either of other storage facilities or of reprocessing capability. Further, presnet lack of high-level radioactive waste storage capability may impose additional restrictions on fuel reprocessing, and consequently on shipping fuel from the reactors. The number of tonnes of fuel requiring shipment for reprocessing between 1975 and 2000 are given in Table 1. In addition to fuel shipments to and from reactors, there is a fairly steady discharge of low-level radioactive materials from reactor coolant water treatment systems, and other sources such as waste water evaporators, filters, and laundries. The magnitude of this shipping requirement is suggested by Table 2.

Reprocessing Plants

Reactors will ship their spent fuels to the reprocessing plants where the uranium and plutonium (and thorium) will be separated from fission products and made available for fuel fabrication. Fuel element burnup (a measure of the fraction of fissile material that has been consumed), decay time (the time between discharge from the reactor and shipment to the reprocessing plant) and

TABLE I

Tonnes of Fuel Requiring Shipment for Reprocessing from 1975 to 2000

Year	LWR	HTGR	LMFBR
1975	400		
6	1100		
7	1700		
8	2332		
9	1955	3.9	
1980	2395	6.6	
1	3030	7.7	
2	3509	36.8	
3	4051	66.3	
4	4195	97.6	
5	4752	169.3	
6	5229	239.2	
7	5689	321.1	5
8	6355	406.3	7.1
9	6999	492.1	77.1
1990	7650	589.6	175.4
1	8158	683.4	306.4
2	9000	764.0	492.1
3	9536	858.1	709.8
4	10,092	954.6	1038
5	10,478	1040	1470
6	10,871	1116	2073
7	11,194	1193	2689
8	10,837	1261	3450
9	11,180	1333	4270
2000	11,041	1415	5123

Taken from J. O. Blomeke, C. W. Kee and J. P. Nichols, Projections of Radioactive Wastes to be Generated by the U. S. Nuclear Power Industry, ORNL-TM-3965 (Feb. '74)

TABLE 2

Typical Amounts of Wastes Shipped Annually from 1000 MWe LWR Power Reactors

Reactor Type	Approx. Volume, ft^3	Approx. Radioactivity, curied
PWR	1000	600
BWR	3900	600

size determine the nature of this transportation problem. Besides spent fuel shipments, other major transportation considerations at the reprocessing plant are those associated with the separated fission products and the separated fissile and fertile materials, i.e., uranium and plutonium (and thorium). The projected annual amounts of plutonium and high-level fission product wastes to be shipped up to the year 2000 are shown in Table 3. More and more, it is becoming apparent that fuel reprocessing plants will convert the uranium product to UF_6, which will be returned to the enrichment plant (see below). This will increase the amount of UF_6 shipped in the U. S.

Enrichment Plants

As shown in Figure 1, UF_6 may be shipped both to and from the uranium isotope enrichment plants. At the present time, enrichment plants are of the so-called gaseous diffusion plant type. The physical properties of UF_6 are such that at usual ambient temperatures the UF_6 may be either gaseous or solid, depending on the pressure. Under ordinary conditions of shipment, it is solid. (If it is vented to the atmosphere it reacts with moisture in the air to form uranyl fluoride and hydrofluoric acid.) Either normal, slightly depleted, or very slightly enriched uranium may be received at the gaseous diffusion plant, depending on whether the uranium has been freshly mined or is being recycled from a fuel reprocessing plant. The ^{235}U content of the entering recycled uranium will depend on the specific reactor type and recycle mode employed. Low-enrichment (2-5%) or high-enrichment (>90%) uranium as UF_6 may be shipped from

TABLE 3

Projected Plutonium and High-Level Fission Product Waste Shipments

	1980	1990	2000
Plutonium			
Metric tons Pu per vehicle (truck)	0.4	0.5	0.5
Shipments per year	32	140	520
Days in transit	2	2	2
Solid High-Level Waste			
Ft^3 per shipment	0	75	75
Shipments per year	0	43	240
Megacuries per shipment	0	10	10
Cladding Wastes			
Ft^3 per shipment	95	95	102
Shipments per year	31	164	495
Megacuries per shipment	0.3	0.3	0.5

Taken from 4th Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials, "Trends and Projected Shipments in the Nuclear Fuel Cycle Industry to the Year 2000," by R. Salmon, J. O. Blomeke and J. P. Nichols, CONF-740901-P1, pp. 349-63 (September 1974).

TABLE 4

Locations and Capacities of Uranium Mills and Conversion Plants for Ore Concentrates in the U. S. in 1973

Mills		Conversion Plants	
Capacity, tonnes of ore/day	Location	Capacity, tonnes UF_6/year	Location
13,500	New Mexico	20,700	Illinois
9,050	Wyoming	7,400	Oklahoma
2,000	Utah	(14,800)*	(Oklahoma)*
1,750	Texas		
1,750	Colorado		
5,000	Washington		

*Planned

Taken from The Nuclear Industry-1973, WASH 1174(73).

the enrichment plant. (The enrichment will depend on whether it is entering the LWR or HTGR fuel cycle.) Since the standard shipping containers hold either 10 or 14 tonnes of UF_6 (natural uranium), or 2 1/2 tonnes UF_6 ($\leq$ 5% enriched uranium), the number of shipments may be estimated. Beyond the shipments indicated above, there is interplant shipment among the gaseous diffusion plants at Oak Ridge, Tennessee, Paducah, Kentucky, and Portsmouth, Ohio. This additional UF_6 transportation increases the number of containers, i.e., amount of material shipped.

Uranium Mills

Uranium mines and mills are generally located on a single site, or near each other, so transportation between mine and mill is confined to short distances. However, transport of the uranium concentrate from the mill to the conversion plant involves large distances. Table 4 lists by state the annual ore processing capacity, and by state the UF_6 conversion capability available in the U.S. in 1973. Figure 3 shows the projected annual amounts of uranium concentrate which must be shipped up to the year 2000. Since the mines and mills are in the western states, and the refineries and conversion plants are in the Midwest, it is clear that long shipping distances are involved. However, since it is natural uranium that is being shipped, there is little or no problem caused by radioactivity during shipment. As is apparent from the fact that uranium ore averages about 0.21% U_3O_8, while concentrate is 98% (or greater) U_3O_8, by far the largest amount of material is transported (on-site) between mine and mill.

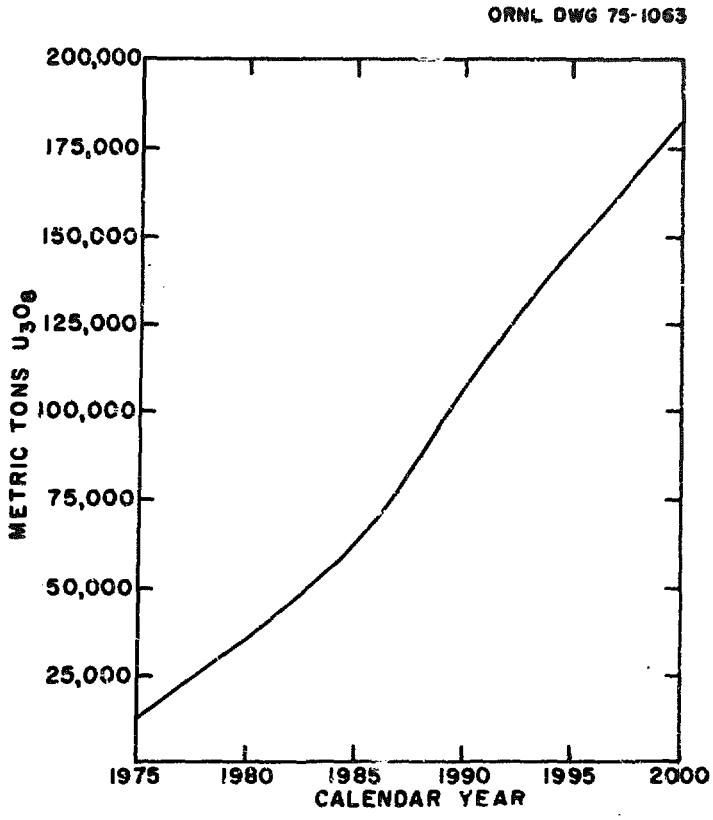

Figure 3
Projected Annual Amounts of Uranium Concentrate (as U_3O_8)
Shipped up to Year 2000
(Taken from ORNL-TM-4631)

Uranium Conversion Plants

Uranium conversion plants (refineries) convert the relatively impure concentrate from the mill to a very pure uranium compound suitable for use in enrichment plants. In the past, uranium was refined in two basically different ways. The first, and oldest, was by solvent extraction of the uranium to remove it from impurities which were not completely removed by the milling operation which produced concentrate. This type of refinery produced pure UO_3 which was either shipped to a fuel fabrication plant or sent to a gaseous diffusion plant. The second was by direct fluorination of the concentrate at the refinery, in which case it was either shipped to the gaseous diffusion plant as UF_6 to be enriched or sent to the fuel fabrication plant. Shipment of UF_6 was discussed in the section on Enrichment Plants. Both types of refineries dealt only with natural uranium.

The recent trend is to combine the fluorination step with the solvent extraction step at the refinery (or to eliminate solvent extraction altogether). Thus, the two types of refineries are not so very different today, and the shipping problems are tending to become virtually the same, namely those associated with shipping UF_6.

As was mentioned above, there is also a move in the direction of putting UF_6 production steps at the fuel reprocessing plants as the last step prior to shipment of the recovered uranium (which may still be more enriched in ^{235}U than the enrichment plant "tails") to the enrichment plant. So it is apparent

that shipment of UF_6, both as natural and as enriched uranium is assuming ever-increasing prominence in the nuclear fuel cycle.

Figure 4 shows the amounts of UF_6 produced from uranium concentrates which must be shipped from conversion plants to meet the projected energy demands in the U. S.

Fuel Fabrication Plants

The uranium received at the LWR fuel fabrication plant (usually as UF_6) is converted to pellets of UO_2 which are usually 2 to 4% enriched in ^{235}U. The pellets are loaded into metals tubes of an alloy of zirconium (which has a low thermal neutron absorption cross section), which are in turn assembled into fuel assemblies. These fuel assemblies are shipped to the reactors. The number of assemblies required for a reactor core depends on the type of reactor. Typically, a 1000 MWe PWR requires 193 assemblies, while a 1080 MWe BWR requires 764 assemblies. Table 5 shows projected shipments of fresh fuel for each of the reactor types up to the year 2000.

Use of recycled plutonium in LWRs would require shipping plutonium (required by regulation to be as PuO_2 after June 17, 1978) from the fuel reprocessing plant to the fuel fabrication plant. The amount of plutonium shipped from the reprocessing plant to the fabrication plant would be about one-third the amount of ^{235}U shipped from the enrichment plant to the fabrication plant, so a plutonium shipping requirement would exist. (However, since the uranium would be, on the average, only about 3% ^{235}U, whereas plutonium is roughly equivalent to 60-70%-enriched uranium, the relative masses of plutonium to uranium would be of the order of 1 to 70.)

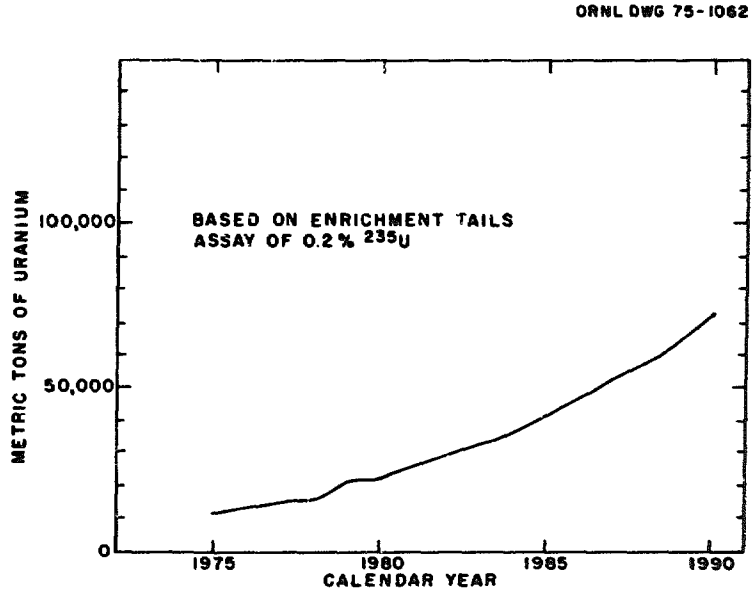

Figure 4
Projected Annual Shipping Requirements of UF_6
Produced from Ore Concentrates up to the Year 2000
(Adapted from *The Nuclear Industry-1973*, WASH-1174-73, Fig. 3-6.)

TABLE 5

Fresh Fuel Shipments Up to the Year 2000

	1980	1990	2000
LWR			
Metric tons per vehicle	5.5	5.5	5.5
Shipments per year	760	2550	4360
Days in transit	2.8	2.8	2.8
HTGR			
Metric tons per vehicle	1	1	1
Shipments per year	30	520	1030
Days in transit	4.0	3.5	3.0
LMFBR			
Metric tons per vehicle	--	2.8	2.8
Shipments per year	--	75	1650
Days in transit	--	3.5	3.0

Taken from 4th Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials, CONF-740901-P1, pp. 369-64 (September 1974).

(To avoid shipping pure PuO_2, with its attendant safeguards problems, it has been suggested that the uranium and plutonium be mixed at the reprocessing plant before shipment to the fabrication plant. This would reduce the fissile material (Pu plus $\leq$ 1% enriched U) content of the material to be shipped to a level well below that which could be used for making an explosive device, though of course the (toxic) plutonium would still be present. It would, however, somewhat complicate the fuel fabrication steps, which more and more are based on receiving UF_6, not a mixture of uranium and plutonium oxides, which may prove to be difficulty soluble, and which would require a difficult assay of total fissile material content prior to fabrication.)

Weapons

Although it is not much discussed, there is a certain amount of transportation of nuclear materials for weapons, and of weapons themselves. In general, weapons-related shipments are by truck or by rail. The sites among which shipments take place are rather widely separated and include major installations at Hanford, Washington; Oak Ridge, Tennessee; Los Alamos, New Mexico; Aiken, South Carolina; and Boulder, Colorado. (Certainly, a discussion of the safeguards aspects of transportation in an overall way would have to pay especial attention to this subject.) Because of the obvious sensitivity of the subject, and the general unavailability of specific information, no more will be said about it in this essay.

Miscellaneous Radioisotopes

Medical and research uses of a wide variety of radioisotopes have led to an extensive traffic in them around the country and the world. The uses determine the nature of the radioisotopes shipped, and include such diverse applications as ^{244}Cm and ^{238}Pu for heat sources, as used, for example, to produce electrical energy for space exploration; ^{238}Pu for heart pacers; ^{131}I for thyroid treatment; several radioisotopes for tumor treatment, e.g., ^{60}Co; ^{252}Cf for use as a neutron source; tritium, ^{32}P and others for biochemical and biological research; and many others for a very broad range of physical research, industrial and medical radiography, and so on.

Many, perhaps most, of these radioisotopes are used in small amounts (very small relative to the amounts of fission products produced in power reactors), and may be shipped in any of the physical forms. Shipment by air is often essential because of the shipping distances and short half-lives of the radioisotopes involved. (Recent releases of radioactivity from packages on airplanes have led airline pilots of passenger planes to refuse to carry radioactive materials other than those used for medical purposes.)

CONTAINERS, PACKAGES, AND MODES OF TRANSPORTATION

Reactor Wastes

Routine operation of a power reactor produces several different kinds of solid wastes which are routinely packaged and shipped to burial grounds operated by one of three commerical firms.* These wastes include spent ion exchange resins, which are loaded with non-radioactive ions plus activation products which have corroded away from the materials of construction of the reactors themselves, and from impurities in the coolant water. The resins also contain fission products from the fuel elements. Some fuel elements leak fission products, and there is some "tramp" uranium on the exterior of the fuel elements which undergoes fission. In addition to resin wastes, there are sludges from evaporators and filters in various process lines, mainly those associated with the water used to produce steam and to cool and moderate the reactor core. These wastes are generally packaged in 55 gallon drums, often admixed with concrete, for shipment to the burial ground. Figure 5 shows the nature of handling operations required for this essentially low-level radiation operation. Each 1000 MWe BWR will ship about 2150 drums annually; the same size PWR will ship about 600 drums. There are also other solid radioactive wastes such as air filters, rags, paper, tools, and small equipment items generated at the power plant. These are often compressed into bales. The major reactor "wastes," i.e., the spent fuel, are given separate treatment in the section which follows.

Spent Fuel

Transportation of spent fuel from the reactor to the fuel reprocessing plant is a major step in the nuclear fuel cycle. The fuel is laden with radioisotopes which necessitate both heavy shielding and very high integrity containment. The nature of the problem is such as to require a major expenditure of money to produce a container which is acceptable for shipping a single spent fuel assembly, and only a fractional cost increase is required to produce a

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*These commericial burial sites are located at: Richland, Wash., Beatty, Nev., Morehead, Ky., and Sheffield, Ill. (operated by Nuclear Engineering Co., Inc., Walnut Creek, Calif.); Barnwell, S. C. (operated by Chem-Nuclear Services, Inc., Bellevue, Wash.); and West Valley, N. Y. (operated by Nuclear Fuel Services, Inc., West Valley, N. Y.).

BOYD

container which will accommodate additional assemblies. Thus there is a strong incentive to produce a container, or cask, which holds as many assemblies as possible. Opposing this incentive for increased size is the fact that each additional assembly imposes a requirement for additional shielded volume, i.e., for additional weight. There comes a point where the cost of the handling equipment for the cask, as well as its sheer size and weight, limit the number of assemblies that it is practical to transport in a single carrier. In general, this limit is reached at a size beyond the load limits for trucks, necessitating rail shipment. However, about half the reactors are without rail siding, so truck-rail (inter-modal) shipments are required. Figure 6 shows a typical carrier for LWR fuel. Shipping containers may carry up to 10 PWR fuel assemblies or up to 24 BWR assemblies, and weigh up to 100 tons or more. The total amount of fuel material or fission products per cask is about the same for both PWR and BWR, even though the number of assemblies differs by a factor of about two. This is so because of the difference of about a factor of two to three in the sizes of their assemblies. Table 6 summarizes shipping modes for spent fuel shipping casks.

An additional factor to consider in the shipment of spent fuel is the heat that is generated by the fission product decay. In general, this is not a serious problem with LWR fuel, amounting to up to about 10 kw per PWR assembly, and 5 kw per BWR assembly at the time of shipment. The problem of heat production may be quite important in the case of LMFBR fuel, where it is proposed that shipping take place after much shorter decay times than those used for LWRs (perhaps as low as 90 days or less vs the 150 days to nearly a year of decay planned for LWRs).

The accidental release of fission products during shipment of spent fuel must be guarded against carefully. Apart from considerations related to safeguards, there is perhaps no part of the nuclear power fuel cycle with greater potential to cause a serious threat than that of spent fuel shipment. For this reason elaborate precautions are taken in cask design and construction;

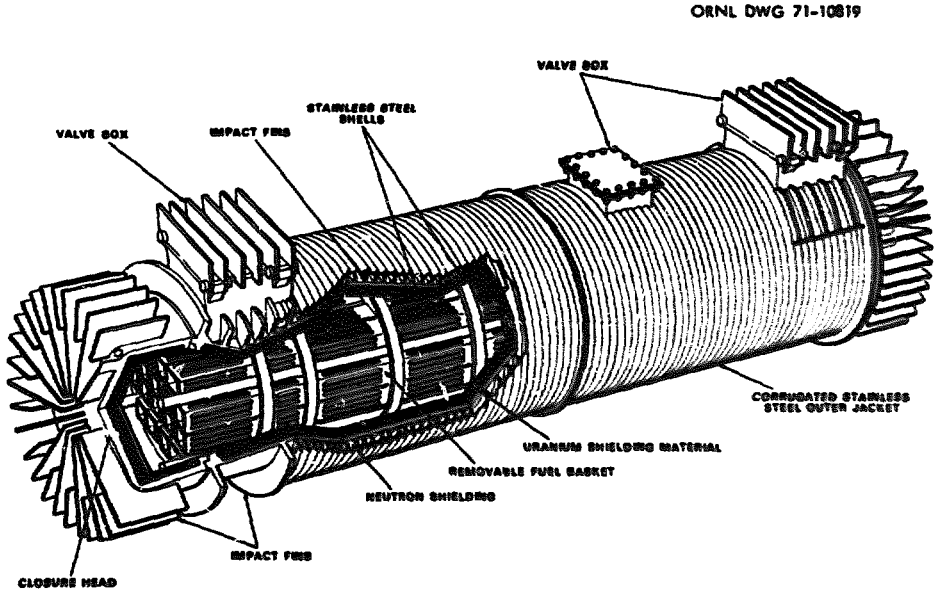

Figure 6
Typical Spent LWR Fuel Cask for up to 10 PWR or up to 25 BWR Fuel Assemblies

TABLE 6

Spent Fuel Shipping Cask Transportation Modes

Capacities and Dimensions	Mode of Transportation				
	Legal Weight Truck	Overweight Truck	Rail	Water	Intermodal (heavy haul to railhead)
Cask capacity, assemblies	1 PWR or 2 BWR	2-3 PWR or 4-7 BWR	10 PWR or 24 BWR	10 PWR or 24 BWR	10 PWR or 24 BWR
Loaded weight, tons	25 (max.)	30-40	100	--	--
Overall dimensions	4' diam x 19'	5' diam x 19'	8' diam x 19'	--	--
Vehicle dimensions	8' x 55'	8' x 55'	10.5' x 75'	10' x 105'	10' x 105'
Gross vehicle weight, tons	36.5	45 to 55	200	175	175
Shipping package dimensions	--	--	--	10' x 40' x 13' high	10' x 40' x 13' high

Taken from Proceedings of the Third International Symposium on Packaging and Transportation of Radioactive Materials, "Spent Fuel Transportation - State of the Art," by R. W. Peterson, CONF-710801, Vol. 1, pp. 415-436 (August 1971).

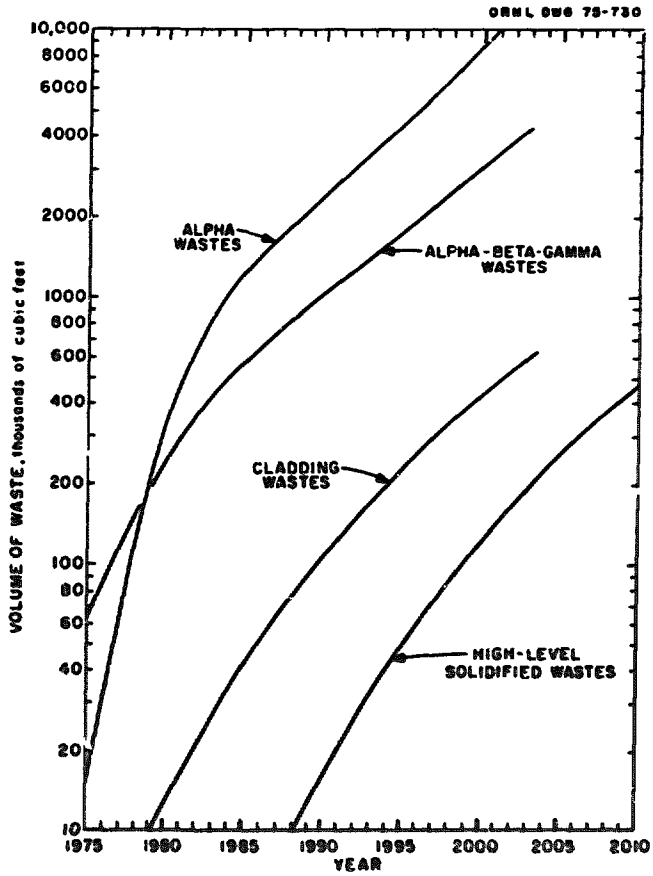

Figure 7
Projected Accumulated Amounts of Various Types of Solid Wastes at a Future Federal Repository

further extensive testing procedures are prescribed and carried out on casks and their prototypes to ensure structural integrity and virtual infallibility of sealing devices for the few openings such casks have. These tests include several kinds of impacts, in addition to stringent fire and water resistance tests. Also, extensive analyses of the likely consequences and remedial actions associated with accidents are carried out, and Nuclear Regulatory Commission approvals are required.

High-Level Radioactive Wastes

After fuel reprocessing, the fission product wastes solutions may be stored in underground tanks for up to five years before solidification preparatory to shipment to a federal repository. There is at present no federal repository for waste, and (as mentioned earlier) no commercial fuel reprocessor for spent fuel. Nonetheless, the broad outlines of how the wastes will be handled are clear, and certainly the amounts of waste to be handled can be predicted accurately from an assumed size of nuclear power industry and relative number of power reactor types, i.e., LWR, HTGR and LMFBF. The projected amounts of accumulated (solid wastes are shown in Figure 7. The size of container used for storing these wastes will be set by the rate of heat release during the first few years of storage, as well as by the nature of the storage facility. It is probable that many wastes will be stored in salt deposits because of the geological stability and physical properties (such as low humidity and plastic flow of the salt which will help to "heal" cracks) of such deposits. The inner containers will have to be shielded for shipment, and shipment may be by truck or rail. Since they are not to be re-opened, the inner containers may be welded shut before shipment, and it is extremely unlikely that any accident could breach the containment and release the fission products during transport. It is more likely that a container might lose shielding during an accident, but this too is not probable, and even if it occurs, appears to be a manageable problem. A typical waste storage inner container, or cannister, may be a 12-inch-diameter cylinder about 10 feet long. About ten such cannisters may be required to hold the high-level waste from a year's operation of one 1000 MWe reactor. Figure 8 shows a possible arrangement of such cannisters and their shipping cask.

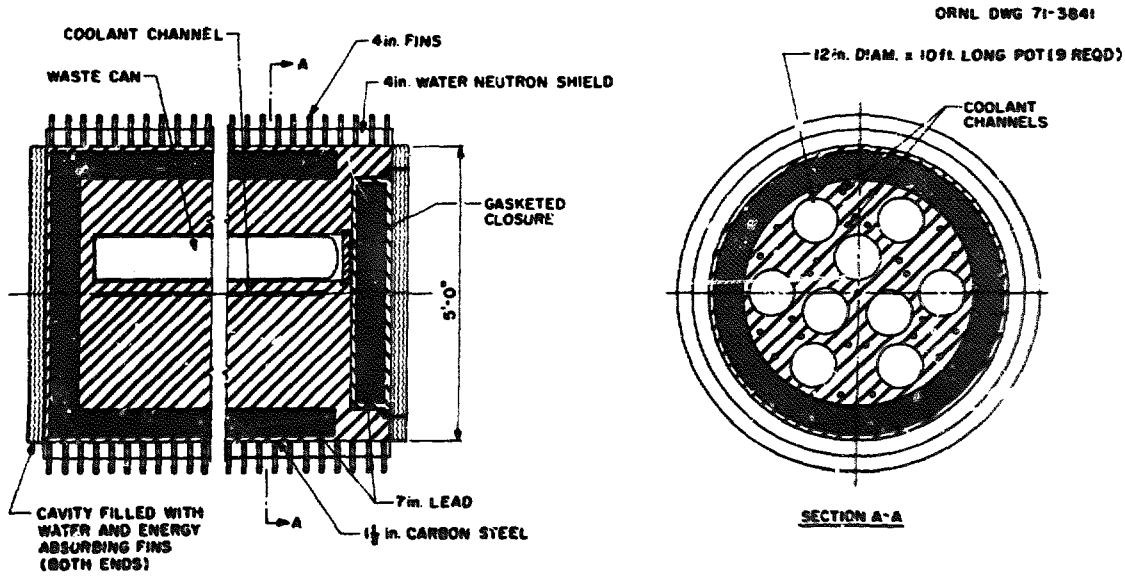

Figure 8
Schematic Representation of a Possible High-Level Waste Storage Cannister and Shielding Shipping Cask Arrangement

Conversion Plant, Reprocessing Plant and Enrichment Plant Products

The uranium product from conversion plants is UF_6; from fuel reprocessing plants it may be either solid UF_6, nitrate solution, or oxides. As was mentioned earlier, the trend is toward shipping UF_6 from reprocessing plants as well as from gaseous diffusion plants for uranium enrichment. Figure 9 shows typical shipping containers for natural UF_6, and Figure 10 shows containers for $\leq$ 5% enriched UF_6. In general, these containers are shipped by truck.

In the past, uranium and plutonium have been shipped as aqueous solutions following fuel reprocessing. Plutonium nitrate solution shipments in particular have been criticized. One criticism is that solutions are more likely to leak from a container than are solids, and if released from the container, could spread more readily than a solid, and might prove more difficult to recover. Another is that radiolysis of the water produces hydrogen and oxygen which would recombine explosively, spreading plutonium. A final point to consider when comparing liquid and solid shipments is the ease of loading and unloading the containers. There is little doubt that liquids have the advantage in this comparison. The operation with liquids is both cleaner and easier, and probably safer. Nonethless, as stated above, the federal regulations now require plutonium to be shipped as solid after June 17, 1978 (probably as PuO_2) when the amount exceeds 20 curies. However, liquid shipments are not prohibited and may continue to be used for uranium.

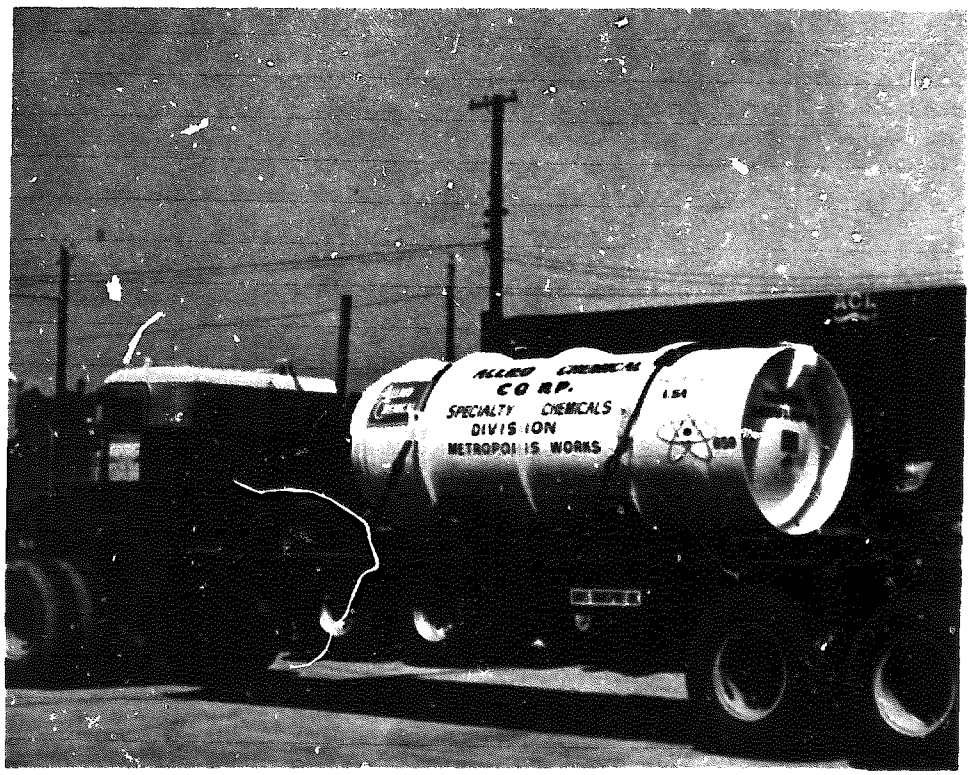

Figure 9
Typical UF_6 Shipping Containers for Natural Uranium
(The near container holds 14 tons and the far container holds 10 tons.)

Figure 10
Typical UF_6 Shipping Container and Protective Carrier for Enriched Uranium.
(Capacity: 2½ tons of ≤ 5% Enriched UF_6.)

Mill Concentrate

The U_3O_8 (or diuranate) concentrate from the uranium mills is packaged in standard 55-gallon drums for shipment by truck or rail to the conversion plant.

Fabricated Fuel

Fabricated fuel, with the exception of future HTGR recycle fuel, is relatively non-radioactive, and the transportation problems associated with it are more those of protecting it from damage than protecting the public from it. (HTGR recycle fuel is an exception, since it will contain ^{232}U, whose decay chain daughters are intensely radioactive, requiring heavy shielding.) There will be, however, a small amount of neutron emission, especially from future LWR recycle fuels which contain plutonium. Care will be necessary to protect workers from the neutron radiation. Because of the value of the fabricated fuel assemblies, only two are entrusted to a single container, and the containers are carefuly packaged in shock-absorbent carriers. Figure 11 shows a typical shipping arrangement for fabricated LWR fuel assemblies. These fabricated fuel containers are shipped mainly by truck.

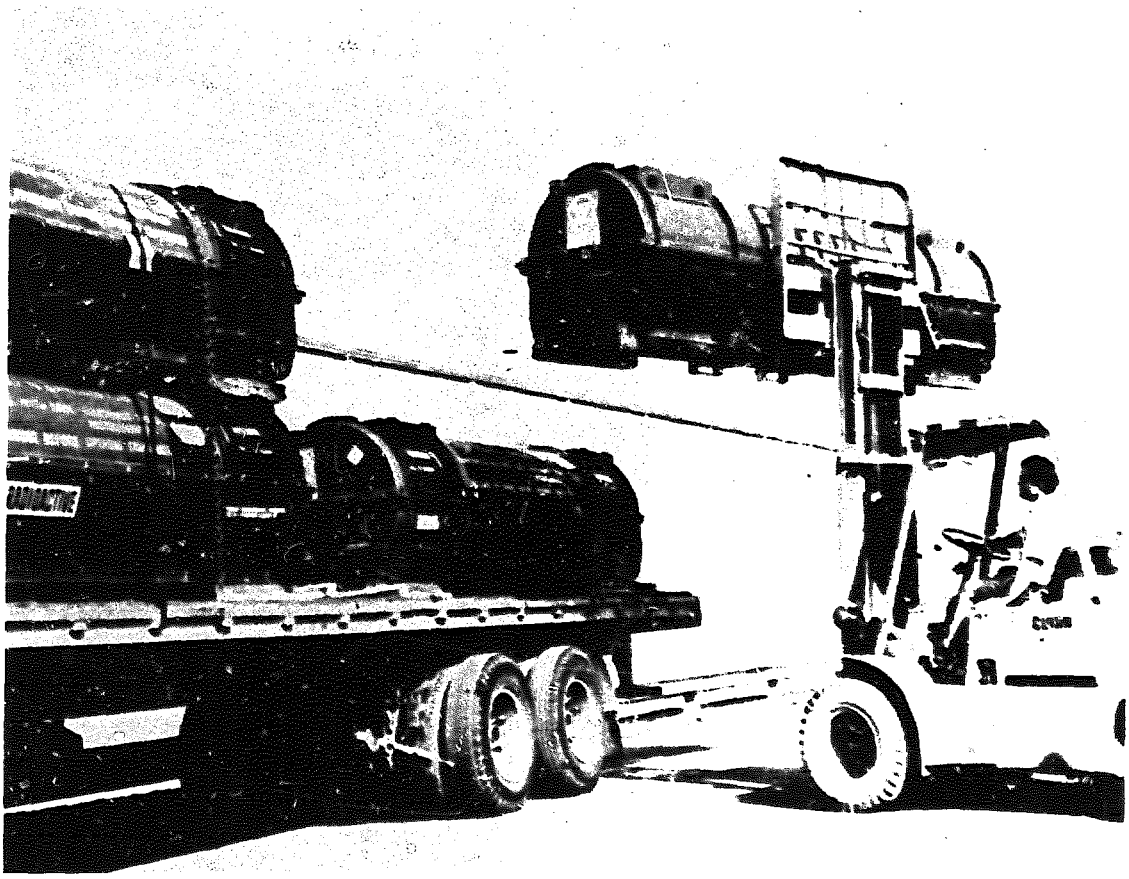

Figure 11
Fabricated LWR Fuel Assembly Shipping Containers

Miscellaneous Radioisotopes

The amounts of radioisotopes used in specific research, medical and industrial applications are usually small. Figure 12 shows a typical disposable shipping container for solids. The specific type used depends on the amount and type of radioactivity. Of course, when radioisotopes emitting large amounts of penetrating radiation, as for example from ^{252}Cf, ^{60}Co or ^{137}Cs are shipped, special containers with heavy shielding are required.

RELATIONSHIP OF SHIPPING TO SITING

It has been mentioned several times that the locations of the various parts of the fuel cycle with respect to each other are very important in determining the nature of the transportation problems. Because the mine and mill are always near each other, the great bulk of ore need not be shipped far before it is concentrated over 100-fold. The concentrate is not a radiation hazard, and is of relatively low value (nominally about $8 per pound) so its transport to the conversion plant is not a significant shipping problem. Further, shipment of natural uranium as UF_6 does not appear to pose many problems, though as has been pointed out, there will be quite a significant amount of this material shipped annually.

Extraordinary attention and precautions are required when uranium enriched to a level suitable for making weapons is shipped, or when plutonium is shipped. Special treatment and handling are also required when highly radioactive materials, such as spent fuel assemblies or high-level wastes, are shipped. If, for example, reactors, fuel reprocessing plants, and fuel fabrication plants were all on the same site, both spent fuel shipment and undiluted plutonium shipment off-site would be obviated. However, while this arrangement would take care of many of the potential shipping problems, it would create problems of its own. One of the most important problems is that

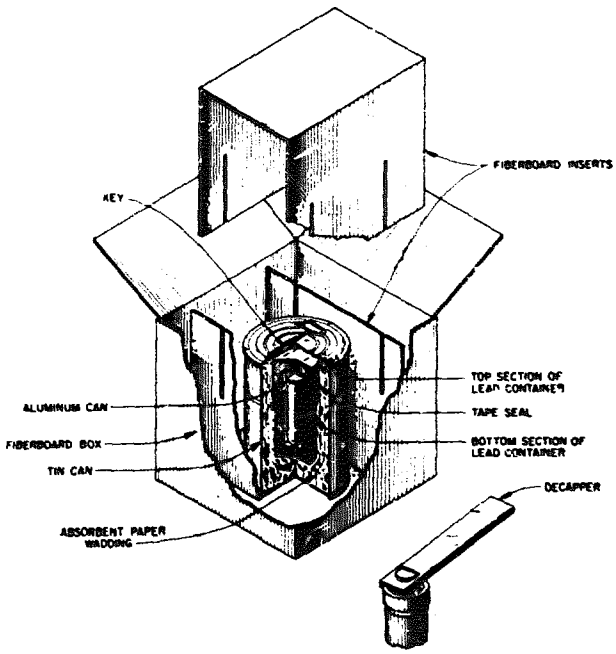

Figure 12
Disposable Shipping Container for Miscellaneous Solid Radioisotopes

TABLE 7

Comparison of Transportation Requirements in the Year 2000 for Dispersed versus Co-Located (Integrated) Fuel Recycle Facilities.

	Dispersed Facilities	Integrated Facility
Fresh Fuel		
Number of shipments	9601	9601
Vehicles in transit	26.3	145
Mass heavy metal in transit, tons	80	440
Spent Fuel		
Number of shipments	15,987	15,987
Vehicles in transit	88	307
Radioactivity in transit, MCi	659	2258
93% $^{235}UF_6$[a]		
Number of shipments	70	70
Vehicles in transit	0.4	1.3
Mass U in transit, tons	0.3	1.0
Plutonium Oxide[b]		
Number of shipments	722	0
Vehicles in transit	2.0	0
Mass Pu in transit, tons	1.0	0
HTGR-Uranium Oxide[c]		
Number of shipments	50	0
Vehicles in transit	0.14	0
Mass U in transit, tons	0.07	0
40% ^{235}U Oxide[d] (recycled U from HTGRs)		
Number of shipments	23	0
Vehicles in transit	0.06	0
Mass U in transit	0.03	0
High-Level Solidified Waste[e]		
Number of shipments	252	0
Vehicles in transit	5.0	0
Radioactivity in transit, MCi	56	0
Alpha Solid Wastes[f]		
Number of shipments	1144	0
Vehicles in transit	25.1	0
Mass actinides in transit, tons	0.06	0
All Other Wastes[f]		
Number of shipments	83,770	0
Vehicles in transit	367	0
Radioactivity in transit, MCi	8.3	0

[a] Isotopic composition is 1.0% ^{234}U, 93.1% ^{235}U, 0.2% ^{236}U, 5.7% ^{238}U.

[b] Isotopic composition is 1% ^{238}Pu, 59% ^{239}Pu, 24% ^{240}Pu, 12% ^{241}Pu, 4% ^{242}Pu.

[c] Isotopic composition is 0.041% ^{232}U, 59.6% ^{233}U, 26.3% ^{234}U, 8% ^{235}U, 6.1% ^{236}U.

[d] Isotopic composition is 1.4% ^{234}U, 40.7% ^{235}U, 43.9% ^{236}U, 14% ^{238}U.

[e] High-level waste is shipped ten years after it is generated in reprocessing.

[f] Wastes are shipped one year after their generation.

[Taken from J. Blomeke, C. W. Kee and R. Salmon, Projected Shipments of Special Nuclear Material and Wastes by the Nuclear Power Industry, ORNL-TM-4631 (August 1974), Table 1.]

a five tonne per day fuel reprocessing plant, which is the size plant under construction by Allied-General Nuclear Services, and being planned by Exxon Nuclear (and is about the minimum size planned for future plants) will take care of fuel from about 60 LWRs. Locating this many reactors on a single site would pose rather enormous problems of energy distribution, as well as of waste heat dissipation. There would also have to be a high-level waste solidification plant on-site, but this is no different from the requirement for any large fuel reprocessing plant. A more reasonable approach appears to be to locate only the reprocessing and fabrication operations on a single site. This would necessitate spent fuel and fabricated fuel shipment, but would minimize plutonium shipment. Table 7 compares transportation requirements in the year 2000 for dispersed versus co-located fuel recycle facilities. Co-location of reactors with the recycle facilities is not included. The reactors are considered to be distributed about the country near the load centers, as they are today.

TRANSPORTATION ACCIDENTS

The subject of transportation accidents is complex, and deserves a separate essay devoted solely to it. Nevertheless, some mention of accidents is in order. Because accidents are by their nature statistical, there is always an element of uncertainty about them, and despite the odds against one occurring, a critic can always say "Yes, I know the odds are very large against one, but what if one happens?" Such questions may lead to subjective responses and to expensive and even unreasonable precautions.

There is a fair body of statistical information on rail and truck accidents. This information may be used to calculate the probable frequency and severity of accidents during the transport of the most important materials in the nuclear fuel cycle. The usual measures of severity of an accident are in terms of human injury and life lost, and in dollar value of property damaged or destroyed. When considering the nuclear fuel cycle, there must be added the somewhat different factor of spread of radioactive materials which may lead to a persistent and serious long-term pollution of a large area, or to the possibility of an unacceptable spread of radioactivity over a large region. This factor is in many ways similar to the spread of toxic chemicals. In both cases there is a continuing hazard from accidentally released material. In both cases, it is possible to clean up the area, though it must be admitted that nature is more forgiving, i.e., better able to assimilate and reduce the hazard to an acceptable level, in the case of chemical spills than in radioactive materials spill. In the former case, dispersion, dilution, and assimilation return the area of the accident to near-normal in months, or at most years. In the case of the most toxic radioactive materials, e.g., the actinides, and especially plutonium, it may be impractical to rely on dispersion and dilution to ameliorate the problem, as decades or centuries may be required. The material must be quantitatively recovered. This could be very expensive in some cases. However, on the other side of the ledger, the radioactive materials would be much more carefully and securely packaged than many toxic chemicals are today, and would be much less likely to be released in an accident.

Experience will tell where an acceptable trade-off lies between the risk of accident and the cost of accident prevention. Certainly at the present time there is a totally different public attitude toward acceptance of "familiar" transportation risks and acceptance of those associated with transporting nuclear materials.

FUTURE TRANSPORTATION PROSPECTS AND OTHER SPECULATIONS

The future of nuclear material transportation will be shaped by decisions being made now and over the next several years. The overriding importance of siting decisions has already been discussed. The implications of the recent suggestion of admixing plutonium with uranium prior to shipment from the fuel reprocessing plant have also been mentioned.

Not mentioned so far in this essay, but being studied is the possibility of very complete removal of the actinides plutonium, curium, americium and neptunium from high-level wastes before sending tem to the planned federal solid waste storage facility. This proposed modification to waste management raises the question of how to handle the separated actinides. One suggestion is to put them back into a reactor, where they woudl eventually undergo fission to produce fission products. This could be accomplished by incorporatin them in reactor fuels, or by fabricating them separately into special assemblies for insertion in a reactor. In either case, their high specific alpha activity would produce neutrons by (α, n) reactions with oxygen and other low atomic weight elements, and special carriers would be needed to carry them safely.

The cost and complexity of all parts of the nuclear fuel cycle are raising questions about the ability of private industry to handle the problems Consortia of industrial firms and various kinds of federal government participation are being suggested to permit development of nuclear power to go forward. Such arrangements would reflect themselves in the transportation area in that they would influence size and location of all parts of the nuclear fuel cycle. They might also affect the nature of the shipping operations insofar as the amount of acceptable risk depends on the nature of the organization underwriting the risk.

APPENDIX - REGULATIONS GOVERNING SHIPMENT OF RADIOACTIVE MATERIALS

U. S. Code of Federal Regulations: 10 CFR Part 71
U. S. Code of Federal Regulations: 10 CFR Parts 173-178
Regulations for the Safe Transport of Radioactive Materials, 1973 Revised Edition, IAEA, Vienna (1973)
Advisory Material for the Application of the IAEA Transport Regulations, IAEA, Vienna (1973).

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AN ELEMENTARY SURVEY OF NUCLEAR SAFEGUARDS PROBLEMS*

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INTRODUCTION

The background for this paper is the author's work in connection with safeguards for a commercial high-temperature gas-cooled reactor (HTGR) fuel recycle plant. In the course of this work, it became apparent that the problems of safeguards are not really those of technology — the customary center of attention of engineers and scientists — but rather those of aberrant human behavior. Technology enters only as a means of response, or control, or prevention of undesirable human action.

In current parlance,[1] safeguards refer to the protection of special nuclear materials (SNM) such as plutonium or uranium enriched in ^{233}U or ^{235}U from theft or diversion. There is an older usage where safeguards meant what we now call safety, as in the name of the ACRS, the Advisory Committee for Reactor Safeguards.

There are two basic aspects of safeguards for SNM — accountability and physical security. The first aims to provide prompt information on inventories to detect thefts or diversions as well as to assure the equally important fact that they have not occurred. Much the same sort of information, although generally not to the same level of precision, is necessary for process control as well. The second aspect, physical security, is intended to prevent undesirable malicious acts through the use of guards, alarms, fences, and related measures.

The discussion which follows will be confined mainly to the subject of safeguards for fixed sites, omitting the very vital matter of transportation safeguards. We will briefly outline the legal and quasi-legal requirements and point out some of the cost aspects as well. The main emphasis will be on physical security.

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*Research sponsored by the U.S. Energy Research and Development Administration under contract with the Union Carbide Corporation.

LIMITATIONS OF ACCOUNTABILITY AND PHYSICAL SECURITY

As has been noted, accountability is a necessary part of plant operation, even when theft or diversion are not at issue. Orderly and economic process management requires knowledge of amounts and locations of inventories. However as safeguards measures, the techniques of accounting are necessarily passive, noting events only after they occur. There is therefore always a time lag between detection and responsive action. (Considerable work is currently under way, designated by the acronym RETIMAC — for Real Time Accounting — to minimize this lag.) Further, assaying devices can never be made tamper-proof or perfectly accurate. Both false alarms and false assurances are possible. Lastly, accountability has little relevancy to acts of sabotage and violence.

The preventive function is supplied by physical security. Physical security measures need not be wholly passive but can be quite as aggressive as the situation demands. For example, fences and walls are perfectly passive barriers, but they could be supplemented by patrols actively looking for intruders. Obviously, by multiplying guards, surveillance, and searches, a fortress-like atmosphere could be created that would be difficult to accept in a civilian industrial context.

Both methods have a limitation in common. They cannot insure that no thefts or sabotage will ever occur and a finite risk must always be accepted since only a finite amount of resources are available for protection.

AN INTUITIVE RANKING OF THREATS

In Table 1, a list of threats is displayed based upon a subjective ranking according to likelihood of occurrence and magnitude of consequences. The less probable an event was thought to be, the lower it was placed on the list; the more an event's potential for destruction of life and property, the higher it was listed. For example, the lowest ranked event, a theft detectable by accountability procedures, will probably not occur in the manner given, that is, as an attempt to remove a substantial quantity of SNM through a network of alarms and guards. Rather, the material would most likely leave the plant with all records and passes in perfect order with the actual diversion to occur elsewhere. In that form, the threat is at least as probable as any of the others, but as a transportation safeguards problem, it is outside our present scope. Threat No. 4 requires thieves to be sufficiently motivated to steal dozens or hundreds of times before they have acquired significant amounts, that is, in the kilogram range. Supposing that the chances of successful theft are 0.95 on each try, the chances of making 10 successful thefts are about 0.6 and of 100 only 0.006.

The other threats are physical security matters. There are no reasonable short-cut methods of dealing with them, moreover. A disciplined band of well-armed commandos, properly trained along military lines, would make short work of any civilian guard force. The latter is prevented by law from even possessing the sort of weapons required unless deputized as local law-enforcement officers. As for No. 3, there is no way to predict when or how a person may become destructive. A company of marines at $10,000—30,000 per man-year may effectively prevent 1 and 2, but does nothing about 3. The view advocated here is that the multi-faceted character of the threats may be met by taking steps to limit the consequences of violence to the point where the payoff is too small or insufficiently probable to be worth the risk. In other words, a nuclear site

Table 1. A Subjective Ranking of Threats to Fixed Nuclear Plants

1.	Sabotage by [illegible]
2.	Armed theft of SNM by [illegible]
3.	Employee sabotage
4.	Theft by employees of [illegible] of SNM undetectable through accountability procedures
5.	Theft of SNM detectable by accountability procedures

should be made unfortunate as an object of attack by safety procedures and design measures intended to meet not only the usual outbreaks of industrial accidents but acts of deliberate destruction as well.

Some may doubt the need for serious consideration of employee crime, sabotage, and theft in the nuclear industry. Some may suggest, but not without justification, that such concerns are more the product of melodramatic imaginings than actual threats. Unfortunately, such problems are a long-time feature of American industry. A quote from an otherwise informatively written text on industrial security should suffice to illustrate the point:

> "...there is no type of felonious activity encountered by the nations in several years of law enforcement and security experience which they have not encountered in a quarter of the time in industrial security. Petroleum theft, embezzlement, kickbacks, forgery, anonymous letters, assault, drunken frivolity, murder, rape, suicide, sabotage, blackmail, trespass, forcible entry, bookmaking, narcotics trafficking, counterfeiting, paternity, intimate exposure, prowling, prostitution, industrial espionage, political subversion, and labor agitation in several forms, to mention only some, are encountered directly or indirectly in industrial security experience."[2]

We may add to the above the particular problem of the vulnerability of our society, based as it is on the proper functioning of innumerable interlinked technologies, to politically motivated violence. In the case of the nuclear industry, it has been suggested[3] that SNM can be used by radicals to make bombs or toxic devices. These are indeed possibilities, but it has been pointed out that those bent on murder can find far more accessible techniques.[4,5] In this writer's view, the chief safeguards problem of the fixed plants of the nuclear industry is, rather, protecting them against sabotage and other destructive acts which might disrupt valuable facilities upon which society will be increasingly dependent.

GUIDANCE IN SAFEGUARDS FROM THE NUCLEAR REGULATORY COMMISSION

To assist private owners of nuclear facilities and to protect the general public, the Nuclear Regulatory Commission both controls and advises in matters of safeguards. The rules for commercial installations are to be found under Title 10 of the Code of Federal Regulations, generally called 10CFR for short.[6]

The sections of most significance in safeguards are:

10CFR50	Licensing of Production and Utilization Facilities
10CFR70	Special Nuclear Materials
10CFR73	Physical Protection of Plants and Materials

These regulations have the force of law and include penalties for violations. The public is notified of these rules through the Federal Register, a daily government publication. As these rules have the force of law, plenty of time is allowed for public scrutiny and comment before final promulgation. An example of one of the most important of such rules is shown in Table 2 reproduced from 10CFR70.51(e)(5) on the subject of limits of error in estimation of material unaccounted for (LEMUF and MUF).

Since rigid, legally binding rules cannot always be provided, advice in the form of regulatory guides is provided. These are short documents which deal with the regulator's views of various nuclear design problems. They are, as Table 3 shows, organized into 10 divisions. The main sources of information for safeguards are divisions 1, 3, and 5 (which are underlined in Table 3). They cover many subjects — in April 1975, 49 were listed in division 5 alone — such as how to organize a guard force, how to prepare a license application, how to design material balance areas, etc.

Table 3. The Divisions of the Regulatory Guides

(Safeguards-related guides found mainly in underlined divisions.)

1.	POWER REACTORS
2.	Research and Test Reactors
3.	FUELS AND MATERIALS FACILITIES
4.	Environmental and Siting
5.	MATERIALS AND PLANT PROTECTION
6.	Products
7.	Transportation
8.	Occupational Health
9.	Antitrust Review
10.	General

The code and the guides do not, however, provide a "cookbook" for solving the safeguards problem in any particular case. They mainly inform license applicants what issues are regarded as important. The safeguards requirements are tailor-made by negotiation between the regulatory staff and the applicant to suit the circumstances; the rules form a minimum starting point for such a negotiation process. The reader is referred to Ref. 7 for a more detailed description than is possible here.

Licensees are also subject to the provisions of the nuclear Non-Proliferation Treaty which came into force in 1970. Under this agreement, the International Atomic Energy Agency (IAEA) has the responsibility for safeguards regulation. While the treaty is in fact a law of the United States, it is probable that conformance to U.S. regulations will be sufficient for the purposes of the IAEA.

Table 2. A Sample Excerpt from the Code of Federal Regulations, 10CFR70.51(e)(5)

...

"(5) Establish and maintain a system of control and accountability such that the limits of error for any material unaccounted for (MUF) ascertained as a result of the material balances made pursuant to paragraph (e)(3) of this section do not exceed (i) 200 grams of plutonium or uranium 233, 300 grams of high enriched uranium or uranium 235 contained in high enriched uranium, or 9,000 grams of uranium 235 contained in low enriched uranium, (ii) those limits specified in the following table, or (iii) other limits authorized by the Commission pursuant to paragraph (e)(6) of this section:

Material Type	Limit of Error of MUF on Any Total Plant Inprocess Material Balance[3] Percent
Plutonium element or uranium 233 in a chemical reprocessing plant	1.0
Uranium element and fissile isotope in a reprocessing plant	0.7
Plutonium element, uranium 233, or high enriched uranium element and fissile isotope—all other	0.5
Low-enriched uranium element and fissile isotope—all other	0.5

[3]As a percentage of additions to or removals from material in process, whichever is greater.

Any licensee subject to this paragraph on December 6, 1973, who requests higher limits pursuant to paragraph (e)(6) of this section at the time he submits his program description under the provisions of paragraph (g) of this section is hereby authorized to operate at the higher limits until the application for license or amendment has been finally determined by the Commission."

...

SOME SPECIFIC ASPECTS OF ACCOUNTABILITY REQUIREMENTS

There are two important aspects of the accountability requirements for SNM. First, they are responsibilities which are to be met independently of plant operation. The rules appear to mean that a "watchdog" group is to be set up with SNM control as its sole concern. The second is that the design of any plant must take into account the need to provide inventory information of sufficient quality to meet regulatory specifications, in particular those which are displayed in Table 2. While temporary exceptions may be granted, sooner or later the standards must be met.

The basic regulatory guide in the field of accountability is R.G. 5.9, Standard Format and Content for the Special Nuclear Material Control and Accounting Portion of a Special Nuclear Material License Application (Including that for a Uranium Enrichment Facility), (12/74). This guide consists of 12 chapters. The applicant is advised to discuss his plans with the regulatory staff before preparing the application. When the plans are received, the staff conducts a preliminary review of their adequacy. Proprietary information can be withheld from public disclosure. (In this connection, it is important to note that actual safeguards plans, particularly physical safeguards plans, are treated confidentially between the regulators and the applicant.) The following technical information is required of the applicant, to be presented in a definite format:

1. Design bases, criteria, and features of the plant important to SNM control and accounting.
2. Material control areas and the reasons for their selection.
3. Capability, if any, for automated SNM control and accounting.
4. Capability for measuring all receipts, shipments and inventories as well as systems to assure continued validity of previous measurements. This portion should also describe the accuracy and precision of the measurements and the effect on total material balance uncertainty.
5. Capability to account for SNM in wastes and scrap.
6. Characteristics of SNM storage and handling used to maintain control.

Physical inventories of fuel reprocessing plants are required every six calendar months, or in the case of uncontaminated uranium enriched more than 20%, two months. A complete description of the methods to be used, the records to be kept, and the management systems used to ensure enforcement and compliance must be provided. Also, the licensee must describe his plans of action should he find that the amounts of material unaccounted for exceed prescribed limits, when significant receiver-shipper differences are noted, or when items or containers of SNM are missing. Responsibility and authority for action under such circumstances are to be specifically pinpointed. The regulations use the phrasing "...establish, maintain, and follow written material and accounting procedures..."; this triple emphasis is plainly intended to convey the idea that lapses can be cause for penalties. The plans presented for the purpose of obtaining a license are not mere provisions which can be unilaterally modified or forgotten. Rather, they will provide a documentary basis for compliance in the continual process of governmental inspection and regulation.

PREVENTIVE MEASURES AGAINST THEFT, TERRORISM, SABOTAGE, OR IRRATIONAL ACTS

Both within the regulatory guides and without, a large number of ideas have been suggested for providing physical security at nuclear plants.

Regulatory Guide 1.17, Protection of Nuclear Power Plants Against Industrial Sabotage, bears most closely on this subject, and a corresponding guide for fuel reprocessing plants is in preparation. Some of the important techniques which might be used are described below:

Preemployment Screening

Regulatory Guide 1.17 rests in turn on ANSI N18.17, "Industrial Security for Nuclear Power Plants." This document recommends an investigation prior to employment or prior to an "unescorted" assignment to disclose adverse character traits and an examination by a psychiatrist or other qualified person qualified to identify aberrant behavior.

Now it is common experience that improper preemployment screening or the lack of it is foolish and can even lead to disastrous results. The circumstances of the recent Purolator robbery[8] suggest that the crime might have been prevented by a routine background check. The convicted "atom spy" Klaus Fuchs was cleared for secret work despite the fact that his Communist sympathies were easily discoverable.[9] The need for such screening is clear, and proper technical methodology appears to exist.[10,11] However, employers must exercise care to avoid conflict with the 1964 Civil Rights Act as enforced by the Equal Employment Opportunities Commission. For instance, overzealous probing can become invasion of privacy; rejecting a job applicant for a condition which may already be present among employees doing the same work may be treated as illegal discrimination. Never a simple matter, the employee screening process is being made more complex by the need to comply with new legal requirements and changing social standards.

Employee Relations Procedures

In the United States, union-management relationships are characteristically fractious. The nuclear industry is no exception, as the recent inspection reports of the Kerr-McGee Corporation's Cimarron Facility suggest.[12] The following policies, if implemented, may help to prevent the generation of attitudes of discontent and suspicion:

1. In enforcing the discipline of work procedures, the benefits to the worker of on-the-job safety and health protection should be stressed, rather than security. Too much emphasis on security will soon suggest that management regards the employee as untrustworthy, an attitude sure to be reciprocated.

2. Employee surveillance methods should be visible and above board. The reasons for them should be clearly explained, with emphasis on the benefit to the employee. Any methods that suggest entrapment must be scrupulously avoided.

3. Since the security profession can be attractive to unstable personalities (such as paranoids or thrill-seekers), special care needs to be taken to select guards and security supervision for positive, down-to-earth attitudes with strong motivations for service.

4. Personal discontent can occur both on and off the job. The services of professional mental health practitioners as counselors should certainly be considered.

5. In this industry, pronounced differences between supervisors and subordinates in education and background are likely to exist. Often these lead to

conscious or unconscious attitudes of superiority, personal slights, permanent stereotyping in inferior roles, and the like. The possession of interpersonal supervisory skills should not be assumed to go with a technical education. Management should take definite steps to ensure that supervisors receive proper training in these matters.

Surveillance Procedures

Polygraphing (the use of the lie detector) depends very strongly on the competence of the operator. Since training of operators is highly variable and equipment is often improperly used or out of date, this technique has little to recommend it. The use of closed-circuit television for direct observation seems to have considerably more merit, but only if practiced openly. Besides being an obvious deterrent to crime, such devices have an important safety value since plant supervision can instantly spot incidents of accident or injury, even recording them for later reference. The subject of visual surveillance is covered by Regulatory Guide 5.14. Personal search methods may be carried out directly by "frisking" or package searches by plant guards. As such procedures are obviously slow and distasteful, Regulatory Guide 5.7, Control of Personnel Access to Protected Areas, Vital Areas, and Material Access Areas, suggests several other approaches aimed at achieving the same results with fewer problems. The use of badges in the form of electronic cards which can be read by a machine to record identity and time is one recommendation. Portal monitors to detect radioactive materials and metal are well established. Explosives detectors, on the other hand, are not presently considered effective.

Clothing Change

This method has all the virtues of impersonality and simplicity. It is easy to design a change room (as in Regulatory Guide 5.7) for the purpose which would vastly reduce the probability of smuggling weapons, explosives, or SNM in or out. Moreover such a room can also serve the function of insuring that radioactive contaminants do not accidentally pass through, particularly if the opportunity for voluntary, self-administered, health physics checks is offered.

"Black-Hat" Testing

A special problem of groups responsible for safeguards, accountability, and physical security is that a good part of the time, hopefully all of it, they cannot be certain that they are acting correctly. They are supposed to prevent theft and sabotage as well as stop those engaged in it. If nothing untoward ever happens, they cannot tell whether this desirable condition results from the measures which have been taken or because no one has gotten around to testing them. Questions begin to be raised over whether this or that procedure is excessive: Are there too many guards? Is it really necessary to spot check packages at the present rate? If a TV camera fails to cover a particular area is it necessary to repair or replace it?

Sometimes such considerations lead to genuine economies; in other cases they may be symptoms of laxness. The latter will sooner or later become evident, either as a result of a crime or as a citation by a regulatory inspector for non-compliance (with subsequent fines). It is therefore worthwhile considering whether limited use ought to be made of "black-hat" operatives to test the effectiveness of security measures in real plant circumstances. For example, an agent could approach the perimeter fence to see if there is an adequate response to a feigned attempt to break in; a counterfeit employee could try to carry out

some nuclear material, or wander into a prohibited area, or act as if he were in the process of sabotage. Obviously, such practices must be carefully controlled, for, if carried to excess, they could lead to injuries, death, or damage.

SABOTAGE BY ARMED GANGS

In the previous discussion of sabotage and other kinds of violence, there was a tacit assumption that these would be the deeds of individuals and that the force required to meet them was that which we associate with civil police and guard forces. The actions of a commando group are another matter, however, and we expressed the opinion earlier that civilian guards could not put up a worthwhile defense against a well armed and trained commando group. There is considerable room for argument over whether industry is supposed to provide its own protection against attacks of such size. The Code of Federal Regulations, paragraph 50.13 states that "an applicant ... is not required to provide for design features or other measures for ... protection against the effects of ... attacks ... by an enemy of the United States, whether a foreign government or other person..."; on the other hand, the provisions of 10CFR73.40 require a licensee to provide physical protection against industrial sabotage and against theft of SNM.

The possibility of commando actions cannot be ignored. Terrorist and revolutionary groups have spread their activities far from their original foci in Ireland or the Middle East. So called "urban guerillas" have blown up a bank branch, a computer center, and power lines. On May 3, 1975, a reactor being constructed at Fessenheim, France was damaged by plastic explosives. It is quite conceivable that groups may arise which view nuclear industry as an evil which ought to be wiped out by violence.

To meet such threats, some have advocated[3] formation of a Federal guard force while others[10] have debated the merits of "hardening" of facilities. The ramifications of these discussions are too broad to be treated here. However, there are other steps which can be taken which do not seem to involve any unusual new initiatives on the part of private industry. One of the most effective defenses against attacks by armed gangs is their ignorance of the target. The secrecy which has long surrounded contractor installations, such as those in Oak Ridge, may well be a major reason for the lack of incidents since 1942. No group of raiders is going to consider an attack if they have no idea what defenses exist, where the weak points are, or even what their objective should be. As has been pointed out, actual plans for physical security are known only to the licensee. This policy could be further extended by attention to publicly available documents such as environmental impact statements and safety analysis reports to see that they do not contain information which would be necessary to planning an attack. Precise information on plant protection systems against fire or other disaster, exact flow layouts which give the location of vital areas or equipment should not be available. It should be possible to present such material in a generic way which would satisfy the legitimate rights of public inquiry. This matter is currently under study by government agencies.[14]

A second important defense against sabotage is that offered by safety measures which, for the most part, are taken in any case as sensible and required parts of the plant design and operation. What we suggest here is that those in private industry planning safety measures have in mind, as an extension of their customary 'fail-safe' philosophy, the idea of an armed gang having complete freedom of action for a limited time (say 30 min) to attempt malicious acts.

(It follows, incidentally, that if a plan is effective against an intentional act, the plan is equally effective gainst an unintentional one. The difference between carelessness and sabotage is only in the state of mind of those involved.) Plants should not have within them means which saboteurs can use for destructive purposes conveniently. For example, chemicals such as nitrates and organics which can easily be turned into explosives should be kept far apart; processes which generate dusts should be designed so they cannot be deliberately mismanaged into producing explosions; the utilization of chemicals such as acetylene, propylene, and hydrogen (frequently used in nuclear fuel reprocessing) should be so designed that if they cannot be prevented from exploding or catching fire, the potential damage from such incidents would not be worth the risk of trying to cause them. Careful attention should be given to the consequences of deliberate disruption of utilities such as electric power, steam, compressed air, or water, both by day and night. The matter of criticality accidents — there is nothing new about this subject's receiving great and detailed scrutiny by regulatory agencies — should be examined from this standpoint by license applicants. Finally, if safety analysis reports prominently advertise the fact that anti-sabotage measures have been actively considered, that in itself would be a deterrent.

COST OF SAFEGUARDS

Some idea of the costs involved in implementing safeguards procedures in fixed plants is given in the GESMO report[15] and in the LMFBR environmental statement.[16] These data are presented in Tables 4 and 5. There is argument over how these costs are to be borne, but regardless of the technique of financing, ultimately the public will find them added to the cost of power.

Table 4. GESMO Report Costs

To Protect a Processing Plant Against	
Theft:	$1 million
Q Clearances:	$800 each
Personal Immobilization Systems	
	$100,000 installed 30,000 annual maintenance
Guards:	$20,000 per man-year
Advanced Identification System	
	$25,000 for central unit 5,000 each access point 5,000 per year operating costs
Portal Detectors:	$3000–15,000
RETIMAC:	$1.5 million plus $150,000 per year

Table 5. Fuel Reprocessing and Fuel Fabrication Plant

	Fuel reprocessing plant costs (millions of $)	Fuel fabrication plant costs (millions of $)
Alarmed Perimeter Fences	1.5	1.5
Internal Intrusion Alarm Systems	1.0	3.0
Internal Communications and Monitoring System	1.0	3.0
SNM and HE Monitors at Personnel Access Control Points	0.2	0.5
Off-Site Communications Systems	0.5	0.5
Physical Barriers Surrounding Process Stream	1.0	2.0
SNM Materials Accounting System	3.0	6.0
Other, Including Special Plant Design Features	3.0	5.0
Number of Guards at $30,000 Per Year Each Per Facility	12	24

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Energy and the Climate

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The global climate has always been changing. Geological evidence leaves little doubt that the prevailing climate of the Earth during the past billion years was warmer than present-day climate by as much as 10°C, and almost totally free of polar ice. Beginning about 50 million years ago, something happened to cause a slow deterioration of climate, until about 2 million years ago when a new mode of global climate was established. During these more "recent" years (the past one or two million years), there have been cyclic variations on several different time scales, but documentation of changes by direct measurement is much more recent.

In the last several decades of quantitative meteorological documentation, more rapid – and in some respects quite systematic – variations of global climate have been identified. Since these fluctuations are the ones which will primarily determine the course of global climate in the years and decades immediately ahead, it is important to note that they are not demonstrably periodic in character and therefore not predictable. The average temperature of the Earth (or at least that of the Northern Hemisphere) has varied during the past century from a minimum in the 1880's (perhaps a consequence of strong volcanic activity then) to a maximum around 1940, and a cooling tendency from 1940 to the present time as shown in Figure 1.[1] One cannot say with confidence whether the cooling of the past few decades will continue in the future, and if so for how long.

Radiative Balance of Earth-Sun-Space

Since any large scale climate change must be associated with the energy budget of the earth and its atmosphere, an examination of the delicate mechanisms which give the balance between incoming and outgoing radiation is in order. Figure 2[2,3,4,5,6] shows the balance between incoming radiant energy and outgoing radiant energy. Any activity which changes the amount absorbed or reflected by the atmosphere or the earth's surface will change the distribution of energy in this system, and therefore the climate.

There are four major distinct ways in which man's energy-related activities can change the distribution shown in Figure 2. These are:

a. Change in the total amounts of energy being exchanged – either that coming from the sun or that leaving the earth.
b. Change in the albedo resulting from increased aerosols and other pollutants.
c. Change in the albedo resulting from increases in cloud cover.
d. Change in the optical properties of the atmosphere with increases in carbon dioxide.

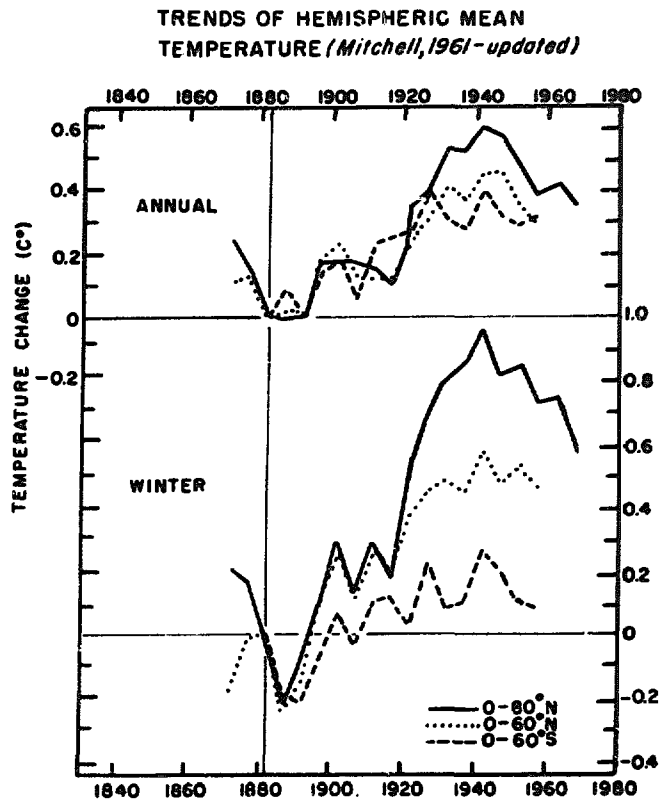

Figure 1

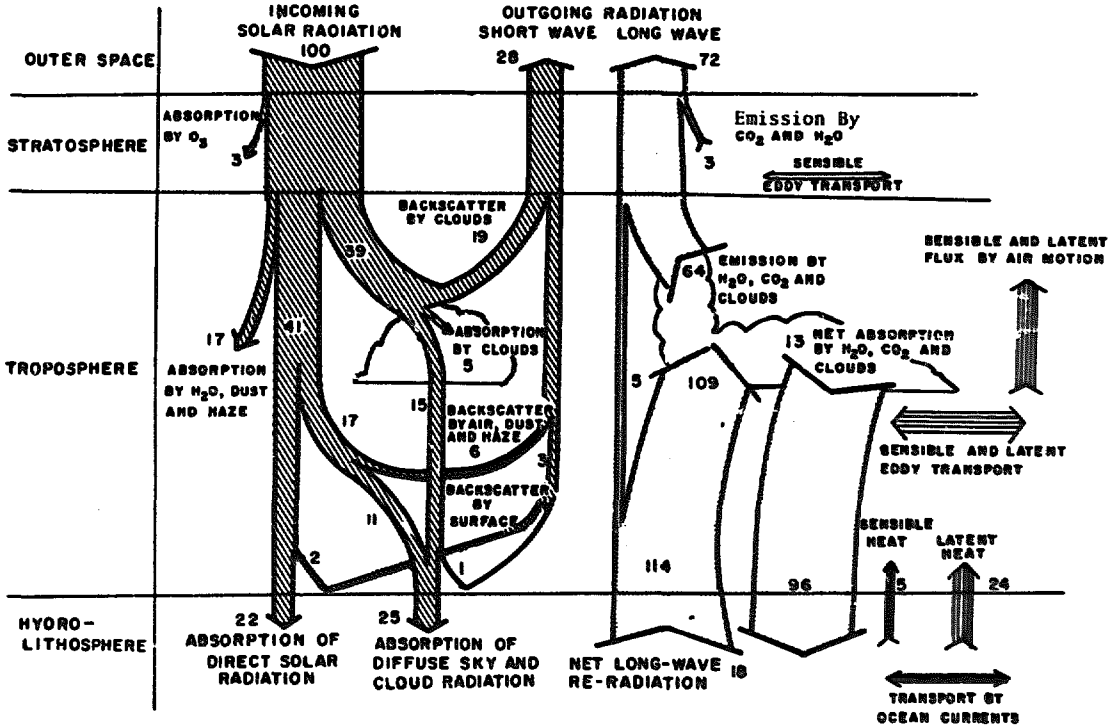

Figure 2

Total Energy Exchange

Most investigators now believe that the energy emitted by the sun remains essentially constant and that reaching the top of the earth's atmosphere is 1353 watts per square meter. Except for that which is reflected and any that might be stored in the earth-atmosphere system, all of it must be radiated back to space in accord with Figure 2. In addition to the amounts involved in the natural radiation budget, all energy removed from long-term storage in the earth's crust must also be radiated out in order to maintain a stable climate.

Since 1860 the energy used by man to power his industry and to provide his comforts has increased at a steady rate of 5.4% per year. This is shown in Figure 3[7,8] and Figure 4, and except for very small (in comparison) amounts of hydro-power, all the energy values shown consist of energy removed from long-term storage. Continued growth at this rate for 75 or more years will give a global energy use of 10^{19} BTU per year – a level significant in relation to the global solar flux of 5×10^{21} BTU per year, only 47% of which is exchanged at the earth's surface.

Even first order, rough calculations indicate that significant global changes must occur to accommodate the disposal of this anthropogenic energy (in addition to the natural flux) when it reaches 1% of the natural flux. From the Stefan-Boltzmann Law of Thermal Radiation, the energy radiated is proportional to the fourth power of the absolute temperature, thus a 1% increase in the energy radiated requires a 1/4% increase in the effective radiating tempera-

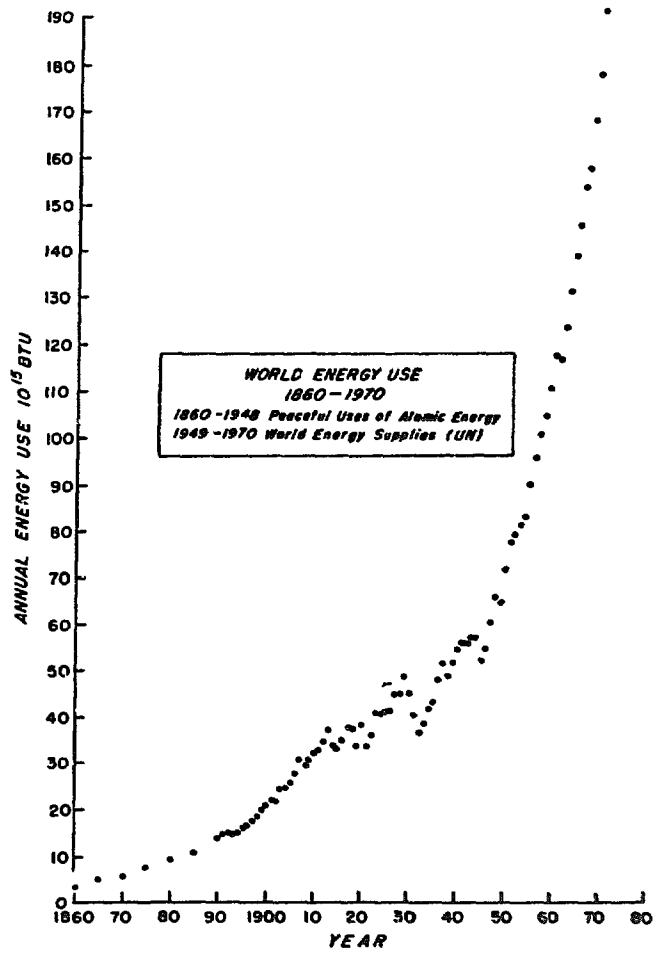

Figure 3

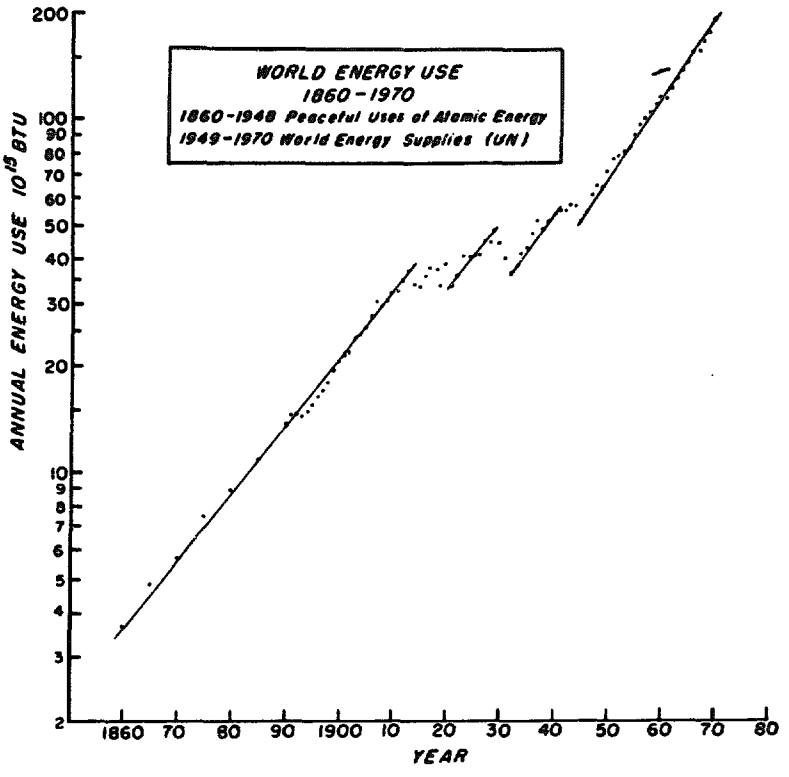

Figure 4

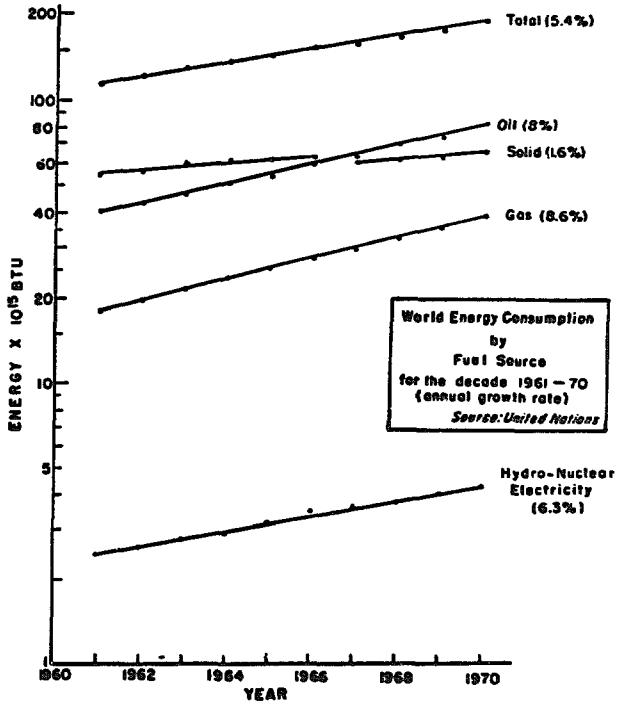

Figure 5

ture. For an effective radiative temperature of 250-255°F,[9] the result must be an increase of 0.6°C(1.1°F) in the effective global temperature. This is approximately the same as the temperature change between 1880 and 1940.

Another way of viewing the total global energy picutre is represented in Figure 5. Here the total energy is divided according to the type of fuel providing the energy. Through the 1960's petroleum fuels passed the solid fuels (coal and lignite) as the sector contributing the largest amount to the total world-wide requirements. Natural gas contributions to the total increased most rapidly during the decade, 8.6% per year, and were approaching the amounts for the solid fuels by 1970. Electricity generated from hydro and nuclear sources is of the order of one-tenth of the energy contribution of the other three main energy sources, but is increasing at the rate of 6.3% per year. Only the curve for solid fuels appears to be other than an excellent approximation to an exponential, showing a break in 1966-67. The growth rate of 1.6% is for the exponential of best fit over the period 1961-70.

A similar view of U.S. energy consumption is shown in Figure 6. The significant difference seems to be: (1) the contribution from solid fuels is well below both oil and gas but is growing at a faster rate than world-wide solid fuel consumption, and (2) the rates of growth of both oil and gas are much less in the U.S. than on a world-wide basis.

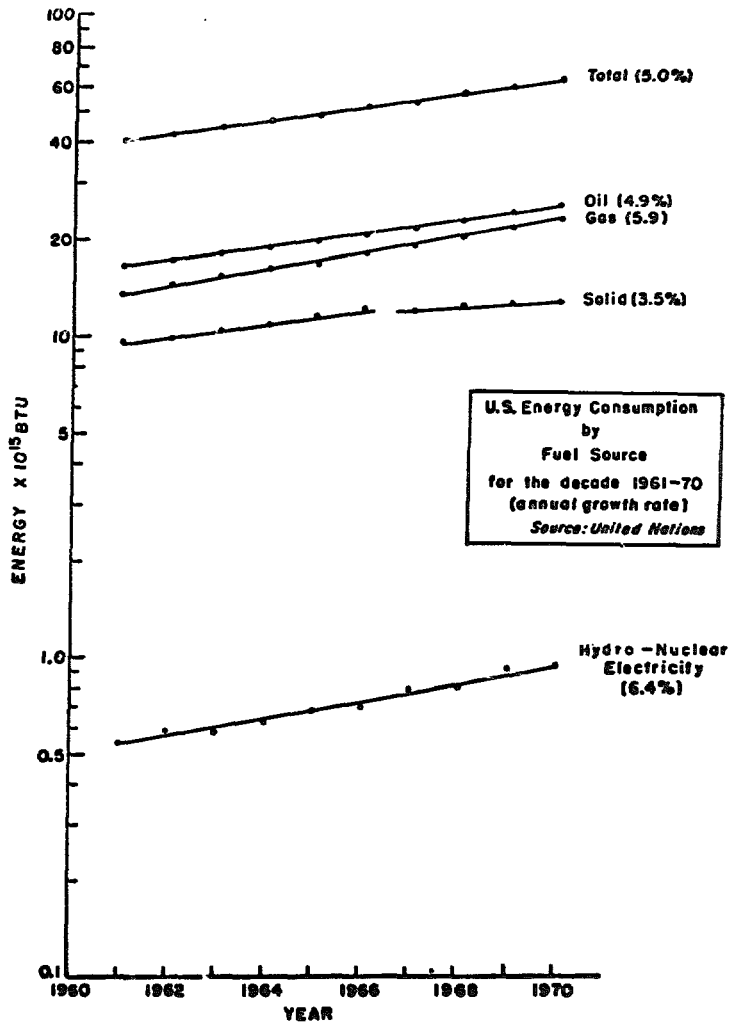

Figure 6

Before attempting to determine where the future may lead, it is informative to look at the global energy picutre on a per capita basis. Figure 3 shows a division of the world's energy consumption on the basis of four economic divisions, both developed and developing. The developing countries, with 47.8% of the population, have a per capita energy consumption rate of 9.01 million BTU per year,[8] while the U.S. with only 5.7% of the world population has a per capita consumption rate of 303.8 million BTU per year.[8] Other developed non-communist countries with 14.5% of the population have an average consumption rate of 105.6 million BTU per person per year.

If population projections prove to be as accurate as they have been in the past, there will be nearly 7 billion people on earth in the year 2000 (a 2% growth rate). UN data[10] show approximate population growth rate for 1963-1970 as tabulated in Table 1. Extrapolating these to 2000 A.D. for the rest of the world and assuming 290 million for the U.S., the approximately 7 billion people will be divided as indicated.

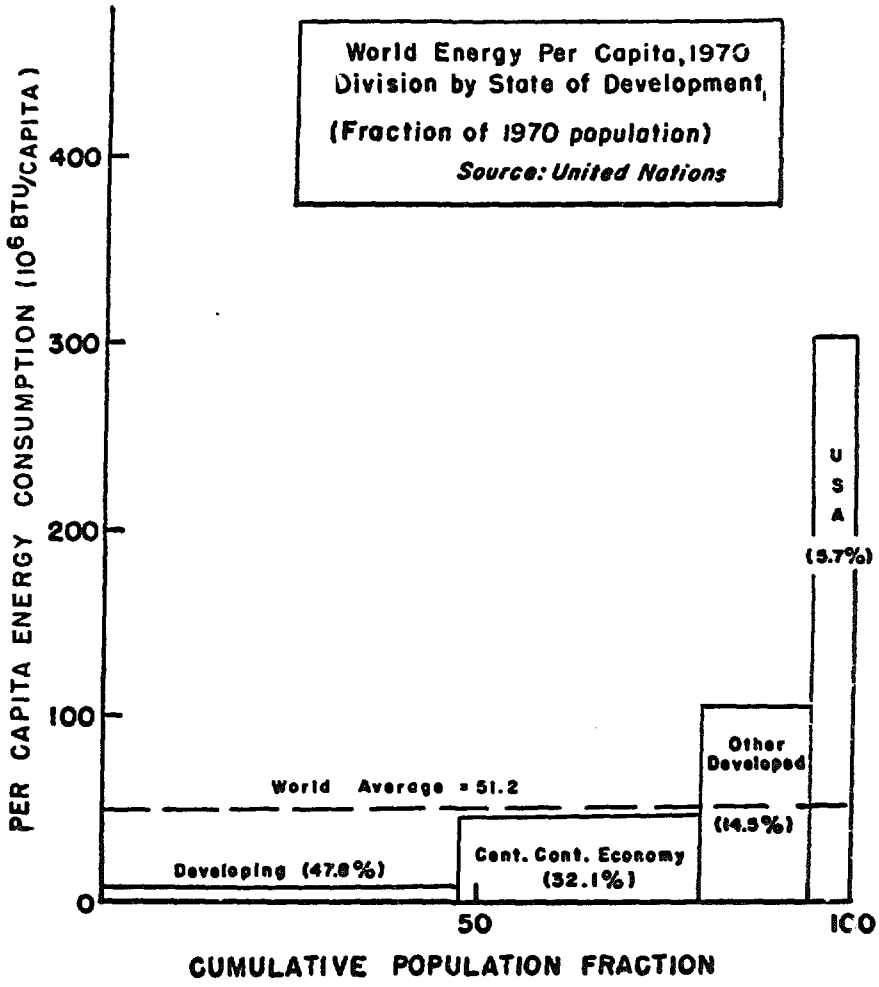

Figure 7

TABLE I

Estimated World Population – 2000 A.D.

	1963-1970 Avg. Annual Rate of Growth	Population in 2000 Millions	%
Developing Countries	2.71%	4,060	57.8
Centrally Controlled Economy	1.54%	1,920	27.4
U.S.A.	1.15%	290	4.3
Other Developed Countries	.99%	730	10.5
World Total	2.0%	7,000	100.0

Weinberg and Hammond[11] point out that population control subordinates all other problems. They point out that a major problem with population control is that of inertia. Age distribution insures a continued increase even if each couple immediately limits themselves to two children; years are required to educate all the people of the world in fertility control methods; people must be confident that they can survive in old age without being dependent on their own children — a situation requiring a standard of living above that now known to a large fraction of the people of the world. Thus, barring a major natural catastrophe or an all-out nuclear war nothing we do now can have much effect on the global population before 2000 A. D.

If the population is to be controlled, the growth rate in the developing countries must be drastically reduced and this will require vastly improved living standards and therefore greater per capita energy consumption. If one assumes as a goal that by the year 2000 A. D. the developing countries have advanced to the level of the 1970 world average per capital energy consumption, the increased population in these countries by then will require 207×10^{15} BTU per year – an average rate of increase of 8.6% compared with 6.7% for the decade of the 1960s.

Figure 8 shows what the per capita energy consumption could look like in the year 2000 A.D. This figure is based on the following assumptions:

a. The 4060 million people in the developing countries consume energy at the 1970 global average rate of 51.2 million BTU per person per year.
b. The centrally controlled economy countries continue to maintain a 5.1% growth rate in energy consumption – resulting in a per capita amount of 130 million BTU per year which will still be below the world-wide averages.
c. The energy consumption in the U.S. will grow to a total of 223×10^{15}BTU as predicted by the National Academy of Engineering.[12] This represents a reduced rate of growth from the 5.0% of the 1960's to 4.26% as an average for the interval 1970 - 2000 – in spite of the probable population growth rate of 1% per year.
d. A similar lowering of the growth rate of energy consumption in the other developed countries to about 5% per year will occur.

Because of the inertia in the population changes, any reasonable modifications in the assumptions above will have only small impact on the predicted

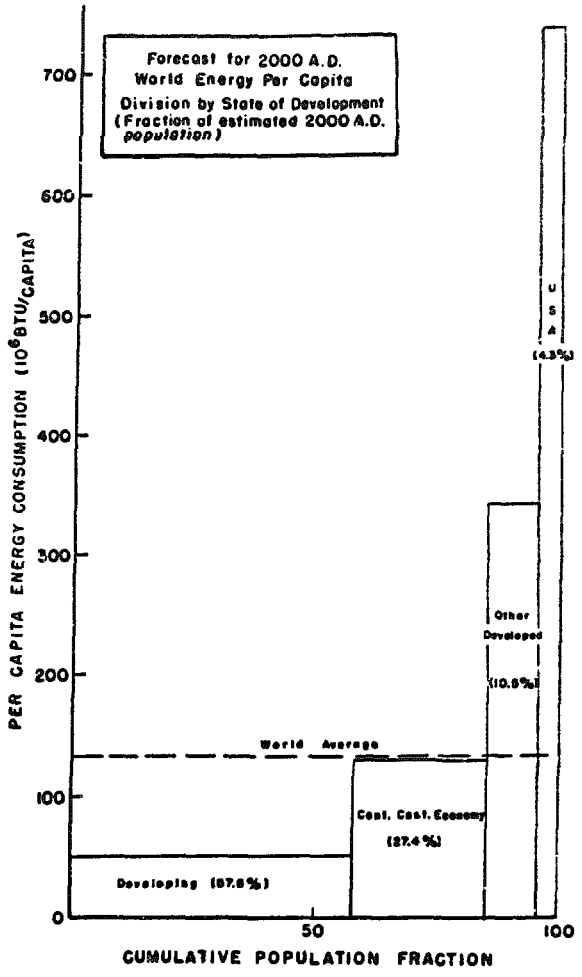

Figure 8

total energy consumed on the globe. Barring large scale changes on the planet, the total must be close to this predicted value. This represents a world-wide annual growth rate of 5.3% between now and 2000 – essentially the same as that of the decade of the 1960's.

The cost per unit of energy is surely going to increase as we begin to use less readily available reserves. This will be partly responsible for the reduced rate of growth in the developed countries but unless total life styles and aspirations are changed, the population growth will assure continued energy consumption growth.

Beyond the year 2000 the picture is much more difficult to predict. Population control measures taken now (and continued) can have an impact if living standards, and hence per capita energy consumption, reach a level at which the factors controlling the population inertia can be minimized. Weinberg and Hammond[11] have hypothesized a world in the mid-twenty-first century in which parents average only two children and population has stabilized at 15×10^9. In order to support this population, significant non-farm energy inputs, i.e., fertilizer, machinery, and water control, will be needed to provide the necessary food. Nearly sufficient supplies of all other necessities are available if enough energy is available to extract them. Weinberg and Hammond[11] have proposed a slightly generous budget of 600 million BTU per person or a world total of 9×10^{18} BTU per year. At these levels of energy use, thermal pollution of the

atmosphere must be considered. Not only the waste heat from thermal machines but also all of the "useful energy" when used is discharged to the environment.

All of this additional energy in the terrestrial environment must be radiated to space if the earth is not to experience a steadily rising temperature. According to the generally accepted Stefan-Boltzmann Law of Thermal Energy Radiation,

$$E = \varepsilon\sigma AT^4,$$

where ε is the emissivity

σ is a constant, 1.69×10^{-7} BTU/cm^{2}yr(°K)^4.

A is the radiating area

T is the absolute temperature in °K.

The total energy received from the sun at the top of the atmosphere is 5×10^{21} BTU/yr, and, as seen from Figure 2, only 47% of this reaches the earth's surface. All except the 28% which is reflected must be radiated back to space in order for a state of quasi-equilibirium to exist. This determines the average temperature of the earth's surface through the Stefan-Boltzmann Law. The energy which man releases to the terrestrial environment, through its increasing the outgoing radiation flux, must result in an increase in the equilibrium temperature of the surface. For a 1% increase in the total radiative flux the temperature must assume a new equilibrium value $(1.01)^{1/4}$, or 1.0025, times as large as with no thermal pollution. For a mean effective radiation temperature of 250-255°K[9] this would result in an average temperature rise of over 0.6°C, or about 1.1°F.

It is impossible now to assign a limit on how much thermal pollution the planet and its atmosphere can stand. As Figure 2 shows many factors affect the total radiative budget. A small change in world-wide cloudiness can have major consequences in the radiative equilibrium temperature through the change of the total planetary albedo.--If an additional 1% of the sun's energy is reflected rather than absorbed, a corresponding thermal pollution of 1% of the sun's energy

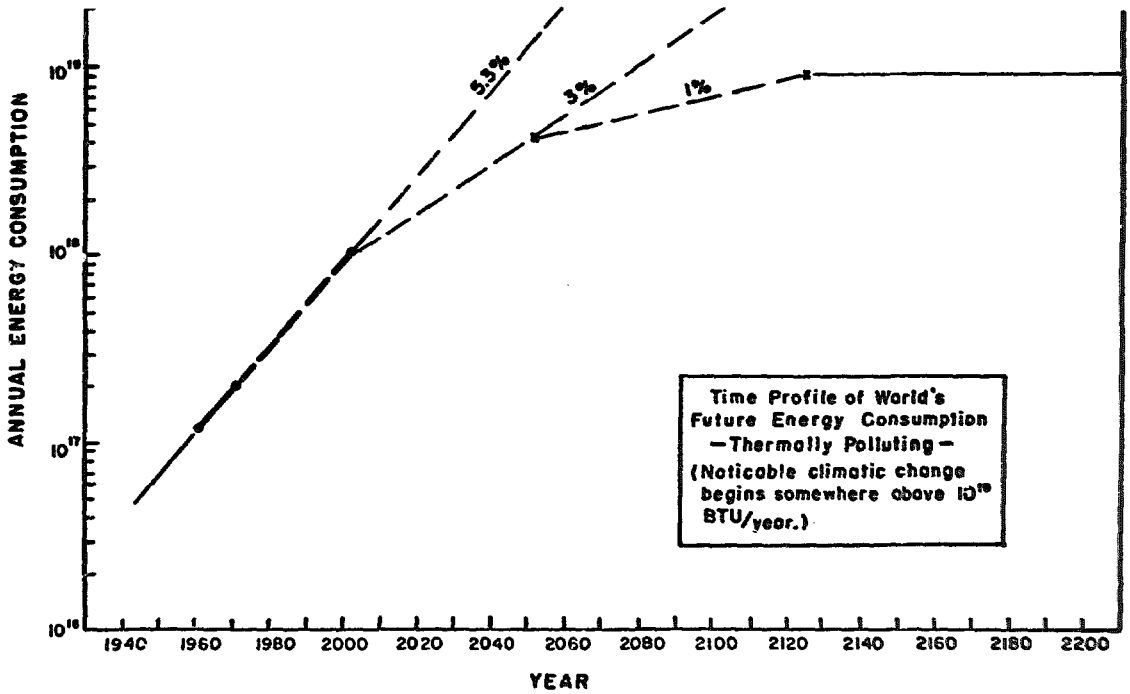

Figure 9

would just compensate and other than changes in the circulation patterns resulting from relocations of the major heat sources, the balances would be maintained.

It is evident that total thermal pollution should be allowed to approach a value of 10^{19} BTU per year only after much greater understanding than now exists of all of the associated phenomena which might be taking place simultaneously.

Figure 9 shows the same exponential growth of global energy consumption on a contracted horizontal time scale in comparison with the earlier figures.

Before the total anthropogenic energy will be noticeable in global changes, smaller scale changes of both local and regional importance should be expected. On a local scale, the additions of heat to the atmosphere has already influenced climate and weather in that large cities are now warmer. Table 2 gives a summary of climate changes produced by cities, although it should be recognized that all of the changes are not a consequence of city heating.

TABLE 2
Climatic Changes Produced by Cities
(After Landsberg, 1962)

Element	Compared with Rural Environs
Temperature	
Annual Mean	1.0 to 1.t F° Higher
Winter Minima	2.0 to 3.0 F° Higher
Relative Humidity	
Annual Mean	6 percent Lower
Winter	2 percent Lower
Summer	8 percent Lower
Dust Particles	10 times More
Cloudiness	
Clouds	5 to 10 percent More
Fog, Winter	100 percent More
Fog, Summer	30 percent More
Radiation	
Total on Horizontal Surface	15 to 20 percent Less
Ultraviolet, Winter	30 percent Less
Ultraviolet, Summer	5 percent Less
Wind Speed	
Annual Mean	20 to 30 percent Less
Extreme Gusts	10 to 20 percent Less
Calms	5 to 20 percent More
Precipitation	
Amounts	5 to 10 percent More
Days with > 0.2 inch	10 percent More

The heat flux density (i.e., energy added to the atmosphere per unit of earth surface) is a quantity which may be a suitable indicator of the onset of meteorological or climatic change. In the United States, the per capita energy consumption in 1970 was 10 kilowatts per person.[8] If this consumption is typical of urban dweller, then a city whose population density is equal to that of Washington, D. C. will have an energy flux density of 44 W/m^2. This value depends on population density rather than the city's size. Other data[13] indicate the effect of the energy release, as measured in temperature increases, and do depend on city size. Clearly the climatic impact depends both on the density of the heat flux and the total area covered. If the flux is low the observed changes are small and less likely to be detected; if the area is too

small the changes are very localized and probably are not reported. It is the combination of the heat flux density and the area scale which must be considered in anticipating the observed effects of energy added to the atmosphere.

Table 3 summarizes the heat flux density for various sources.

TABLE 3
Energy Release Concentrations (Heat Flux Density)

	Area Km^2	Heat Flux Density W/m^2	Fraction of Solar Flux At Ground
Solar Constant		1352	
Average Solar Energy Trapper in Earth Atmosphere System (24 hour average)	$5.1x10^8$	246	
Average Solar Energy Flux at ground	$5.1x10^8$	160	1.00
Anthropogenic Heat from Cities:			
Manhattan, New York City	59.8	630	3.94
Moscow	878	127	.79
Washington, D. C.	173	44	.28
Los Angeles	3,500	21	.13
Boston-Washington Metropolitan Area - (Projection for 2000 AD)	31,200	36	.23
Sheffield, England	48	19.2	.12
Waste Heat from Power Plants:			
Dresden and Braidwood (over area for city of 1 million people)	230	35.3	.22
Dresden LaSalle, Braidwood (area sufficient to include all three)	634	19.5	.12
Summit, Salem, Hope Creek (12 mi. x 5 mi.)	155	73.8	.46

Recent studies of radar echo initiations[14] reinforce the concept of increased convective activity over and downwind of large cities. In a 17-storm sample during the summers of 1972 and 1973, an unusually high number of radar echo initiations occurred over the industrial complex just south of Wood River, Illinois (9 times the network average). Other areas of high frequency of echo initiations were in and east of St. Louis. Particularly in South St. Louis, the statistics showed unusually high values – 5 times the network average.

While heat flux densities provide an indication of the impact of large "waste heat" sources as heat islands comparable to cities, the heat released is frequently so concentrated as to suggest far greater impacts. As suggested by Hanna and Gifford (1974), large heat releases from very large power generating stations may, under some conditions, produce convective effects that have the potential to generate thunderstorms and possibly associated squalls.

Table 4 summarizes the heat-flux densities from several known large sources of heat addition to the atmosphere and a brief summary of the meteorological effect of each where possible. The questions of what value of heat flux density is sufficient to give vortex formation and under what atmospheric conditions must remain unanswered at present.

TABLE 4

Effects of Large Heat Additions to the Atmosphere

Phenomenon	Energy Rate (Mw)	Area (Km^2)	Energy Flux Density (W/m^2)	Meteorological Consequences
a. Large brush fire	100,000	50	200	(Relatively small energy flux rate, very large area) Cumulus cloud reaching to a height of 6 km formed over 1/10 area of fire. Convergence of winds into the fire area.
b. Forest Fire Whirlwind				Typical whirlwind: Central tube visible by whirling smoke and debris. Diameters few feet to several hundred feet. Heights few feet to 4,000 ft. Debris picked up – logs up to 30 inches in diameter 30 ft. long.
c. WWII Fire Storm		12		Turbulent column of heated air 2 1/2 miles in diameter. Fed at base by inrush of surface air. One and a half miles from fire, wind speeds increased from 11 to 33 mph. Trees 3 feet in diameter were uprooted.
d. Fire at Hiroshima				(10-12 hours after A-bomb). "The wind grew stronger, and suddenly – probably because of the tremendous convection set up by the blazing city – a whirlwind ripped through the park. Huge trees crashed down; small ones were uprooted and flew into the air. Higher, a wild array of flat things revolved in the twisting funnel..." The vortex moved out onto the river, where it sucked up a water spout and eventually spent itself.
e. Surtsey Volcano	100,000	<1	100,000	Permanent cloud extending to heights of 5 km to 9 km. Continuous sharp thunder and lightning, visible 115 km away. (Phenomenon probably peculiar to volcano cloud with many small ash particles). Waterspouts resulting from indraft at cloud base, caused by rising buoyant cloud.

f.	Surtsey Volcano	200,000	1	200,000	Whirlwinds (waterspouts and tornadoes) are the rule rather than the exception. More often than not there is at least one vortex downwind. Short inverted cones, or long, sineous horizontal vortices that curve back up into the cloud, and intense vortices that extend to the ocean surface.
g.	French Meteotron	700	.0032	219,000	"artificial thunderstorms, even tornadoes, many cumulus clouds...substantial downpour. Dust devils.
h.	Meteotron	350	.016	22,400	15 minutes after starting the burners, observers saw a whirl 40 meters in diameter...whirlwind so strong burner flames were inclined to 45^{o}.
i.	Single Large Cooling Tower	2250	.0046	484,000	Plume of varying lengths and configurations.
j.	Array Large Cooling Towers (48,000 MW(e)NEC; area 48,000 acres)	96,000	194	495	Unknown

SOURCES: a. R. J. Taylor, S. T. Evans, N. K. King, E. T. Stevens, D. R. Packham, and R. G. Vines, 1973: Convective Activity above a Large-scale Brushfire, *J. Appl. Meteor, 12,* 1144-1150.
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Change in Albedo Because of Aerosols

The problem of aerosol effects on temperature can be looked at this way: Considering the Earth as a whole, the warming effect of the Sun is a function of the reflectance (albedo) of the Earth at solar wavelengths. A black earth would reflect little solar radiation and the climate would be relatively warm; a white earth would reflect a great deal of solar radiation and the climate would be relatively cool. Now, if a white aerosol cloud is injected into the atmosphere above a black earth, it is clear that the effective brightness (albedo) of the Earth-aerosol system would be increased and the overall planetary temperature would be lowered. Conversely, if a black aerosol is injected above a white earth, the effective brightness of the system would be decreased and the overall temperature raised. In the case of real aerosols injected into the real atmosphere above the real earth, there is, of course, no black or white but various shades of grey. When grey aerosols overlie a grey earth, their thermal effects are obviously smaller and not necessarily discernable except through very careful measurements.

For any given atmospheric aerosol it is sufficient to determine in some manner two "bulk" optical properties of the aerosol: (1) the incremental fraction of incident solar radiation that is backscattered to space by the aerosol (over and above that which would be backscattered by the atmosphere in the absence of the aerosol, as by Raleigh molecular scattering); and (2) the incremental fraction of incident solar radiation that is absorbed by the aerosol layer (over

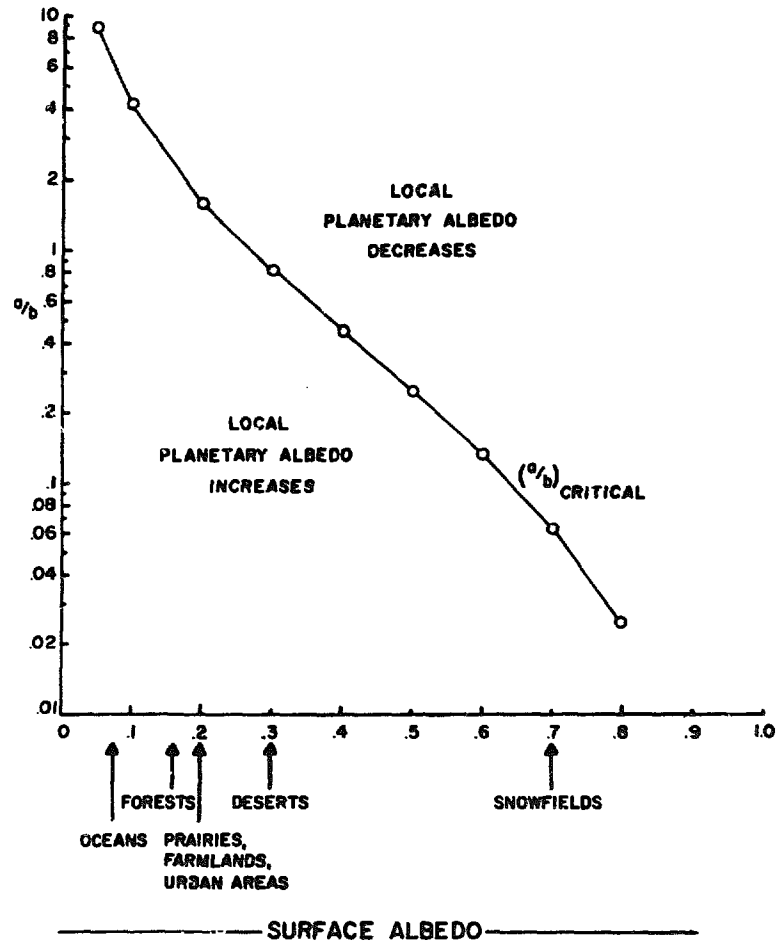

Figure 10

and above the absorption by selective-absorbing gases in the layer which would occur in the absence of the aerosol). If the incremental backscattering fraction is denoted as b, and the incremental absorption fraction as a, the optical geometry of the situation is such that the net thermal impact of the aerosol is either warming or cooling, depending on whether the ratio a/b is greater than a critical ratio given by

$$\left(\frac{a}{b}\right)_o = \frac{(1 - A)^2}{2A}$$

where A is the reflectance (or albedo) of the underlying surface.[15] This is plotted in Figure 10.

Tentative values of the ratio a/b applicable to real aerosols lie near unity. The critical ratio $(a/b)_o$ is seen from Figure 4 to be greater than unity for all values of surface albedo less than about 0.27, which is characteristic of most regions of the Earth except snowfields and deserts. Thus, aerosols will likely increase the planetary brightness (or planetary albedo) except over snowfields and deserts, and therefore result in a general cooling of climate. Thus, we see how it happens that cooling effects of aerosols have become engrained in our conventional wisdom as to such matters.

Change in Albedo Because of Cloud Cover Changes

As in evident from Figure 2, any change in cloud cover will have a direct influence on the planetary albedo. Any mechanism which tends to lower the average atmospheric temperature will reduce evaporation, reduce the cloudiness, reduce the albedo, and tend to increase the temperature. On the other hand, any tendency to raise the average temperature will increase evaporation, increase cloudiness, increase the albedo, and cool the planet (lower the temperature). Through the evaporation process and variation in cloudiness, any change in temperature of the lower atmosphere will result in a "negative feedback" loop which will tend to cause a temperature change in the opposite direction.

Hobbs, et. al.,[15] have also concluded that the way aerosols influence the climate most is through their effect on clouds. The importance of certain chemical species in providing cloud condensation nuclei and ice nuclei is one of the frequently overlooked, yet potentially most serious, forms of industrial pollution. Controls must be directed to a chemical's potential effect on cloudiness as well as to its adverse effects on public health.

In modern technological society, man has the capability of influencing the amount of cloudiness over major areas of the earth's surface by modifying the evaporation from the surface. The scale of modern irrigation projects and the size of artificial impoundments for flood control and electrical generation have caused some localized weather changes.

The extensive use of evaporative cooling for power plant heat rejection is beginning to cause increased cloudiness in some areas. The presence of fogging around cooling ponds and lakes as well as the plumes from cooling towers which are visible in some instances for miles, are examples of how man has increased cloudiness through the quest for larger amounts of electricity. The negative feedback characteristic of cloudiness is not only fortunate on a global scale, but with the presence of induced cloudiness may counter the sensible heat rejected from power plants.

Change in the Absorptivity of Atmospheric Gases

Both water vapor and carbon disoxide absorb radiation in bands of the longer wave lengths where a greater fraction of the terrestrial radiation from the earth is encountered. Any net change in total atmospheric water vapor content is undoubtedly reflected in a change in the global cloudiness and as discussed previously cloud cover can give major changes in planetary albedo. The absorption by carbon dioxide of longer wave length radiation while having high transmissi-

vity in the spectrum of the incoming solar radiation, leads to the "greenhouse effect" and resulting predictions that as the atmospheric carbon dioxide content increases, the planetary temperature will also.

Man adds CO_2 to the atmosphere through the combustion of fossil fuels, and this addition is superimposed on the natural exchanges between the atmosphere, the biosphere, and the oceans. Since the use of energy has increased exponentially since the beginning of industrialization around 1860 (See Figure 3), it is not surprising to see that the best estimates of CO_2 production from fossil fuels and cement as presented in Figure 11 show the same pattern.[17,18]

Beginning in 1958, regular and systematic measurements of the atmospheric carbon dioxide content have been made at the NOAA Observatory at Mauna Loa, Hawaii. The record of the CO_2 measurements made at Mauna Loa is shown in Figure 12. The seasonal variaton is obvious and regular, showing an October minimum with increases in the later autumn and winter months and a maximum in May. However, of greater importance to possible climate changes is the continued year-to-year rise. Both the seasonal variation and the annual increase have been confirmed by measurements at other locations around the globe.

Projecting the world-wide needs for energy, even with the present problems, indicates a long term global growth in the consumption of fossil fuels and the associated production of carbon dioxide. In so far as possible impact on the climate is concerned, it is the amount of CO_2 which remains in the atmosphere which is most important. In addition to the atmosphere, the oceans and both land and marine biospheres serve as reservoirs for carbon dioxide. Based on estimates of preindustrial levels of atmospheric carbon dioxide of 290 ppm and the 1958-1971 Mauna Loa data, between 58 and 64% of the CO_2 produced from burning fossil fuels remains in the atmosphere.

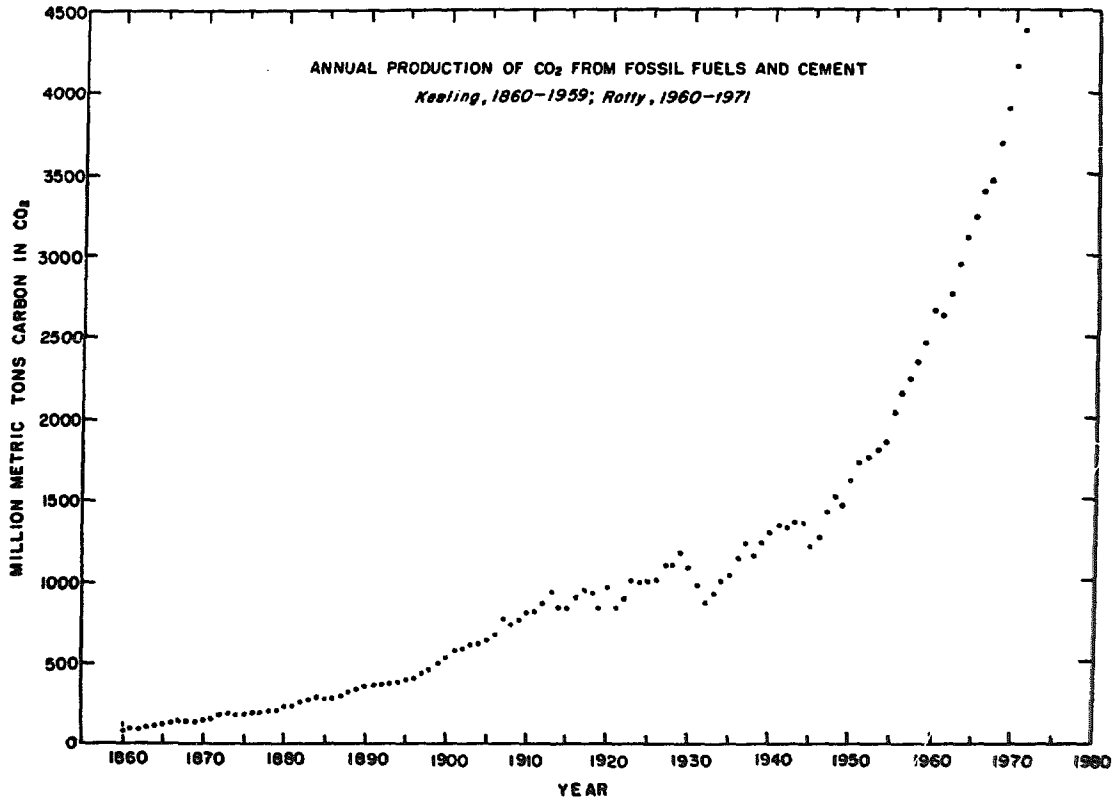

Figure 11

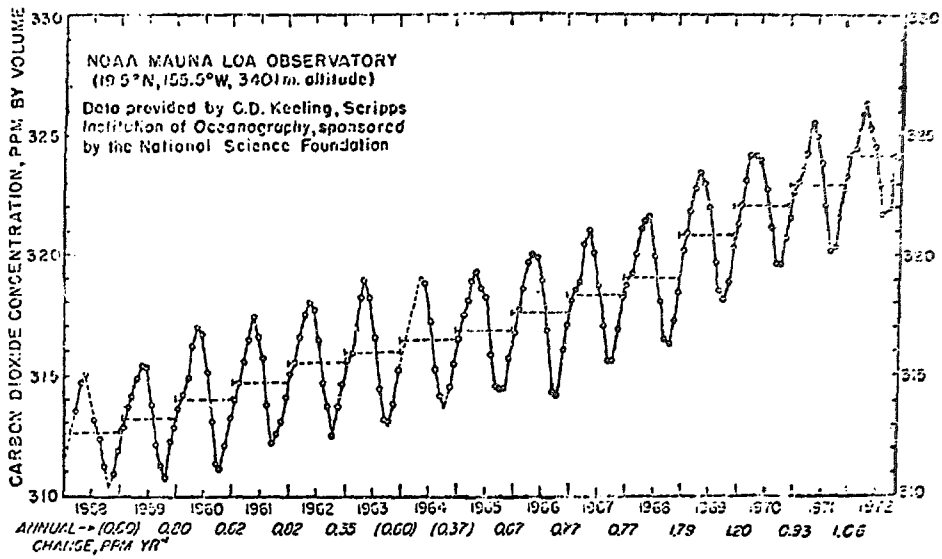

Figure 12

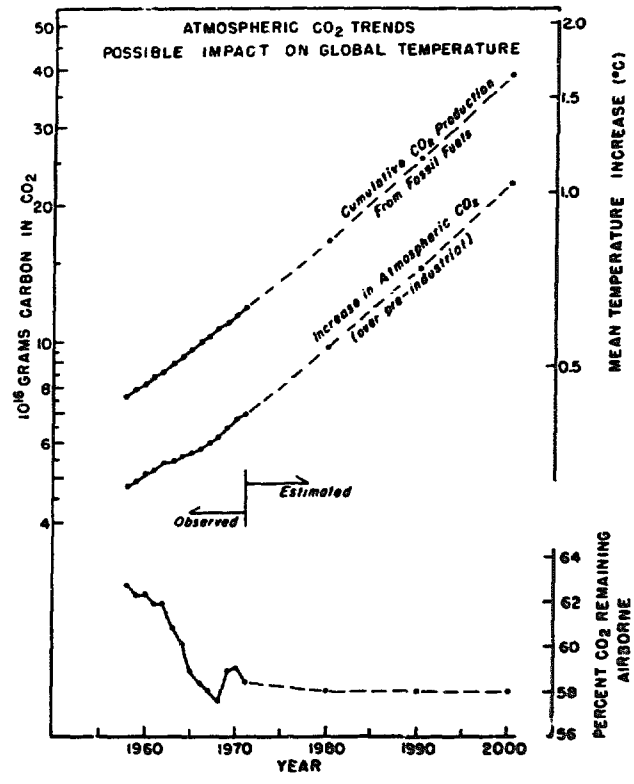

Figure 13

Figure 13 shows the cumulative production from fossil fuels and its projection with an estimate of future atmospheric levels of CO_2.[19] The future atmospheric CO_2 levels are heavily dependent on the fraction remaining airborne. The projections to the year 2000 are based on an assumed 58% fraction remaining airborne, although it is suspected that values higher than 58% are more likely than lower values.

The atmospheric carbon dioxide is likely to be close to 400 ppm compared with the 324 ppm reported at Mauna Loa at the end of 1972. According to the "greenhouse effect," increased carbon dioxide should give increased planetary temperatures. By use of a rather complex numerical model, Manabe and Wetherald[20] have studied temperature changes resulting from addition of CO_2 to the atmosphere. The results of their studies are indicated by the scale to the right in Figure 13. These are temperature averages, — in localized areas the changes may be more or less, with the higher latitudes being affected more than lower latitudes.

Conclusions:

It has been shown that anthropogenic factors and especially energy releases can affect the world's climate.

1. The release of energy to the atmosphere for eventual radiation to space causes a global warming. Per capita energy uses must be evaluated in making any projections as to the future global energy consumption rates, but any reasonable projection shows energy use rates, which give climatic concerns.
2. Localized energy releases give local and regional changes which will be (are) apparent before the global changes. Cities have different climates than the nearby rural areas.
3. Heat flux density is an important consideration in evaluating meteorological changes resulting from large localized heat sources. Enhancement of convective cloud activity (including showers and thunderstorms) is possible if the heat flux density is high.

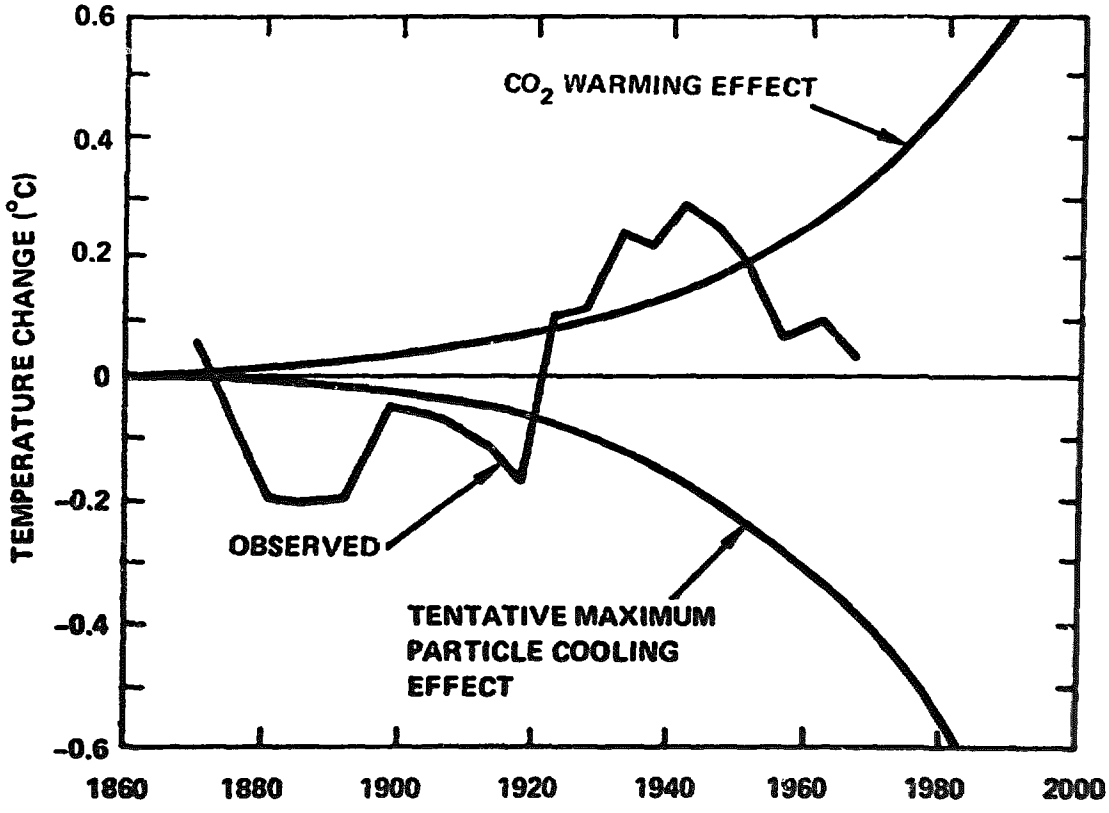

Figure 14

4. Aerosols released to the atmosphere can cause a warming or cooling depending on the nature of the aerosol and the albedo of the surface below.
5. Changes in cloud cover are important in changing the radiation budget of the planet. Extensive irrigation, artificial reservoirs, and large cooling towers all add humidity to the atmosphere, but any resulting increase in cloudiness will tend toward overall cooling which will tend toward a reduction in cloudiness.
6. Increases in atmospheric carbon dioxide (e.g., from the combustion of fossil fuels) adds to the absorption of long wave radiation and the resulting "greenhouse effect." The resulting planetary warming depends on the amount of CO_2 uptake by the biota and by the oceans.

Some of the consequences of man's energy use suggest a warming and a cooling. Figure 14[20] shows the trends of global mean temperature. The upper smooth curve represents the projected warming from increased atmospheric CO_2, and the lower smooth curve the probable maximum cooling from aerosol increases. The irregular curve is the observed temperature change in the Northern Hemisphere from 1870 to the present, replotted from Figure 1.

The many uncertainties in cause-effect relationships between energy and climate make a single summary impossible. Even localized changes from heat and aerosols from cities and from power plants are difficult to identify with positive assurance. Whether man is causing a warming or cooling (or which he will cause in the future) is still speculative.

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ENERGY USE AND ECONOMIC GROWTH

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Introduction

One of the key insights that has surfaced in connection with the world's newly-formed awareness of the developing shortage in energy and the mal-congruence between regions of resources and regions of high consumption, is the intimate connection between energy use and the general development of a nation's overall economy. Differing here, as they do in most areas, economists, are by no means in agreement as to the precise nature of the relationship involved. Some economists believe that the amount of energy used in a given economy is not necessarily inflexibly tied to the productivity of the economy since much is wasted which could be conserved, and cite as evidence the fact that many countries with relatively similar standards of living appear to use quite different amounts of energy.

Other economists feel that energy is so intimately tied to the production of nearly all goods, that reducing the amount of energy used will reduce the productivity nearly in proportion, and they cite the fact that within any given economy, the ratio of energy used per capita to the productivity per capita tends to change only quite slowly with time.

This paper, therefore, presents a brief survey of the available data bearing on this question, and tries to mention some of the studies recently done to address these problems.

Definitions and General Considerations

In order to analyze the relation between energy use and the behavior of the economy, it is first necessary to define clearly how each of these terms is to be quantified and defined. The more difficult problem relates to the productivity of the economy. Ideally, what each economic system strives for is to provide as high as possible a "quality of life" for as many of its members as possible; but quality of life is difficult to put in quantitative terms. Surely, it includes such things as the quantity of material goods and services available to each member, as well as their quality, but it also includes many intangibles such as clean air, beautiful surroundings, available leisure time, and many similar factors, which often tend to be diminished or vitiated by the very same activities that produce the material goods and services. There is the further question of whether a society with more people in it is taken to be "richer" just because it has more goods in toto than the same society would have if its territory were more sparsely occupied. All these questions make a numerical evaluation of the quality of life almost impossible.

What economists choose to use to represent this parameter is usually the Gross National Product (hereafter referred to as GNP) which is the sum of the value of all the goods and services produced by the given economy.

This is, admittedly, an imperfect measure, but it is a datum which is collected and available, not only for the United States but for most countries, so that relative evaluations can be made. Such comparisons, however, have to be treated with caution because the definitions used and the way they are applied are not always consistent, and other factors, to be discussed below, also enter which may make a simple numerical comparison misleading.

The other quantity to be defined is energy use. Basically, this is all the energy flowing through the economy which is identifiable and quantifiable as such by being produced, transformed, and used in metered or commercial applications. This includes all types of fossil fuel energy, water power, nuclear energy, and some small amounts of geothermal and tidal energy, but it does not usually take account of human or animal energy, nor are solar inputs into agriculture and other photosynthetic processes included. So, economies with relatively low development, in which these latter energy forms are used to a proportionally greater extent appear to be using relatively less energy than they do in fact use.

The measure of the efficiency with which energy is used in a given economy is thus the ratio $C = (E/G)$ where E is the total energy used, and G stands for the total dollar value of the GNP. Note that C, from its definition, is independent of whether per capita or gross values are used for the values of E and G.

Another way of looking at the value of C is to think of it as the energy content per dollar's worth of the GNP. In other words, if one considers the whole "mix" of goods and services which makes up the GNP, then evidently there is associated with each item or component of this "market basket" an amount of energy that was required, or at least expended, to produce one dollar's value of this item (including services), and it is the average of these energy use quantities, weighted by the amount of dollar value of the given item in the total mix that defines C. Thus, assuming that there are i different goods that make up the mix of the GNP, and that the total dollar value of the i'th item in the mix is D_i, and that C_i units of energy are expended to produce one dollar's worth of the i'th item then:

$$\sum_i D_i = G$$

$$C = \frac{i}{G} \sum_i D_i C_i$$

Thus, it is clear that to reduce the energy content of the GNP, i.e., to reduce C without diminishing G, two fundamental methods are available: one is to change the "mix" that makes up the GNP in the direction of increasing the amounts and types of goods that have lower values of C_i, at the expense of more energy-demanding goods and services, and the other is to modify the C_i so as to produce the given good with a smaller expenditure of energy.

An example of the first type of change would be a shift in urban transport considered as a service, from private automobiles to mass transit. The same service would be provided, namely transport from place to place, but it would, perhaps, be provided with lower energy expenditure. Another example would be a shift to re-usable containers for beverages, instead of once-used aluminum cans.

An example of the second type might be the use, in industry, of furnaces with better insulation to do a given process, so that less energy would be expended to perform the same function.

In the past decade, as we shall point out further below, the rates of growth of the GNP and the demand for energy in the U.S. have tended to be rather parallel, which is another way of saying that C, the energy content per unit value of the GNP has changed rather little. So, the question naturally arises, "what would be the consequences of a long-term divergence in the two rates?" These can be quite dramatic. Assume, for example, that the GNP is to rise at an annual rate of 5% for the next 25 years, and the rate of growth of energy demand over the same time period is to be only 2.5% per annum. In that case, C would change by the factor $(e^{25\times0.025})/(e^{25\times0.05}) = 0.53$, which is to say that the energy content of each unit of GNP would, in the mean, have to drop to almost half of what it was at the starting point. This would be a very major change indeed. The other fact implied by this simple consideration is that, in the long run, the rates cannot diverge permanently unless there are continuing changes in technology that make ever less energy intensive goods possible and economically competitive.

A further factor tending to work against such long-term trends, is the evident truth that as high-concentration natural resources become scarce, more dilute sources will have to be utilized, which will tend to increase the energy required for their extraction and refining.

Historical Trends

Based on the dictum "The past is prologue.", it is often considered useful, in projecting what might happen in the future, to look at the trends of the recent past so as to infer from them what the future might be like. In the energy area, this is a particularly hazardous undertaking since it is difficult to separate the purely secular trends, imposed by improving technology, growing population density, increasing standard of living, and like factors, from the effect that has been exerted on energy use by the historic trend towards decreasing prices of energy (as measured in constant dollars).

Figure 1, taken from a study by J.D. Parent at the Institute of Gas Technology, plots the energy use against the GNP for the U.S., with points for the years from 1909 to 1973. It is interesting to observe how nearly linear the relation is from the 1940's on, except for a somewhat more rapid rise in the early 1970's, which had its origin in the decreasing price of energy, the rapid growth of energy-intensive products such as air conditioning, the decreasing gas mileages for cars due to the imposition of emission standards and increasing use of power options, and artificially low prices on natural gas.

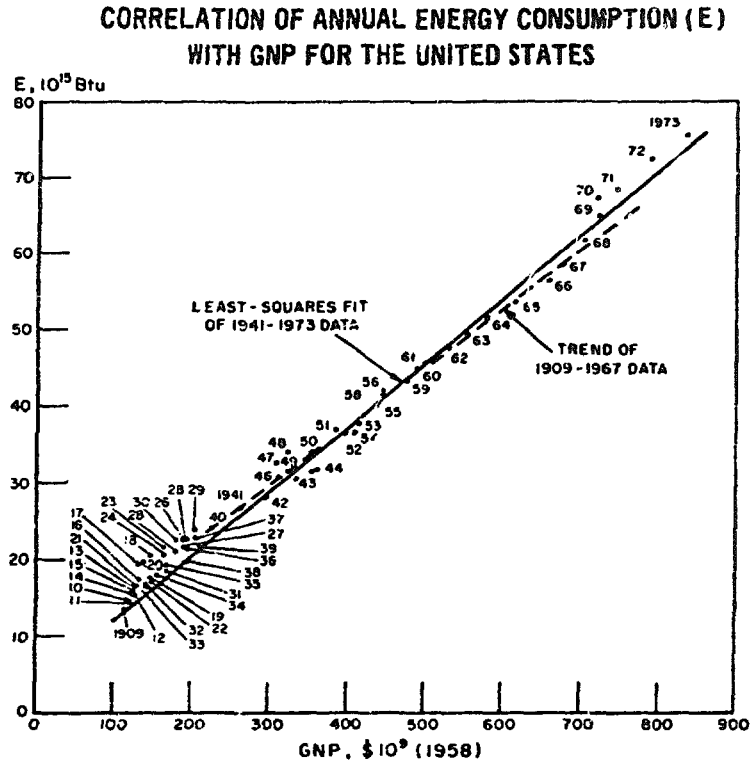


Figure 1

Looking at the ratio in more detail, we see from Figure 2 (taken from the same source as Figure 1) what the secular trend in the ratio has been. The trend has been towards increasing efficiency, but at a relatively slow pace in recent years.

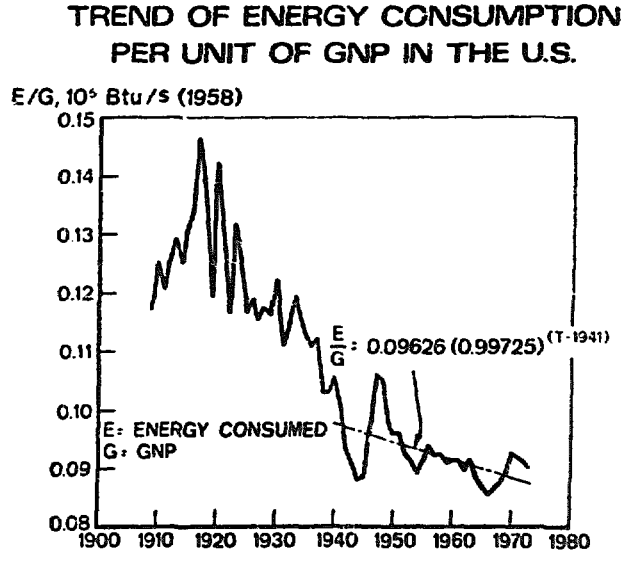


Figure 2

The close parallelism between E and G is clear from Figure 3, which shows both parameters (also from Parent's paper).

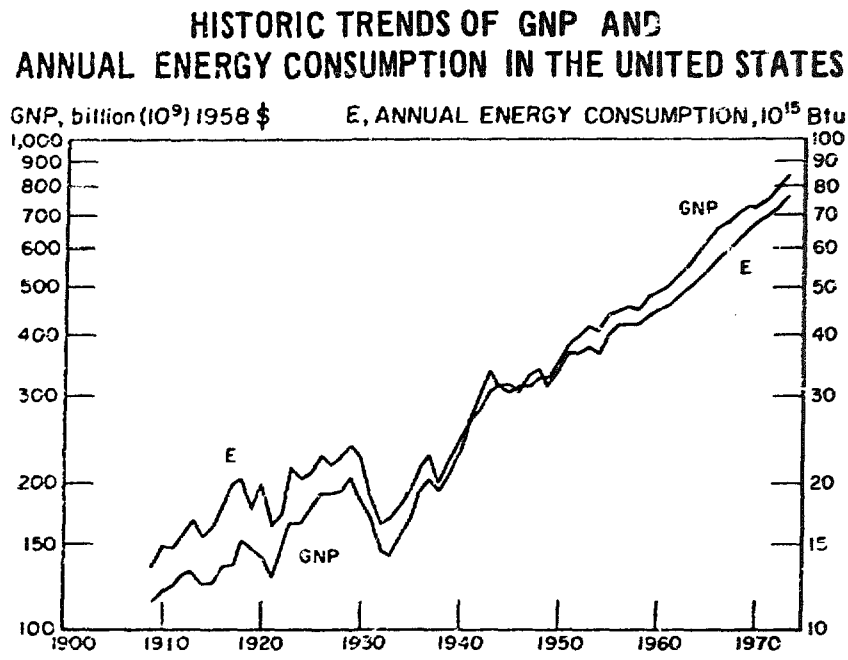


Figure 3

The increasing use of electricity (which has been growing at nearly 7% per annum) for heating and similar uses where direct combustion was used before, with its attendant lowering of overall thermal efficiency, plus the slow-down in the improvement in the heat-rate (See Figure 4) have tended to counter the improvements in overall technology.

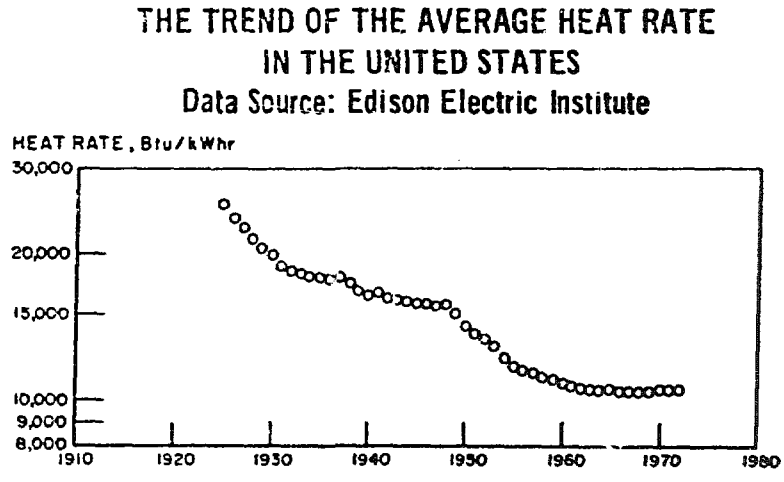


Figure 4

Thus, it would be very optimistic, given no changes other than those presaged by experience up to 1973, to expect a major reduction in the energy content of the GNP. Figure 5 shows the projection extrapolated from the line fitted to the data in Figure 2, and a projection by Dupree and West taken from the "United States Energy Through the Year 2000", U.S. Department of the Interior, 1972. Thus, using the Parent projection, if the GNP were to continue to grow at 3.5% per year between 1974 and 2000, the energy use would grow by 227% by the year 2000 (relative to 1974) while the GNP would grow by 248%.

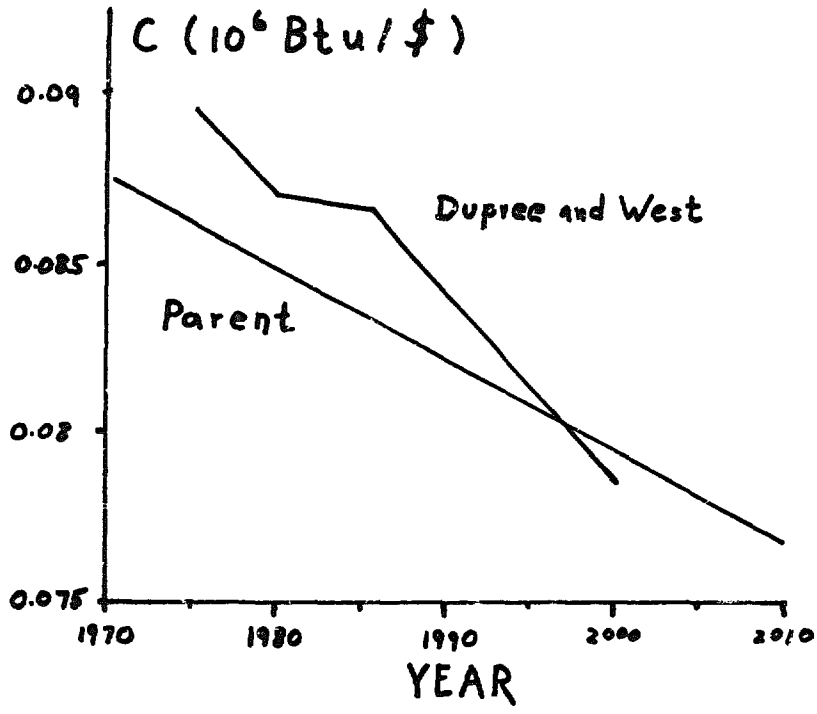


Figure 5

To recapitulate, the projection forward of trends from the recent past for the U.S. does not lead one to expect any major reduction in the energy content of the GNP, but rather, a growth rate of energy use very closely coupled to GNP growth, with some factors foreseeable that would tend to make even such a prediction seem optimistic.

On the other hand, the increase in energy prices, which has no historic parallel, is not factored into these projections, and it is not yet known what the long-term price elasticity will be, i.e., what effect market forces driven by higher prices, will have on the consumption of energy and the development of the economy.

Data From Other Economies

If historical trend analysis is unreliable as guide to the future, for reasons outlined above, then one may turn to other economies, which in this instance means other countries, to see whether the energy content per unit of GNP is a more-or-less fixed parameter, given a certain level of technological sophistication, or whether this coefficient is capable of taking on widely varying values in different countries.

Figure 6 (also taken from Parent's report cited above) plots the GNP per capita against the energy consumption per capita for a number of countries. The range in both values is very broad, spanning a factor of 400 in energy consumption per capita and a factor of about 80 in GNP per capita. The fact that the points do not lie at random on the graph, i.e., that there is a correlation between energy use and GNP is hardly surprising, though the wide range covered in both the parameters is a perhaps instructive commentary on just how unevenly the world's goods are distributed among the world's populations.

RELATIONSHIP BETWEEN GNP AND ENERGY CONSUMPTION PER CAPITA
FOR 52 COUNTRIES—1972 DATA

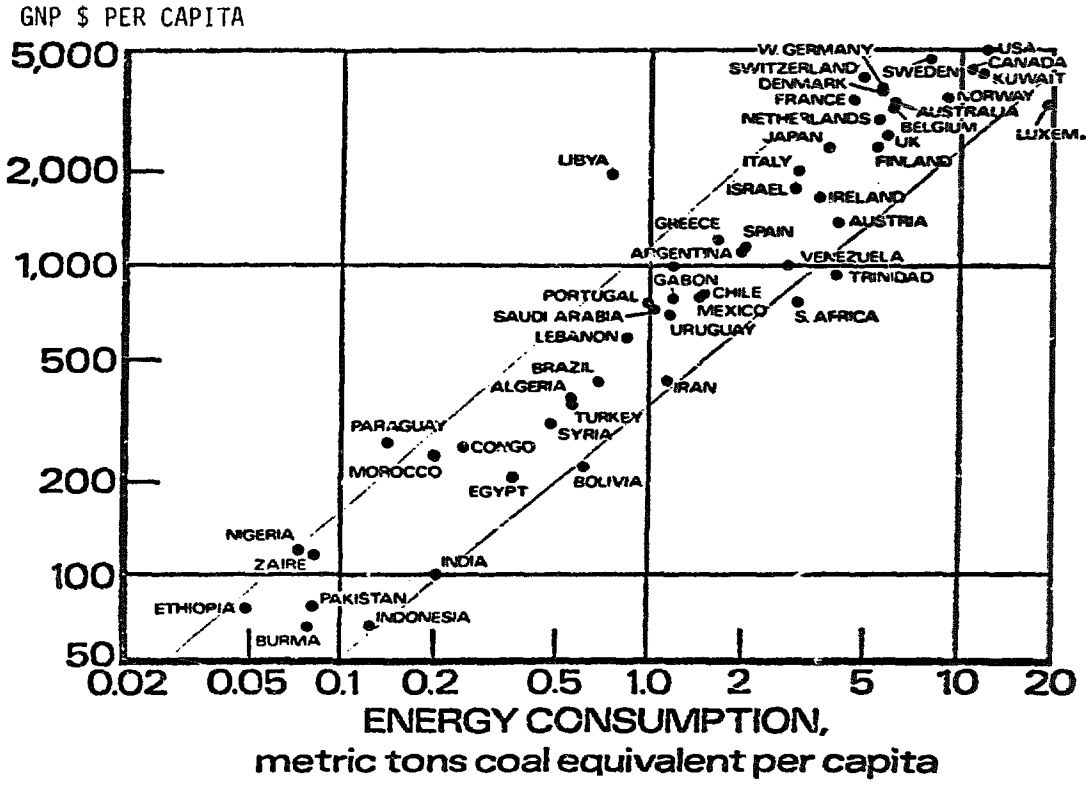
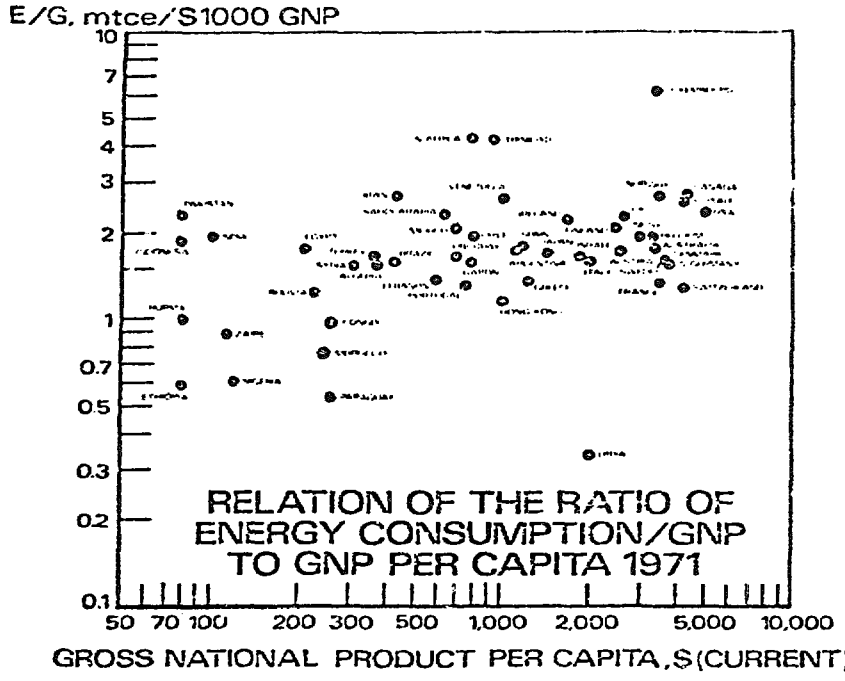


Figure 6

It is perhaps more instructive to plot C = E/G against GNP or energy use (Figure 7). Here, it is seen that there is a correlation according to which countries that use more energy or produce more GNP (always per capita) also use more energy per unit amount of GNP. However, the "spread" for a given amount of GNP, say, is almost as large as the range of the ratio.



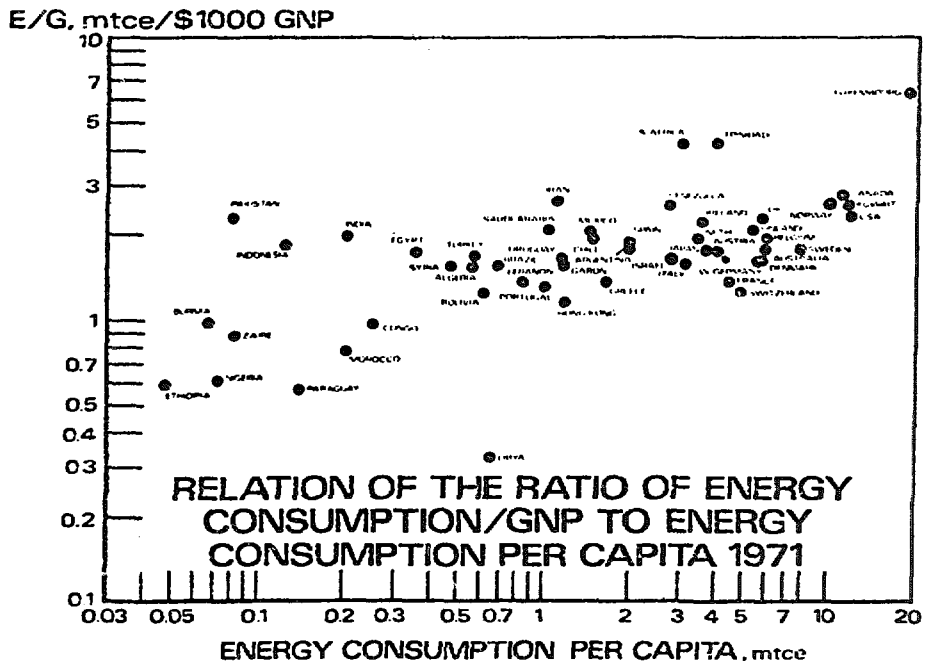


Figure 7

Before we try to draw conclusions from these findings, it may be well to consider some of the possible sources of error that attend an uncritical comparison of such inter-culture comparisons. A number of possible problems come easily to mind. For one thing has been mentioned before, human and animal energy is probably not included, so that a country which is still at a developmental level where much energy of this type is used, will appear to have an anomalously low energy useage, i.e., an anomalously efficient energy use factor.

Another source of error is the relative energy intensiveness of imports and exports. These trade flows may, in effect, import or export energy if the energy content of the imports and exports differs significantly in a way not included in the calculation. An outstanding example is Luxembourg, which appears to have an anomalously high energy use because it mostly exports steel, which is very energy intensive. By contrast, Libya, which imports almost all its energy-intensive manufactured goods, and exports low energy-intensive crude oil (the energy used to produce it is low, the energy content represented by the oil as fuel does not enter here) appears to have an anomalously efficient energy use coefficient.

Nevertheless, after allowance is made for such factors, it remains true that certain countries, whose life styles and living standards are quite comparable with our own, such as Germany, France, Switzerland, Australia, the Netherlands, and the Scandinavian countries, manage to use quite a bit less energy, and have lower values of C. To some extent, this is surely explainable as a result of higher population densities, requiring less transportation energy for much of the transport of people and goods. Climate differences and similar effects may also play a part, as well as national habits and characteristics in general. However, there surely remains much to be learned and evaluated from such cross-cultural differences that could be usefully applied to our society in the area of energy conservation and efficient energy use.

Studies on the Relation of Energy Use and the Economic Condition

I would like to comment briefly on some recent studies based on extensive computer models, which try to predict the amount of energy use reduction that may be achievable, and what their effect on the economy is likely to be.

E.A. Hudson, working at Data Resources, Inc., has written a report on the results of a simulation of the growth of the American economy in the period 1975-2000, under various energy demand and supply conditions. The reference system, relative to which comparisons are made, is a continuation of historical growth trends, which would result in a total energy demand in the year 2000 which is 2.37 times as high as in 1975. In particular, electricity use would climb by a factor of 4.03 in this time interval, use of gas by 1.72, coal by 2.6, and petroleum by 1.69. In view of recent data on finding rates of gas and oil, it already appears that such growth rates cannot be sustained, but that is what a continuation of recent trends would lead to.

For comparison with this projection, two others are made: "Technological Fix" and "Zero Growth" (TF and ZG, hereafter). In TF, it is assumed that "..energy conservation practices and known energy saving technologies are incorporated into production and consumption patterns to the extent possible within existing life styles and economic organization." In the ZG scenario, in addition to the modifications assumed in the TF case, changes in life style and economic structure are introduced to move toward a situation in which there is saturation in the energy use per capita.

To give a quick over-view of the impacts of these two alternative scenarios, Table I will show the cumulative change factors from 1975 to 2000 (i.e., Quantity in 2000/quantity in 1975) for a few of the key parameters, as well as the percent change relative to historic growth (HG).

TABLE I

ITEM	HG	TF	% Change (TF-HG) x 100 / HG	ZG	% Change (ZG-HG) x 100 / HG
GNP	2.32	2.23	- 3.8	2.24	- 3.4
Employment	1.54	1.54	0.0	1.57	+ 1.9
Energy:					
Coal	2.62	1.91	-27.1	1.67	-36.3
Petroleum	1.69	1.07	-36.6	0.93	-45.0
Electricity	4.02	1.98	-50.7	1.72	-57.2
Gas	1.72	1.31	-23.8	1.11	-35.4
Nuclear & Other	9.23	4.07	-55.9	3.60	-61.0
TOTAL	2.37	1.47	-38.0	1.27	-46.4
Energy Consumption:					
Industry	1.37	1.14	-16.8	1.28	- 6.6
Transport	1.82	1.56	-14.3	1.44	-20.9
Personal Consumption	2.09	1.18	-43.5	0.96	-54.1
Prices (for GNP)	2.56	2.68	+ 4.7	2.72	+ 6.3

It is apparent that the conclusions of this study are very optimistic, in the sense that the technical fix scenario would predict that, without major life-style or institutional changes, it would be possible to reduce energy consumption 38% below the unmodified trend demand in the year 2000, and that this would be achieved with no net impact on employment (though certainly not without localized shifts or impacts) and with only a 4.7% additional increase in over-all prices over the 25 year span. With zero growth, the employment would be even larger (due to some substitution of labor for energy) and inflation only slightly worse.

One must, of course, ask how realistic such a model is, i.e., how well it reflects the actual world, and thus how reliable its predictions may be. Predicting the future is always a hazardous enterprise, and a study such as this should perhaps be regarded more as a model of what may be possible, rather than an actual prediction.

The reductions in energy use were modelled to result as a consequence of increased prices for the energy supply commodities resulting from unfavorable supply situations, import restrictions and the like. However, this means that the use reductions had to be calculated on some assumed elasticity rates, and these are not well known for periods of increasing energy prices. The reason that electricity demand is even more severely reduced in the two saving scenarios, relative to the HG case, than are coal, petroleum and gas, is to be explained by the fact that electricity is secondary energy, subject to the inescapable efficiency limitations in converting primary energy to electricity, and thus is much more disadvantaged by the cost increases in primary energy. In other words, users will be tempted to substitute direct use of primary energy in such applications as heating and processing, for electricity, because of the latter's higher sensitivity to price increases in primary energy supplies.

A quite different modelling approach to the same question is embodied in a study by Dr. M. Seidel, done for the Office of Energy Conservation of the Federal Energy Office in 1973-74. In this study, an attempt was made to see what energy savings would become economically desirable, and hence introduced by market forces, as a result of increased prices for energy, based on the assumption of various levels of petroleum prices, namely $6, $8, and $10 per barrel in 1973 dollars. A number of scenarios are worked out which aggregate and extrapolate the substitution actions that would result from such price levels.

The lowest of the price-predicated scenarios, dubbed "Business as Usual" predicts that about 15% of the energy that would be used if there were no price increases, will be saved per year by the year 2000 as a result of the installation of more energy-efficient capital equipment as present equipment comes due for replacement. Nonetheless, despite its minimum dislocation, such a program is envisioned as having a very favorable effect on both environment and resource depletion, because it is the most costly (in terms of environment, etc.) energy which is marginal and will be saved. The savings are relative to the amount estimated to be used on the assumption of constant real energy prices between now and the year 2000, using the AUI-Brookhaven Reference Energy System as data base. It is worth noting, in connection with the study, that the savings to be realized in various sectors, and the time schedule on which the savings are assumed to occur, were derived from the conclusions of the consensus of the participants in the Conservation Panel for the Five-Year Energy R & D Program.

The "Reasonable Conservation" scenario analyzes the saving of about 30 percent of the energy that would be used in the year 2000 under the "Reference Case" scenario. The conservation thus obtained is based on an assumed real energy price of $8 per barrel (in 1973 dollars) to reflect both scarcity and environmental costs in the price of the energy. Gas rationing and forced life style changes are not assumed. The study concludes that executing this scenario would make the nation fully energy self-sufficient or would permit a high level of environmental restoration. In addition to the efficiency improvements envisioned in the "Business as Usual" scenario, this scenario involves specific substitutions made to lessen direct demand for energy. Included in the scenario are reductions of 20 percent in demand for air conditioning and space heating and 30 percent for miscellaneous electricity, all based on improved building insulation and improved appliance design, without change in life style or comfort.

On the industrial side, a 35% reduction in petrochemical feedstocks and a 10% reduction in primary aluminum is assumed, based on increased recycling, as well as a 30% reduction in miscellaneous electricity use. (It must be remembered that all "reductions" are relative to the reference scenario level. They are not absolute reductions, but lesser increases.)

In transportation, a 40% reduction in air travel and a 15% reduction in auto travel are predicted, compensated by a 12% increase in bus, rail, and mass transit travel. Again, all changes are relative to the reference model.

The third scenario, labeled "Project Independence," is intended to achieve a 40% reduction in overall energy use relative to the reference system. This scenario does assume interferences with free market choices, forcing reductions in auto travel, industrial electricity, and process heat use, and forcing some level of discomforts in dwellings.

In the residential/commercial sector, improvements in new building shells and retrofitting for present buildings would be needed to attain an additional 10% saving in heating and 15% in air conditioning, over the saving assumed for the "Reasonable Conservation" scenario, coupled with temperature adjustments in existing structures until the retrofits are done. Industrially, a doubling of the decrease in process-heat utilization is projected, as compared with the "Reasonable Conservation" scenario (which would mean a 40% reduction by 2000 as against the reference projection), and a 50% reduction in miscellaneous electricity use. It is agreed that such a reduction will require shifts from energy-intensive to less intensive products, and thus significant dislocations in the economy, and government action will be required to produce such shifts. The transportation sector calls for a 30% reduction of auto travel compared with the reference system, even with some intercity travel shifted to automotive from air travel.

Some extremely interesting trends emerge from the tables projecting use of various energy sources to the year 2000. The "Reference Case" projection for coal use, for example, shows that, starting at about 600 million tons of coal used in 1975, the demand would rise to about 1600 million tons by the year 2000. Under the "Business as Usual" case, it would rise to about 1250 million tons in 2000; with "Reasonable Conservation," only to 800 million tons; and under "Project Independence," it would decline to about 500 million tons in 2000 after having reached a peak at about 620 million tons per year in 1985-1990. Crude-oil use (in million barrels per year) would rise from the present level of about 6000 to 11,600 in 2000 in the base-line case, to only about 6400 for "Project Independence," 7400 for "Reasonable," and 9200 for "Business as Usual" — all in the year 2000. The conserved amounts as projected here are thus truly enormous.

Another category of projections with important consequences deals with the environmental effects of the scenarios. Strip mining, for example, which is at a level of 160 square miles per year now, would rise to 390 square miles per year by 2000 under the base-line projection while rising to 300 square miles per year at that time with the 15% conservation "Business as Usual" strategy, and actually declining to 140 square miles per year in the 40% conservation "Project Independence" scenario. Similar projections for the amounts of CO_2 produced per year range from 2×10^{13} pounds per year for the base line projection, 1.6×10^{13} pounds per year under "Business as Usual," and 1.1×10^{13} pounds per year for the 30% "Reasonable" projection, down to 8.1×10^{12} pounds per year for the 40% "Project Independence" case, all for the year 2000, and compared with about 1×10^{13} pounds per year in 1974. Sulfur oxide emissions also show similar trends, with even more sensitivity to the selection among the options.

All the conservation measures projected by this study had, by definition, a capital cost less than the present value of the energy savings from the measure, so that, in principle, pricing alone would implement them. However, the costs include valuations of social, environmental, and developmental costs, and these are not now passed on to the consumer, so that prices do not necessarily reflect them correctly. Further, since the impacts of higher prices on different people and activities will differ, inequities would result from a simple reliance on pricing as an implementation method.

Conclusion

To summarize, there is no doubt that, although the direct value of energy in the overall economy represents only a small percentage of the GNP, energy is so intimately woven into the fabric of much of the economic activity that curtailment of its availability or unusual increases in its price may well have very serious effects on economic health.

Nonetheless, despite the fact that in recent history the growth rates of energy and the economy have been rather closely parallel, consideration of other economies and studies of the details of the interaction between the use of energy and specific economic activities suggest that the growth of energy use can be reduced by eliminating waste and substituting more efficient processes for some of those now in use, and that such actions will not necessarily entail economic stagnation or reductions in standards of living.

However, a number of cautionary points must be considered, and many uncertainties remain to be resolved. For example, although waste elimination can reduce energy use, this is to a certain extent a "one-time thing" and the reduction rates probably cannot be maintained indefinitely. Also, many of the waste-reduction processes have built-in time lags since the present, less efficient methods represent capital investments that must be amortized before the more efficient alternatives will, in the normal run of things, be implemented.

Another area of concern is the availability (and cost) of the capital required for many of the energy-conservation proposals. Although any one such modification to a process or product may well be profitable in terms of the capital invested compared with the savings achieved, the implementation of large numbers of such changes in a relatively short time may well make sufficient demands on the capital resources to drive interest rates up to a point where the profitability is reduced or destroyed.

Although the studies cited above imply that the labor market will not be adversely affected by the modifications envisaged, local labor and business conditions may well be subject to severe and painful adjustments.

Many questions on the acceptability of life style changes imposed by such energy use reductions (for example, mass transit vs. private car, installation of insulation to save heating and air conditioning costs, etc.) are unresolved, and in general, the effective elasticities of energy demand in a period of increasing prices, for which little historic precedent exists, are not yet on firm foundations.

Much can be achieved, but much remains to be learned and done.

THE IEA LONG-RANGE ENERGY SIMULATION MODEL

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Oak Ridge Associated Universities

Abstract

A model has been developed for simulating plausible U.S. energy supplies and demands for the last part of this century and the early part of the 21st century. The model falls into the category of simulation technology models, but because of the long time span of the model, econometrically determined parameters would be of doubtful value and are not used. By postulating future energy demands under given technical, resource, and policy assumptions, the decision maker is provided with useful information for bracketing the probable outcomes of policy changes. Demand functions have been generated for each of the energy carriers — electricity, liquids, gases, and solids — by examing the industrial, the residential and commercial, and the transportation demand sectors in terms of their component activities. Supply functions have been generated independently for each of the energy carriers based on the best available data and estimates for the fossil fuels, uranium, hydro-electricity, geothermal heat, and solar energy, and on present knowledge and projections about extraction and conversion technology. For a given set of assumptions, the carrier demands, the total energy demand, the carrier supplies, and the total energy supply are calculated and displayed for the years 1985 through 2040. If the domestic carrier supply is within reasonable proximity of the carrier demand, the match is considered to be operationally feasible, such that the economic marketplace will operate. A simple computer method for combining the independently generated supply and demand functions for the various energy carriers has been developed, and the combined results can be displayed in tabular and graphic form.

The Problem

A primary task, assigned to the Federal Energy Office at its inception late in 1973, was the development of detailed strategies for reducing the dependence of the United States on imported fuels and for achieving a maximum degree of independence from the policies of other countries in meeting the Nation's energy needs. In response to this task, the Federal Energy Office and its successor, the Federal Energy Administration, developed a detailed "blueprint" for what has come to be called "Project Independence". The major part of this effort focused on the period between now and 1985.

The Research and Development Task Force for the project, working in conjunction with the Energy Research and Development Office of the FEA, was charged with assessing the potential impact of research and development on future U.S. energy supply and demand and of various long-range (post-1985) energy strategies. Both of these tasks involved an evaluation of existing and emerging technologies, of resource and environmental constraints, of the lead times required to introduce new technologies, and of long-term national

policy options. The quantitative interrelationships between the various factors required the use of appropriate modeling techniques for the evaluations.

An integration model, Project Independence Evaluation System (1), was developed to provide the quantitative analysis for the near-term period through 1985. The extensive input data required for this model made it too complex and cumbersome for a long-range analysis beyond 1985. However, in June, 1974, the Institute for Energy Analysis was asked to develop a suitable model for assessing various long-term research and development strategies which were likely to have an impact on the U. S. energy system between 1985 and 2040.

Responses to the Modeling Problem

Several models of the U.S. and world energy system had been developed elsewhere to analyze the implications of various policy issues (2,3,4). Each of these models has attempted to represent the interactions between supply, demand, prices, and other energy variables. The modeling representation is usually made through graphical and pictorial displays and, if possible, through mathematical relationships derived from historical data using statistical techniques, or by systems analysis. An energy model, in the narrow sense, is a set of mathematical relations, usually equations, expressing relationships between energy variables. This definition, however, is much too narrow for most current energy modeling purposes. Current efforts are concerned not only with economic theory, but with technological development, environmental quality, and the evaluation of alternative private and public policies. The nature of a particular energy model depends on the questions one wishes to have the model answer.

Prior to the Project Independence efforts, energy modeling had proceeded in four major directions (5), which can be characterized as follows:

1). Optimization models are linear programming models with an objective function that usually minimizes the costs of meeting certain postulated energy demands from known supplies. The World Energy Model of Queen Mary College (6) and the United States Energy Model of Brookhaven National Laboratory (7) are examples of this type. However, these models cannot trace the path of events between current and projected values.

2). Simulation models using econometrically fitted parameters attempt to depict the dynamic structure and movement of the marketplace. These models, unlike the optimization models, show the time path of development for scenarios of different policy assumptions. These models assume that one can derive satisfactory econometric and energy relationships from historical data. MacAvoy and Pindyck's model (8) of the natural gas industry in the U.S. is an example of this type.

3). Economic structure models are input-output and interindustry type models, and are tied to the general microeconomic models of the total economy. These models attempt to describe the effect of changes in the energy sectors on the total economy and the effect of changes in the total economy on the energy sectors. The University of Illinois' model of Hannon and Herendeen (9), the MIT model of Polenske (10), and the Texas State model (11) are examples of this type.

4). Simulation models using parametrically fitted parameters are models that, under assumed parametric values, simulate the markets for bracketing the probable outcomes of policy changes. The Baughman model at MIT (12) and the State of Wisconsin model (13) of the University of Wisconsin are examples of this type.

Efforts to predict the future with any model are difficult and complex, and large complex models often seem to predict no better for the long-term than highly simplified ones, especially if there are uncertainties in the best available input data. Models incorporating explicit economic variables are generally considered to be better models, if one has good input data. At the present time, the values of economic parameters, such as supply-and-demand elasticities, are so uncertain that some model builders are reluctant to incorporate these economic variables explicitly into long-term models. For a model to be useful for 15 to 20 years or longer into the future, an alternative method is to use broad aggregative relationships in which the economic parameters are implicit. Such a model is usually called an engineering or technological model.

The Project Independence Evaluation System (1), designed for the near-term analysis, is a hierarchy of different models. It incorporates several of the econometric techniques described above, as well as the techniques of the engineering models, to estimate future energy demands and fuel supplies. The multiregion, multifuel linear programming model combines the various inputs to find the lowest cost solution for 1977, 1980, and 1985. This integration model reflects regional differences in fuel and transportation costs and provides fuel costs averaged on a national basis.

The farther one goes into the future, the more difficult it becomes to predict either the costs of energy or the regional distribution of supply and demand. Major new fuel transportation links can, and probably will be, built over the coming decades, further complicating the long-term analysis problem. Since cost differentials — rather than absolute costs — drive the model, relatively small errors could, over the long run, cause misleading results.

Two approaches to the long-term modeling effort were considered. One was to start with an existing complex multidimensional model and make a series of simplifying assumptions to conform to the available data base. The other was to design a simplified model, based on physical data and explicit policy assumptions. The IEA effort has followed the second approach with the design of a systems model to answer questions about resources, new technologies, and related policy questions (14). The resulting energy systems model lacks the analytical details of the linear programming approach, but the transparency of the underlying assumptions and the ease of analyzing a wide variety of cases will make it useful to policy makers and other potential users.

The Modeling System

The overall energy modeling framework consists of four simple systems: social and economic factors, energy demands, primary energy sources and carrier supplies, and environmental impacts. Using this framework, one can develop different models for different purposes. The details of a particular model can be developed after the questions to be answered are identified. A particular model can require the specification of a detailed structure for one or more of the systems or the components may be combined or linked in a

particular way. The variables associated with one or more parts may be considered to be implicit variables in other parts of the total system. This modeling framework allows maximum flexibility in model building, and allows for the evolution, testing, and refinement for a particular effort.

The long-range, energy-balance model described here was designed to answer technology and policy questions as they relate to the feasibility of an operational match between U.S. domestic energy supplies and demands for the period 1985 through 2040. The model focuses on the energy consumed by the residential and commercial, industrial, and transportation sectors and on the domestically produced energy sources that can supply the demand. The consuming sectors purchase liquid and gaseous fuels, some coal, and electricity. These four forms, called energy carriers, are distinct from the basic energy resources needed to produce them.

The model generates the supply and demand for each of these carriers and then compares them. Since the market forces can be expected to handle the precise balancing of carrier supply and demand, it is necessary to achieve only a reasonable match with the model (such as carrier supplies within about 15 percent of the demands). Balancing supply and demand is accomplished by varying the resource, technology, and policy assumptions. The decision to match supply and demand outside the model, rather than to include a balancing algorithm within the model, stemmed from a desire to make the underlying assumptions most apparent. The resulting simplicity of the calculations involved permits the policy maker or the analyst to generate several scenarios in a short time, and to achieve an appropriate energy balance through conscious policy choices.

Alternative model configurations were considered, ranging from a focus on total energy to one on actual and derived demands for individual fuels. By focusing only on total energy, the interrelationship between supply and demand technologies is lost. On the other hand, projecting the demands for individual fuel forms, such as gasoline, heating oil, natural gas, coal gas, electricity, etc., in the long term becomes increasingly difficult, and the opportunities for interfuel substitution grow. The carrier approach represents an effort designed to highlight the anticipated limits on the petroleum and natural gas resources. While liquids and gases are shown separately throughout the analysis, it is really their sum that is most critical. Except in transportation, their large uses are interchangeable with present technology, and coal is potentially convertible into either carrier.

The supply of each carrier is tied to basic energy resources — petroleum, natural gas, coal, uranium (and thorium), geothermal heat, solar energy, and fusion. The consumption of each carrier is tied to basic physical processes — transportation, processing, heating and cooling, feedstocks, appliances, and lighting. Since the specification of a unique supply or demand curve for a particular fuel or demand sector is neither warranted nor desired, a set of curves is generally provided for each. High, medium, and low options, or optimistic, pessimistic, and expected values of supply and demand, allow the policy maker to determine the sensitivity of his assumptions. Choices of introduction or takeoff dates for new technologies provide an opportunity to vary research and development assumptions.

The specification of each supply and demand projection reflects both explicit and implicit assumptions about population, gross national product, prices, manpower, capital and water availability, as well as energy resources and technology. The model is also designed to provide gross data on environmental impacts by summing water requirements, waste heat release, and eventually other items of concern, such as land used.

The resulting model allows one to consider a variety of long-term policy questions: what happens to the energy system if only traditional sources are used to meet the demand? if various new and different technologies are introduced at various times? if various policy assumptions are made related to environmental impacts?

Calculating the Energy Supplies and Demands

The results of the individual energy supply and demand analyses indicate either the quantitites of liquids, gases, electricity, or direct coal consumed or supplied. The matching or balancing process involves choosing an appropriate series of supply options, adding up the quantities of liquids, gases, and electricity available and comparing them with the projected demands in the corresponding year. Operationally, this means selecting three demand options (one for each sector) and five or more supply options — petroleum, natural gas, coal, nuclear power, hydroelectricity, and any of the new supply options. The calculations for 1972, 1980, 1985, 1990, 2000, 2010, 2020, 2030, and 2040 may then be made by hand with the help of a desk calculator.

Long-range energy policy analysis requires the selection of various sets of energy supply and demand options, representing consistent policy objectives. For example, one might select the consumption patterns reflecting past trends and then try to supply them with existing sources. New technologies could be introduced as needed to balance the supplies and demands. Alternative policy directions such as conservation or modal shifts could be represented and appropriate supply options identified.

A simple computer method for combining the independently generated supply-and-demand functions for the energy carriers has been developed, and the results are displayed in tabular and graphic form, so that the degree of matching the supply to a given demand can readily be assessed.

An interactive calculation mode is available on Oak Ridge National Laboratory's IBM 360/75 computer, using the TSO time-sharing system and a remote telephone terminal. All optional selection choices can be made by the user at the teletype, and requested in user-oriented fashion. As a result, the user requires no programming knowledge or familiarity with the internal structure of the program. The output appears on the same teletype unit in tabular and also, at the user's option, in graphic form.

Operating the Model

A composite picture of the various operational energy supply and demand futures can be obtained by combining several selected scenarios of the individual supplies and demands. A combination of scenarios for the energy carriers derived from coal, natural liquids and gases, shale, nuclear, etc., gives a supply case. A combination of scenarios for carrier demands from the industrial, residential and commercial, and transportation sectors gives a demand case. If a given set of supply scenarios brings the energy carriers within a reasonable match of the projected demands on the carriers, the case is said to be operational. For such a case, the clearing market prices on the energy supplies should bring the supplies and demands into an exact balance. The definition of a reasonable balance can be set at a given percentage, such as 10 or 15, or it can be set at a given energy value in mQ, depending on the judgment of the policy maker.

Operating the model involves selecting three demand options, one for each sector, and five or more supply options, one for each of the currently used energy sources. One can then add up the carrier demands required for the demand options and the carrier supplies furnished by the supply options for each of the years 1972, 1980, 1985, 1990, 2000, 2010, 2020, 2030, and 2040. The supply options can then be modified to bring the supplies of liquids and gases and of electricity within a reasonable match of the corresponding carrier demands. The heart of this process is illustrated in Tables 1 and 2 which list 53 independent supply and demand estimates developed for this model. Thirty-eight are supply cases, and 15 are demand cases. (See the appendix for detailed titles and assumptions.) Two cases are illustrated here as examples.

Individual Supply Scenario Example

Code Name: COHI2

Short Title: Coal High - Coal Electric Phased Out - High Synthetics

Assumptions: High production of coal - high growth rate for industry - Q_∞ of 600 billion tons - high synthetic production - phased out coal to traditional electricity - new mapping, mining, and processing increases recovery rate with time - plant capacity and transmission factor and efficiency improve with time.

TABLE 1

List of Supply Scenarios

a. Coal

1	COHI1	4	COHI4	7	COIN3
2	COHI2	5	COIN1	8	COLO1
3	COHI3	6	COIN2	9	COLO2

b. Natural Liquids and Natural Gas

10	NLHI1	14	NLIMP1	17	NGLO1
11	NLIN1	15	NGHI1	18	NGLO2
12	NLLO1	16	NGIN1	19	NGIMP1
13	NLLO2				

c. Nuclear

20	NUHI1	22	NUIN2	24	NUIN4
21	NUIN1	23	NUIN3	25	NULO1

d. Hydroelectricity and Geothermal Energy

26	HYDRO1	27	GEOTH1

e. Shale

28	SHHI1	30	SHIN1	31	SHLO1
29	SHHI2				

f. Solar Types and Wastes

32	SOLAR1	35	SOLAR4	37	SOLAR6
33	SOLAR2	36	SOLAR5	38	SORGW1
34	SOLAR3				

Table 2

List of Demand Scenarios

a. Industrial Sector

39	INHI1	41	INHI3	43	INLO2
40	INHI2	42	INLO1	44	INLO3

b. Residential and Commercial Sector

45	RCHI1	47	RCIN1	49	RCLO2
46	RCHI2	48	RCLO1		

c. Transportation Sector

50	TRHI1	52	TRIN2	53	TRLO1
51	TRIN1				

Individual Demand Scenario Example

Code Name: RCHI1
Short Title: Residential and Commercial--High Scenario
Assumptions: Extrapolation of the Base Case of the A.D. Little report to 2040 - assumes that the 1990 fuel mix will remain constant to 2040 and that the average energy intensiveness, EI, for the residential and commercial sector will be unchanged - the residential unit growth rate is expected to decline from a current annual rate of 1.9 percent to an annual rate of 0.4 percent by 2040, and the commercial space growth rate is expected to decline from 4 percent in 1990 to 0.4 percent by 2040.

The calculations required for combining supply and demand scenarios and checking the energy balance can be done by hand, starting with the projected data. In fact, three supply and demand cases were originally analyzed by systematic hand calculations with a desk calculator. Within an hour or two, one can generate and check the energy balances for a given set of assumptions about the future supplies and demands. However, it is much quicker to check a wide variety of assumptions about the future, if one stores the generated data in a computer file and manipulates the combinations of carrier supplies and demands by prompting the computer to do so. A simple computer method for combining the independently generated supply and demand functions for the various energy carriers — liquids, gases, and electricity — has been developed (16). The combined results can be displayed so that the degree of matching the supply to a given demand can be assessed.

Data File

The input data for the individual supply and demand scenarios can be summarized and brought together physically for ease of retrieval during calculations. The data files for the supply and demand scenarios have the same format. Each scenario requires 11 lines; the first two lines are a label for the scenario and the next nine lines are the data. Line 1 is a six-character identification label, for example, COHI1, SOLAR5 RCL02. Line 2 is a short description of the scenario and its assumptions. The next nine lines have eight columns of data for each of the nine years — 1972, 1980, 1985, 1990, 2000, 2010, 2020, 2030 and 2040.

Supply Scenarios

The first column is the year. The next three columns contain the projected annual energy supply by carrier — the order is liquid, gas, and electric. The units are in mQ per year. Most supply sources only produce one of the carriers; the primary exception is coal which can produce all three carriers. Column 5 is zero except for coal scenarios. For coal scenarios, column 5 has the net amount of coal in mQ used to provide the carriers in columns 2, 3, and 4. This data does not include the coal required for direct use in the industrial demand sector. Column 6 is the amount of uranium mined (in units of 1,000 tons per year) to provide the electricity in column 4, and therefore is zero except for the nuclear scenarios. Column 7 contains the amount of water (in units of 1 million acre-feet per year) required for producing the supply of carrier shown in columns 2, 3, and 4. Column 8 contains the waste heat lost (in units of mQ) in producing the carriers shown in columns 2, 3, and 4.

Demand Scenarios

The first column is the year. The next 4 columns contain the projected annual energy demand by carrier — the order is liquid, gas, electric, and solid. The units are mQ per year (1 milli Q = 10^{15} BTU). Columns 6 and column 8 is the total net energy consumed and is equal to the heat discharged to the environment at the point of consumption.

The Computer Program

For the production of summary tables and figures to display the results and to minimize numerical errors, a computer program (SCEN) and the data file (SUDE10.DATA) are presently stored on a permanently mounted disk on the Oak Ridge National Laboratory IBM 360/75 computer. The data file and computer program can be updated using the time-sharing option (TSO) of the IBM operating system. When using SCEN at an interactive terminal, the user first specifies the terminal line size, allocates the input and output files to the terminal and allocates the data file to SUDE10.DATA. Next, the user loads the program (SCEN.OBJ) and execution begins. The user is first prompted for the number of scenarios (NSCE) to be read from the input file which causes

the first NSCE scenarios on the "SUDE10.DATA" file to be read into the computer memory. The user is then prompted to select a listing of the entire input file section read into memory, just their identifiers and short descriptions of one line each, or no listing at all.

A scenario title is then asked for by the program (up to 72 characters), and after the title is typed, the user is requested to specify the desired supply scenarios. Presently, up to 11 are allowed, and they are specified by merely typing in their sequential number in the input file as listed with the scenarios. The numbers do not have to be typed in any particular sequence. The demand scenarios are requested next, and there are always three of these to list. The demand scenarios are specified as above, in any order desired. The user is then requested to indicate if plots of the results are desired.

The program forms the sums and ratios and begins the output listing in summary format. This consists first of a recapitulation of a list of the input scenarios selected, followed by a list, for each of the nine years, of the supply and demand for the carriers (liquids, gases, electricity) and the sum of liquids plus gases in mQ units. Immediately below each supply/demand pair, there is listed the difference (the gap between demand and supply) in mQ and the percent gap in percent of the demand. In addition to these four category columns (each entry consisting of a quartet of numbers as described above, for example, supply, demand, and the difference in mQ and difference in percent), the fifth column group presents a quartet of numbers which give the amount of coal mined in mQ, the amount of uranium mined in units of 1,000 tons, the amount of water used in million acre-feet, and the total heat discharged to the environment.

The program constructs the graphs by forming and then outputting a two-dimensional matrix whose entries represent character spaces in the output graph. Since the program is tailored to an 80-character-per-line typewriter unit, there is a limitation on the number of possible ordinate values. The program interpolates between the tabulated values by using a four-point LaGrange interpolation scheme. It searches for the maximum value among both the supply and demand curves and scales the calculated values to fit the curves. The ordinate scale is always a multiple of 50 mQ for the total graph height. The first graph plots both the supply and demand values for the sum of liquids and gases. The user may then specify whether the second curve, which plots the electricity supply and demand, is to be scaled to the same value as the first plot, or whether the scaling is to be separately optimized.

After the second graph is completed, the user is asked to enter input for a further case or to terminate the running of the program. The plotting package labels the ordinate and abscissa axes and provides axis lines and interval tick marks as well as a caption, which includes the title for the case and the quantities plotted. The supply is plotted with "S" characters and the demand with "D's". Where the demand "overlies" the supply curve such that both have the same value and the curves coincide, only the "D" symbol appears.

The Interative Matching Process: Eighteen Cases

In general, a step-by-step iterative process is used for seeking feasible solutions or matches of supplies to demands by carrier. Several supply scenarios have been projected in an attempt to find the best match or matches for each of three postulated future energy demands — a high future demand, an intermediate case, and a low case. The high case, B1, was one of the demand

cases presented in the examples of the last section. This case represents a continuation of recent energy demand trends with some moderation due to the downturn in U.S. population projections. The intermediate case, B4, represents a combination of some conservations and some shift to electricity. The low case, C4, represents a combination of strong conservation with major shifts to electricity. These demand cases bracket the most likely U.S. energy demand futures.

Results of the Model

In presenting the summary of results, it must be made clear that uncertainties underlie all of the projections used. It is not possible to predict what the energy demand will be in the next century nor how the demand will be supplied. The U.S. population and economic growth rates are not known for that future time. However, projections used here do bracket a range of plausible energy futures and can serve as a guide in helping policy makers lead the Nation into the future with some understanding of the consequences.

The following points are offered as observations from this study of the U.S. energy system through 2040:

- The most urgent energy supply problem during the long term will be the shortfall of oil and natural gas. Although there are differing opinions among the experts on how much oil and natural gas will be available, the difference between the pessimistic and optimistic estimates makes only about a ten-year difference in depletion times for these resources.

- Synthetics from coal and oil shale will be required to offset some of the expected short-falls in natural liquids and gases. These industries will need to grow rapidly starting by 1980 to have the desired impact on energy supplies after 1985.

- The oil and gas shortfall will be so large that supply strategies alone will not be sufficient. Energy demands will need to be shifted to electricity to help alleviate some of the impending shortage in liquids and gases.

- In addition to demand shifts to electricity, conservation measures will need to be implemented to some degree to decrease the growth in overall demand, unless the Nation is willing to operate its energy system at the environmental limits.

- Use of conventional nuclear reactors will be required to meet the shifts in demands to electricity, and uranium resources are also limited and will be exhausted without the development of the breeder reactors.

- New energy sources not limited by conventional fossil fuels and uranium resources will be needed in the long term. Technologies, such as the breeder reactors, fusion reactors, and solar systems will be needed, but will take several decades to develop and introduce. The breeder technology has been demonstrated, but fusion reactors and solar-electric systems are yet to be made operational.

- The other energy sources— hydroelectricity, organic wastes, and geothermal heat— are important but will not contribute much to the total energy supply, unless there is an unexpected breakthrough in technology to recover geothermal heat from hot rocks.

There are several technologically plausible energy futures from which the policy maker can choose. This model needs to be developed further to estimate the related environmental quantities for each of the feasible solutions or operational matches between supply and demand.

Limitations of the Model

In the process of using the model, its basic structural limitations as well as the limitations due to uncertainties in the best available input knowledge become apparent. First, the amounts of exhaustible energy resources which will eventually be recoverable are uncertain, and hence, optimistic, intermediate, and pessimistic resource estimates based on different expert opinions are required. Second, the future relationships between energy and economic variables are unknown for the long-term analysis, although assumed alternative energy-economic relationships can be evaluated implicitly through the various supply and demand estimates selected. Third, the future relationship between the U.S. energy system and the worldwide energy system is uncertain. This model treats the U.S. energy system in isolation. It does assume, however, that reasonable shortages of liquids and gases could be made up by imports from other parts of the world system. Uranium resources could conceivably be imported also, if necessary, as they were for a period in the past, although imports were not used in this analysis. Fourth, the structure of the model is inconsistent on several points, but especially in the treatment of the energy resource, conversion, and distribution industries. For example, the energy losses for conversion to electricity and its subsequent transmission are treated on the supply side, while the energy used in the mining and processing of coal and uranium and in the drilling, pumping, and transportation of oil and gas is counted on the demand side. The effects of some of these uncertainties listed here can be assessed to a degree by estimating the marginal supplies or demands needed to compensate for alternative resource or policy assumptions.

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APPENDIX

DETAILED LIST OF SUPPLY SCENARIOS FOR TABLE 1

a. Coal

1 COHI1 Coal High - Coal Electric High - No Synthetics
2 COHI2 Coal High - Coal Electric Phased Out - Synthetics High
3 COHI3 Coal High - Coal Electric Intermediate - Synthetics Intermediate
4 COHI4 Coal High - Coal Electric Intermediate - Synthetics Low
5 COIN1 Coal Intermediate - Coal Electric Intermediate - No Synthetics
6 COIN2 Coal Intermediate - Coal Electric Phased Out - Synthetics Intermediate
7 COIN3 Coal Intermediate - Coal Electric Phased Out - Synthetics Intermediate
8 COLO1 Coal Low - Coal Electric Low - No Synthetics
9 COLO2 Coal Low - Coal Electric Phased Out - Synthetics Low

b. Natural Liquids and Natural Gas*

10 NLHI1 Natural Liquids High - Q of 500 Billion Barrels
11 NLIN1 Natural Liquids Intermediate - Q of 300 Billion Barrels
12 NLLO1 Natural Liquids Low - Q of 220 Billion Barrels
13 NLLO2 Natural Liquids Low - Q of 220 Billion Barrels Accelerated
14 NLIMP1 Oil Imports Scenario 1 - 8 Million Barrels of Oil Per Day
15 NGHI1 Natural Gas High - Q of 2000 TCF
16 NGIN1 Natural Gas Intermediate - Q of 1500 TCF
17 NGLO1 Natural Gas Low - Q of 100 TCF
18 NGLO2 Natural Gas Low - Q of 1000 TCF - Accelerated
19 NGIMP1 Gas Imports Scenario 1 - 5 Trillion Cubic Feet Per Year

c. Nuclear

20 NUHI1 Nuclear High Nonbreeder
21 NUIN1 Nuclear Intermediate Nonbreeder
22 NUIN2 Nuclear Intermediate Nonbreeder - Breeder 1990
23 NUIN3 Nuclear Intermediate Nonbreeder - Breeder 2000
24 NUIN4 Nuclear Intermediate Nonbreeder - Breeder 2010
25 NULO1 Nuclear Low Nonbreeder

d. Hydroelectricity and Geothermal Energy

26 HYDRO1 Hydroelectric Power - Scenario 1
27 GEOTH1 Geothermal Power - Scenario 1 - Steam and Hot Water

e. Shale

28 SHHI1 Shale High - 19.4 Billion Barrels by 2040 - Unlimited Water
29 SHHI2 Shale High 2 - 12.7 Billion Barrles by 2040 - Ample Water
30 SHIN1 Shale Intermediate 1 - 5.8 Billion Barrels by 2040 - Ample Water
31 SHLO1 Shale Low 1 - 1.0 Billion Barrels by 2010 - Limited by Water

* The numbers for oil and gas have since been revised in agreement with the latest U.S.G.S. estimates for total recoverable resources.

f. Solar Types and Wastes

32	SOLAR1	Solar Scenario 1 - One Solar Source - Takeoff 1990
33	SOLAR2	Solar Scenario 2 - One Solar Source - Takeoff 2000
34	SOLAR3	Solar Scenario 3 - One Solar Source - Takeoff 2010
35	SOLAR4	Solar Scenario 4 - One Solar Source - Takeoff 2020
36	SOLAR5	Solar Scenario 5 - One Solar Source - Takeoff 1990 - Limited Growth
37	SOLAR6	Solar Scenario 6 - One Solar Source - Takeoff 2000 - Limited Growth
38	SORGW1	Organic Waste Scenario 1 - Burn Waste - Produce Electricity

Detailed List of Demand Scenarios for Table 2

a. Industrial Sector

39	INH11	Industrial - High Scenario 1 - Reference Energy
40	INH12	Industrial - High Scenario 2 - Conserve Oil and Gas
41	INH13	Industrial - High Scenario 3 - High Oil and Gas
42	INL01	Industrial - Low Scenario 1 - Reference Energy
43	INL02	Industrial - Low Scenario 2 - Conserve Oil and Gas
44	INL03	Industrial - Low Scenario 3 - High Oil and Gas

b. Residential and Commercial Sector

45	RCH11	Residential and Commercial - High Scenario
46	RCH12	Residential and Commercial - High Electric
47	RCIN1	Residential and Commercial - Intermediate Scenario - Conservation
48	RCL01	Residential and Commercial - Low Scenario - Solar Heating & Cooling
49	RCL02	Residential and Commercial - Low - Solar Electric

c. Transportaiton Sector

50	TRH11	Transportation - High Scenario - Maximum Demand Mode Shift
51	TRIN1	Transportation - Intermediate Scenario - Middle of the Road
52	TRIN2	Transportation - Intermediate Scenario - Mode Shift - Conservation
53	TRL01	Transportation - Low Scenario - Technological Fix

SUPERCONDUCTIVITY AND MAGNET TECHNOLOGY*

by

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Introduction

Although superconductivity has been studied for a long time (over 60 years) and only recently been applied to science and technology, the occurrence of superconductivity is not really a rare phenomenon. In fact, the contrary is true since more than 1000 compounds and alloy systems as well as 26 elements are known to exhibit superconducting properties under normal conditions (at very low temperatures). A wide variety of crystal structures are represented amongst the known superconductors. However, the most important ones do seem to have cubic symmetry such as the body centered cubic (NbZr and NbTi), face centered cubic (NbN), and the A15 or β-tungsten structures (Nb_3Sn, V_3Ga, Nb_3Ge, Nb_3Al, and V_3Si).

Today, we quite rightly regard superconductivity as a phase change with well-defined critical parameters rather than as a property of the material such as zero resistance. I shall first discuss a little background then the three parameters that characterize superconducting materials with values of commercial materials as examples. I will then discuss our attempts to understand some of the particular phenomena associated with superconductors as a necessary prelude to constructing superconducting magnets. The origin of degradation will be mentioned and methods to stabilize magnets illustrated. Finally, I will discuss the results of our design studies of toroidal magnet systems for fusion reactors.

Background Theory

Superconducting behavior is a quantum mechanical effect on a microscopic scale. At low temperatures, most of the conduction electrons are in their lowest energy states. Viewed as a band model, some of the electrons near the top of the sea can form pairs with an attractive interaction. An electron interacts with the lattice through the phonons, and this slight polarization of the lattice is transmitted to another electron which is also interacting with the lattice. The net result of this electron-phonon coupling is a positive interaction between electrons. The electrons are paired with equal and opposite momentum, and in their ground state the total electromagnetic momentum of the pair is zero. This leads to a phenomenon called the Meissner effect which holds for all superconductors at low enough fields and a particular class (type I superconductors) entirely. It is very easy to understand the derivation once the assumption of the total momentum being zero is accepted.

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In Figure 1, the total momentum includes a mechanical momentum plus a vector potential term due to the presence of a magnetic field. After solving for the velocity and substituting for the current density, we find that the current density is proportional to the vector potential. If we take the curl of both sides and substitute Maxwell's equation for curl A, we obtain an expression known as London's first equation. London's equation curl j proportional to field takes the place in superconductivity that Ohm's law takes in electricity. The current density is no longer proportional to the electric field ($j=\sigma E$) but rather curl j is proportional to the magnetic field. If we now substitute another Maxwell equation in London's equation, we have curl curl H proportional to H. But curl curl is equal to gradient divergence minus del squared, and since the divergence of field is zero (another Maxwell equation), we obtain the Meissner equation with the solution given on the bottom line of Figure 1. The next figure (Fig. 2) shows what this looks like.

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$$\vec{P} = 2m\vec{v} + 2\frac{e}{c}\vec{A} = 0$$

$$\therefore \quad \vec{v} = -\frac{e}{mc}\vec{A}$$

$$\vec{j} = -\frac{ne^2}{mc}\vec{A} \quad (\text{AS } \vec{j} = ne\vec{v})$$

$$\text{CURL } \vec{j} = -\frac{1}{\lambda^2}\vec{H} \quad (\text{AS } \vec{H} = \text{CURL } \vec{A})$$

LONDON'S 1st EQ + MAXWELL (CURL $\vec{H} = \vec{j}$)

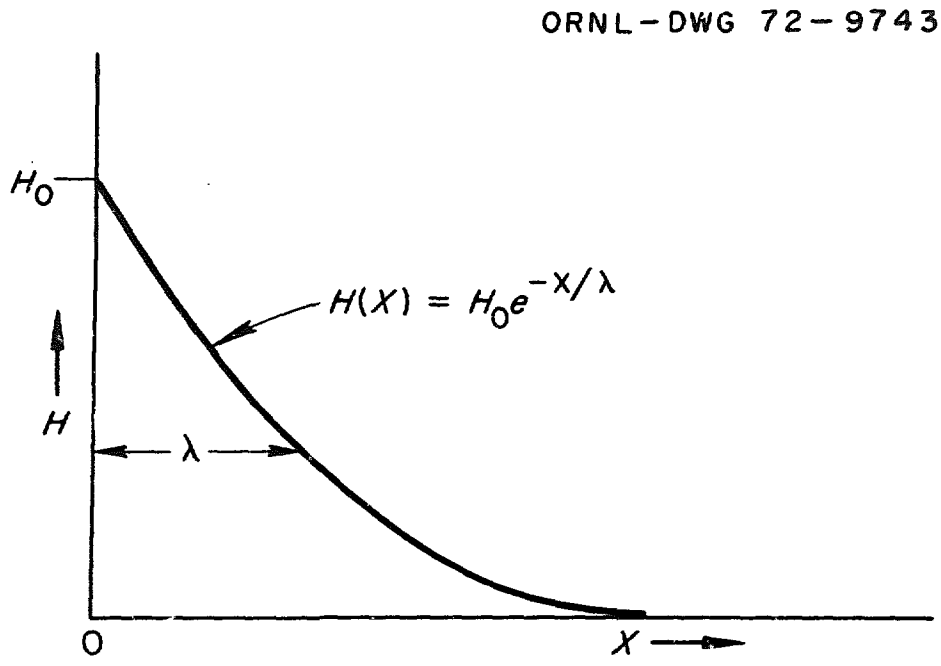
$$\nabla^2\vec{H} = \frac{1}{\lambda^2}\vec{H}$$

$$H(X) = H_0 \, \text{EXP}(-x/\lambda)$$

Meissner Effect.

Figure 1

A semi-infinite piece of superconductor with a magnetic field increasing in magnitude will have a current induced on the surface which serves to shield the magnetic field from the interior. The shielding depth λ is called the London penetration depth and it is approximately 1000 Å in order of magnitude. Values between 500 to a few thousand angstroms have been measured, so the shielding distance is very small. As expected from our derivation, this penetration is also consistent with Maxwell's equation in that the tangential component of a magnetic field is continuous. Superconductors on a macroscopic scale are consistent with Maxwell's equations. It is only on microscopic details that one finds Maxwell's equations inappropriate and has to employ quantum electro-dynamics.



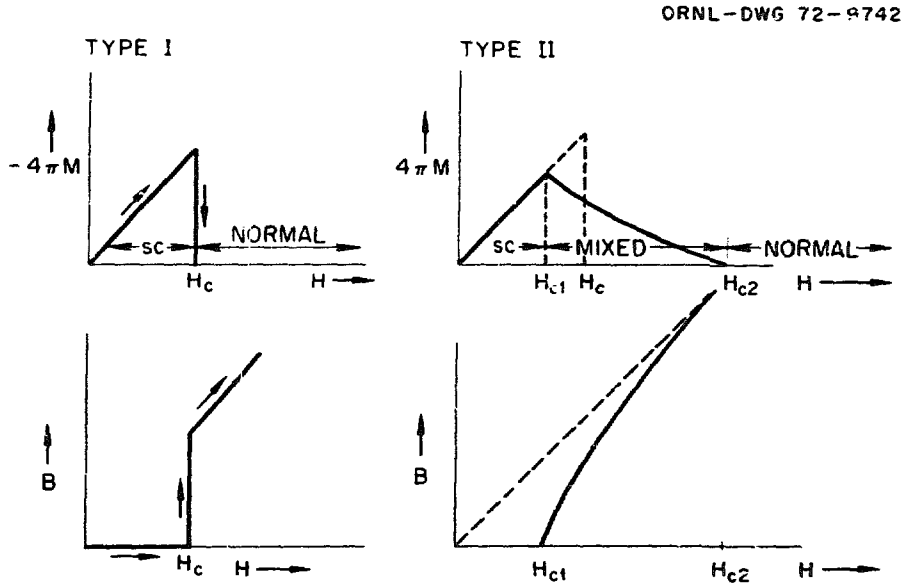
Meissner (Shielding) Currents.

Figure 2

Critical Parameters

There are two classes of superconductors: type I and type II. For many years only one kind, the type I, was known, and they are generally not of technological interest except very recently in the area of superconducting transmission lines. The reason can be best understood by looking at the magnetization properties. Since superconductors are diamagnetic, the magnetization is shown as $-4\pi M$ vs H. For type I superconductors, the magnetization ($-4\pi M$) increases with increasing field until a field H_c called the thermodynamic critical field is reached. At this value of external field, the type I superconductor reverts back to the normal state. Above this field value it is entirely in the normal state and below this field it is perfectly superconducting with the Meissner currents shielding the field from the interior. If we look at the magnetic induction $B=H+4\pi M$ for this case, we see that it is zero until the critical field is reached and then it is proportional to field. The magnetic induction is zero in the bulk of the type I superconductor and hence the origin of the term that a type I superconductor expels flux from its interior. Unfortunately for superconducting materials, H_c is the order of 1000 G. In lead (Pb) for instance H_c is about 575 G. This is too small a value for magnets because if you try to make a magnet out of lead wire, it would go normal and quench itself when it produced a self field higher than H_c at the surface of the wire. This is what happened to the early experimenters who first discovered superconductivity 60 years ago.

If we turn our attention to the type II superconductors (Fig. 3 also) and they have been widely studied for the last fourteen years, we see the magnetization properties more typical of alloys and compounds. The magnetization vs field undergoes a change at a particular field, called the lower critical field, well below the thermodynamic critical field value. The magnetization persists all the way up to a particular field called the upper critical field. Only above the upper critical field is a type II material completely normal. Below that value it is in the so-called mixed state and below the lower critical field it is in a pure superconducting state. The meaning is clearer by observing the magnetic induction vs field curve. At the lower critical field, flux starts to enter the bulk of the type II superconductor but there is still some difference between the induction inside the material and the external field. This persists all the way up to the upper critical field when the material is then completely normal. This curve is for an almost reversible type II superconductor. There are other features to the magnetization property, and these will be discussed below.

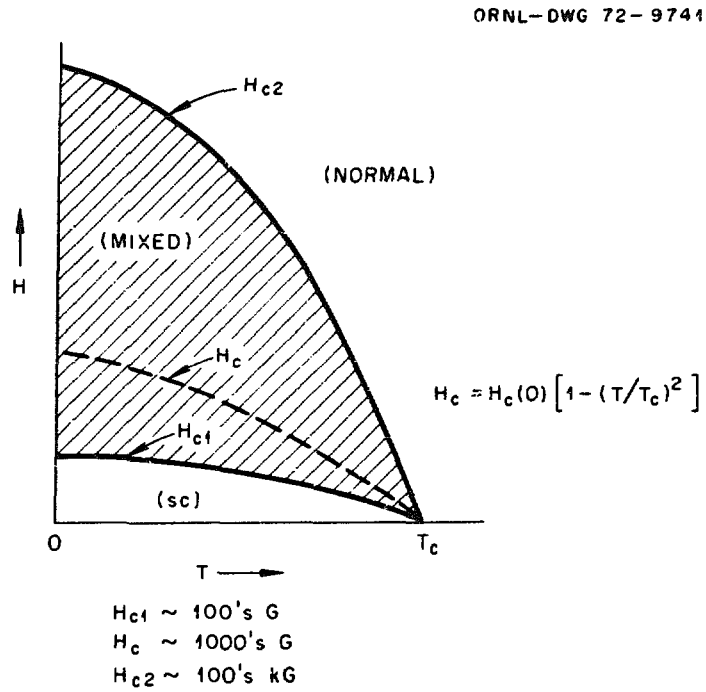


Magnetization and Induction.

Figure 3

The second critical parameter which characterizes superconductors is temperature and the critical fields depend on temperature. The next figure shows the variation of magnetic field with temperature for the three magnetic fields discussed above. The order of magnitude of the critical fields at 4.2 K is listed. The upper critical field drops off with increasing temperature in almost a linear fashion as T_c is approached. The critical temperature T_c of a superconductor is defined for zero field. At any field value the critical temperature (transition from superconducting to normal state) is less than the zero field T_c. At constant temperature, the pure superconducting state exists up to H_{c1}, the lower critical field. Above this, the mixed state region persists

until finally the normal state transition occurs at the upper critical field H_{c2}. The thermodynamic critical field H_c is not measured for type II superconductors but it can be defined and it has physical meaning which we will discuss later, so it is indicated here by a dashed line. This is the only critical field with a fairly well defined temperature variation. Many superconductors have critical fields which decrease with a quadratic temperature dependence above 4.2 K, the normal boiling temperature of liquid helium.



Critical Fields vs Temperature.

Figure 4

Properties of Commercial Materials

In Fig. 5, values of the critical temperature and upper critical field are listed for three commercial materials used in the construction of magnets. NbTi

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DUCTILE ALLOY	T_c(K)	H_{c2} (kG)	H_{c2}(PRACTICAL)(kG)
NbTi	8-10	100-120	80
BRITTLE COMPOUND			
Nb_3Sn	18.3	225-250	150
V_3Ga	14.5	210-230	170

Commercial Materiai.

Figure 5

is a ductile alloy and various compositions are used commercially, such as Nb-50% Ti up to Nb-78% Ti, so this is indicated by a range in critical temperature. It must be noted that each composition has only one critical temperature. The values of the upper critical field are those measured at 4.2 K. For NbTi, it is between 100 and 120 kG (i.e., 10 tesla = 10 Wb/m^2 = 10 $V\text{-}sec/m^2$). I have also listed the practical upper critical field which is limited by the current density which decreases with increasing field. For NbTi the practical field limit is 80 kG, for above this value it becomes economically unsound to make magnets. The current density is too low and it is more sensible to use another material above the practical limit. The two high field materials are brittle A-15 compounds and are not yet available in wire form. They are available only as thin films. The practical upper limit for Nb_3Sn is 150 kG although some small magnets have been made with fields close to 160 kG. V_3Ga could extend magnets up to 170 kG but as yet no large high field magnets have been made with this material which is available only from Japan within the last three years. There are stability problems with these high field materials and that is why there have not been many large high field magnets constructed. Note that although the upper critical field of V_3Ga is a little lower than Nb_3Sn, it could be used to produce higher field magnets and this is due to the field dependence of the critical current density.

Let us take a look at the cross section of a modern NbTi magnet wire:

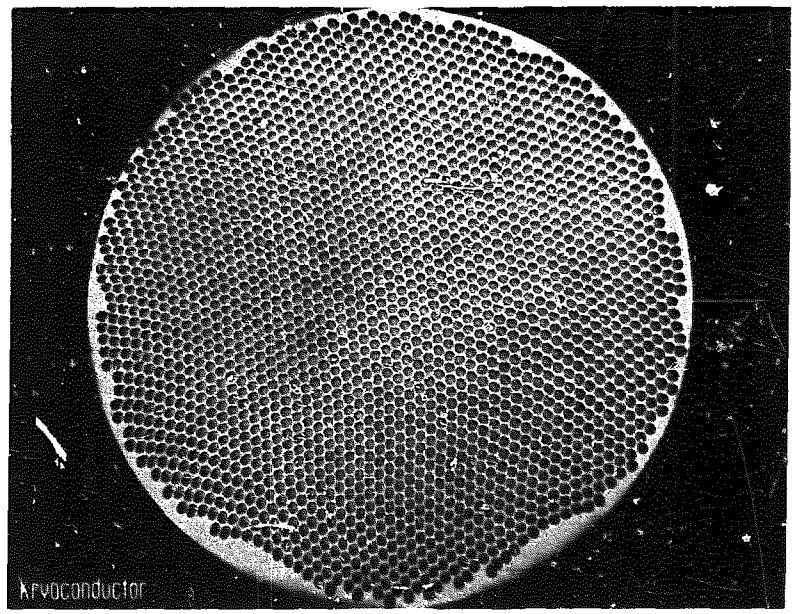

Figure 6

This wire is one-tenth of an inch in diameter overall, has a copper to superconducting ratio of 2 to 1, and each of the 2133 superconducting filaments is 1.25 mils in diameter. The wire carries 2000 A at 50 kG for an average current density of about 42,000 A/cm^2. If used in a magnet with a packing factor of 0.6 one could easily obtain a magnet with an overall current density of 25,000 A/cm^2. The filaments in addition to being small are also twisted with a pitch of one twist per inch. This gives dynamic stability in a rapidly changing magnetic field. This wire with fine, twisted filaments is the so-called adiabatically stabilized NbTi conductor and wires like this can then be stranded up and made into flat braids of transposed strands or cables with twisted strands. In this

form they can be used for pulsed magnets and today find application in synchrotron magnets and superconducting generators and motors.

The NbTi material is prepared by arc melting the powders in an inert atmosphere to form ingots weighing between 100 and 1000 lbs. The ingot is then extruded and swaged into rods. The rods are drawn down and co-drawn inside a tube of high purity copper (OFHC) with which it forms a cold welded bond. The units are stacked in a billet can of copper and extruded into a 2-inch rod. It is reduced down to a wire by swaging and drawing and some annealing is used to assist in the drawing operation. After reaching final size, they are given a heat treatment of about 350-400°C for about a half hour. This accomplishes two things: it produces percipitations (probably dissolved gases) at dislocations which produce optimum critical current density. Simultaneously, the copper is annealed and its conductivity is increased which is necessary for stability. A certain amount of copper or high conductivity normal metal is required to be in good metallurgical bond with the superconductor to remove the heat which always gets produced when the magnetic field is changed. It is now possible to fabricate multiple arrays of fine filaments in a conductor with a round, square, flat, or even tubular matrix. The latter configuration is used for forced flow of compressed helium much in the same manner as water cooled conventional copper coils.

The next figure illustrates the cross section of the high field ribbon conductor, Nb_3Sn, manufactured by IGC (formerly GE Superconducting Department).

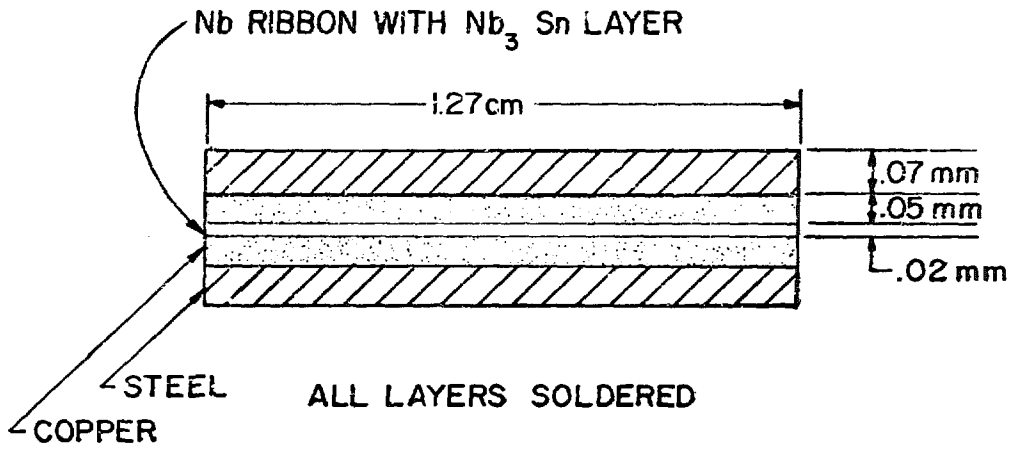

Figure 7

The particular sample is 0.5 in. wide and approximately 8 mils thick. It is prepared by passing a Nb-1% Zr ribbon first through a bath of molten tin which adheres to its surface inside a furnace with an inert atmosphere. Then the tape is heated to 950°C for 15 minutes also in an inert atmosphere. The tin diffuses forming Nb_3Sn. Copper and stainless steel if needed for strengthening are then soldered to the Nb_3Sn with Pb-Sn and finally the surface is coated with a varnish insulation.

A material such as the one shown in the figure is capable of transporting between 300 to 800 A at 100 kG. The value of the current carrying capacity depends on the length of heat treatment and thus the thickness of the Nb_3Sn thin film layer formed. One pays more per foot for higher current material, i.e., the longer processing time adds significantly to the cost.

Critical Parameters of Type II Superconductors

I should like to return now to a closer look at the critical parameters previously mentioned and see what theory predicts about them. The thermodynamic critical field, H_c, while small for practical purposes is important to know. In zero field, the difference between the superconducting state and the normal state is known as the condensation energy in analogy with phase changes. This energy is equal to $H_c^2/8\pi$ which is determined experimentally by integrating the area under the magnetization vs H data. This is the amount of energy per unit volume that must be supplied to raise the superconducting state to the normal state. Figure 8 is a plot of the Gibbs free energy. The sign of the superconducting state is minus as it is a more ordered state and hence has less entropy associated with it. As a magnetic field is increased on a superconductor, the free energy of the superconducting state (solid line in Fig. 8) approaches the normal state and the difference ceases at the upper critical field, H_{c2}. We can predict the value of the upper critical field from normal state parameters of the material. The GLAG theory which has been successfully applied to many aspects of type II superconductors predicts the value as $H_{c2}(kG) = 3.1 \times 10^{-5}$ $\rho_n \gamma T_c$ where ρ_n is the normal state resistivity ($\mu\Omega$-cm), γ is the coefficient of the electronic specific heat term in the normal state (ergs/cm^3-K^2), and T_c is the critical transition temperature in zero field (K). This expression works fairly well for type II superconductors if the upper critical field is not too high (below 100 kG). When H_{c2} gets too high, other effects start to play a role. For instance the normal state is paramagnetic and as such it is also affected by a magnetic field. When a correction is made for the Pauli spin paramagnetism, one predicts an upper critical field $H_p(kG) = 18.4\ T_c$ dependent only on T_c. Refinements to this theory include spin orbit corrections to the superconducting state yielding $H_p^*(kG) \sim 13\ T_c$. Other more sophisticated approaches allow a little better fit with experimental observation, but the real importance of these theoretical calculations was the prediction that a high critical field requires a high critical temperature. Some recent experiments violate this simple proportionality between H_{c2} and T_c because small increments in T_c (10%) have yielded increases of a factor of almost two in H_{c2}. For example, $Nb_3(Al_xGe_{1-x})$ has a critical transition temperature about 2 K higher than Nb_3Sn yet its upper critical field at 4.2 K is 420 kG as opposed to 225 kG for Nb_3Sn.

Let me turn your attention to the critical transition temperature. The theoretical expression shown in Fig. 9 was derived in the BCS paper (the first successful treatment of superconductivity was given in a classic 1957 paper by Bardeen, Cooper, and Schreiffer). The critical temperature depends on the product of the Debye temperature, θ_D, and the exponential term containing $N(E_f)$, the density of states at the Fermi surface, and V the electron-phonon interaction parameter. Since θ_D and $N(E_f)$ can be determined from phonon spectra and specific heat data, the critical temperature can be determined once V is known. Unfortunately, V cannot be experimentally measured or predicted by theory. We have one equation with two unknowns. Hence, T_c cannot be predicted from basic material parameters. If we turn the equation around and solve for V, we can find out its value by measuring T_c [and independently θ_D and $N(E_f)$]. A plot of the high T_c superconductors shows that the ones with a large value of $N(E_f)$ have a small value of V and vice versa. Since there is no theoretical reason why a superconducting material could not have a large value of both parameters, the search for higher transition temperature superconductors continues. The optimists predict an upper transition temperature of 40 K. In the next figure I have plotted the transition temperature against date of discovery only when it was an increase over previous known ones. It is interesting to observe that the data can be fit by a straight line and also that a new increase in the superconducting transition temperature has been found each decade. If the trend continues, a 30 K superconductor will be available at the turn of the century. However, a liquid N_2 superconductor will not be available until 2200 A.D.!

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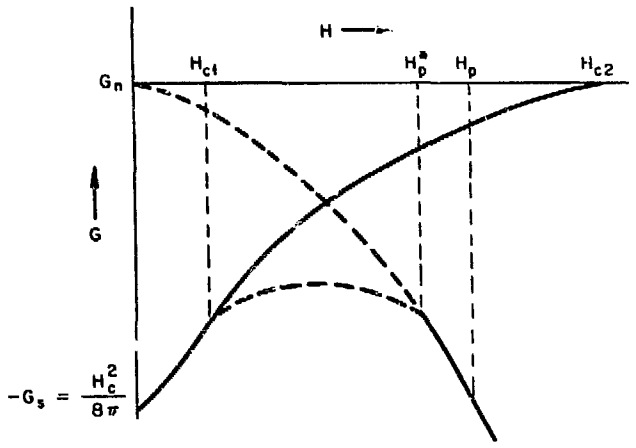


$H_{c2} = \text{CONST}\ \rho_n \gamma T_c$

$H_p = 18.4\ T_c\ (kG)$

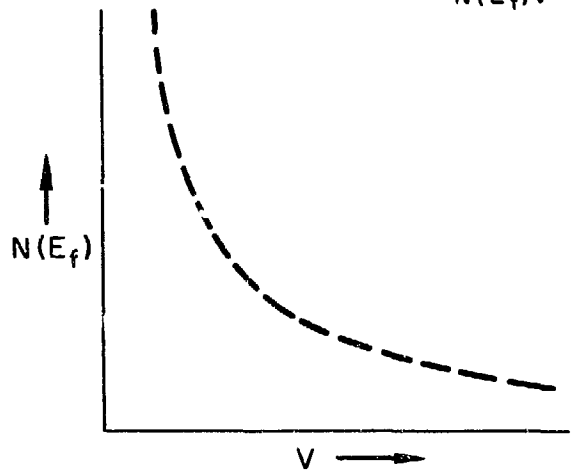
$H_p^* \sim 13\ T_c\ (kG)$

Free Energy vs Field.

Figure 8

ORNL-DWG 72-9738

$$T_c = \theta_D\ \text{EXP}\ \left(-\frac{1}{N(E_f)V}\right)$$



Critical Temperature.

Figure 9

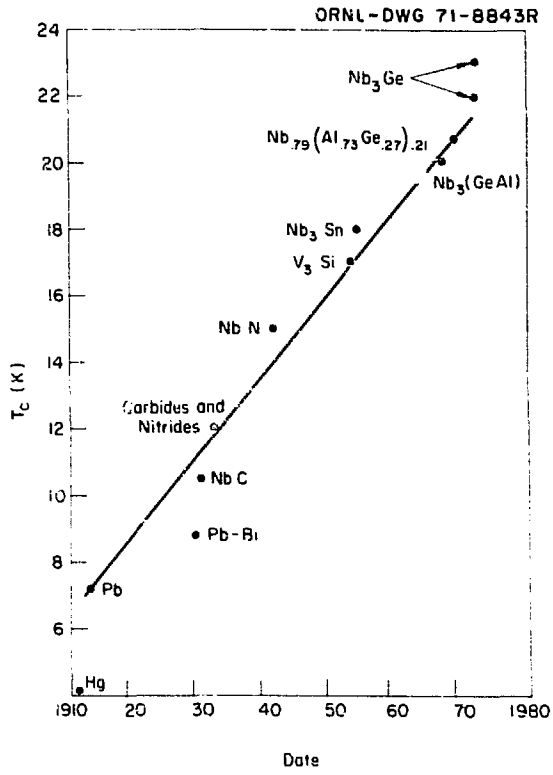


Figure 10

The last of the three parameters which are used to characterize type II superconductors is the critical current density, j_c. In Fig. 11 I have compared the magnetization curve of a superconducting material almost free of defects, i.e., almost a reversible curve with little hysteresis with one containing metallurgical defects which act as pinning sites. Below the magnetization curve is a schematic showing what the critical current density would look like for the two cases. In fact, if there were no defects at all (perfectly reversible magnetization curve) the critical current density would drop to almost zero just above the lower critical field. In order to raise the critical current density of a superconductor, one must add defects which can be dislocations, second phase precipitations, impurities, grain boundaries, etc. Even damage due to radiation often raises the critical current density. Thus with defects which can act as flux pinning sites, a superconductor will likely have a high j_c. With some superconductors j_c decreases sharply to zero only in the vicinity of H_{c2}, the upper critical field while with others j_c degrades well below the value of H_{c2}. For each superconductor, the useful range of j_c has to be determined by a complete j_c vs H measurement.

In discussing the three parameters H_{c2}, T_c, and j_c which characterize a superconductor, it seems to me that the first two are more fundamental than j_c. Both H_{c2} and T_c are properties of a particular alloy or compound while j_c

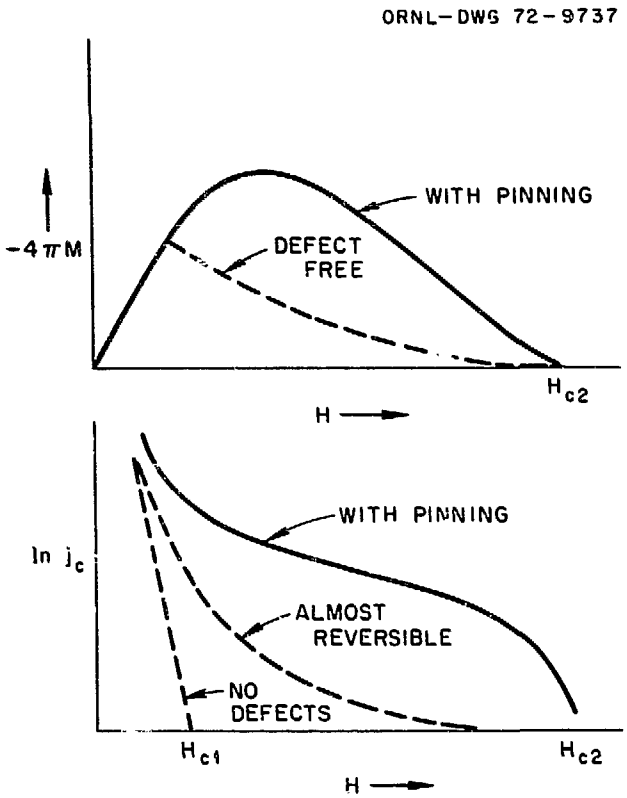
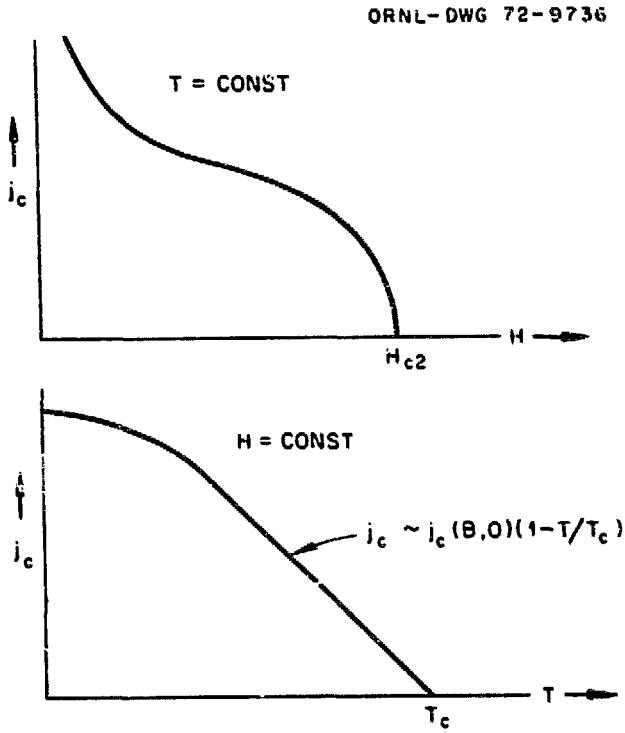


Figure 11

depends on the metallurgical art. Two pieces of the same alloy may have essentially similar H_{c2} and T_c but widely different j_c. Much experimental work has gone into finding the proper heat treatments and cold working to optimize j_c. Some of the physics reasons for the differences in properties will be discussed below.

In Fig. 12 the critical current is given as a function of H for constant T and T for constant H. The j vs H curves vary widely, but the one shown is quite typical of the commercial supperconductors. On the other hand, the j vs T curve is similar for many superconductors in that j depends linearly on T with the onset of the linear drop off coming between 1/3 and 1/2 T_c. Note particularly that for all superconductors of commercial interest, j_c decreases as temperature increases. This is one of the major reasons for the magnetothermal instabilities leading to thermal runaway. Some superconductors have been found to have regions where j_c increases as temperature increases for true intrinsic stability, but unfortunately the magnitude is too low to be of technological importance. In the next figure, the values of short sample critical current density vs field are shown for commercial superconductors. The current density is for the superconductor only. For example Nb_3Sn has a short sample j_c value greater than 10^5 A/cm^2 between 100 and 130 kG but in a magnet values of 2×10^4 is about the maximum achieved because it is necessary to couple the superconductor in close



Critical Current vs H and T

Figure 12

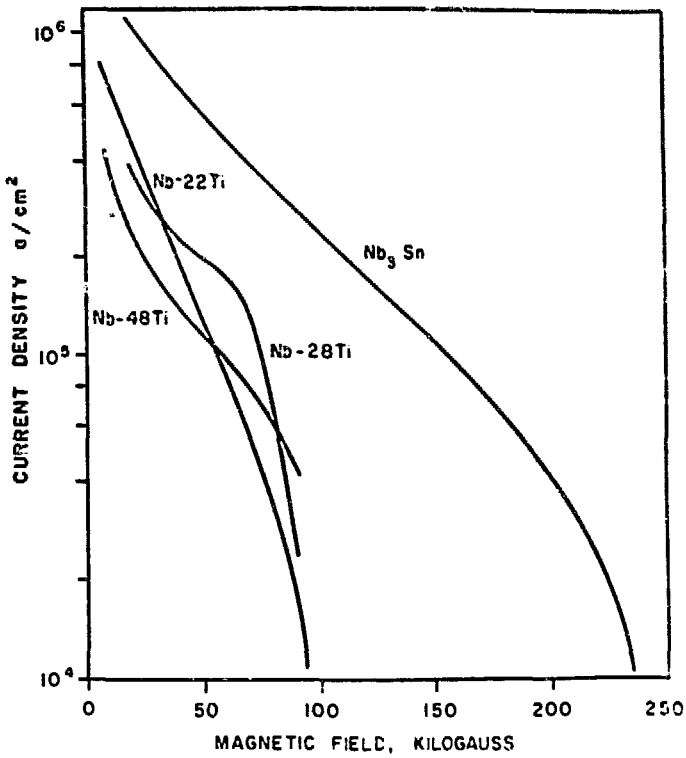
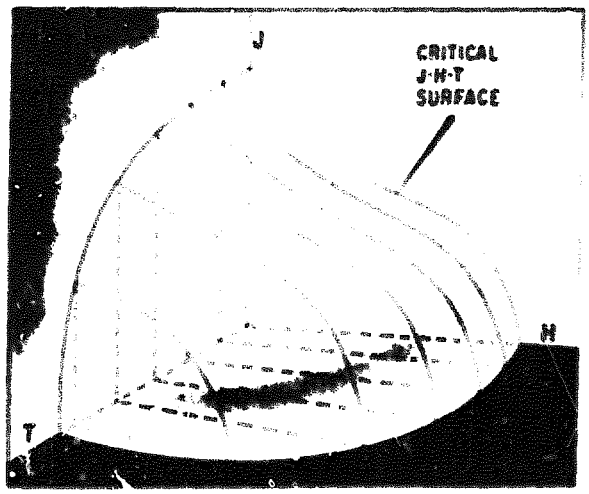


Figure 13

contact with copper or aluminum for protection, stainless steel for strength, and additional packing factors to provide stability. A similar situation exists also for the NbTi conductor. In small magnets (stored energy less than 10 kJ), overall current densities of 30 kA/cm^2 and 60 kA/cm^2 have been achieved at fields of 70 kG and 30 kG, respectively, which is a higher percentage of the short sample values at those fields than can be attained with Nb$_3$Sn. This is due to a better stabilization technique and greater ease in working with the ductile alloy over the brittle compound. Large magnets made with NbTi such as those used for bubble chambers have overall current densities less than 1 kA/cm^2 reflecting the extreme conservative nature of the design. While this is quite an acceptable solution for a bubble chamber magnet where size and weight are not important, it may not be possible for some fusion applications where much consideration matter. To sum up the variation of j with H and T, all three parameters can be plotted together as in Fig. 14.



Superconducting region bounded by critical J-H-T surface.

M G Benz, General Electric Report No 66-C-044 (February 1966)

Figure 14

Superconductive behavior is exhibited inside the bounded surface and normal properties outside. The desire of the magnet technologist is to operate at constant T as close to the surface as possible in a controllable fashion.

Microscopic Properties of Type II Superconductors

Now I should like to take a closer look at certain microscopic properties and explore the question of how the magnetic flux penetrates the superconducting material in the so-called mixed state region (above the penetrating field, H_{c1}, and below the normality transition at the upper critical field, H_{c2}.). The flux penetrates in the form of quantized vortices, i.e., the field in a superconductor exists in units of the flux quantum $\phi = ch/2e = 2 \times 10^{-7}$ G-cm^2. The core of the flux line is essentially normal with the field penetrating the pure superconducting region a distance of the London penetration depth. The radius of the flux line is called the coherence distance ξ which is closely related to the distance over which the long range pairing of the electrons exists. Note that the

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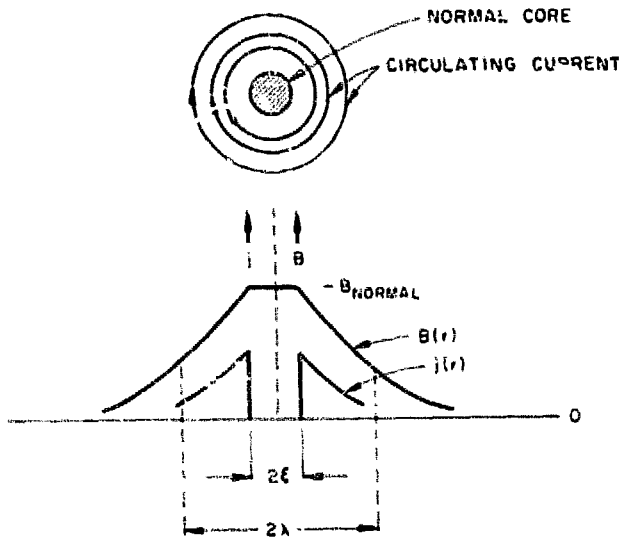
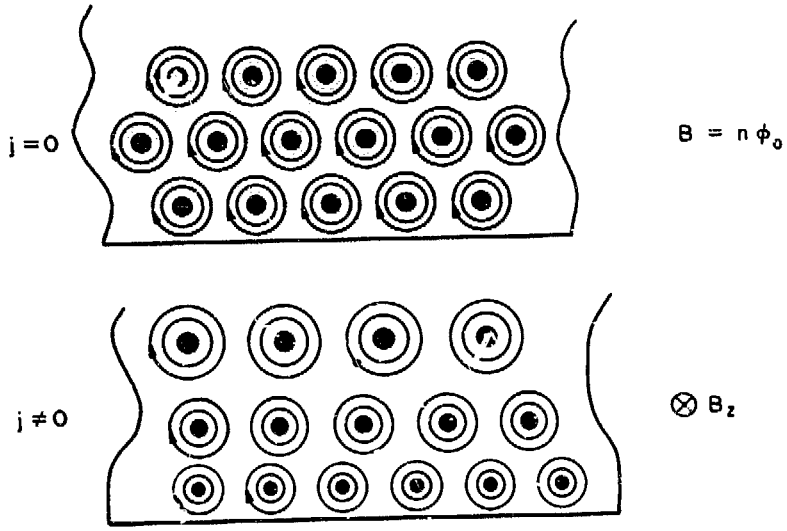
$$\phi_0 = \frac{ch}{2e} = 2 \times 10^{-7}\,G - cm^2$$



Flux Line (Fluxoid)(Quantized Vortex).

Figure 15

supercurrent flows to support the magnetic induction (recall London's first equation discussed in Fig. 1, curl $\vec{j} = -(1/\lambda^2)\vec{B}$). Inside the core $j \simeq 0$ and $B \simeq B_{normal}$, while outside the core $j \simeq j_0$ and $B \simeq 0$. The difference between a type I and a type II superconductor is the relative magnitudes of ξ and λ. For a type II superconductor $\xi < \lambda$ while for a type I, $\xi < \lambda$ and no flux vortices are formed. It is energetically more favorable to expel the flux in a type I superconductor than to break up into quantized flux lines. If we look at a slab of superconductor in a magnetic field perpendicular to the plane of the slab but without transport current, we observe the flux line pattern shown schematically in Fig. 16. The fluxoids form a triangular lattice, and the magnetic induction in the material is just the product of the denisty of fluxoids with the flux quantum, $B = n\phi_0$ with B in gauss when n is fluxoid number/cm^2 and ϕ_0 is 2×10^{-7} G-cm^2. Such a lattice has been seen and photographed experimentally. If we now pass a transport current through the slab in the direction parallel to the surface, we then find a gradient of the fluxoid distribution in accordance with Maxwell's equations, curl $\vec{B} = \vec{j}$. It is the establishment of the gradient that causes many problems. The fluxoids have to redistribute themselves and in doing so, heat is created. The fluxoids transport entropy and consequently heat. The steady state distribution can exist without problems but a change in B or j means a change in the flux distribution and the evolution of heat. As discussed above, the heat leads to a decrease in j_c and hence additional penetration of the magnetic field which causes more heating, etc. Thermal runaway is always lurking in the background because of the basic physical facts that all materials have small heat capacity at low temperatures and supervonductors have poor thermal conductivity and thus any heat formed cannot be dissipated rapidly.



Fluxoid Distribution.

Figure 16

In the next figure, I wish to take a closer look at one of the fluxoids.

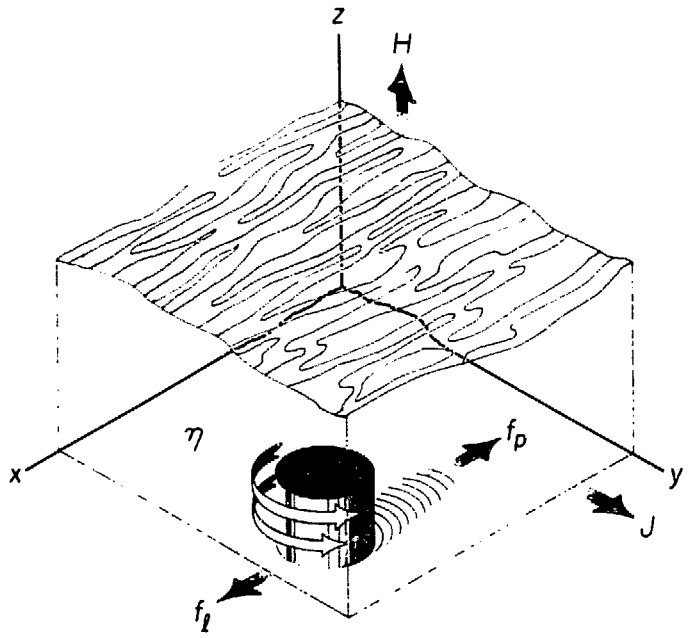


Figure 17

Suppose the field is in the z-direction and the current flows in the y-direction (hence the gradient of the flux distribution is along the x-direction), then by the Lorentz equation a force exists in the x-direction $(F_\ell)_x = j_y \times B_z$ on the fluxoid. The fluxoid would move creating heat were it not for metallurgical defects which react against the Lorentz force and pin the fluxoids. Without pining centers, superconductors would not carry transport current because a gradient of fluxoids could not be established. Much confusion is avoided if one keeps in mind that it is the current vortices which move, not the magnetic flux. Motion of the vortices is possible in a steady magnetic field when the Lorentz force exceeds the pinning force. If we assume that the vortices move in a viscous-like medium with viscosity coefficient η, we can obtain an expression for the voltage associated with fluxoid motion and for a differential resistivity called flux flow resistivity. In Fig. 18, the equations for the most simple approach to flux motion are given. When the Lorentz force is less than the pinning force, there is no motion of fluxoids (here assumed to all move uniformly), $v = 0$ and consequently $E = 0$ (note one could also incorrectly view the voltage as arising from a Faraday induction $\vec{E}_y = \vec{v}_x \times \vec{B}_z$). However, when the Lorentz force is greater than the pinning strength, motion at velocity v is assumed and consequently power is generated as $v \cdot F_\ell$. If this power is equated to $E \cdot j$, then an expression for E is obtained which to a first approximation is verified by

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$$F_\ell = j \times B$$

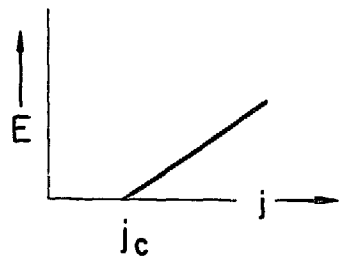
$$F_\ell \leq F_p ; \; E = 0 \;\; \text{AND} \;\; v = 0$$

$$F_\ell > F_p ; \; F_\ell - F_p = \eta v$$

$$F_\ell = j \frac{\phi_0}{c} \;\; \text{AND} \;\; F_p = j_c \frac{\phi_0}{c}$$

$$P = E \cdot j = v \cdot F$$

$$E = \rho_f (j - j_c)$$



Flux Flow Voltage

Figure 18

experiments, i.e., E is proportional to the difference of j and the critical value of current density, j_c at which the fluxoids initiate motion. One can also use the equations given in Fig. 18 to obtain a value of the flux flow resistivity, $\rho_f = B\Phi_o/\pi c^2$, and it is experimentally given as the slope of the E vs j line, $\rho_f = dE/dj$.

Flux Penetration and Magnets

If you are willing to accept the fact that we have a metal in the superconducting state below some critical temperature and critical field which can carry loss less transport current, the next question to face is how do we build a superconducting magnet. If one takes some superconducting wire and proceeds in a direct manner to wind a magnet with a load line, H = const. (j), where the constant is determined by the geometry, one discovers that the anticipated critical j is not attained. The situation is shown schematically in Fig. 19. The design point, although shown right on the short sample value, should obviously include some safety margin to avoid a quench of the magnet. However, many magnets constructed from a wire with such a short sample characteristic are known to suffer degradation or the quenching at a current value usually one-half or even in some cases one-third of the value that a short piece will carry when exposed to the same maximum field. Rather than considering this situation--degradation by two or three--I prefer rather to use the load line and the percent attained which in many cases has been only 50 or 60%.

The origin of degradation is a phenomenon known as flux jumping which is initiated by a magnetothermal instability. The necessity to change the magnetic flux in a superconductor is accompanied by a release of heat and unfortunately superconductors along with all other metals have very

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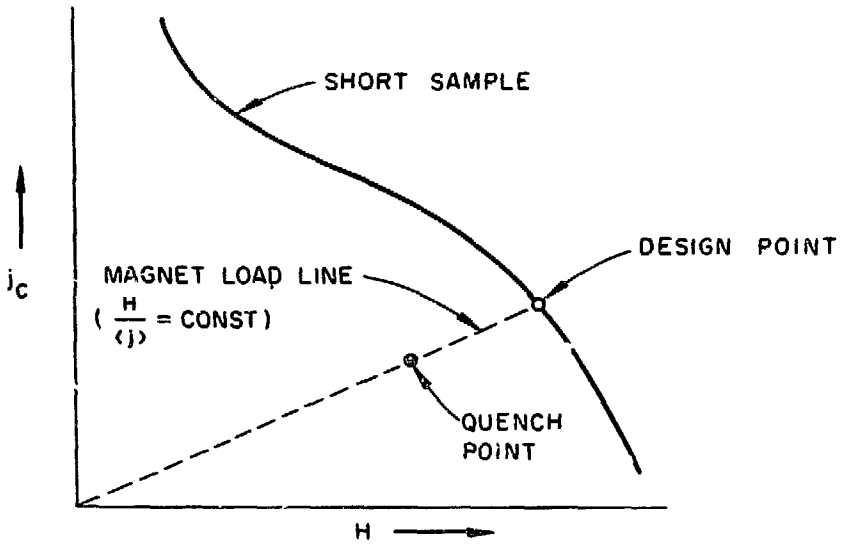
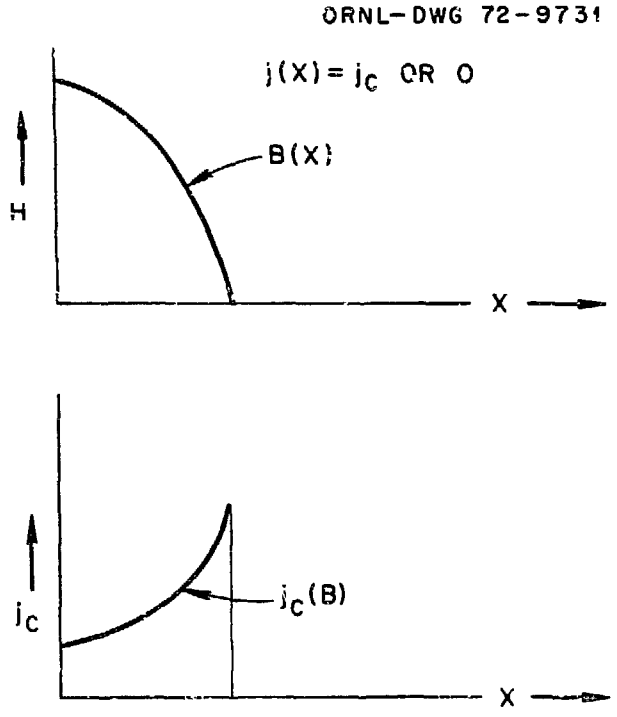


Magnet Degradation

Figure 19

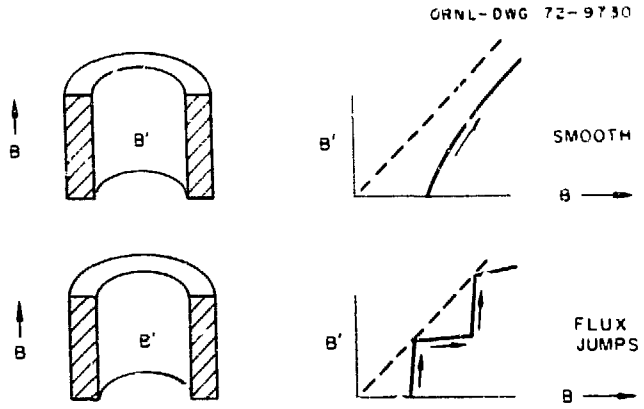
small heat capacity at low temperature. Considering the picture of fluxoids given previously, note that increasing a current j in a wire or ribbon in a magnetic field B causes a Lorentz force j x B on the flux which tends to drive the flux through the supervonductor against the pinning action of the metallurgical defects (areas of different free energy than the superconducting phase). The process of establishing a transport current therefore requires a certain amount of energy and this energy is dissipated as heat. In steady state conditions, the heat and also the resistance drop to zero. It should be readily appreciated that if, during a change in current or field, heat is generated anywhere in the superconductor at a rate faster than it can be conducted away and transferred to the cooling bath, an unstable condition will develop in which the local temperature will rise and the material will revert to the normal state in a thermal runaway. When this process occurs in a magnet, the dissipation of the stored energy ($E_s = (1/2)LI^2$) occurs rapidly and spectacularly. A closer look can now be given to the origin of the flux jumping phenomena. The penetration of flux by a changing magnetic field produces the critical state in type II superconductors. Briefly, this means that everywhere in the superconductor the current density is either zero or flowing at the critical (maximum) value determined by the local magnetic induction and temperature. Flux enters at the surface and moves usually in bundles rather than as individual flux lines. The induced current density $j_c(B)$ shields out the magnetic field from the interior. The schematic on this page (Fig. 20)



Field Penetration.
(Type II)

Figure 20

illustrates the penetration of an increasing field on a semi-infinite slab without any transport current. Maxwell's equation curl B = $4\pi j_c/10$ (in practical units) is valid. For type II superconductors, j_c is high at low fields and low at high fields, hence the shape of the j_c vs x curve. Conversely, if one has knowledge of the j_c vs B behavior of a superconductor, then the penetration distance can be calculated for known field values. One can then determine if the field has penetrated to the center of a wire or strip. Instead of a wire or strip which is what we use in magnets, the observation of flux jumping can be illustrated best by using a cylinder. In Fig. 21, a field probe (Hall or magnetoresistance is most commonly used) inside the tube is plotted on the ordinate and the changing external field is plotted on the abscissa. The induced current in the walls shields out the external field until penetration reaches the inside of the wall.



$$\Delta T_i \rightarrow \Delta j_c \rightarrow \Delta \phi \rightarrow \Delta Q \rightarrow \Delta T_f$$

$$\Delta T_f < \Delta T_i \quad \text{STABLE}$$

$$> \Delta T_i \quad \text{UNSTABLE}$$

$$H_{fj}^2 \leq \text{CONST } C\left(\frac{j_c}{\frac{-dj_c}{dT}}\right) \sim C(T_{cn} - T_b)$$

Flux Jumps.

Figure 21

At this point one of two events is possible. Either the field will rise in the interior along with the external field (although still lagging by an amount determined by the value of j_c) or a breakdown of the induced currents will occur and the internal field will jump to the value of the external field (hence the origin of the name flux jump). Of course, a jump can occur before the induced current fills the wall, and this is usually the case for solid cylinders (i.e., the flux front doesn't reach the center). Once the center is reached without a flux jump, the possibility of a flux jump decreases because the gradient of flux profile decreases. For a calculation of the field at which a flux jump will occur, we assume there is a small local temperature excursion, ΔT_i, which leads to a decrease of the current density ($\partial j_c/\partial T$ is negative) leading to the penetration of more flux which results in more heating and an increase in the local temperature ΔT_f.

If ΔT_f is smaller than ΔT_i, then the condition is a stable one but if it is greater, then the regenerative process leads to a rapid temperature increase which we refer to as a thermal runaway. Using an adiabatic model one can derive the field for the onset of a thermal runaway. It depends most strongly on the heat capacity of the superconductor and the temperature difference between T_{cb} (transition temperature for field desired) and T_b, the bath temperature (usually liq. helium at 4.2°K). Experiments have verified all the qualitative features of the theory but quantitatively the theory is pessimistic. Note that the theory implies complete stability for a material with $\partial J_c/\partial T$ positive, and for material with small enough cross section, no flux jumps will occur. These predictions have been shown to be valid by experiments. A look at Fig. 22 will clairfy the physical limitation caused by the poor thermal conductivity and low heat capacity--the latter a universal property of all metals at 4.2 K. In a superconductor (NbTi is used in the example but it is typical of all type II superconductors), the magnetic diffusivity is high because of the high value of the flux flow resistance while the thermal diffusivity is low owing to the low value of thermal conductivity. Thus in a pure superconductor the adiabatic approximation is usually good (however, many disagreements between theory and experiment may arise from the fact that the dynamic resistivity of superconductors is a few orders of magnitude less than the flux flow value and thus decreasing the magnetic diffusivity until it is the same order of magnitude as the thermal diffusivity). The values of D_{th} and D_{mag} are well

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	NbTi	COPPER	
$D_{th} = \frac{K}{C}$	1.2	7900	(cm^2/sec)
$D_{MAG} = \frac{10^9 \rho}{4\pi}$	1900	2.4	(cm^2/sec)
D_{th}/D_{MAG}	0.0006	3300	

Thermal and Magnetic Diffusion.

Figure 22

known for commercial metals such as copper and aluminum where the situation is reversed from that in superconductors. The ratio of D_{th} to D_{mag} for Cu (with resistance ratio of 100) is the order of 10^3. The addition of copper in close bonding with a superconductor serves to both stabilize against flux jumps by the fast removal of heat and protect on a quench by providing an alternate path for the current flow. Since magnetic field changes can occur rapidly in a superconductor and thermal energy can only be removed slowly, there has been a trend to first break up the superconductor into many filaments and then to decrease the diameter until today where it is now possible to obtain a 30 mil diam wire with thousands of superconducting filaments each 0.2 mil in diam.

Our next figure tabulates some of the most common methods employed in fabricating superconductors which avoid catastrophic flux jumps. The

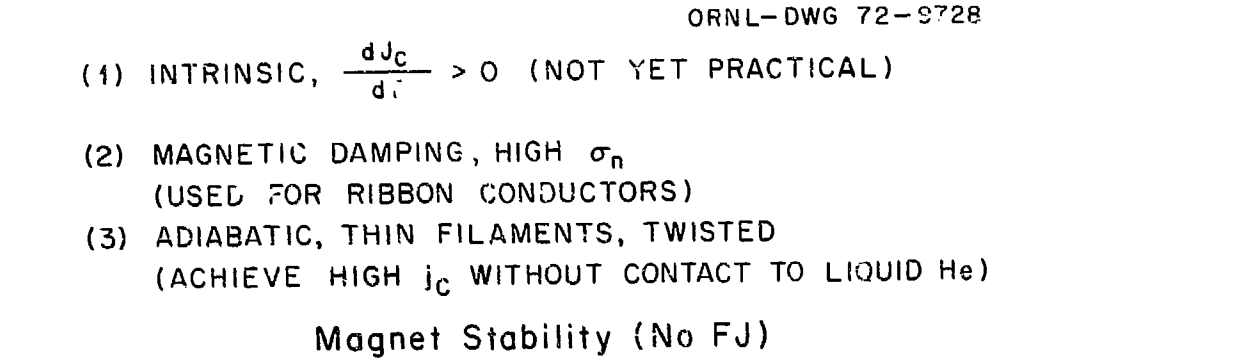

Figure 23

intrinsic method is clearly most desirable but as yet has not been available for commercial material. Magnetic damping has been applied to high field ribbon conductors and is achieved by interleaving and very high conductivity normal metal such as Al or Cu with the superconducting ribbon in the hope that the average magnetic diffusivity can be reduced below some critical value. The adiabatic method has been applied to the ductile alloys and consists as mentioned above in reducing the diameter of the superconducting filaments to below about 1 mil and subsidiary effects require the twisting of the filaments to magnetically decouple them. The major side benefit of this technique is mainly that the superconductor does not have to be in intimate contact with liquid helium and the windings of magnets utilizing adiabatic NbTi are usually completely potted in some sort of epoxy. If we recall the flux jump formula previously derived for an adiabatic process wherein the magnetic diffusivity was assumed much larger than the thermal diffusivity, $H_{fj}^2 \leq$ const. CT_o, we can interpret this in terms of the superconducting dimension perpendicular to the direction of the changing magnetic field.

$$d^2 \leq \frac{\text{const. } CT_o}{j^2}$$

At low fields, j is highest and this low field value determines the dimension d necessary for adiabatic stability. If d is small enough, the energy due to a flux jump cannot drive the superconductor normal and its own heat capacity can stabilize it. Reducing the diameter d of the superconductor filament means that many filaments have to be carried in a strand to keep the current carrying property high. A subsidiary problem is thereby introduced, namely the magnetic coupling between the filaments. This problem is resolved by having the filaments twisted about each other with the amount of twist pitch necessitated by the desired rate of change of magnetic field achievable. Finally, to provide stability to changing self-field, the individual composite strands can be transposed into a braid or cable. Another technique employed is to introduce a low conductivity sheath around the NbTi and Cu which serves to decouple the filaments. Copper nickel alloys are used, and the conductors are referred to as mixed matrix conductors.

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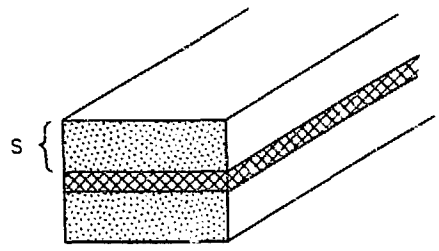
(1) CRYOSTATIC (LOW j_c, HIGH Cu/Sc RATIO, INTIMATE CONTACT WITH LIQUID He)



$$\text{STABILITY} \quad \frac{I^2 R_n}{S} \leq \dot{q}$$

$$\text{RESULTS IN} \quad j_{COND} < \frac{\text{CONST}}{I^{1/3}}$$

$$\text{WHERE CONST} = \left(\frac{\dot{q}\,k}{\rho_n}\right)^{2/3}$$

$$\text{PROTECTION} \int_0^{\infty} j^2 dt = \int_{4.2K}^{500K} \frac{\delta C(T)}{\rho_n(T)}\, dT$$

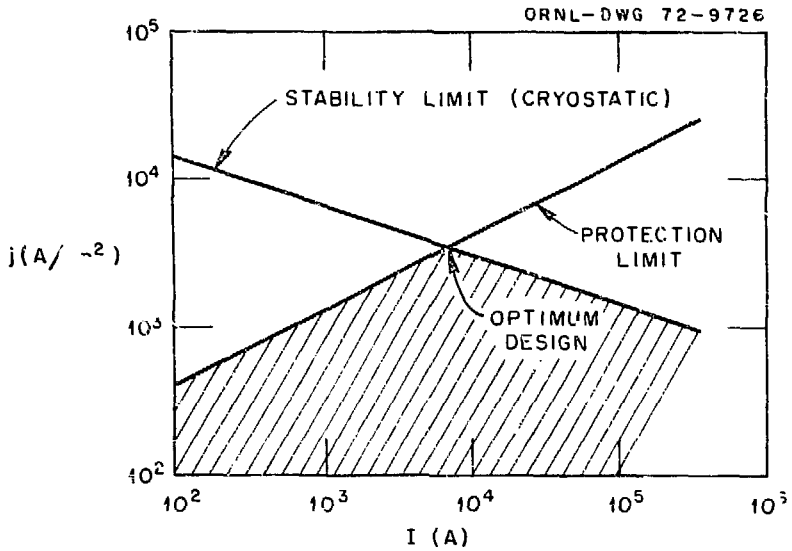
$$\text{RESULTS IN } j_{COND} < \text{CONST } I^{1/2}$$

$$\text{CONST} = \left(\frac{f(T)\,v}{E_s}\right)^{1/2}$$

Magnet Stability (Allow FJ).

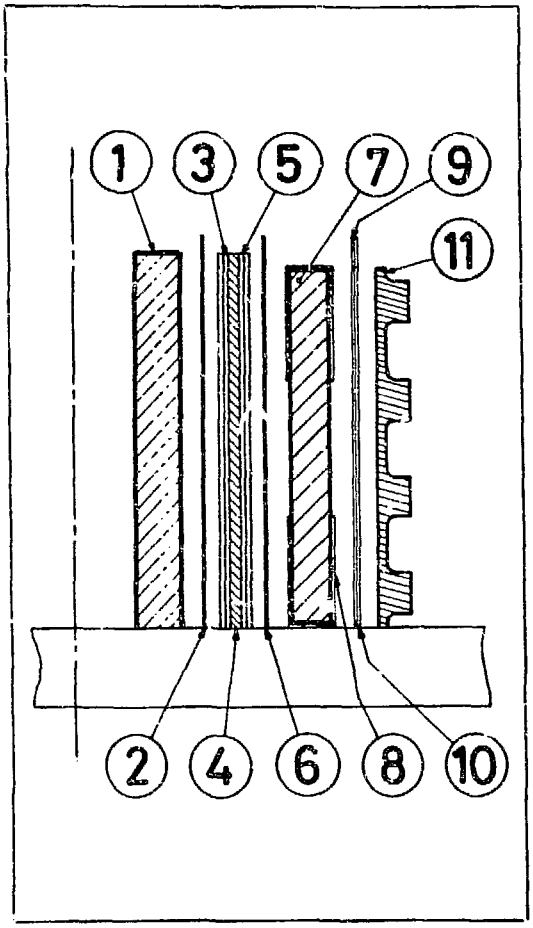
Figure 24

Figure 24 illustrates the principal technique which allows flux jumps to occur but renders their consequence harmless. The principle is to surround the superconductor with enough copper or aluminum so that even in the event that all the current flows in the normal metal, the heat generated can be conducted to the surfaces in contact with helium and transferred to the liquid bath without exceeding some critical heat flux (usually considered at most to be about $0.4 W/cm^2$). When conditions are optimized, the requirement of current density depends differently on current level for stability and protection. An optimization of these parameters is shown only approximately in Fig. 25 for a very large system ($E_{stored} \sim 10^{10}$ J). Only values below both the protection and stability are low overall j, high copper to superconductor ratio, and intimate contact with helium. For really large magnets, low j is now much of a disadvantage since the length of the superconductor and hence cost does not depend strongly on j. However, low j implies a large volume (of copper) and hence a large weight which increases the cryogenic problem. The large copper to superconductor ratio also means the strength of the composite material is similar to copper or poor. This means that a large amount of stainless steel must be employed to withstand the



Limit for Stability, Protection
Large Magnet.

Figure 25



2.

Figure 26

magnetic forces. For reactor size magnets, detailed studies indicate an overall average current density of about 1000 A/cm^2 or possibly 2000 A/cm^2 as the highest practical value with today's materials.

To obtain some idea of the degree of sophistication and complexity possible in the manufacture of superconductors and construction of large magnets, the following two figures show the composite conductor and one-half of the large bubble chamber magnet at CERN (Switzerland). In this figure, No. 1 is the NbTi conductor 6.1 cm x 0.03 cm with 200 superconducting filaments; Nos. 2, 3, 5, 6, 8, 9, 10 are thin insulators (polyester sheets and polyamide film); No. 4 is on Al heating strip 0.01 cm; No. 7 is a 316L stainless steel reinforcing strip 6 cm x 0.2 cm; No. 11 is a Cu cooling strip 6 cm x 0.19 cm. This conductor was made before twisting of the filaments became available and thus today there would be no need for the Al-heating strip to remove the residual magnetization, Figure 27 is a picture of one completed section of the magnet. This is the largest magnet built to date and has a stored energy of 800 MJ or almost an order

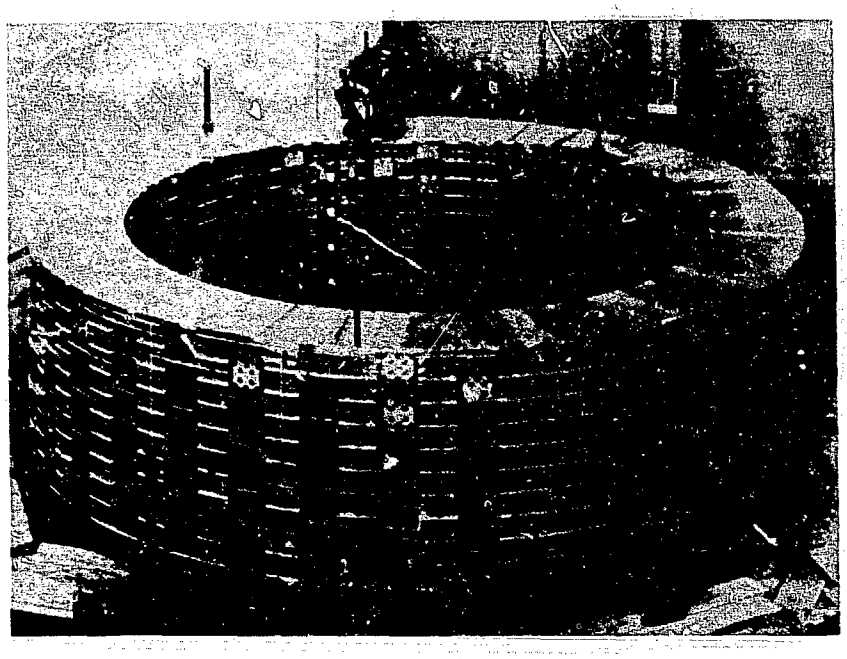


Figure 27

of magnitude larger than the Argonne bubble chamber. The design field is 35 KG in the 4.72 m bore and this means a 51 kG field at the windings. The construction and successful operation of such a magnet system is a great engineering feat necessitating simultaneous solutions to superconducting, cryogenic, thermal, structural, and vacuum problems.

Large Magnets for Fusion

I should now like to compare the size and field of the large superconducting magnets with the values anticipated by the reactor design studies performed at laboratories in this country as well as around the world. The operating regime of magnets as of the beginning of 1975 (same as June 1971) is shown in Fig. 28 as are the proposals of the various fusion laboratories. Our

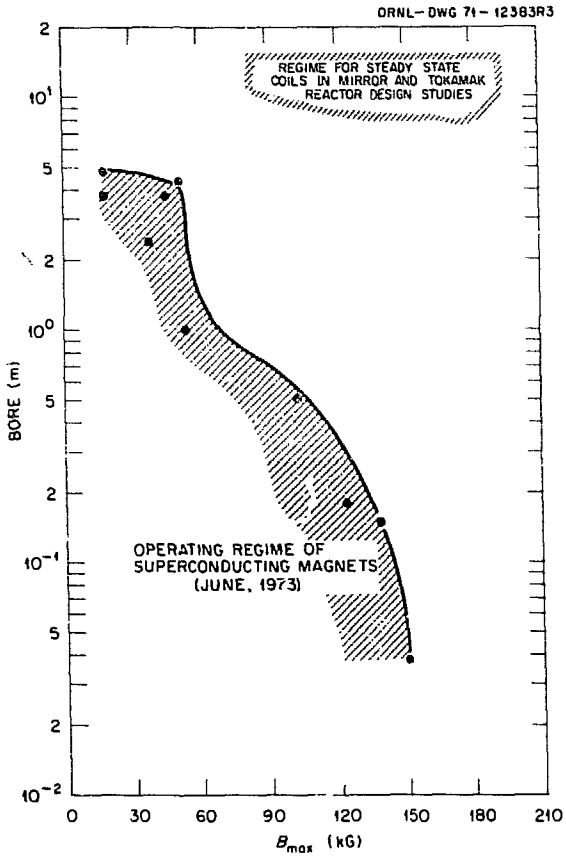
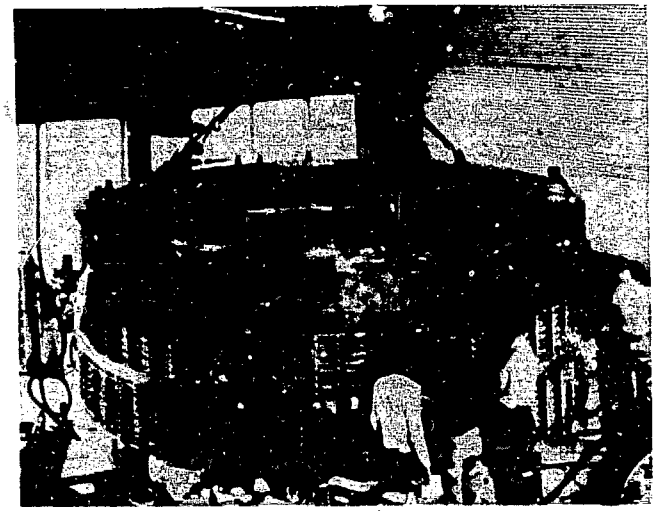


Figure 28

own study represents the least extrapolation in field (only 80 kG, well within the overall achievable field and also within the range of NbTi), and the extrapolation in bore size is about one order of magnitude which we believe to be quite feasible on the present time scale for reactors (~20 years). Before viewing the needed size, take a good look at the 4.8 m Argonne bubble chamber magnet shown in Fig. 29. Now compare this magnet with our requirements for a reactor in the next figure (Fig. 30). With a proper development program, we believe that this magnet system is within the present state of the art and should certainly present no problem 20 years from now. What we don't know for a certainty is whether this field value, 37 kG, will be sufficient for an economically viable reactor. Assuming it is, we have looked in more detail at the toroidal magnet system to convince ourselves that it is indeed technically and economically



One of the two 4.8 m i.d. coil halves of the 1.8 T hydrogen bubble chamber magnet showing details of the 15 pancake assembly. The vertical braided copper thermal interconnections between separate pancake units minimize temperature differentials and hence thermal stresses during cooldown. A section of the stainless-steel helium can is shown suspended above the assembly. This can forms the vacuum tank for the magnet.

Argonne National Laboratory
3.9-m Hydrogen Bubble Chamber
(ANL/HEP 6811, ed. C. Laverick)

Figure 29

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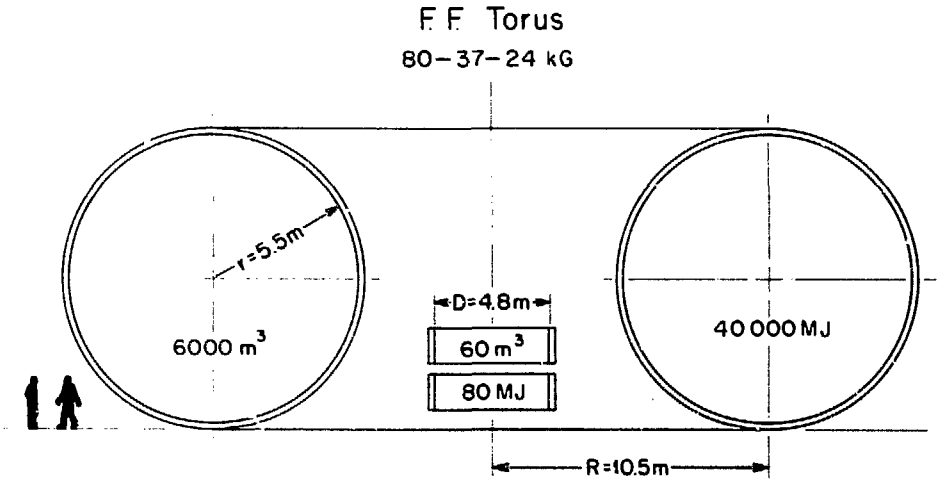

ANL Bubble Chamber Magnet
18kG

(Prepared by W.F. Gauster)
Figure 30

feasible. The superconducting design utilizes the cryostatic stability criterion. With the development program we are pursuing at the present time, we believe substantial improvement can be made over these conservative design parameters. The structure presented considerable problems because of the enormous forces on each coil to the torus central axis and the subsequent bending moments on each bobbin once compensation of the central forces is achieved. In Fig. 31 the central force per coil for a 40 coil toroidal system is shown plotted against the major radius. For reactor size systems the force per coil is the order of 10^4 tons.

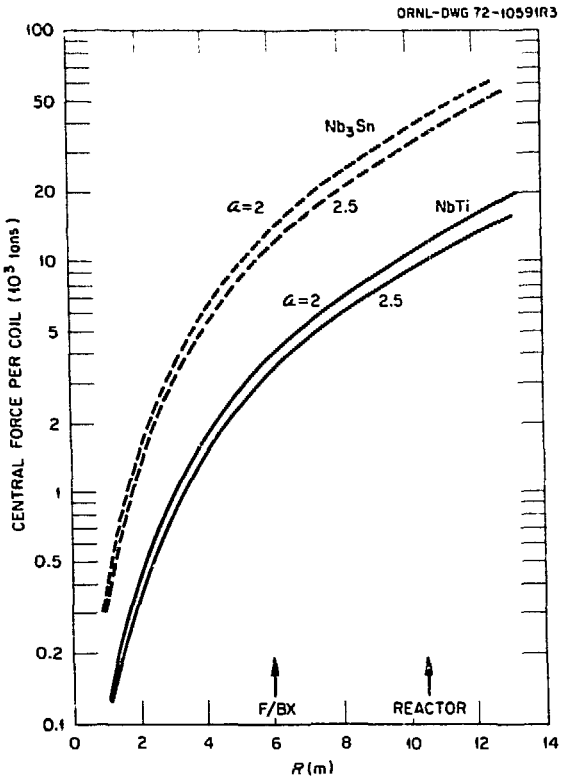

Figure 31

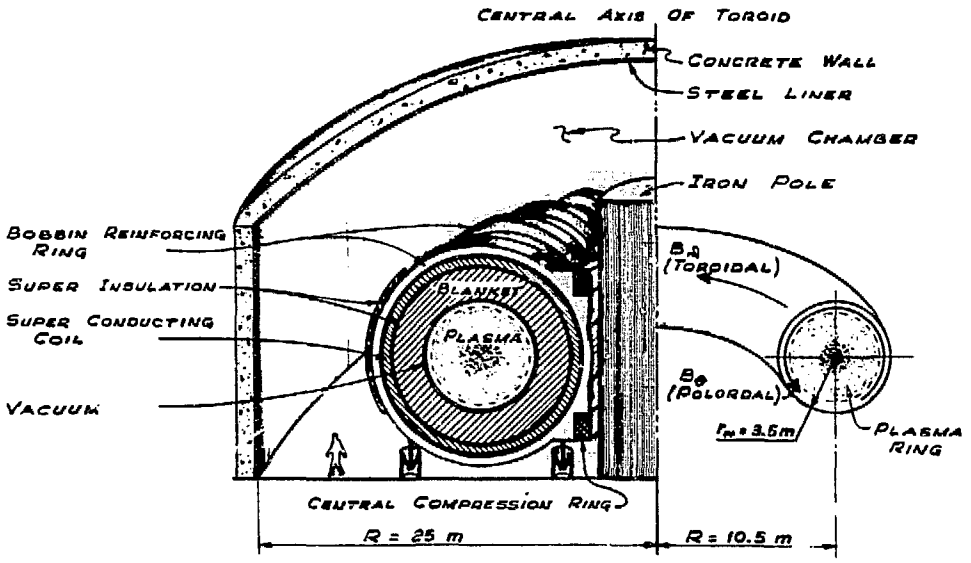

Figure 32

Figure 32 shows a schematic cross section of a toroidal magnet system designed for a 5000 MW(th) reactor operating on the tokamak principle. The summarization of the design parameters is given in Fig. 33. The cost is

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$B_0 = 37$ kG

$B_{MAX} = 80$ kG

$R = 10.5$ m

$r = 5.6$ m

$E_S = 4 \times 10^{10}$ J

$\ell = 4.75 \times 10^6$ ft (COND)

TOTAL WEIGHT = 9025 TONS

TOTAL COST = 70.5×10^6 \$

$\simeq$ \$30 kW(e)

Toroidal Magnet System
[5000 MW(th)]

(Costs in 1971 Dollars)

Figure 33

in 1971 dollars. At the present time, it would be prudent to double the cost of the magnet system. In addition to this design study, I have generalized the work to yield the cost of any large toroidal system in terms of the stored energy. The stored energy of any toroidal superconducting magnet is really only a function of R since the maximum field is fixed for each superconductor and the variation with the aspect ratio is not strong. Thus in Fig. 34 the stored energy is given vs R, the major radius for magnets made from both NbTi and Nb_3Sn for the range of aspect ratios likely to be employed. The cost in terms of the stored energy is then given in Fig. 35.

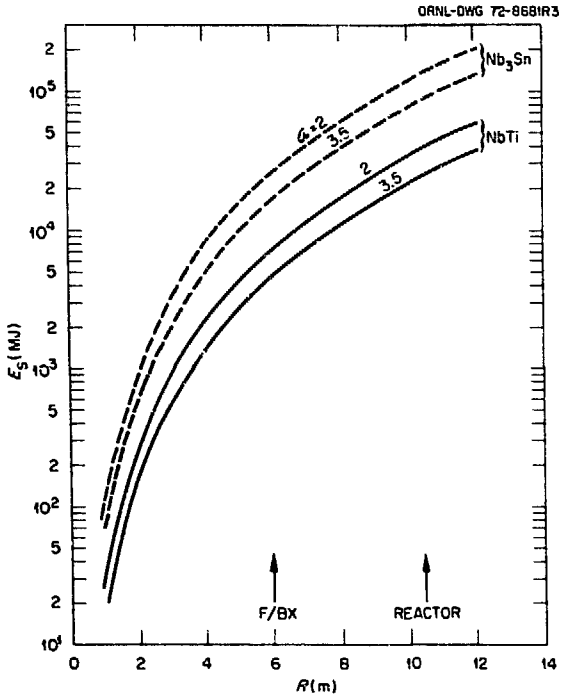
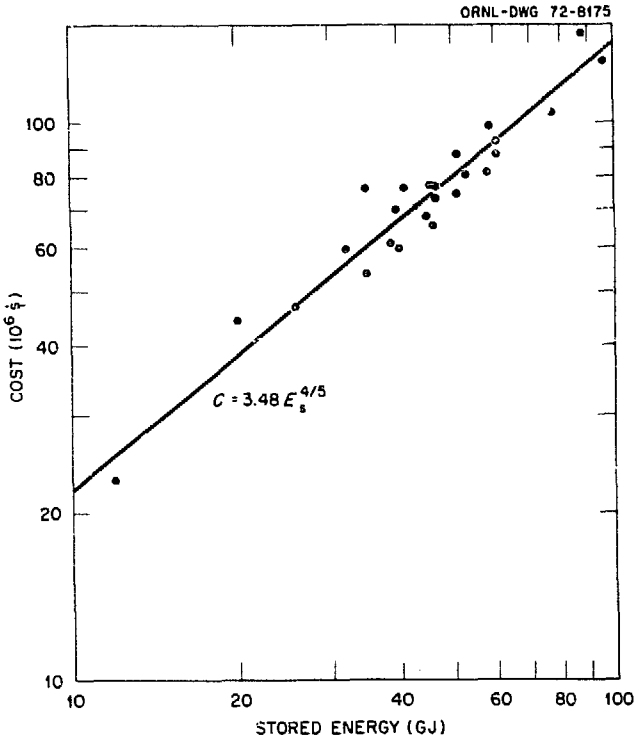


Figure 34

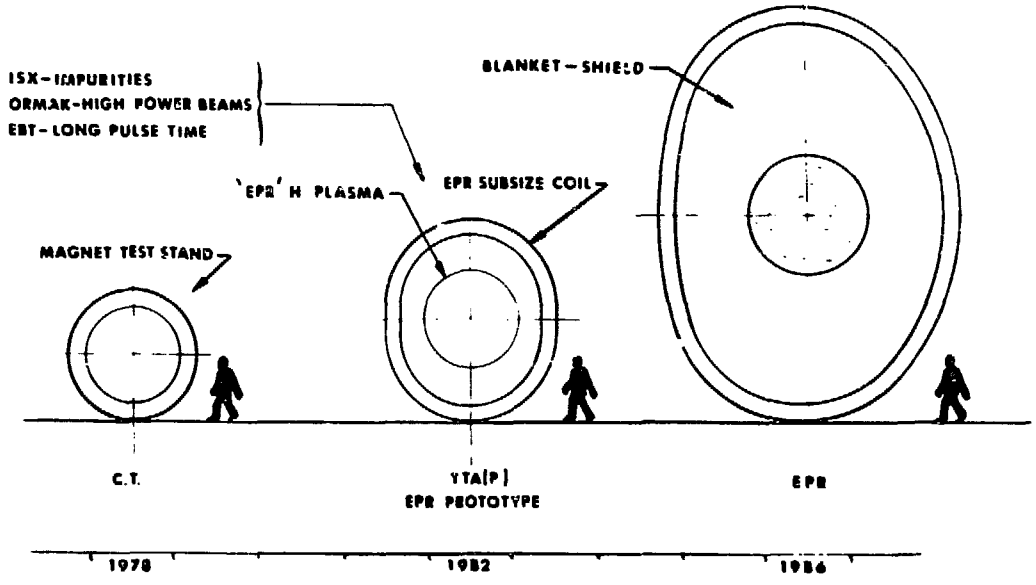
The range covered in stored energy, 10^{10} to 10^{11} J, takes into account most of the serious proposals for fusion reactors and the cost (1971 dollars), \$22 to \$131 x 10^6, is well within the tolerable limits for this major component.

In summary then, I would say that we have viable solutions to all aspects of constructing large, high field superconducting magnets. In order to prepare for future demands, we must perform the necessary development taks to extrapolate and refine our techniques. A development program has been proposed to ERDA-DCTR and accepted by them. The scale of magnet size to be developed and tested up to the experimental power reactor (EPR) size is shown schematically as a function of time in Fig. 36.



(1971 Dollars)

Figure 35



ORNL EPR RELATED SYSTEMS

(Prepared by P. B. Thompson)

Figure 36