

Energy for the Year 2000

Edited by Richard Wilson

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Series Editor: Antonino Zichichi

PHYSICAL SCIENCES

Energy for the Year 2000

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Edited by

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PREFACE

The Third International School on Energetics was devoted to the subject of Energy for the Year 2000. By this title we hoped to avoid discussion of such matters as the role of OPEC in raising oil prices. In one sense, therefore, our task was made easier; we could merely look into our crystal balls.

The choice of lecturers was made with the idea that no reasonable source of energy can be overlooked. We omitted detailed lectures on oil and natural gas because we took it as a given fact that we would continue to use as much of these fuels as we can get at a reasonable price.

To give us an overview we started the School by discussing U.S. energy policy and possible U.S. energy scenarios. As might be expected, there was some disagreement about the current energy program in the U.S., but little disagreement about the facts presented.

Various energy options were examined. They included nuclear power and the breeder reactor where the lecturers focused primarily on controlling various problems inherent in using fission power for energy production. There were lectures on coal--a source which will, hopefully, be used in more and more environmentally superior ways, and two sets of talks on solar energy--one a general survey and the other a detailed discussion of photovoltaics. The talks on solar energy were realistic about the current state-of-the-art and very optimistic for long-term research and application. Energy production using waves was a topic scheduled but was not presented due to illness. However, the lectures do appear in this volume as originally prepared.

Richard Wilson

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ENERGY FUTURES: STRATEGIES FOR THE U.S.A.

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THE STRATEGY ISSUES

Introduction

The recent history of U.S. energy policy does not reveal a consistent strategy behind our actions. There are many reasons for this, but outstanding is the fact that no clear popular view has emerged to support a comprehensive strategy for dealing with the mixed aspects of the U.S. energy problem.

We have instead dealt with the discreet issues on which a consensus appeared, such as a 55-mile-per-hour speed limit, mandatory auto efficiency standards, and new building standards. Similarly, long-term research and development programs have been initiated, particularly in solar energy. Policy in both these cases could go forward politically before settlement of the difficult issues of oil pricing, environmental standards for coal mining and use, or any of the many controversial aspects of nuclear power.

This piecemeal approach and preoccupation with the detail of short-term factors has failed to assure the long-term availability

*Dr. Starr used materials from three reports in his lectures. The first is printed here, but due to copyright laws, we are unable to reproduce the other two. They were entitled, "Energy and Society" and "Energy Systems Options," and are contained in Current Issues In Energy, Chauncey Starr, Pergamon Press, New York, 1979.

of energy in the U.S. The means by which this objective should be reached continues to be the center of the U.S. energy policy debate.

The purpose of this talk is, first, to consider the ways in which the elements of the energy problem are generally understood, to question that understanding, and to pose alternative statements of the problem; and, second, to summarize specific aspects of energy and electricity supply and demand which relate to strategy alternatives.

Conventional Energy Analysis

Conventional analysis of energy issues presumes generally that economic cost-benefit analysis of the issues can produce a reasonable guide to optimum energy policies. Unfortunately, economic analysis appears to be limited to the effects of changes that are quite small relative to basic reference parameters, such as the effect of small changes in energy price or supply. Effects of this nature are referred to as marginal. The limitation of this type of analysis is that large nonmarginal changes are obviously more important, yet conventional extrapolations generally result in the misestimation of their effects.

In addition to the limitation that changes be small or "marginal," conventional analysis is also limited to those aspects of the problem that can be quantified. For example, the point that economists underestimate the social cost of energy supply has been a central tenet of environmental groups, and they are correct. But there is a corollary missed by the environmentalists--we similarly underestimate the social value of energy use. Neither has been well quantified. By looking only at marginal changes, we equate the benefits with the social value of the last unit of energy used, and, of course, this generally tends to be wasteful or frivolous, as well as the most costly unit.

Conventional energy analysis also frequently suffers from a static view of social values. Those values which we currently hold may change rapidly, as, for example, on the importance of environmental protection versus economic growth, or on the equitable control of resources versus unrestricted competitive opportunity. As a more familiar example, conspicuous, energy-consuming, large automobiles have suddenly been displaced as status symbols by the diesel Mercedes and the solar collector.

Complexity of Energy Issues

The mix of complex issues that goes into the formation of U.S. energy strategy includes the following:

Supply Issues

- o The Geology and Geography of Energy Resources
- o Supply Technologies and Alternative Sources
- o Environmental Impacts and Public Risk
- o Imported Fuel--Cost, Availability, and Supply Security

Demand Issues

- o Conservation--Price Effects and Technology
- o Energy Needs of the U.S. Economy
- o Lifestyle Benefits of Energy Use

Political and Economic Issues

- o Impacts of Energy Imports
- o Equity and Distributional Effects vs. Aggressive Economic Growth
- o Energy Producers--Size, Power, and Profit
- o Demand Modification vs. Supply Modification
- o Energy Policy in Conflict with Social Goals
- o Energy Policy as a Surrogate for Social Policy

The length of the above list is a big part of the problem, because the array of feasible strategies does not contain any capable of resolving all these issues. Save for some possibility that a lucky long shot will occur (for example, a miraculous photovoltaic discovery or extremely large domestic oil and gas finds), no easy comprehensive solutions are visible. And those solutions which require personal sacrifices (President Carter's "moral equivalent of war") have not been judged politically salable to the American public--at least by the politicians.

Free Markets vs. Political Tension

Another aspect of conventional analysis is its assumption about how world energy markets work. It treats energy trade (principally oil trade) as if a free market exists. The attraction of this view is obvious. The economic description of such a market is most

familiar to economists, and this model is a powerful analytical tool.

The free market view is clearly oversimplified and exaggerated. Certainly, even the strongest proponents of a free market recognize the existence of OPEC and the potential for using oil exports to influence political objectives. But what distinguishes the conventional view is an assumption that political decisions will bend to market forces, that is, that prices cannot be maintained at "artificially" high levels indefinitely.

The contrasting view is that we have a political world market, and that optimization from the seller's viewpoint does not mean maximizing only the present value of revenues, but includes influencing the foreign policy of the buyer. Lest we believe that political intervention of this sort is a recent or temporary effect, it is useful to recall that the U.S. has acted this way for a number of years in specific areas, for example, by trade embargoes with Cuba or by linking trade conditions with human rights policies. The point of these examples is not to critique such actions; it is rather common and that these policies have, in many cases, persisted for decades. The key issue for the U.S. raised by the political nature of the international market for fuels is the uncertainty of supply continuity, and the national security and economic vulnerability to a sudden and large reduction in supply.

Marginal Analysis vs. Supply Vulnerability

As an alternative to a policy based upon the premises of economic marginal optimization, it may be more important to the national interest to seek a policy which reduces both the likelihood and the effect of energy supply interruptions.

To some extent this position is exemplified by the decision made by several nations to create a strategic oil inventory. The U.S. has initiated such a reserve, recognizing that strategies should reflect the flexibility needed to deal with the political uncertainties.

But we failed to carry this understanding over to internal aspects of energy policy, despite painful evidence of the interruptible character of virtually all primary energy sources. In the past several years, shortages or interruptions of coal, natural gas, hydro, and nuclear power have occurred in addition to the oil embargo. It would be justifiable to subsidize high cost courses (and conservation) more aggressively to reduce the national vulnerability arising from dependence on any single source, either domestic or foreign.

On this basis, the U.S. would be wise to subsidize synthetic fuels from coal, oil shale, and liquid biomass fuels. If, as is occasionally alleged by proponents of these technologies, the lack

of private industry commitment to these systems stems from the possibility that foreign oil producers can undercut their price, then Government support guarantees are appropriate. It may well be to the self-interest of the U.S. to pay \$25/barrel for synthetic fuels rather than \$20/barrel to OPEC, when the intangible costs of vulnerability to supply interruption are included.

We undertook our strategic oil reserve precisely because of the insurance it provides against interruption, yet the issue of electric utility reserve margin is rarely given the same consideration. In the past, the rule of thumb that developed was that a 20 percent reserve margin was roughly the desirable level to handle plant outages, maintenance, and uncertainty in demand due largely to the effect of extremes of weather. Today we have an added factor, supply uncertainty. Since the 1973 embargo, the United States has experienced several rather extreme weather conditions: the Western drought, which reduced hydroelectric availability, and Midwestern blizzards, which left coal barges stranded and coal stockpiles frozen solid. In both cases the high reserve paid off, as the less affected oil and nuclear capacity met the demand. The 1977 coal strike was another case of supply interruption, as is the current mandated shutdown of five nuclear plants for seismic analysis.

If we allow the implications of our intuitive understanding of supply vulnerability, we should consider policies to reduce this vulnerability by replacing insecure sources, such as imports, with more secure domestic sources, even at higher prices. The obstacles to such policies arise from several sources. First, and most apparent, is the ideologic and political opposition within the U.S. to policies which would accelerate either the rise in energy price or the expansion of coal and nuclear power, or early commitment (particularly with Government guarantees) to synthetic fuels from coal. This aspect, like the political component of the world oil market, is not quantifiable, but is quite clearly a primary obstacle to reductions of imported oil.

A second aspect of expanding domestic sources to reduce imports is the magnitude of the capital and other resource requirements needed to do so. A rough estimate is that to replace all oil imports with conservation, coal, nuclear, solar, oil shale, and other sources would require an investment of about \$250-\$500 billion. Currently, direct investments in the U.S. energy system are roughly 2 1/2 percent of GNP, or \$50 billion per year, and conservation investments add to this unknown additional amount. But these conventional investment rates have merely sufficed to meet some demand increases and compensate for the depreciation of existing equipment. The investments of the past several years have not even been sufficient to hold oil imports constant.

Attempting to achieve this substitution by the end of the century would require that we double our investments into energy systems during

the next decade. This would represent a national peacetime investment less than half the military budget. President Carter's "moral equivalent of war" description is, indeed, accurate in describing the level of effort needed, if reduction of oil imports is the objective.

DEMAND AND SUPPLY PROJECTIONS

At present we do not have an extraordinary U.S. effort to accelerate alternative domestic energy sources which are technically feasible and almost economically affordable (even if not yet competitive). In the absence of such a program, our energy demand and supply projections continue to be based upon the criteria of commercial availability. Within the present conventional framework, the projections for the U.S. here presented assume the acceptability of oil imports and of expanding coal and nuclear power.

Demand Projections

Historically, the growth of our economy and energy have been closely coupled in both time and magnitude, as shown in Figure 1. In the future, the relationship between these factors can be expected to be modified to some degree by conservation, new technology, and changes in the relative size of the service versus the industrial sectors of our economy. A slow historical trend of reducing energy demand per unit of economic output is inherent in the relationship displayed in Figure 1. This was primarily motivated

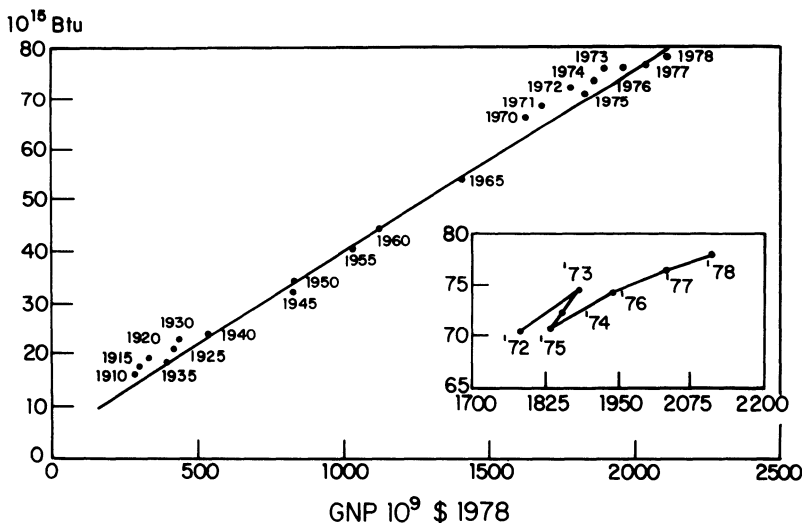


Fig. 1 Historical growth of energy use vs. economy

by the saving in capital cost of energy-converting and -using equipment which resulted from increased thermodynamic efficiency. The recent increases in primary fuel costs have motivated supplementary conservation efforts in addition to those in the historical trend, and in this paper, the term "conservation" refers to this supplement.

In recent years this strong relationship between energy and economic output (as measured by GNP) has continued despite the 1973 oil embargo and the recession of the mid-1970's. As Figure 2 illustrates, GNP and energy have been tightly linked.

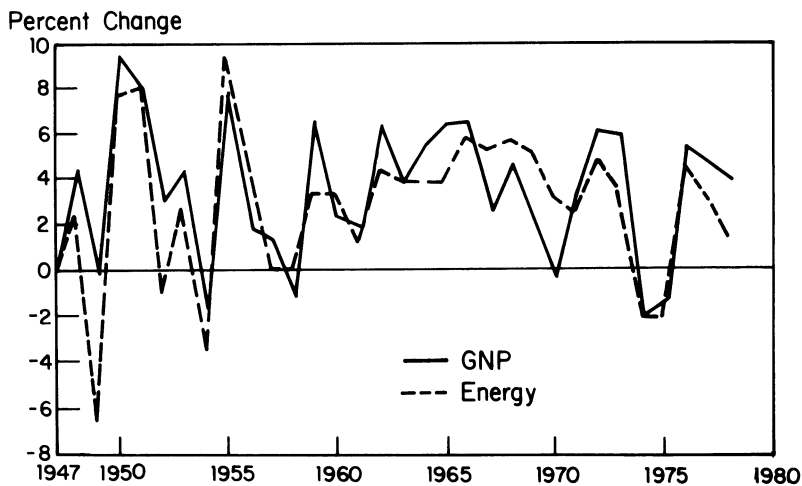


Figure 2. Changes in energy and GNP.

We expect the coupling of energy and economic growth to continue into the future, with the coupling coefficient depending on the course of the principal variables. Four important variables to consider in terms of future energy requirements are: the productivity of labor, employment level, the impact of conservation, and the energy required to meet national air and water quality goals. We know that the year 2000 labor force will be about 1 1/3 times the present, because most are already born. In this analysis we have assumed a 4 percent unemployment and a continuing trend of female participation.

Figure 3 shows a base case total energy requirement of 157 quads in the year 2000, assuming a plausible projection of economic data and continuation of the historical relation to energy use. The trapezoidal box shows the range of projections which occur if the growth rate in the productivity of labor is varied between 0 - 2.3 percent per year and conservation is varied between 28-46

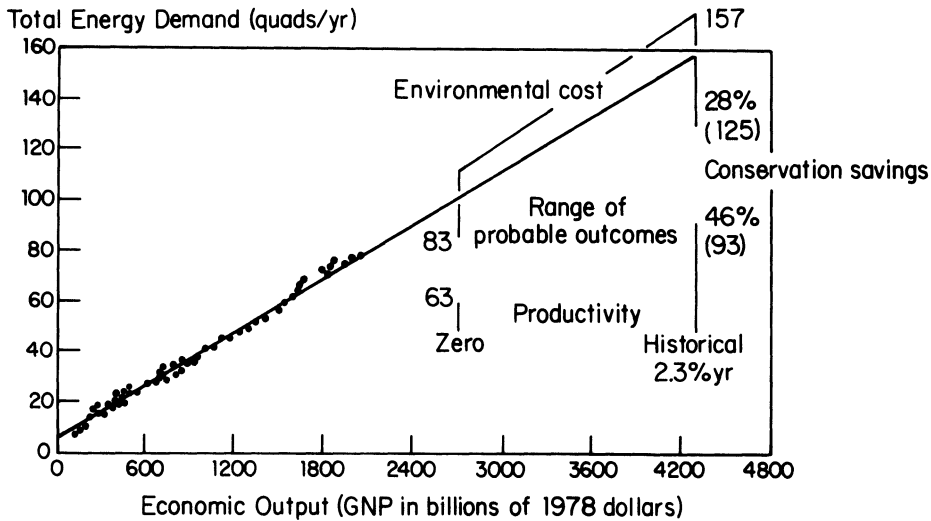


Figure 3. Projection of year 2000 energy and GNP.

percent savings from the year 2000 base case. It is expected that the pressure for environmental improvement will remain, and a 10 percent primary energy cost is estimated for this purpose.

There is a reasonable possibility that actual energy demand and GNP will fall near the top of this box. The lowest demand shown in the lower left-hand corner of the box indicates a year 2000 energy demand of about 63 quads, if 46 percent energy conservation could be achieved, and the productivity of labor were frozen at today's value, a combination that is possible but unlikely. Nevertheless, it is analytically correct that full employment could be maintained without increasing the present levels, if individual economic output is held fixed and conservation is pushed to its technical limit.

Based on the importance of modest planning for a surplus rather than a deficit, the upper right-hand corner of the box, which is equal to 125 quads, may be the prudent target. This assumes 28 percent conservation by the year 2000, 10 percent environmental clean-up cost, and historical growth in the productivity of labor. The 28 percent conservation savings appears to be an optimistic, yet achievable, objective. It should be realized that, as a nation, we have been for many decades increasing the efficiency with which we use energy, and that conservation savings much in excess of 28 percent will require either massive economic investment or significant technical changes. Economic pressures alone may motivate the 28 percent conservation, as the cost of all primary fuels is expected to increase steadily.

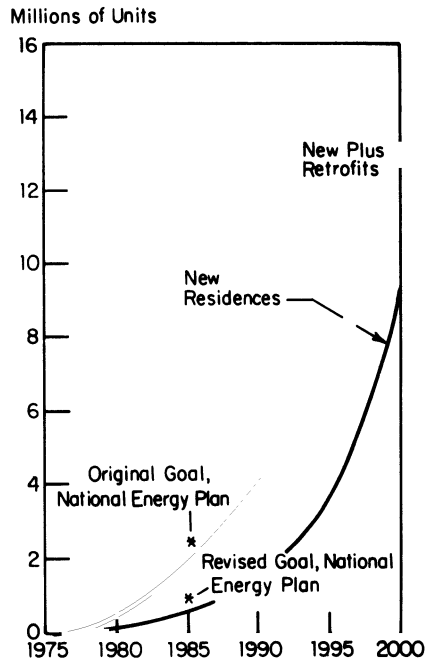


Figure 4. Solar heating of residences (installation rate).

Without going into a detailed discussion of how this future supply will be provided, it is valuable to examine the likely role for technologies currently under development, but not yet commonly in use. Of these sources, solar space and water heating is the technology furthest advanced. Space heating with solar is somewhat more expensive. An EPRI solar heating study analyzed the likely energy savings under several different rates of utilization. This is shown in Figure 4. As this figure indicates, an optimistic estimate is that 13 - 14 million residences would use solar heating in the year 2000, these out of about 106 million residences projected.

The conventional energy displaced by this solar heating is shown in Figure 5. As this study indicates, the fuel savings amount to about one quad. Thus, even if we installed solar heating in 60 or 70 million residences, the savings would be about 5 quads. This could make a significant impact on natural gas consumption, but it only one part of the answer to our supply problems.

In considering how fast new energy sources can contribute to supply, it is instructive to consider nuclear power as an example

for rapid integration. This is valid because, despite its current problems, nuclear power had virtually unanimous support in its early years. In those years plants were built much more rapidly than today, because of the less detailed regulatory requirements. Figure 6 indicates the path taken by nuclear power from the proof of the scientific concept to its integration into utility systems. Also illustrated in this figure are the paths for developing electricity options, assuming that integration will follow the nuclear example.

Electricity Demand

Perhaps the most difficult part of the job of supplying energy in the amounts projected is the portion consumed as electricity. This is because electricity consumption has been growing much faster than total energy consumption, due to extremely long lead times needed to build power plants and due to public opposition to the expansion of any of our current major electricity sources: coal, nuclear, and oil.

The range of credible estimates for electricity demand growth (taking into account both very extensive conservation and deeply reduced economic growth) is roughly 3.8 - 5.5 percent per year, which results in more than a doubling to tripling of annual demand between now and the year 2000. Our pre-1973 experience in electricity growth was about 7 percent per year, which would have quadrupled present production for the year 2000 electricity. Last year's growth was 5 percent (April 1978 to April 1979). It may now be lower, due to reduced economic growth. We should note that during the national reduction in total energy use that occurred between 1973 and 1975, electricity growth increased. Electricity's uses to the consumer are too great to keep the growth rate down.

Even the minimum forecast (3.8 percent) leads to at least a more than doubling of electricity generation (2.3 times) by the turn of the century. How can a doubling of output be realized? Obviously, the bulk must come from coal and nuclear.

Coal plants now supply about 41 percent of our electricity needs and consume 480 million tons of coal annually in the process, two-thirds of a total production of 720 million. Considering all the constraints of environmental regulations on end use, and the delays and institutional constraints on increasing coal supplies, by 2000 coal-produced electricity may be realistically limited to slightly more than double that of today (a 5 percent per year growth), perhaps providing a 45 percent share.

The increasing difficulty of building coal power plants is not generally understood. From time of decision to availability now

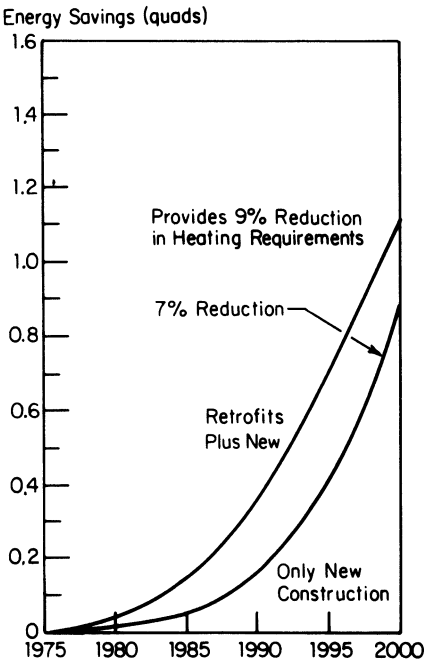


Figure 5. Solar heating of residences (energy savings).

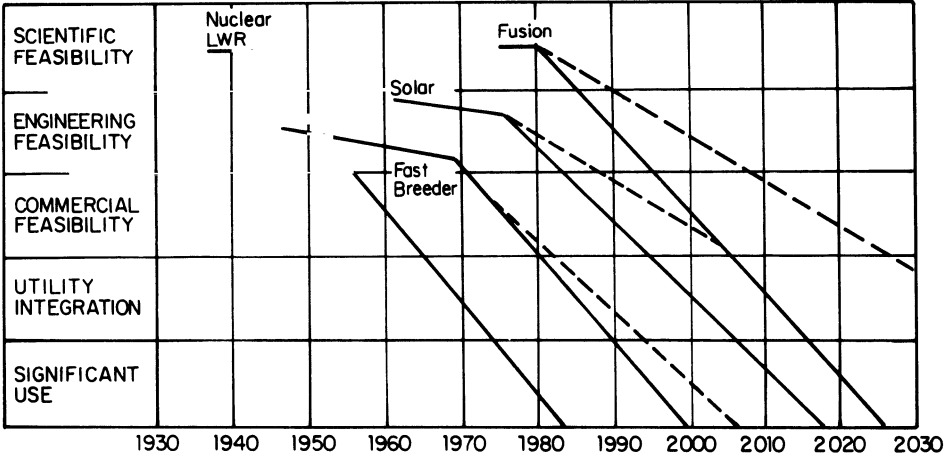


Figure 6. Development phases for future power options.

takes eight to ten years, of which about half is used for the approval chain. Coal use also faces the Clean Air Act, the Resource Conservation and Recovery Act, the Toxic Substances Control Act, and the Clean Water Act. For new coal stations designed to meet the environmental requirements of those Acts, the estimated cost of environmental controls is about 60 percent of the total, and, as a result, the total cost of a coal station is now about the same as that of nuclear. Coal fuel costs are, of course, much higher than nuclear. Coal expansion may be further constrained, if it is extensively used to make synthetic liquid fuel. One ton may hopefully convert to three barrels of oil. So half of our present coal production converted to oil would produce about one billion barrels of oil per year--about 16 percent of our present use and about a third of our imports.

Hydroelectricity provides about 11 percent of our generation output now, and could possibly be increased during the next twenty years, but not to the extent of doubling, so that it may provide about 7 percent of the output in 2000. Geothermal supplies are about 0.2 percent now, and hopefully will be about 2 percent in 2000.

With regard to the solar distribution, the February 1979 report to the President of the Domestic Policy Review of Solar Energy presents an interagency forecast of the year 2000 contribution of solar electricity (thermal, photovoltaic, and wind) based on very optimistic (in some cases unrealistic) assumptions of successful technical development. Their projection for an equivalent energy displacement by solar is 2 - 6 percent of the minimum year 2000 electricity demand we project.

The total from these sources is 56 - 60 percent of that required to meet the low projection for the year 2000. The remainder will need to come from nuclear, synthetics, oil, and gas. At present, about a third of our generation depends on oil and gas. Given our national need for liquid fuels for transportation and the strong federal policy to diminish their use for electricity generation, it is unlikely that synthetics and new oil and gas can be considered for electricity expansion purposes. Oil and gas will probably generate somewhat less electricity than today, perhaps 13 percent of the year 2000's minimal needs. We are left with about a fourth of our needs to be provided, even with our minimum growth estimate, and nuclear is the only source that can fill this gap.

The year 2000 shortage, if nuclear is not pursued, is substantial. This is more easily perceived in terms of the number of nuclear power plants involved. A nominal plant would be about 1 GWe (Gigawatt) size (one million kW), and costs in the neighborhood of one billion present dollars. The equivalent generating capacity in the year 2000 to meet our minimum projection is about 1,200 GWe, so the gap we need to fill by nuclear is roughly 300 GWe. Nuclear

stations now operating and soon approaching completion (if that is permitted) will supply only about 100 GWe, so the shortage will be about 200 GWe on the lowest growth assumptions for electricity demand. Note that this is about 10 years of a reasonable and maximum annual construction target. Because of regional variations, the impact on the high-growth areas of the country would be much larger. If the most recent rate of growth of 5 percent were to continue, the shortage would be about 600 GWe. Recognizing that these forecasts already include more than a doubling of coal generation, you can understand why utilities perceive nuclear not as a matter of preference, but rather, as a crucial necessity.

One point should be understood concerning the utility view of solar energy. As these estimates indicate, the utilities believe they will need every bit of generation capacity that they can find, and they therefore have no reason to downplay the role of solar power. In fact, when solar-electric generation arrives, it will probably be used for the intermediate portion of the load currently filled by oil. But it is not yet available at costs that are even remotely acceptable to customers--present costs are 10 to 20 times conventional delivered costs. Only wind supplement is near to approaching competition with oil. The idea that solar-electric could be a pre-2000 source of base-load power, capable of eliminating the need for either nuclear power or of expanded coal use, is totally false.

The shortfall without nuclear energy is at least 25 percent by year 2000, and may range up to twice that at the higher growth

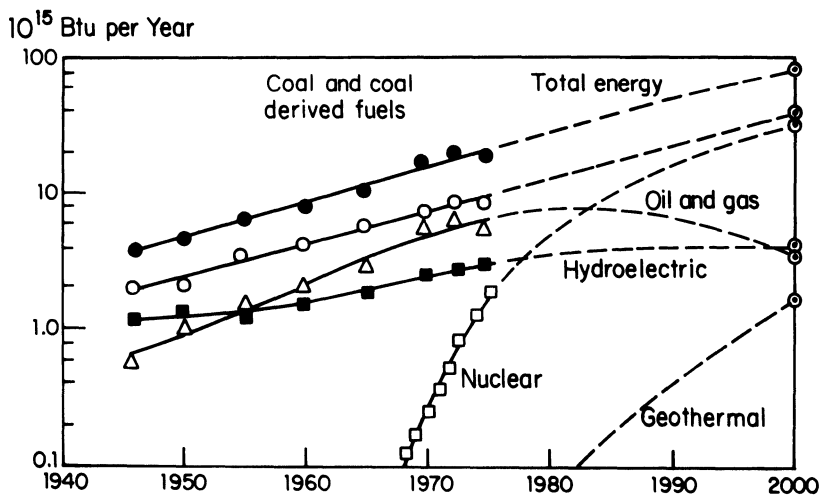


Figure 7. Energy input for electricity (Year 2000 planning targets.)

rate. This gap may take the form of measurable physical shortages, or it may be partially absorbed by the gradual adjustments to constrained supply that will occur as a chronic condition in the 1980's and 1990's. Conversely, if the use of both coal and nuclear power is expanded, the demand can be met. Figure 7 illustrates the mix of sources that could plausibly be used.

Conclusion

Given all these uncertainties in the framework for U.S. planning--both as to the resource assumptions and as to the objectives and their priorities--what should be the U.S. posture? A pragmatic policy, free of ideologic content, would be to seek implementation of a large diversity of energy sources. Those that are now commercial are clearly the most certain and should be fully deployed. Those that are experimental should certainly be brought to the demonstration stage. The vulnerability of a nation to an energy shortage is so large that the economic costs of energy research, development, and commercialization are relatively modest by comparison. It is a national insurance policy which is both affordable and necessary.

Unfortunately, the U.S. energy debates have politicized the development of energy alternatives--renewable versus non-renewable sources; solar versus the breeder; centralized versus decentralized; conventional versus exotic, and so forth. A propagandized and confused public can hardly separate reality from fantasy, present availability from future hopes. When political leaders simultaneously hinder oil development, constrain coal use, and limit nuclear, one wonders which world they live in. Further, surprisingly for a nation whose history enshrines private enterprise, government control of the energy sector in the past few years has become overpowering--so much so that market competition among energy sources has become highly distorted, and conventional evaluations of alternatives have lost their significance.

Faced with the probability of such a dismal outcome resulting from our present national posture, what should we be doing now to avoid it?

I believe that the nation must develop new energy concepts for future deployment beyond 2000, and expand every existing energy and electricity source that technology has brought within range of economic feasibility. A "must" is extensive deployment of nuclear power, which still has a U.S. industrial infrastructure sufficient to close the electricity gap that would otherwise occur although it is slowly fading away. Recognizing the uncertainties of future alternatives and the on-shot nature of the conservation opportunities, we cannot, in common sense, neglect the practical option of nuclear power.

SOLAR PHOTOVOLTAIC ENERGY CONVERSION

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GENERAL INTRODUCTION

The lectures presented under this title consisted largely of material drawn from the American Physical Society's Study Group on Solar Photovoltaic Energy Conversion. The panel was chaired by the author. The other members were D. DeWitt (IBM), J.P. Gollub (Haverford College), R.N. Hall (General Electric), C.H. Henry (Bell Labs), J.J. Hopfield (Princeton University), T.C. McGill (CalTech), A. Rose (Boston University), J. Tauc (Brown University), R.M. Thomson (National Bureau of Standards), M.S. Wrighton (MIT), and J.H. Martin (Harvard University), who served as Executive and Technical Assistant to the Study. The following material is abstracted from the Study Group's report on which the lectures focused, with some editorial alterations from the original. The reader should refer to the published report, "Solar Photovoltaic Energy Conversion" (1979, American Physical Society, 35 E. 45th St., New York, NY 10017) for definitive information concerning the Study Group's conclusions. The following precis, however, should serve to convey the substance of these conclusions.

The lectures also included background material concerning photovoltaics, but this is widely treated in the literature. There is a list of some general references at the start of the reference section.

The material is organized around five summary statements, which may be regarded as extended chapter headings. In the APS report these statements formed part of the executive summary.

1. It is unlikely that photovoltaics will contribute more than about 1% of the U.S. electrical energy produced near the end of the century. Central power production is the most extensively studied and clearly perceived long-term, large-scale application of PV for this country. Barring unforeseen rises in the cost or availability of fuels, prices for 12-16 % efficient flat plate modules or concentrator arrays of about 10-40¢ per peak watt (W_p) in 1975 dollars will be required to compete with the projected cost of coal-generated electricity (about 45-70 mills/kWh levelized busbar cost in the year 2000).

INTRODUCTION

Because of the uncertainties in the future cost of the alternatives for electricity generation and in the future cost of PV systems, the extent of the photovoltaic contribution to future U.S. electrical power generation is not known. The probable range of competitive PV costs during the next few decades will be discussed in this section. These estimates are based on a synthesis of information contained in the major systems design studies that have been performed to date and various cost estimates for the fabrication of solar cell modules.

It will be seen (Table 3) that the systems design studies are mutually consistent within a factor of two. We estimate forecasts for silicon module production costs to have an associated uncertainty of perhaps -20 to +100 %. It is to be emphasized that in all cases these estimates represent projections of the present technology which include technological improvements of various kinds and increased automation, but not breakthroughs.

The year 2000 has been commonly chosen as a time period in which central power PV in the U.S. might first become significant, because it is about a decade after the development of present technology would have reached fruition. Within this scenario, the last decade of the century or so would remain for large scale production of PV systems. It seems reasonable to call a power source "significant" if it provides 1 % or more of U.S. electricity. Table 1 presents a rough estimate of the requirements for PV to provide that amount of generation in the year 2000.

The results shown in Figures 1 and 2 summarize the conclusions of this section. The captions give self-contained descriptions of these figures. Except for the cost of coal electric generation, the uncertainties resulting from the absence of accurate cost infor-

mation are not indicated. They should however be kept in mind by the reader, as should the fact that the conclusions derived from the input information represent the Study Group's judgment in all cases.

ALLOWABLE COST RANGE FOR PV SYSTEMS

A build-up at uniform rate to the 1 % level in ten years would require a PV production rate of 2000 MW_p per year beginning in 1990, more than 1000 times our present level of production. Because of the time required for public and utility acceptance, production scale-up, development of automated factories, and most importantly inventions needed to reduce costs, we do not expect the 1 % level to be reached much before the year 2000 unless an emergency deployment of PV is necessary. We will therefore try to estimate the costs of conventional and PV generation in the 2000-2030 time period.

Barring unforeseen developments, the large-scale use of PV in the U.S. will not occur unless PV electricity is competitive in cost with conventional forms of electric power generation. Only then will PV be used by utilities to supply electricity to the power grid or be purchased in significant quantities by customers who have the option of receiving power from the grid.

The market potential for nongrid-connected (remote) applications has been studied by the Solar Energy Research Institute (SERI).² While this market can be served by higher-cost PV systems, it is quite uncertain in magnitude (30-340 MW_p/year) and rather small in comparison to U.S. electricity consumption. Furthermore, much of this market comprises applications, such as pumping water in foreign countries, which provide no direct fuel savings to the U.S.

Several major conceptual design studies of grid-connected PV systems have been made for Sandia,³⁻⁶ for JPL,⁷ and for the Electric Power Research Institute (EPRI).⁸ Grid-connected applications can be roughly divided into central power station and on-site applications, the latter including the residential, commercial, and industrial sectors.

The central power application of PV is reasonably well defined at this time. There is rough agreement on the cost of the non-module parts of the system and the methodology⁹ for evaluating the life cycle cost of PV and conventional systems. Thus, the allowed capital investment CI in cents per watt of peak capacity ($\text{¢}/W_p$) for competitive PV central power systems and the allowed module costs C_W in $\text{¢}/W_p$ can be approximately calculated. In Section 2 we point out that PV can be expected to displace mainly intermediate load generation. Therefore, we will determine the range of allowed CI by comparison with the expected price range of future intermediate coal generation.

Table 1

Requirements for PV to contribute 1 % of U.S.
electricity generation in the year 2000

1975 U.S. electricity generation	$1.92 \cdot 10^{12}$ kWh
Plausible U.S. electricity generation in 2000 ¹ (3.9 % projected growth rate) ^a	$5 \cdot 10^{12}$ kWh
Significant PV generation (1 % of total generation)	$5 \cdot 10^{10}$ kWh
Required PV capacity in the Sunbelt ^b (1 W_p produces 2.5 kWh/year)	20 000 MW_p
Annual production rate for 10-year build-up	2000 MW_p /year
Thermal fuel displaced (1 $kW_{electric} = 2.9 kW_{thermal}$; 1 Quad = 10^{15} BTU)	.50 Quad/year
Capital investment (50-100 ¢/ W_p system cost, 1975 \$)	$1-2 \cdot 10^9$ \$/yr
Array area (10 % efficiency from light to electricity)	200 km^2
Total land area required	400-600 km^2

^a Moderate growth scenario; most current estimates lie in the range from 0 to 6 % per annum.

^b The rating of a PV plant in peak watts (W_p) is the electrical output of the plant with an insolation of approximately $1 kW/m^2$.

The on-site applications are less well defined at present. The installed cost per watt of these systems will probably be greater than for central power systems.¹⁰ Although there are savings associated with the use of roofs as support structures in some designs, installation costs will be higher than for central stations and the price of system components at the "retail" level will be higher. The smaller scale of on-site systems results in higher relative costs of power conditioning. Either expensive storage and local back-up or back-up connection to the utility grid is required. Because of the erratic nature of residential loads, residences must throw away excess PV energy, store it, or sell it back to the utility. When a residence is grid-connected and returning excess power to the grid, it becomes in effect a small costly central power station.

Unless current development practice can be modified, the adoption of residential systems will also be hampered by the lack of suitable roof orientations, by the constraints this requirement places on the design of new homes powered in part by PV, by the difficulty of using tracking concentrators residually, and by the burden of system maintenance on the home owner.

The major advantage of on-site applications over central power PV is the opportunity for cogeneration of heat and electricity using a single system. However, studies of cogeneration in residential systems^{4,6,11} show no significant cost advantage of combined PV and thermal arrays over side-by-side generation of electricity and heat. Cogeneration does appear attractive for application at large load centers or for industrial sites where high concentration liquid cooled PV systems are employed. Preliminary studies¹² indicate a definite advantage when all the thermal heat generated can be used.

It is not yet established whether on-site PV with cogeneration is advantageous compared with central power in the U.S. Because of the existing uncertainties, we have used studies of central power systems to determine the range of competitive module costs.

In summary, we have studied the case of PV use in central power generation because the application requirements are quite well defined, the potential market is large, either flat plates or concentrators may be used, and the cost requirements for PV modules used in central power appear no more stringent than, for example, residential U.S. PV applications.

COST REQUIREMENTS FOR COMPETITIVE PV POWER

The levelized busbar energy cost $\overline{\text{BBEC}}$ is a figure of merit used by utilities to compare the economic value of alternative generating options. It is the price per unit energy which, if held constant

throughout the life of the system in current dollars, would provide the revenue required to meet all costs of the system. We will use the levelized busbar energy cost, expressed in 1975 mill/kWh, to compare PV plants and intermediate-load coal plants operating in the 2000-2030 time period.

The $\overline{\text{BBEC}}$ of a generating station is given by⁹

$$\overline{\text{BBEC}} = \frac{10^4 \text{ FCR} \cdot \text{CI}(\text{¢/W}_p)}{H_A(h)} + \overline{\text{OM}} + \overline{\text{FL}} \quad (1)$$

where $\overline{\text{BBEC}}$, $\overline{\text{OM}}$, and $\overline{\text{FL}}$ are measured in mills/kWh (1 mill = \$.001) and we have defined

CI: the initial capital investment

FCR: the fixed charge rate, an annual percentage rate covering taxes, interest and return on equity, repayment of principal, and insurance

H_A : the effective number of hours per year of operation at rated capacity (the annual plant output in kWh divided by the plant's rated capacity)

$\overline{\text{OM}}$: the levelized cost of operations and maintenance

$\overline{\text{FL}}$: the levelized fuel cost.

Typically, FCR = 0.15/yr. For an intermediate load coal plant, H_A is nominally 4380 h/yr (capacity factor 50 %).¹³ With these assumptions and a CI estimated by EPRI¹³ as (67 ± 9) ¢/W_p for a coal plant with SO₂ scrubbers, the first term in Eq. (1) is (23 ± 3) mill/kWh. EPRI¹⁴ has estimated $\overline{\text{OM}} = 4$ mill/kWh. Using these figures the range of $\overline{\text{BBEC}}$ for future coal plants is then specified by the estimates of the future price of coal.

Table 2 shows a variety of coal price estimates and the resulting levelized busbar costs. The references in the table give the sources of the coal estimates. The range of busbar costs extends from 44 to 72 mill/kWh. To be competitive in this application, a PV plant must have a value of $\overline{\text{BBEC}}$ which falls into this range unless a large value is assumed for the so-called external costs of coal generation. A plant efficiency of 10^4 Btu/kW_eh, corresponding to a thermal efficiency of 34 %, was used to calculate $\overline{\text{FL}}$. The range of $\overline{\text{FL}}$ corresponds to a range of 2.0-4.2 \$/MBtu (1 MBtu = 10^6 Btu) for the levelized price of coal (1975 dollars).

The cost of coal delivered to electric power plants in 1975 was 86 ¢/MBtu for the U.S. average and 56 ¢/MBtu for the Southwest. If this cost remained constant in real terms, rising only at the general inflation rate assumed, $\overline{FL}$ would be 16 mill/kWh (U.S. average) and 11 mill/kWh (Southwest) in the period considered. The higher values for $\overline{BBEC}$ and $\overline{FL}$ in Table 2 are associated with assumed increases in the real cost of coal up to and during the 2000-2030 time period.

In order to evaluate the allowed capital investment of a PV plant, we have calculated the $\overline{BBEC}$ of a PV central station plant using the same FCR (15 % per annum) as for coal plants, assuming a nominal insolation of $H_A = 2500$ h/yr, corresponding to the most favorable areas of the U.S. Southwest, and estimated operations and maintenance costs of 4 mill/kWh.^{7,15} The same annual insolation was used for flat plate and 2-axis concentrator systems because, while the latter only utilize the direct component of the sun's radiation, they remain facing the sun throughout the day. These effects approximately cancel each other in most of the U.S.¹²

In comparing PV and conventional plant electricity costs, one must be careful to take into account that the PV plant must contribute the same amount of effective system capacity as the conventional plant it displaces. One way to do this is to add gas-turbine back-up generation during cloudy periods to insure that the PV plant is as reliable as a conventional plant. A 10 % PV energy penetration in the U.S. Southwest requires about 125 hours/year of back-up generation,⁶ costing about 9 mill/kWh when averaged over the 2625 effective h/year of power generation at rated capacity. This approach leads to a break-even capital investment CI in the PV plant of 52-98 ¢/W_p, the range resulting from the spread in levelized $\overline{BBEC}$ of conventional coal plants indicated in Figs. 1 and 2.

Another approach we took to determining the allowed CI of PV plants was based on the results of a study⁸ which concluded that in the Southwest the effective capacity of a PV plant with no back-up is about 50 % that of a conventional plant. Therefore 1 kW_p of PV capacity displaces about .5 kW_p of conventional plant. This approach leads to a CI = 50-93 ¢/W_p, in good agreement with our other estimate.

FORECAST OF PV SYSTEMS COSTS

A PV plant beginning operation in the year 2000 will make use of PV technology developed and in manufacture by the mid 1990's. There are no accurate cost estimates available for PV system components in that period. We have tried to estimate the minimum costs of some of today's most clearly defined PV options for the mid 1990's by making

use of systems studies, of the detailed cost goals of the Si flat plate program, and of cost information on low cost heliostats designed for power tower applications.

Non-module Costs

The cost of a PV system can be divided into the module cost (cost at the factory of the flat plate panel or concentrator) and the cost of the remainder of the system. Table 3 gives two estimates of the components of the non-module system cost, along with the numbers used here. The first column is an average over several designs in a recent detailed engineering study for JPL.⁷ The second column is a Sandia summary¹⁹ of a number of recent studies. Our estimate of only 20 \$/m² for land, structures, and installation is much less than the 38.5 \$/m² of the engineering study,⁷ which is based on current technology. This lower number does not derive from an engineering study. It is attainable only if low-cost structures and highly automated installation methods, such as those described in a recent study of an enclosed heliostat design,¹⁸ are developed.

Table 2

Various projections of the cost of intermediate load
coal electric generation in 2000-2030
(1975 dollars)

	14 EPRI	15 DOE (high)	15 DOE (moderate)	16 GE (high)	16 GE (low)	17 Aerospace Southwest US
<u>FL</u> (mill/kWh)	20-26	41	21	35	27	28-42
<u>BBEC</u> (mill/kWh)	44-56	65-71	45-51	59-65	51-57	52-72

Table 3

Non-module system costs:
near-future estimates and cost model
for central power stations

Item	JPL-Bechtel ⁷	Other Conceptual Design Studies ¹⁹	Cost Model Used Here
Power	AC wiring	5.6	
Conditioning	1/2 DC wiring	5.6	
(\$/kW)	Converter	66.0	
(1975 dollars)	Switch yard	66.0	
		<u>143.2</u>	60-125 140 \$/kW
Land,	Land	0.8	
Structures,	Clear and Grade	4.3	
Installation	1/2 DC wiring	0.8	
(\$/m ²)	Lightning		
	protection	1.6	
	Foundations	9.6	
	Support	4.3	
	Frame	<u>17.1</u>	
		<u>38.5</u>	20-40 ^a 20 \$/m ²
Indirect	Engineering	5.6	10
Costs	Contingencies	8.2	5
(%)	IDC ^b and other	<u>30.6</u>	<u>15</u>
		<u>44.4</u>	<u>30</u> 35 %
Operation and		3.3	5
Maintenance			
(mill/kWh)			4 mill/kWh
Plant Efficiency		91	95
(%)			90 %
Back-up ^c			9 mill/kWh

^a 10 % overall efficiency for converting sunlight to busbar
AC electricity assumed

^b Interest during construction

^c Back-up generation is assumed to contribute 125 kWh/year
per kW of capacity; the cost model figure is averaged over
the total PV system electricity generated and includes both
capital and fuel costs for the back-up.

Flat Plate System Costs

The non-module costs of Table 4 are used to plot the capital investment required for the PV system $CI(\text{¢}/W_p)$ as a function of area related costs in Fig. 1 for flat plate systems. For such a flat plate system

$$CI(\text{¢}/W_p) = .1 f_{\text{ind}} \left(\frac{C_S + C_A}{e_p e_m I_p} + C_{PC} \right), \quad (2)$$

where we have defined

	<u>cost model value</u>
f_{ind} : indirect cost factor (see Table 3)	1.35
C_S : site cost (land, structure, installation, etc.)	20 \$/m ²
C_A : area cost of modules in \$/m ²	variable
e_p : plant efficiency for module output to busbar AC	.9
e_m : module efficiency for transforming light to electricity at the module terminals	variable
I_p : peak insolation	1 kW/m ²
C_{PC} : power conditioning capital cost	140 \$/kW _p

The .1 is a conversion factor: $1 \text{ $/kW}_p = .1 \text{ ¢/W}_p$. The module cost per peak watt, $C_W(\text{¢}/W_p)$, is related to the module area cost, $C_A(\text{\$/m}^2)$, by

$$C_W = \frac{C_A}{10 e_m I_p}. \quad (3)$$

Eliminating the module efficiency e_m from Eq. (2) using Eq. (3) gives

$$CI = f_{\text{ind}} \left(\frac{C_W}{e_p} \left(\frac{C_S}{C_A} + 1 \right) + .1 C_{PC} \right). \quad (4)$$

The curved dashed lines in Figs. 1 and 2 correspond to constant module cost C_W . As the module efficiency is decreased, C_A decreases for constant C_W and CI increases, as Equation (4) shows; CI diverges as C_A approaches zero.

Table 4

Flat plate module costs:
1986 DOE goals and cost model for
central power stations

	JPL 1986 Technology Goals ²⁰ 46 ¢/W _p 11.5 % Efficiency Crystal Si Flat Plate Module		Cost Model for Thin Film Flat Plates
<u>Cell Cost^a</u>			
Metallization	7.0 ¢/W _p	8.0 \$/m ²	6.5 \$/m ²
A-R Coating	0.8	0.9	1.0
	<u>8</u>	<u>9</u>	<u>7.5</u>
<u>Noncell Cost</u>			
Interconnection	4.2	4.8	3.5
Encapsulation	12.0	13.8	14.0
Test	0.1	0.1	
Package	0.1	0.1	
	<u>16 ¢/W_p</u>	<u>19 \$/m²</u>	<u>17.5 \$/m²</u>

^a The costs of silicon preparation, sheet fabrication, p+ back layer formation, etching, ion implantation, and pulse annealing, which form 22 ¢/W_p of the JPL total of 46 ¢/W_p, are omitted since these processes will not carry over to thin film cells.

Table 5

Concentrator system costs:
cost model for central power stations

	Cost per Unit Area of Aperture
<u>Non-Module Cost</u>	
Land, clearing/grading, wiring, lightning prot.	12.5
Installation of heliostat ¹⁸	7.5
	<u>20.0 \$/m²</u>
<u>Module Cost</u>	
Heliostat ¹⁸	17.5
Additional cost for parabolic reflector shape	15.0
Cooling	10.0
	<u>42.5 \$/m²</u>
<u>Cell Cost</u>	
Si cells (250 \$/m ² of cells at conc. ratio C = 50)	5.0 \$/m ²
GaAs-GaAlAs cells (7500 \$/m ² of cells at C = 500)	15.0
Multicolor cells (10/000 \$/m ² of cells at C = 500)	20.0

The diagonal shaded regions in Fig. 1 indicate the projections of the possible range of cost of future flat plate systems. The shading for Si flat plates ends at $C_W = 50\text{¢}/W_p$, the 1986 DOE cost goal for the Low-Cost Silicon Solar Array Project (LSSA) managed by JPL.

The cost goals of the 1986 Si flat plate program, excluding the cost of Si wafers and junction formation, are listed in the first two columns of Table 4. Similar costs will be encountered for thin film flat plates. As a result, the minimum area costs of a thin film module are estimated in the right-hand column of Table 4 to be only slightly less than the corresponding cost items taken from the cost goals of the Si program. We attribute an interconnection cost to the thin film flat plates, because while large area thin film cells may be fabricated, many small cells wired in series are needed in order to keep module currents reasonable.

The largest part of the module cost is $14 \text{ \$/m}^2$ for encapsulation. This estimate is based on the assumption that hermetic glass encapsulation will be required for reliable thin film systems. If durable thin film modules encapsulated in plastic could be developed, this cost might be substantially reduced, but whether this can be accomplished is an open question.²¹ Our minimum estimated cost for the thin-film module of $25 \text{ \$/m}^2$ is obtained by adding the cell and noncell costs in Table 4 and assumes negligible cost for the thin film itself. This value determines the cut-off of the shaded thin film region in Fig. 1. Figure 1 shows that the nonfilm area related costs require minimum thin film module efficiencies of near 10 %.

Concentrator System Costs

The minimum costs for two-axis concentrators are estimated in Table 5. This table is based on two designs for low-cost enclosed heliostats^{22,18} for power tower collectors, made of Mylar-like plastic sheet. Each design uses a plane reflector of about 60 m^2 area enclosed in an air-supported plastic enclosure. Zimmerman²² has recently modified one of these heliostat designs for PV use, replacing the flat reflector with a lightweight parabolic plastic reflector which can focus sunlight on PV cells at high concentration. In Table 5 we list our own rough estimates of the additional cost expected for cooling the cells with a circulating fluid and for modifying the reflector into a focusing element.²³ The cost estimates used in Fig. 2 are only expected for large volume production, on the order of 250,000 concentrators (about 3000 MW_p) per year.

The installed concentrator cost, including metal foundation but without cells, is estimated to be $50 \text{ \$/m}^2$ ($42.5 \text{ concentrator} + 7.5$

installation; see Table 5). This is much less than current manufacturing costs of conventional concentrators: the current installed cost of a two-axis tracking Fresnel lens concentrator is estimated to be 246 \$/m² without cells. For comparison, a 50 ¢/W_p 12 % efficient flat plate module would cost 60 \$/m². The enclosed plastic concentrators have the potential for extremely low cost at high volume because they are made of lightweight inexpensive materials. While these plastic structures are extremely attractive because of their low-cost potential, they have not yet been proven to be durable under service conditions. Problems could arise, such as the degradation of the optical quality of the plastic enclosure after several years. Their success is therefore not assured. However, the plastics industry is only now beginning to consider this application and better enclosure materials may be developed. This area of materials research is of great potential importance.

The expected CI for these concentrator systems was calculated from Eq. (2) and is plotted in Fig. 2. We assume an optical concentrator efficiency of .7 ($e_{\text{module}} = 0.7 e_{\text{cell}}$) and cell operating temperatures of 50 C. The cell efficiencies at 50 C are shown on the figure. The lower efficiency in each shaded region corresponds approximately to the current state of the art. The higher efficiency in each case is our estimate of what might be achieved. The cutoff of each shaded region is determined by the cost estimates of Table 5.

No correction has been made in Figure 2 for the power requirements of the cooling system. Cooling of cells has been estimated¹¹ to consume about 3-15 % of the output power, depending upon the system constraints.

CONCLUSIONS

Figs. 1 and 2 show that the allowed cost of PV systems operating in the U.S. Southwest (H_A about 2500 h/yr) will be 50-100 ¢/W_p. The corresponding range for average-insolation areas of the United States (H_A about 1750 h/yr) would be 35-70 ¢/W_p. This range is largely determined by the uncertainties in future coal prices. From Figure 1 it can be seen that the allowed factory price of modules necessary to meet these system cost requirements is 10-40 ¢/W_p.

The relative potential of each PV option should be judged by the required size of its capital investment. Reasonable lower limits are shown by the cutoffs of the shaded regions in Figs. 1 and 2. These cutoffs have been determined by considering each option using the same degree of "reasonable optimism" as a criterion. However, in the absence of accurate cost information these graphs represent our own judgments in all cases.

According to our projections, Si flat plate modules will not be competitive at the 1986 DOE goal of 50¢/W_p module cost. This cost level will principally provide insurance against unexpectedly high future fuel costs of economic, environmental, or political origin.

Thin film flat plates have the potential to become competitive if modules with efficiencies near 10 % can be developed, if the cost of the thin film without contacts can be kept down to a few \$/m², if low-cost support and installation costs are achievable, and if electricity prices are high.

Si cells used in inexpensive concentrators are promising candidates for competitive electricity generation. The main obstacles to the success of this approach are the development of low-cost two-axis concentrators and the production of Si concentrator cells with efficiencies near 20 % at a temperature of 50 C.

High efficiency cells, such as improved GaAs-GaAlAs cells or multicolor cells, appear to offer the greatest potential for becoming competitive at currently projected fuel prices, provided that extremely low-cost concentrators capable of operation at a concentration of about 500 can be developed and that adequate service life of cells and concentrators can be achieved.

Concentrators appear to have an advantage over flat plates. The flat plate approach requires deployment of large areas of low-cost and durable materials, which at the same time are sophisticated electronic devices capable of converting light efficiently into electricity. The concentrator approach separates the conversion problem into two parts. To make use of the highly collimated nature of direct sunlight, inexpensive durable materials are used to focus the sunlight on a small efficient PV converter. A very sophisticated converter (which is costly per unit area) can then be afforded.

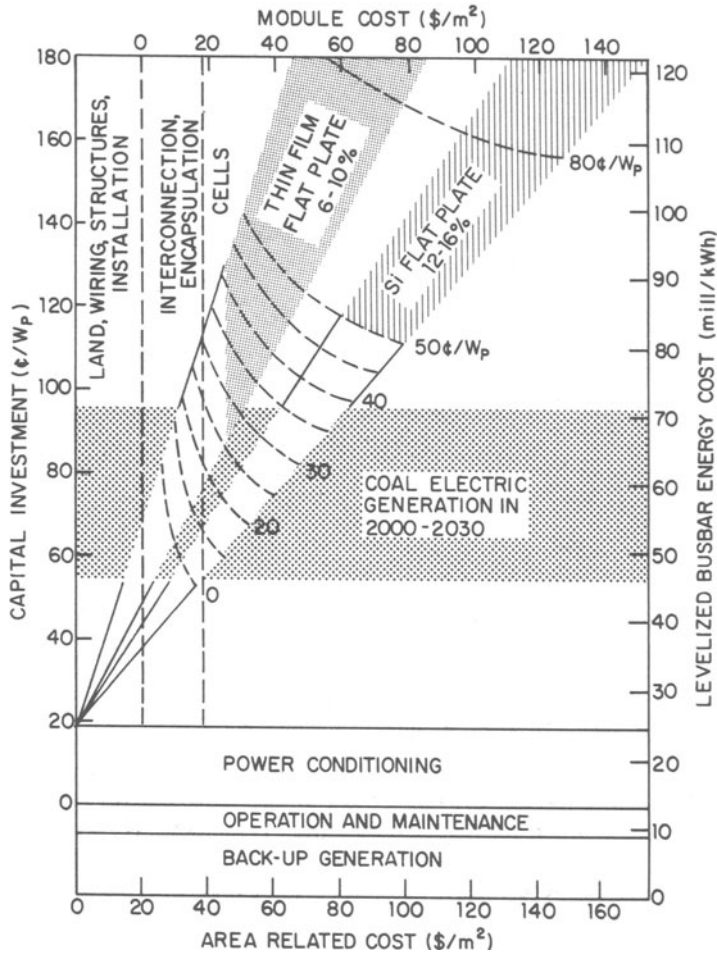


Figure 1

Allowed costs for flat plate PV systems used in Southwest U.S. central power stations, circa 2000-2030

The vertical axis on the right-hand side of the figure corresponds to the levelized busbar energy cost. The horizontal shaded band represents the probable range of levelized busbar energy cost for future intermediate load coal plants. It thus determines the probable range of allowed capital investment for competitive PV systems of equivalent reliability.

The left-hand vertical scale gives the capital investment per peak watt in a PV system which produces a given busbar energy cost in the U.S. Southwest (see Eq. 2). The left and right scales do not have the same zero because of the operation costs required by the model PV system and the necessity for back-up generation to insure reliability equal to that of an equivalent coal plant. The back-up cost is indicated at the bottom of the graph.

Area-related costs are plotted on the horizontal axis. Non-module (land, wiring, structures, installation), noncell (interconnection and encapsulation), and cell costs per unit area are separated by vertical dashed lines. The diagonal lines represent the linear relation between the capital investment cost per peak watt of PV plants and the cost per unit area as determined by Eq. 2 for various module efficiencies. Efficiency ranges of 6 to 10 % for thin film modules and 12 to 16 % for silicon modules are shown.

The curved dashed lines plot the system capital investment for constant module cost per peak watt. The lines curve upward as module efficiency decreases because greater collector area is required for a given output and the area related non-module costs raise the cost of the total system. The vertical line corresponding to zero module cost represents the asymptote.

The shaded portions of the pie-shaped regions referring to thin film and Si flat plates respectively represent cost ranges that are attainable by straightforward extensions of present technology. The demarcation line between shaded and unshaded portions, corresponding to the lowest attainable cost, is better visualized as a smeared-out region reflecting a healthy degree of uncertainty resulting in part from the choices of the cost model given in Table 3. The limit for thin film cells is determined by assuming negligible cost for the film itself, the cell costs being those associated with metallization and antireflection coating as shown in Table 4.

For silicon the range extending to the 1986 DOE module cost goal of 50 ¢/W_p has been shaded. It appears that major technological advances will be required to achieve significant reductions below 50¢/W_p.

As an example of how to interpret Fig. 1, consider a thin film module with an efficiency of 10 %. Our projected lowest costs for this system are given by the lowest point on the right-hand side of the shaded region for thin film flat plates: a module cost of 25 $\text{¢}/W_p$ (the curved dashed line) or 25 $\text{\$/m}^2$ (from the upper horizontal axis); a total area cost of 45 $\text{\$/m}^2$ (lower axis); a system capital investment of 86 $\text{¢}/W_p$ (left-hand vertical axis); and a levelized busbar cost of 65 mills/kWh (right-hand axis).

To understand the origin of these numbers, note that 1 m^2 of module at 10 % module efficiency generates 100 peak watts (W_p). At 25 $\text{\$/m}^2$, the module cost is then 25 $\text{¢}/W_p$. The total area cost of 45 $\text{\$/m}^2$ is projected as 20 $\text{\$/m}^2$ for land, wiring, and installation; 17.5 $\text{\$/m}^2$ for interconnection and encapsulation; and 7.5 $\text{\$/m}^2$ for metallization and antireflective coating. Nothing has been allocated for the cost of the thin film itself in the minimum cost projection.

The plant efficiency is 90 % and hence 1 m^2 delivers 90 W_p to the grid. The contribution of the area related costs to the system cost is then $45/90 \text{ \$/}W_p = 50 \text{ ¢}/W_p$. To this must be added 14 $\text{¢}/W_p$ for power conditioning. This sum is then multiplied by 1.35 to cover the costs of engineering, interest during construction, and contingencies. Thus the total capital investment is $1.35 \cdot 64 = 86 \text{ ¢}/W_p$. The fixed charge rate of 15 % per annum requires the system to generate an annual revenue of 13 $\text{¢}/W_p$ to pay the interest, return on equity, taxes, etc. on the capital investment. In the U.S. Southwest the system would on average produce 2.5 kWh/ W_p each year, resulting in a levelized electricity cost of 5.2 $\text{¢}/\text{kWh}$ or 52 mill/kWh. To this must be added 4 mill/kWh for operations and maintenance and 9 mill/kWh for back-up generation, giving a total cost of 65 mill/kWh.

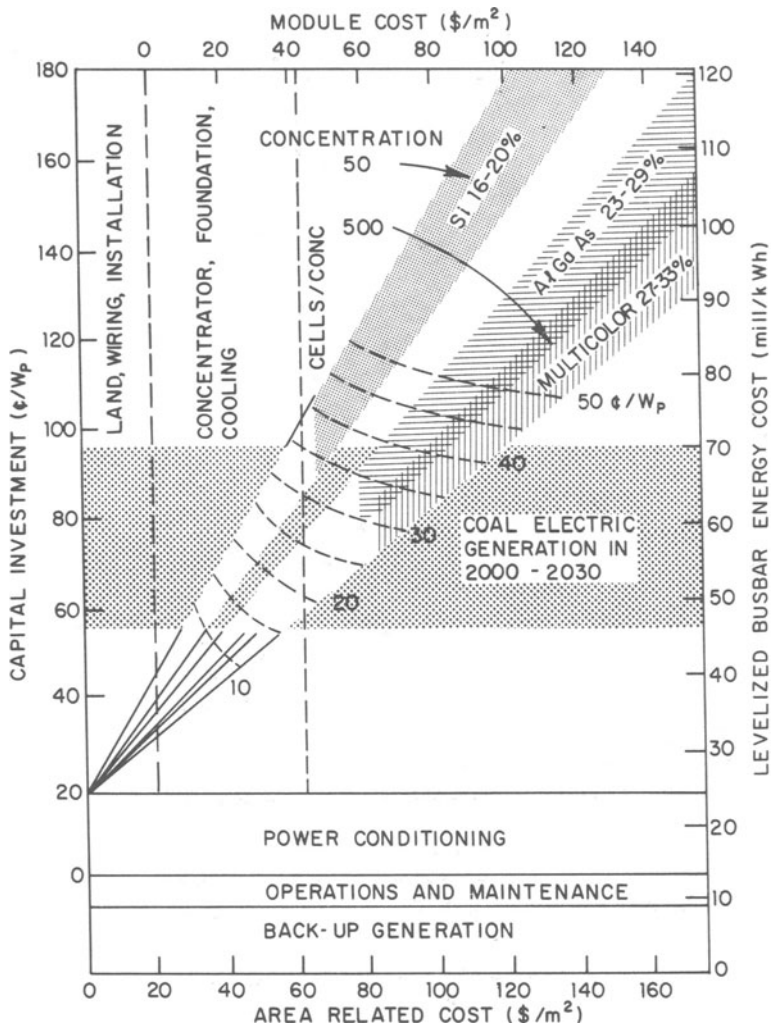


Figure 2

Allowed costs for concentrator PV systems used in Southwest U.S. central power stations circa 2000-2030

The vertical and horizontal axes and many of the other features are the same as those in Fig. 1. Structural costs are based on the use of enclosed, lightweight, 2-axis tracking concentrators (see Table 5 and text). The optical efficiency of the concentrators is assumed to be 70 %. The module cost includes the cost of the concentrator complete with cells, foundation, and cooling equipment, ready for shipment from the factory.

Three types of concentrator cells are considered: Si, GaAs, and multicolor cells. The efficiency ranges shown for each category are estimated obtainable cell efficiencies at a temperature of 50 C for the indicated concentration ratio of each system.

The demarcation line separating shaded and unshaded portions of each pie-shaped region is based on our estimates of the probable minimum capital investment required for the various concentrator systems and is determined by cell, module, and structure costs (see Table 5 and text). The cell cost contribution to the total system cost per unit aperture area is given by dividing the assumed cell cost per unit area of cell by the concentration ratio; the different cell costs of the three systems determine the minimum area-related costs of the systems, as can be seen in the region labeled CELLS/CONC.

The horizontal shaded band has the same meaning as in Fig. 1. The region marked "back-up generation" shown at the bottom of the figure represents the cost of peaking power which must be added to the PV system to insure a reliability equivalent to the comparison coal station.

The curved dashed lines give the system capital investment for fixed module (or array) cost per peak watt. The lines curve upward for the same reason as in Fig. 1: fixed area costs such as land and installation penalize less efficient systems. Comparison of Figs. 1 and 2 indicates that the noncell module cost per m^2 is considerably higher in a concentrator than in a flat plate system.

As an example, our minimum projected cost for a 2-axis concentrator employing Si cells of 20 % efficiency is the lowest point on the right-hand edge of the shaded region for Si. Its position relative to the curved dashed lines indicates an uninstalled array (or module) cost of 33 $\text{¢}/W_p$. Projecting this point onto the four axes shown on the sides of the graph gives: 47.5 $\text{\$/m}^2$ module cost (upper axis); 67.5 $\text{\$/m}^2$ total area cost (lower axis); 91 $\text{¢}/W_p$ system capital investment (left axis); and 68 mill/kWh levelized busbar energy cost (right axis).

The contributions to the area cost are 20 $\text{\$/m}^2$ for land, wiring, and installation; 42.5 $\text{\$/m}^2$ for concentrator, foundation, and cooling; and a cell cost of 5.0 $\text{\$/m}^2$ of collector aperture. Since the concentration is 50X, the cell cost is 250 $\text{\$/m}^2$ of cells. The optical collection efficiency is 70 % and the cell efficiency (at the assumed operating temperature of 50 C) is 20 %. Thus peak insolation of 1 kW/m^2 yields 140 W_p of module output. The cost of the array per peak watt is then $(47.5/140) \text{\$/}W_p = 34 \text{ ¢}/W_p$. The plant efficiency is 90 % and thus 1 m^2 of collector delivers 126 W_p to the grid. The system cost per m^2 of module is $67.5/126 \text{\$/}W_p = 54 \text{ ¢}/W_p$. To this we must add 14 $\text{¢}/W_p$ for power conditioning and multiply the sum by 1.35 to cover the cost of engineering, contingencies, and interest during construction. The total system cost is 91 $\text{¢}/W_p$.

With a fixed charge rate of 15 % per annum the annual cost of capital is $.15 \cdot 91 = 13.6 \text{ ¢}/W_p$. The system generates an average yearly energy that is equivalent to operation at peak capacity for 2500 hours. The cost per kWh is thus 5.5 $\text{¢}/\text{kWh}$ or 55 mill/kWh. To this we must add 4 mill/kWh for operations and maintenance and 9 mill/kWh for back-up generation. Thus the total levelized busbar energy cost is 68 mill/kWh.

2. It is anticipated that only a small fraction of the electricity generated after 1990 will be based on gaseous and liquid fuels. Therefore photovoltaics will not significantly reduce the use of these fuels. The major effect of photovoltaic generation will be a displacement of some combination of coal and nuclear fuels.

PV will be used by utilities primarily to save the fuels used in conventional electricity generation. Table 6 shows the U.S. generation mix (the fraction of total electricity produced by each source) existing in 1975 and four predictions of future generation mixes of the nation's utilities. Over 80 % is expected to be coal and nuclear generation, about 9 % will be hydro and other renewable sources and only about 9 % will be liquid and gaseous fuels. The percentage contribution of hydroelectricity and renewable sources decreases because hydro remains essentially constant in total output power while total production of power roughly doubles. Very limited production of solar electricity by the year 2000 is assumed, although other solar energy sources (e.g., solar heating) may be significant by that time.

A recent study for EPRI²⁸ which considered fuel displacement in three representative utilities showed that PV displaced all fuels used to some extent, but primarily the fuel used in the plants which meet the increased daytime load, as one would expect. In the future, such generation will probably be served by intermediate-load coal plants or by baseload coal or nuclear plants combined with load-leveling batteries. Therefore, PV will not curb the nation's rising liquid fuel costs: the value of PV lies in reducing the nation's future dependence on coal, uranium, and plutonium.

Table 6
Recent and predicted future generation mixes

	U.S. ²⁴ (1975)	Exxon ²⁵ (1990)	El. World ²⁶ (1995)	EPRI ²⁷ (2000)	Aerospace ²⁴ (2000)
Liquid and gaseous fuels	30 %	10 %	9 %	8 %	6 %
Coal	45	54	56	45	54
Nuclear	9	27	28	38	33
Hydro/renewable	16	9	7	9	7

3. Because of the costs associated with encapsulation, foundations, support structure, and installation of PV array fields, there is a large economic penalty for the use of low-efficiency cells. To compete in the U.S. central power generation market, even zero cost PV cells must have a limiting minimum efficiency. The use of modules with efficiency as low as 10% will probably require substantial reduction in these other costs, even if the modules themselves are inexpensive.

Estimates of non-module system costs based on current technology are listed in Table 3 of Section 1.²⁹ The non-module area related cost obtained is 38.5 \$/m². In the cost estimates used in Fig. 1 (and in Fig. 2, which applies to concentrator systems), we have reduced this estimated cost to 20 \$/m², assuming that low cost structures and automated installation methods will be developed. If these developments do not occur, the additional area related cost of 18.5 \$/m² will increase the capital investment (CI) for a system with 10% efficient flat plate modules by 28 ¢/W_p and increase the CI of a system with 50 ¢/W_p 14% efficient Si modules by 20 ¢/W_p. These systems would then be significantly further from the allowed range of 50-100 ¢/W_p.

Figure 1 also illustrates the great sensitivity of CI to module efficiency. Under the assumptions used in this study, the minimum value of CI rises above the competitive range as thin film module efficiencies decrease below about 10 %. The requirement of a minimum module efficiency of nearly 10 % is due to the approximately fixed costs per unit module area of land, clearing and grading, wiring, lightning protection, support structures, installation, encapsulation, and metallization. In Tables 3 and 4 these costs are estimated to be at least 20 \$/m² for the non-module cost and 25 \$/m² for the minimum module cost, even if the thin film itself is of negligible cost.

4. The minimization of materials usage in the overall PV system must be emphasized. New designs for PV systems should be tested against the availability of materials at high rates of construction of generating capacity, because political or economic developments might produce a need for accelerated rates of deployment. Some current designs, in addition to being extremely expensive, would make major demands on U.S. ability to supply certain materials in sufficient quantity.

INTRODUCTION

Federal government interest in PV must be based on the assumption that PV will ultimately be capable of being deployed on a scale sufficiently large that production of a significant fraction of U.S. electricity or fuel is possible. As an insurance option, the value of PV is determined not only by the cost of PV systems but also by the nation's ability to deploy these systems in a reasonable length of time without excessive demands on raw materials resources and energy production. Attention must be given to the supply of cell materials such as gallium, indium, and cadmium, to the materials used in module fabrication, and to the support materials such as concrete, steel, and aluminum.

A simple test model, which we will discuss now, examines some conceptual designs of structures. It should serve as a useful illustration of the questions which must be answered. A similar model will then be used to examine cell materials. A more detailed study of materials questions is in progress.³⁰

ASSESSMENT OF STRUCTURAL MATERIALS REQUIREMENTS

In order to assess resource production requirements, a reasonable build-up rate for PV must be assumed. A plausible rate of US electricity use at the end of this century can be taken as $4.0 \cdot 10^{12}$ kWh/yr, about twice the 1975 rate. We estimate the materials requirement to construct new PV plants capable of producing 1 % of that energy and express it as a fraction of current U.S. production. Three structural systems to support the photovoltaic devices have been examined. They are:

1. Steel and concrete structures to support flat plates, typical of designs now being considered by JPL.³¹

2. A plastic bubble-enclosed concentrator³² (1000X) with additions to mount and cool the PV cells.
3. A steel-structure concentrator (20X) proposed to Sandia.³³

The PV system efficiencies assumed for converting insolation to busbar AC power are 10 % for flat plate silicon and 12 % for concentrator systems.

The results appear in Table 7. Note that the PV resource requirements are compared with 1974 annual consumption or production, not with that projected for the year 2000. The structures considered all use significant amounts of structural material, though no structure is ruled out for the construction rate considered. The advantage of lightweight designs such as the bubble-enclosed concentrator is obvious, however. If the projections of the utilities industry are correct, an annual construction rate producing new generation of about $2 \cdot 10^{11}$ kWh/yr would be required to meet all the marginal increase in demand for electricity around the year 2000. Meeting that demand through PV construction would make major demands on some materials in some designs, as can be seen from the table.

ASSESSMENT OF CELL MATERIALS REQUIREMENTS

In order to assess cell materials requirements, we again assume a PV capacity increase of $2 \cdot 10^{10}$ W_p. We assume that Si and Cu₂S/CdS cells are used for flat plate applications, and that the cell thicknesses are taken to be 250 microns and 20 microns respectively. The overall system efficiencies are taken to be 10 % for Si and 7 % for Cu₂S/CdS. We also consider stacked cells for concentrator use (500X concentration) composed of thin active layers of 10 microns of various compounds using In, Sb, and other more abundant elements. These concentrator cells are assumed to be grown on either Ge or GaAs substrate single crystals of 300 micron thickness, and to produce overall system efficiencies of 25 %. The corresponding cell materials requirements are given in Table 8. The contemplated use of Ga and Ge is as the substrate material of a stacked cell; of In and Sb, as one of the constituents of the material in a thin film active layer in a concentrator cell; and of Cd and Si, as flat plate sheet.

The requirements shown would permit construction of PV plants to generate about 1 % of U.S. electricity in the year 2000.

From this table it can be concluded that a build-up to high utility penetration by PV would affect the materials supply picture for each of the cells considered. Ga is available from imported

bauxite ores and could be produced from domestic coal. Costs for extraction from coal may be prohibitive, however. Ge is present in coal in about the same amounts as Ga, but extraction cost estimates are unavailable. Other materials problems for cells may arise from cell designs which require contact or barrier materials such as gold and platinum.

Table 7

Structural materials to support and illuminate PV cells. Materials requirements to add $4 \cdot 10^{10}$ kWh ($2 \cdot 10^{10}$ W_p) of generation, compared with 1974 U.S. production or consumption.

Array Type	Material	PV Requirement	1974 U.S. Annual Consumption (Production)	Requirement as % of Cons. or Prod.
Flat Plate	steel	$5.2 \cdot 10^6$ T	$(1.1 \cdot 10^8)$ T	5 %
	cement	$1.4 \cdot 10^7$	$(8.3 \cdot 10^7)$	17
Concentrator (steel)	steel	$1.4 \cdot 10^7$		13
	cement	$6.0 \cdot 10^6$		7
	aluminum	$8.6 \cdot 10^5$	$6.0 \cdot 10^6$	14
Concentrator (plastic)	steel	$2.8 \cdot 10^6$		3
	cement	$7.0 \cdot 10^5$		1
	aluminum	$3.3 \cdot 10^5$		6
	oil	$2.5 \cdot 10^6$ Bbl	$6.0 \cdot 10^9$ Bbl	.04

1 T = 10^3 kg

The requirements shown would allow approximately 1 % of the year 2000 electrical generation from PV.

Table 8
Cell materials requirements^a

Element	$2 \cdot 10^{10} W_p$ Production Requirements	Present Annual Production	Comments
Ge	250 T	76 T (world) 13 (US)	World reserves of Ge are estimated at 2000 tons. ³⁴
Ga	120	7	Up to 140T/yr could be recovered from Zn and Al refining. ³⁵
Sb	4	$2 \cdot 10^4$	U.S. use of primary Sb
In	4	76 (world)	
Si	$1.2 \cdot 10^5$	$1 \cdot 10^5$	Metallurgical grade; 1974 production of high-purity Si was about 300T/yr. ³⁴ Estimated 1978 produc- tion is 1000 T. ³⁶
Cd	$2.1 \cdot 10^4$	$6 \cdot 10^3$	U.S. use.

^a Because the numbers in this table are based on schematic rather than actual designs, they should be regarded as giving only order of magnitude estimates.

1 T = 1000 kg

5. Energy storage would be necessary if photovoltaics came to supply more than about 10-20 % of electrical energy in a typical region.

Storage is not necessary when PV generation represents only a small fraction of a utility's total capacity. The normal ability of a utility to change its generation of power to meet changing loads and to deal with generating failures can compensate for the PV system's intermittent output. The rough coincidence of the PV power time profile with the daily load curve for most utilities leads to some capacity credit for the PV system (that is, the addition of a PV plant reduces the total amount of non-PV generating capacity required to maintain a fixed total-system loss of load probability).³⁷

In fact, at low PV penetration* system electricity storage and PV may be in competition, since storage and PV are both sources of peaking power.³⁷ On the other hand, storage or back-up is required when the PV penetration of a utility becomes large enough to undermine system reliability because of simultaneous forced outages of all PV (clouds), or when PV is considered as a source of baseload rather than peaking electricity for a utility or a source of stand-alone residential power.

Simple considerations lead to the conclusion that at 20% energy penetration storage or fast back-up is necessary with PV. For the Sunbelt, insolation provides about 2500 kWh/m² per year at a peak level of 1000 kW/m². To average 20 % of total generation, PV must produce about $.2 \cdot 8760 / 2500 = .7$ of the average generation when sunlight is at its peak. This large fraction of system generation is vulnerable and must clearly be backed up by large spinning reserve or storage.

* "Penetration" is often defined as the percentage of a utility's maximum generation capacity represented by a given energy source. Since PV systems have a low load factor (ratio of average to peak power output), this definition exaggerates the importance of PV to a utility system. We prefer to use "energy penetration", the fraction of annual energy output of a utility due to the system under consideration. For PV in a normal utility, a capacity penetration of 20 % is equivalent to an energy penetration of roughly 10 %.

Several studies of storage economics in specific conceptual PV applications have been undertaken.³⁸ However, no study has, to our knowledge, attempted to deal with the technical problems of the massive amount of storage which PV would require at high penetration.

If PV is to have a truly major impact on the U.S. energy picture it must be technically and economically ready to do much more than make a small penetration in the Southwest. We need realistic goals for PV, storage, and long distance transmission against which to measure progress. These goals should be supplied by national electric system studies which model optimized systems using all power resources and the sharing of PV power between regions.

In order to obtain a rough estimate of the amount of storage needed in a very high PV penetration model, we have used results from a study³⁹ made for another purpose. This study involved conceptualized homes at seven geographically separated locations in the U.S. Each home was designed to be completely independent of the utility grid and received its electricity from a combination of PV, an oil-fired engine generator, and battery storage. On average, PV and the engine generators supplied about 90 % and 10 % of the primary electrical energy for the seven homes respectively.

A national power system estimate made on this base is at best approximate for a number of reasons. The load curves of the seven houses do not correspond to those of any complete power system, which must also supply industrial and commercial establishments. Our model makes no use of hydroelectricity or the possible advantages of sharing facilities and electricity between adjacent regions. The assumption of 90 % energy penetration by PV uniformly over the nation is extreme in its implication that PV has become much more desirable than all other forms of electric generation. However, the estimate does set an upper bound on storage requirements and develops an intuition for the requirements associated with very high PV penetration.

In constructing the national model, it was necessary to assign a nominal nameplate peak capacity (kW_p) rating to the PV equipment at each location. This was done by assuming an average energy production of 1720 kWh/yr per kW_p of PV. Furthermore, the PV generation energy which was wasted in the isolated house model of Ref. 39, about 16 % of the PV electricity, was taken to be usable in the national model. The characteristics of the individual systems and their sum, which forms the basis for the national model, are shown in Table 9.

Table 9

Annual performance of 7 stand-alone
residential systems,^a and their sum

LOCATIONS	Atlanta,GA	Madison,WI	Phoenix,AZ	Wilmington,DL				
	Cleveland,OH	Mobile,AL	S. Maria,CA	Sum ^b				
PV kW _p	5.7	6.5	5.2	7.7	5.5	4.4	5.7	40.7
Aux kW _p	1.5	1.5	1.5	1.5	1.5	1.5	1.5	10.5
Storage kWh	20	20	20	25	25	15	20	145
MWh from PV	10.2	8.4	8.5	11.7	15.3	7.4	8.6	70
MWh from Aux	1.1	1.3	0.6	1.3	1.4	0.4	1.1	7.2
MWh total	11.3	9.7	9.1	13.	16.7	7.8	9.7	77.2
kW avg	1.3	1.1	1.0	1.5	1.9	0.9	1.1	8.8

PV kW_p: rated peak output power of PV generation in system
 Aux kW_p: " " " " " auxiliary generators
 Storage kWh: kilowatt-hours of battery storage required in system
 MWh from PV: megawatt-hours per year from the PV primary source
 MWh from Aux: " " " " " auxiliary generators
 MWh total: " " " " " sum of auxil. and PV
 kW avg: average rate of electrical power consumption

^a Source for systems data: Westinghouse R&D Ctr., Ref. 39

^b The sum is used as the basis of the national model. See text.

The national system is based on the sum of the seven, given in the last column of Table 9, and has the following properties:

A PV installed capacity of .53 kW_p per MWh of system electrical output each year

An auxiliary generation capacity of .14 kW_p per MWh of system electrical output each year

1.9 kWh of storage per MWh of system electrical output each year, about three hours of storage at system peak capacity

90.7 % of the national system's electricity is associated with the PV capacity and the remaining 9.3 % with the auxiliary generation capacity.

The contributions of storage and auxiliary generation to the cost of each kWh of electricity generated are estimated using EPRI sources. These levelized costs are:

Storage using mid-1980's batteries ⁴⁰	.03 \$/system kWh
Storage using mid-1990's batteries ⁴¹	.01
Auxiliary generation from liquid-fueled turbines ⁴²	.01

(Numerical details are given in the footnotes.)

These considerations show the importance of developing economical storage technology if success in the PV program is to be used to affect the U.S. energy picture significantly.

The massive amount of storage needed at high penetration rules out the use of batteries based on lead. The typical lead content of such batteries is 30 kg/kWh. In this model, 90 % PV energy penetration of an electricity system assumed to produce $4 \cdot 10^{12}$ kWh/yr would require $7.6 \cdot 10^9$ kWh of storage, using $2.5 \cdot 10^8$ T of new lead. By comparison, 1973 U.S. lead production was $6 \cdot 10^5$ T and world production was $3.9 \cdot 10^6$ T.⁴³ U.S. resources are estimated at $1.2 \cdot 10^8$ T and world resources at $3.3 \cdot 10^8$ T. Hence, for large PV penetration another storage system would be required.

INTRODUCTION TO REFERENCES

The references included in this report do not by any means constitute an exhaustive set. They are instead intended to provide entry points to the literature, and for that reason they stress the most recent work.

References which are identified by report numbers without report sources (e.g., SAND77-0909) are reports of the Department of Energy (DOE) or its antecedents such as ERDA. Such reports can usually be obtained from:

National Technical Information Service (NTIS)
U.S. Department of Commerce
Springfield, VA 22161

or

U.S. Department of Energy
Technical Information Center
P.O. Box 62
Oak Ridge, TN 37830

Other sources of reports cited in these references are:

Electric Power Research Institute (EPRI) Research Reports
Center P.O. Box 10090
Palo Alto, CA 94303

Jet Propulsion Laboratory (JPL)
4800 Oak Grove Drive
Pasadena, CA 91103

Solar Energy Research Institute (SERI)
1536 Cole Boulevard
Golden, CO 80401

The frequently used abbreviation PVSC refers to the Conference Records of the IEEE Photovoltaic Specialists Conferences (Institute of Electrical and Electronics Engineers, 345 E. 47 St., New York, NY 10017). Thus the reference "PVSC 13, 1 (1978)" translates as "Thirteenth IEEE Photovoltaic Specialists Conference--1978, page 1". Because the photovoltaic field is so diverse and interdisciplinary, the number of journals containing relevant articles is large. The PVSC proceedings form the most compact source of information on the subject, although the areas of semiconductor/liquid junctions and photoelectrochemistry are not included.

Along with the many books dealing with solar energy in general which contain sections on photovoltaics, there are several works

on the specific areas of solar cells and photovoltaic conversion. Some of these are:

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D. Schueler, Sandia, private communication of PV System Definition Project results.
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Lead-acid battery capital cost in 1985	40 \$/kWh of
	storage rating
Renovations to extend life to 20 years	40
Buildings	20
Total capital investment	<u>100</u> \$/kWh of
	storage rating

At a fixed charge rate of 15 %, the cost of storage per kWh of electricity generated by the total system using mid-1980's batteries is

$$(.0019 \text{ kWh}_s/\text{kWh}_e)(100 \text{ $/kWh}_s)(.15) = .03 \text{ $/kWh}_e,$$

where kWh_s denotes storage capacity and kWh_e denotes system electrical output.

41. From Reference 37, Vol. 2, p. E41, we obtain:

Improved lead-acid battery in 1995	35 \$/kWh _s
Lifetime of 30 years with no renovations needed	

Then the cost of storage using mid-1990's batteries is

$$.0019 \cdot 35 \cdot .15 = .01 \text{ $/kWh}_e$$

42. From Reference 4, Tables VII-8, VI-3, and VI-5, we obtain the following information concerning auxiliary generators:

Turbine costs

Advanced combustion turbine	150 \$/kW _p rating
Availability	85.5 %
Annual O&M (fixed)	.6 \$/kW _p capacity
Annual O&M (use-related)	.00207 \$/kWh generated by turbine
Levelization factor used for O&M	1.87

Fuel costs (assumed heat rate 11 500 Btu/kWh)

Liquid fuel at 3.6 \$/MBtu	.041 \$/kWh generated by turbine
.35 % annual real inflation of fuel cost assumed, giving a levelization factor of 1.98	

With the system data given in Table 9 and on the page following it in the text, the contribution of auxiliary generation to the cost of each total system kWh generated is then calculated as

$$\begin{aligned}
 &.00014 \text{ kW}_p/\text{kWh} \cdot .15 \cdot 150 / .855 \text{ $/kW}_p && \text{(capital cost)} \\
 &+ (.6 \cdot .00014 / .855 + .0021 \cdot .093) \cdot 1.87 && \text{(O\&M)} \\
 &+ .041 \cdot .093 \cdot 1.98 && \text{(fuel)} \\
 &= .01 \text{ $/kWh}
 \end{aligned}$$

43. Reference 34.

SOLAR ENERGY: THE QUEST AND THE QUESTION

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INTRODUCTION

I have borrowed the title for these lectures from a slide show prepared by the Solar Energy Research Institute (SERI) for the International SunDay, 3 May 1978. That was the day of celebration of the great promise of solar energy utilization for human needs. In these lectures, I will review the progress we have made in translating that promise into a reality. The first four lectures will cover solar energy technologies. In the last lecture, I will discuss the basis of solar energy policy formulation and give some of my own views on planning the transition from exhaustable to renewable resources.

These lectures are intended to be introductory. That is, they should provide you an entry into the rich and complex literature now developing in the area of solar energy. I will try throughout these lectures to avoid using the special jargon that has developed very quickly among those who work in this field. However, I am sure at times I will use words or phrases whose meaning will be new to those who have not studied this literature. I will give a number of references which I consider useful sources for further study. However, the field of solar energy is rapidly changing, and so I also provide as Appendix I a list of some journals and newsletters in which you can follow developments as they occur in coming years.

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In the first four lectures, I will be reviewing the various processes and conversion paths by which we can utilize solar energy. There is a great variety in these processes. In order to provide some structure to this review, I first give in this introduction a brief map of the different paths by which solar energy may be converted from its initial resource into the forms in which it is finally utilized (Grosskreutz, 1979). The first major distinction I make is between paths in which the primary process of absorption of sunlight is as heat and paths in which the absorption is by quantum processes. The former I shall call thermoconversion, the latter, photoconversion. In thermoconversion, the energy of the sunlight is instantly degraded in quality to the temperature of a heat reservoir. At this point, the normal laws of thermodynamics apply, including, for example, limits such as Carnot efficiency. In photoconversion, there is no such degradation in the quality of the energy. It remains in a high quality form and can be further converted with high efficiency to electricity, chemical energy, or mechanical energy.

The primary process in thermoconversion paths can occur in either natural or man-made systems (See Figure 1). Within the former, we have the absorption of solar energy at the surface of the earth to produce the evaporation and precipitation cycle of the weather, winds, waves, and the warm surface waters of the tropical oceans. Each of these can be further converted to useful end products including, for example, electricity. Among these many paths, in these lectures I will review only the conversion of energy through winds and the warm surface waters of oceans. I will not review the process of conversion through the evaporation and precipitation cycle which leads to hydroelectric conversion, nor will I review conversion of the energy contained in waves.

When thermoconversion occurs in a man-made system, the solar energy becomes available as heat in a hot solid, liquid, or gas. We can then use this heat directly for heating buildings, water, or industrial processes, or we can convert it into another form by some kind of heat engine. Such engines might use familiar thermodynamic cycles (Rankine, Brayton, etc.) or might use more advanced thermoelectric, thermochemical, or thermomechanical effects. The ultimate product might be direct heat, mechanical power, electricity, or chemical energy.

In solar photoconversion, we can again distinguish between paths in which the initial conversion occurs in natural or in man-made systems (See Figure 2). In natural systems, the conversion is through the biological process of photosynthesis leading to the storage of energy in biological form. In man-made systems, the absorption can occur either in a solid, leading to the familiar conversion path of photovoltaic conversion, or can occur in a liquid

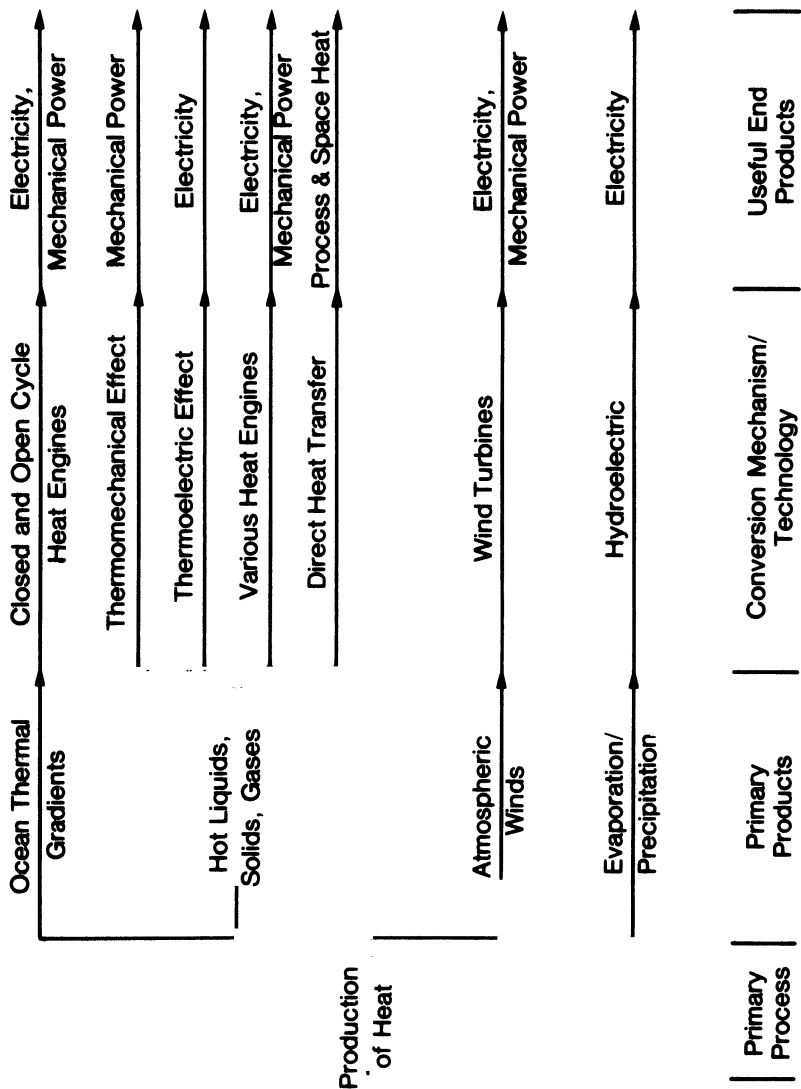


Figure 1. Paths for utilization of solar energy through thermoconversion as the primary process (Grosskreutz, 1979).

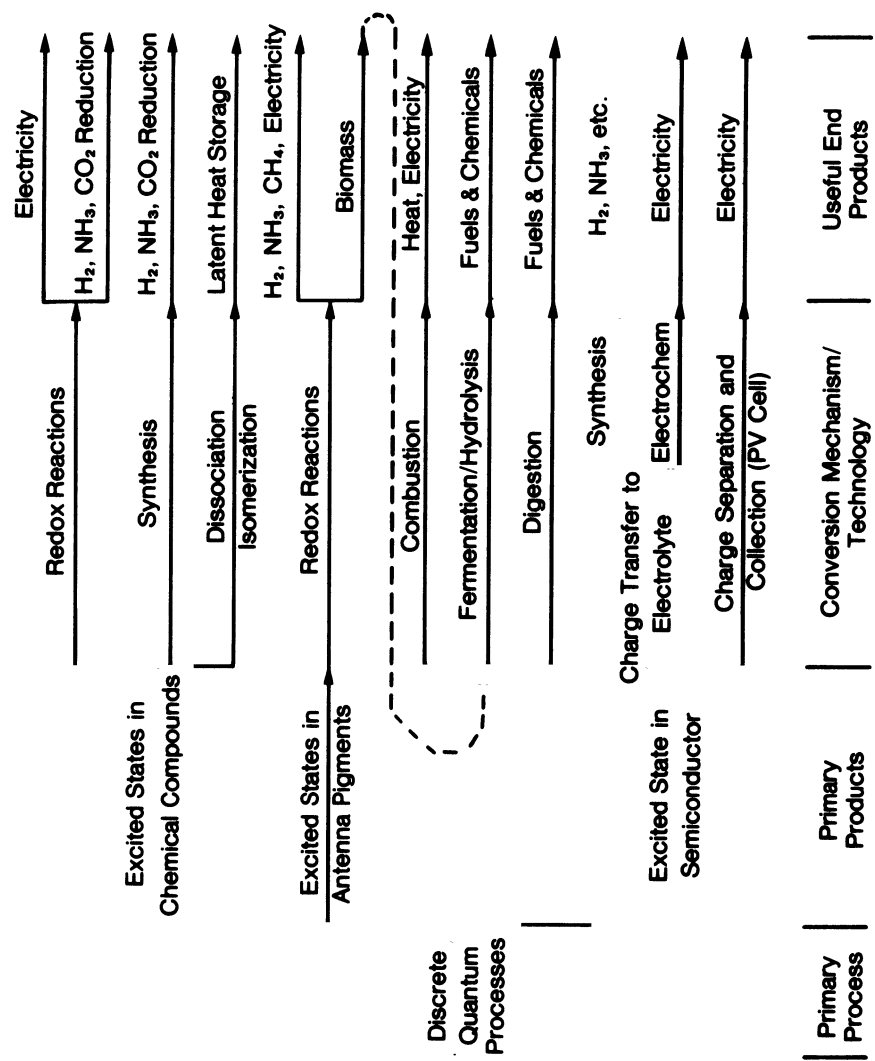


Figure 2. Paths for utilization of solar energy through photoconversion as the primary process (Grosskreutz, 1979).

or gas leading to the less familiar processes of photochemical conversion.

The pathway of photosynthetic conversion leads to the storage of energy in the form of biomass. The efficiency of this process is generally low, 1% or less. However, it does have the desirable property of yielding an energy form that is easily storable and transportable. Biomass can be burned directly to provide space heat or electricity, or can be further converted by a variety of processes to desired fuels or chemicals. In some cases, biological organisms will naturally convert solar energy to some useful chemical forms, for example, hydrogen, fixed nitrogen compounds, or hydrocarbons.

When the initial photoconversion step occurs in a man-made system, the energy is readily available in the form of electricity or chemical energy. In the photovoltaic cell, the collection is in the form of free charge carriers leading to electricity. If the absorption occurs at the surface of a semiconductor in contact with an electrolyte, then the energy can be available either as electricity or in a chemical species. When the absorption is by a liquid or a gas, the energy can be converted in a wide variety of ways to useful chemical forms for storage or utilization.

These two maps of the pathways for solar energy conversion have introduced quickly the variety of technologies that will be reviewed in these lectures. The complexity of these pathways demonstrates clearly that there are many different ways that solar energy can be utilized. Just as there are many potential technologies, there are many disciplines of scientific and engineering endeavor active in developing solar energy conversion and utilization. Thus, these lectures will provide a quick overview of a large number of fields of active research, each of them worthy of a more detailed review than I can give here.

SOLAR ENERGY RESOURCES, COLLECTION AND CONVERSION

In this first lecture, I will review the nature of the solar energy resources and their measurement, and then give a quick overview of the physics of the collection and conversion of this solar energy with particular reference to thermoconversion.

Insolation

Insolation is the term used to describe the incoming solar energy radiation: the starting point for all solar energy conversion pathways. For our purposes in these lectures, the details of the physical processes occurring within the sun are unimportant. To us, it is sufficient to describe this source of solar energy as being a large black body with the surface temperature of about

6000°K. This body produces a radiation flux at the outside of the earth's atmosphere with a nearly constant intensity of 1354 watts per square meter (Watt, 1978). Because of the eccentricity of the earth's orbit, this insolation outside the atmosphere varies by $\pm 3\%$ during the year. This insolation outside the atmosphere also varies by $\pm 1\%$ with sunspot cycles. However, both of these variations are minor in comparison to what occurs to the solar radiation during its passage through the atmosphere. During this passage, the effects of interest to us occur.

Even on a clear day, much of the sunlight that reaches the top of earth's atmosphere is either absorbed or scattered before it reaches the earth's surface. The ozone layer at the top of the earth's atmosphere absorbs part of the ultraviolet spectrum. An upper dust layer, air molecules, water vapor, and a lower dust layer absorb or scatter anywhere from 10%-40% of the incident sunlight on a clear day. Thus, even though insolation is about 1354 watts per square meter at the top of the atmosphere, the peak sunlight observed at the surface of the earth is about 1000 watts per square meter.

Because of these processes, a solar collector pointed up into the sky will see more than just the light coming directly from the sun. A collector will typically see four major components of solar energy. First, the direct beam of light from the sun that is not scattered in its passage through the atmosphere. Second, it will see light which has been scattered by small angles and appears to come from regions near the sun in the sky. This is called circumsolar radiation. It also will see diffuse sky radiation from both the clear sky and clouds. And, finally it will see light reflected from the ground or other nearby objects. Types of solar energy collectors differ in their ability to use these components of solar energy. For example, highly concentrating collectors can use only the direct solar energy component. Some types of low temperature collectors can use all of these components fairly well. Thus, no single measure of insolation is adequate to describe the amount of energy available for all types of solar collectors. An adequate description of the solar energy available at a site can usually be given by the values of six solar energy components. The total energy on a horizontal surface is the first and simplest of these. This is the quantity usually given in tables of insolation data. More important for most low temperature thermal collectors is the total energy falling on a tilted surface (tilted south in the northern hemisphere). Separate measurement is required if this component is to be known accurately for a certain tilt angle (Berdahl, 1977). Direct beam energy is necessary for highly concentrating collectors. For collectors with a moderate concentration ratio, circumsolar radiation may also be important. Diffuse sky energy is usable by nonconcentrating collectors, and at many sites can be an important contribution. Finally, radiation scattered from the ground can be important for flat plate collectors and for passive

solar energy systems. A complete characterization of the insolation resource at a site would include information on all six of these components. However, such detailed information is very seldom available. Much more often, data on only one or two is available, and the others must be estimated by various techniques (Hulstrom, 1978).

Instrumentation is available to measure each of the solar energy components. The instruments now available generally can do an adequate job when new. A major problem is that instruments have not been maintained well over the years in which the presently available data has been collected. Instruments lose accuracy with time and exposure to the elements, and the resulting data may be unusable. This has happened often during the past several decades of collection of insolation data (Berdahl, 1977).

The instrument commonly used for measuring total radiation on a horizontal surface or on a tilted surface is the pyranometer. Pyranometers measure the total amount of radiant energy in a field of view of 180° . Their accuracy can be fairly good, about 3%, though this accuracy may degrade over time. Pyranometers are the instruments most commonly used in insolation data networks such as that operated by the National Weather Service throughout the United States.

The instrument commonly used for measurement of direct solar radiation is a pyrheliometer. This is a much more complex instrument than a pyranometer because it has a small field of view and must track the sun during the day to perform its measurement. The accuracy of such instruments can be quite good, up to 1%. There have been very few of these instruments used in the past, and there is not yet very much data available on direct insolation. Recent installations should provide much improved data within the next few years. This will be particularly important for future installations using concentrating solar collectors.

The discussion to this point has been about the total amount of radiant energy available to a collector. However, also important for many systems is the spectral distribution of that energy. This is important to some degree for all collectors, but is of greatest importance for systems based upon photoconversion: biomass and photovoltaic or photochemical systems. Figure 3 shows the spectral distribution of direct radiation from the sun (Hulstrom, 1978). The top curve is a spectrum as seen outside the earth's atmosphere. It is approximately a black body spectrum corresponding to a temperature of 6000°K . The curves below that one are the spectra of sunlight that has passed through various thicknesses of the earth's atmosphere. Air Mass 1 refers to the spectrum seen when the sunlight comes from straight overhead and thus passes through one thickness of the earth's atmosphere. Air Mass 2 is seen when the sun is at a lower angle in the sky and passes through twice as much

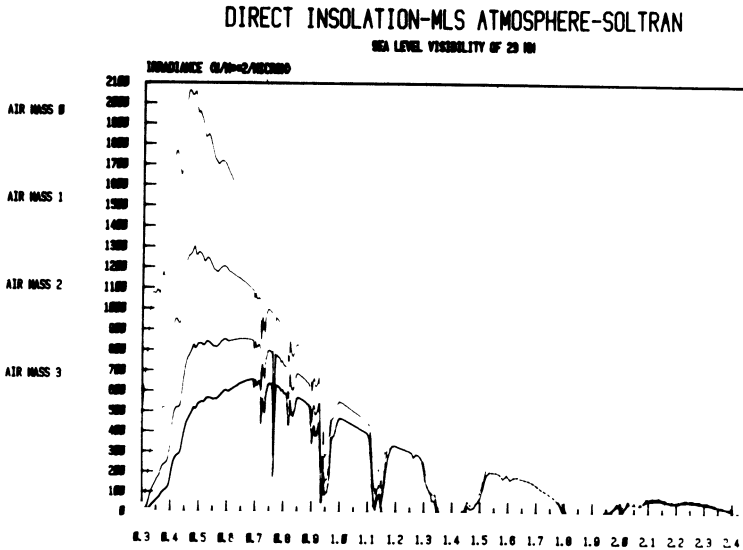


Figure 3. Spectrum of direct solar radiation on a clear day (Hulstrom, 1978).

total mass of air. Air Mass 3 is seen when the sun is even lower toward the horizon, and three thicknesses of atmosphere are in the path of the sunlight. It can be seen that both the total amount of radiation and also the spectral distribution change with air mass because of the selective absorption of various wavelengths of light by the earth's atmosphere. This means the efficiency of photovoltaic or photochemical systems can depend strongly upon the characteristics of the atmosphere at a site as well as upon the total amount of radiation available.

The stochastic nature of the effect of weather on insolation is important in understanding the performance of solar energy systems. There is no single measure of the randomness of the insolation at a site that suffices to describe the effects of such variations upon all possible solar energy systems. Instead, a simulation is necessary of the interactions between the solar energy system, its energy storage, the variations in insolation at a site, and the load to be supplied. Of particular importance to systems designed to supply large fractions of a load from solar energy (i.e., high solar fraction) is the occurrence of long periods of low insolation. Such occurrences are very site dependent. For example, the number of times per year that there is an occurrence of a one day duration of insolation loss is about equal all along the California Coast. However, occurrences of five days duration are ten times more likely

in the northern part of the state than in the south (Berdahl, 1977). Thus, assessments of solar systems intended to deliver large fractions of load require careful simulation of the insolation reliability at a site.

Wind Energy Resources

The resource used in wind energy conversion is the flux of kinetic energy of a moving air mass. This flux, which has the units of power, is given by

$$P = \frac{1}{2} \rho v^3 A$$

where

ρ = density of air

v = velocity

A = area intercepted by conversion device.

The factor of v^3 that appears in this equation is crucial to the nature of the technology used and the problems encountered in wind energy conversion. Because wind varies greatly in speed from time to time and from site to site, and because of this v^3 relationship, the power available from wind energy shows huge variations. These variations are even more important for wind energy than for solar energy systems. Indeed, because of this v^3 factor, it is usually not informative to describe a wind energy system as having a certain power rating. One must specify also the wind velocity at which that rating is given. Systems of the same power output can be different in size by factors of 2 or more if they are designed for sites with different average wind velocities (Justus, 1978).

The average annual wind power available at a site varies from less than 100W/M^2 to more than 500 W/M^2 . Thus, wind energy is comparable in intensity to the power density of sunlight but is subject to much larger variations. Wind power availability varies according to geography, climate, local terrain, and height above the ground. I will review each of these items briefly.

Maps have been developed of the large scale geographic variations of wind power in the U.S. and in other nations. These show, for example, that the mountainous areas of the United States are areas of high wind energy resource, as might be expected. They also show that the Great Plains of the U.S. are a significant wind energy resource. While these maps are interesting, they are of limited usefulness in estimating the energy actually available at a particular site (Wegley, 1978). This is because the small scale geography is of vital importance.

Wind energy availability also varies strongly with climate and local weather patterns. Variation with climate is predictable, at least on the average, but the short term variation is not subject to useful prediction.

Small ridges, valleys, hills, or other topographical features cause strong variations in wind energy. For example, when passing over a ridge, the wind speed may double from that at nearby sites on flat ground (Wegley, 1978). From the previous equation, we see that this increases the wind power by a factor of 8.

Wind speed also varies significantly with height above the ground. Wind velocity is zero at the surface and increases in a complex way with height, up to several hundred feet above the ground. The shape of this wind speed profile depends upon the characteristics of the surface and surrounding terrain. This profile is important, not just because it affects the amount of wind energy available, but because it puts great strains on wind devices. In the usual design of wind turbine with a horizontal axis of rotation, blades pass on each rotation from a region of high wind speed to a region of low wind speed and back again. This exerts great dynamic forces on the blade which must be designed against.

Just as wind energy power varies greatly in space from site to site, it also varies greatly in time at a fixed site. The seasonal variation is often quite large. For example, the average wind power available by month can vary by factors of 3 or more (Marsh, 1979a). It is usually, but not always, the case that wind energy is higher in winter than in summer.

The hourly variation of the wind during the day is also important. There is a strong random variation that cannot be predicted accurately. However, in some sites, there is a regular pattern in the daily wind patterns, for example, in certain ocean shore and mountain regimes. Not so important for estimating the energy output of the device, but crucial for its design, are the faster than hourly variations in wind speed. Wind gusts can be both fast and severe and are a challenge to the designer of a wind machine. Quite often, data on wind gusts at a site is inadequate, and very conservative design approaches must be taken.

Biomass Resources

The rate of capture and conversion of solar energy by natural photosynthesis is estimated to be about ten times the present use of energy by man (Boardman, 1977). We often speak of this as a biomass resource. However, it is not an inexhaustable resource in the same sense as solar energy and wind energy. Biomass resources are renewable only if they are carefully managed. The need for their management to ensure future productivity will restrict our use of this resource.

Table 1. World Annual Photosynthetic Primary Productivity

	Dry Organic Matter (tonnes)	Biomass Energy Content (Joules)	Incident Energy Content (Joules)
Land	$10-14 \times 10^{10}$	$1.6-2.2 \times 10^{21}$	0.6×10^{24}
Oceans	$7-8 \times 10^{10}$	$1.1-1.3 \times 10^{21}$	1.4×10^{24}
Total	$17-22 \times 10^{10}$	$2.7-3.5 \times 10^{21}$	2×10^{24}

Table 1 gives one estimate of the world annual photosynthetic production of biomass. For comparison, world energy use outside Communist areas will be about 4.5×10^{20} Joules in 1985. It can be seen that although the oceans have a larger area than the land, they produce much less biomass. Indeed, the biomass production on the earth's surface is concentrated in a relatively small fraction of its area. The measure of total photosynthetic activity is usually called primary productivity by ecologists and has been estimated for a number of different regimes and ecosystems (Ehrlich, 1978). Primary productivity is very low, almost zero, in the open ocean, in the desert, and in Arctic regions. It is extremely high in tropical forests and in estuaries and coastal areas. It is not well understood how much of this total primary productivity we might harvest for energy without adversely impacting the operation of the ecosystem. But it is clear that careful policies for management of these resources will be necessary if we wish to use them for production of energy as well as for their traditional roles in production of food and fiber.

Collection and Conversion of Radiation

As a background to our discussion in the next lecture of various solar-thermal conversion systems, I review here the physical processes involved in the collection and conversion of solar energy. Most of this discussion will be directed towards thermal collectors, though some of the principles also apply to photovoltaic or photochemical systems. We begin by looking at the processes that occur when incident sunlight falls on a surface (Figure 4). We would like to collect and convert to useful form as much of this incident energy as possible. Thus, we would like to minimize each of the processes of loss of energy shown in Figure 4. First, some of the sunlight will be reflected and not absorbed. To control this loss mechanism, we coat the surface to give it a very high absorptance. Good surface coatings typically have absorptance of .9 or higher. However, because the surface has a finite temperature, it will lose energy

by black body radiation. The higher the temperature of the surface, the higher the rate of loss by this mechanism. We control such losses from the surface by controlling the emittance of the surface. Our objective is to achieve a very low emittance for black body radiation while still maintaining a high absorptance for the incident sunlight. Energy will also leave the surface by convection. The ways to avoid this include evacuating the region in front of the surface or providing barriers that restrict natural thermal convection. Finally, energy is also lost out the back and sides of the collector by heat conduction. This loss is easy to control in a good design by proper insulation.

There has been significant progress in the last few years in developing surfaces that meet our dual requirements of high absorptance and low emittance. That such a surface is possible is due to the different spectral distributions of sunlight and of black body radiation from a collector at normal operating temperature. Almost all of the energy from the sun passing through an air mass of one is at wavelengths shorter than 1.5 microns. For collectors at temperatures up to 700°C or so, almost all black body radiation emitted is at wavelengths longer than 1.5 microns. Thus, the perfect surface for a solar energy collector would have absorptance of one for short wavelengths (below 1.5 microns) and zero absorptance (and thus zero emittance) at wave lengths longer than 1.5 microns. A number of real surfaces approximate this behavior, though none do so perfectly. The most common material now used for such a selective surface is called black chrome. This is a specially treated,

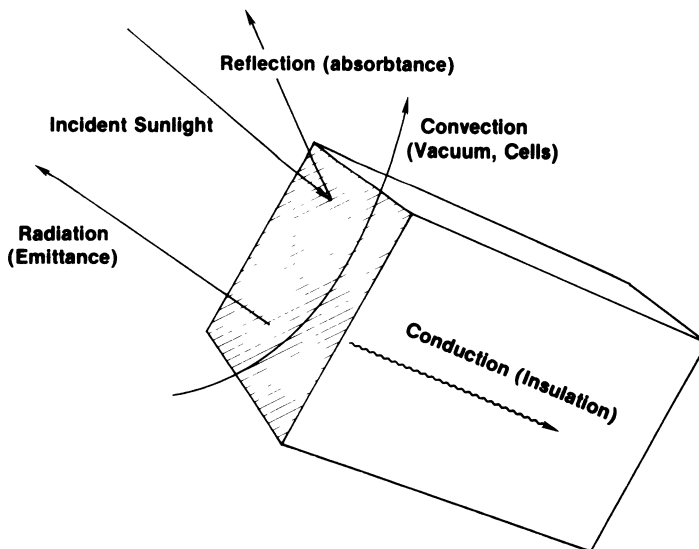


Figure 4. Processes of energy loss at the surface of a solar energy collector and (in parentheses) means for the reduction of losses.

do so perfectly. The most common material now used for such a selective surface is called black chrome. This is a specially treated, electrodeposited chrome oxide material. It has an absorptance for solar energy of .94 to .96, and an emissivity at a temperature of 300°C of .05 to .1. Thus, it is highly selective. This material is now used frequently in commercial solar energy collectors. A number of such materials are available which have good properties of absorptance and emittance at low to moderate operating temperatures. However, there is still a need for development of selective surfaces that operate reliably and for long periods of time at high temperatures. There is research now underway on developing such surfaces, and a number of promising new materials have been identified and are undergoing evaluation (Call, 1979).

Two basically different approaches have been suggested for control of the convective losses of energy from a collector's surface. The approach considered first to be most promising was inclusion in the collector of baffles to control the convective flow of air and thus reduce the rate of heat loss. Typical of such designs is a honeycomb of a transparent plastic placed in front of the collector's surface (Kreith, 1978). However, such designs have shown various undesirable properties, and this approach does not now seem promising. A more sophisticated way to control convection is by evacuating the region around the collector. This approach has been gaining popularity over the past few years. A number of evacuated tube collectors are marketed now. These collectors show significantly reduced rates of thermal loss, especially at high temperatures. Their costs are still high, but this is sometimes compensated by their better efficiency in high temperature applications.

The amount of solar energy incident upon the absorbing surface can also be altered by system design. We can concentrate the incident energy on the surface and greatly increase the ratio of energy input to the thermal losses by the modes discussed above. Thus, concentration of sunlight can lead to significantly higher collection efficiencies, especially for collection at high temperatures.

When one thinks of concentrating sunlight, what usually comes to mind is a lens or a mirror constituting an optical system which projects an image of the sun upon the collecting surface. However, not all concentrating systems are of this type. Indeed, the most efficient concentrating systems are not image-forming at all. Instead, these systems are designed simply to bring all of the solar flux incident upon an aperture area onto a much smaller absorber area. The concentration ratio is then simply described as the ratio of these two areas. There is a theoretical limit to the ideal concentrating collector (Welford, 1978). For full, three-dimensional geometries, the concentration ratio cannot exceed $1/\sin^2\theta$ where θ is the acceptance angle of the concentrator. For two dimensional

concentrators which concentrate sunlight onto a line collector, the maximum concentration ratio is $1/\sin\theta$. The values of these ratios when θ is the angle subtended by the sun as seen from the earth are 52,000 for three dimensional concentrators and 230 for two dimensional concentrators. The ideal concentrator with this ratio would have a uniform acceptance of sunlight across the disc of the sun and have zero acceptance elsewhere. Such concentrators have been designed. They consist of compound parabolic reflecting surfaces. This geometry is desirable for certain applications, but not for all. The geometry is interesting because it represents the ideal performance which other geometries approximate. In many cases, practical considerations of design, assembly, and cost will dictate that a geometry other than the optimum be used.

A great number of different designs of concentrators have been proposed, constructed, and used. The simple lens concentrator corresponding to the magnifying glass is seldom of practical interest. However, lenses based upon the Fresnel principle are sometimes used for thermal collectors or for photovoltaic arrays. The concentrator design now most commonly used is the parabolic trough collector which focuses the sun's image into a line. These range from fairly low precision collectors of moderate concentrating power to some very high efficiency trough collectors with precise reflecting surfaces that can produce quite high temperatures. Compound parabolic concentrators have also been built and operated for both thermal and photovoltaic conversion systems. For high temperatures, it is generally considered that three dimensional concentration is necessary. Here the traditional design is that of a paraboloidal dish. However, this design has the disadvantage that the entire reflecting surface must move to track the sun. This limits size of each individual concentrator, and in turn requires that systems of large energy output must have many such concentrators.

The concentrating collector design that now seems to offer the best potential for advances in efficiency and economics is the heliostat field with a central receiver. This is a type of Fresnel reflector. The concentrating system consists of a large number of individually directed flat or nearly flat reflective surfaces called heliostats. They are aimed so as to create a stationary image of the sun at a central receiving point. Thus, they use light as the medium of transmission of energy from the field to the central point of energy conversion. This seems to be both more efficient and less costly than designs in which the heat is collected at points throughout the field and piped via a hot fluid or other means to a central conversion plant. The heliostat most often is thought of as a component of a large central station solar thermal plant for production of electricity. However, it is also quite amenable to application for small scale thermal or electrical processes.

A major challenge for solar energy technology is the development of efficient and economical concentrating systems. In this effort, the heliostat now appears the best contender. Parabolic troughs now cost about \$200-\$300 per square meter. By 1995, I think that they might be reduced to a cost of \$150-\$200 per square meter, but I consider it unlikely they will become less expensive than that. Paraboloidal dishes are even more expensive now, about \$1000 per square meter, and might come down to about \$200 per square meter; but again, I think further cost reductions of this design are unlikely. The heliostat now costs about \$250 per square meter, about the same as parabolic troughs. But, I think this design has greater potential for cost reduction. Studies recently completed for SERI suggest that heliostats can be mass produced for about \$90 per square meter by about 1995 (Doane, 1979). Because heliostat based systems also have efficiency advantages over trough or bowl systems, this gives them a very strong economic advantage over those designs.

I had planned at this point in the lecture to review the theoretical limits to the efficiency of conversion of solar energy. However, this topic has been covered quite adequately by Henry Ehrenreich in his lectures on photovoltaic conversion, and only a few brief remarks are necessary here. There is a theoretical limit given by thermodynamics for any device that tries to convert a beam of solar energy into another energy form. However, these limits are not usually of practical importance. In thermoconversion, a Carnot limit applies to any heat engine we wish to drive from our collector. Thus, in practice, the conversion efficiency is limited by the temperature of the collector, and collector materials usually determine a maximum practical operating range. In photoconversion, quite different limits apply. Here, the size of the band gap in a semiconductor (or the excitation energy in molecules) and the reversible nature of quantum processes determines the basic parameters that limit the efficiency of conversion. For a review of these limits to photoconversion, see Hall (1979) or Porter (1976).

THERMAL CONVERSION AND USE OF SOLAR ENERGY

In this lecture, I will review technologies for utilization of solar energy in which the initial conversion step is collection of the insolation as heat on a surface or in an absorbing substance. This will include technologies being developed for thermal conversion to electricity and for the direct utilization of heat in industrial processes and in buildings. I will not review efforts, still in the preliminary stages, toward development of technology for conversion of thermal energy to chemical forms.

Thermal Conversion to Electricity

The development of technologies for the collection of solar energy as heat and its conversion to electricity has been a major part of the solar energy effort in the U.S. over the past seven years. I cannot review here all of the activities that have taken place and all of the technologies now under development. I will, however, review briefly a variety of system designs now under consideration for small scale solar electric plants. I also will describe briefly the project which dominated the U.S. effort in this area over the past two years, the design and construction of a ten megawatt solar thermal pilot plant in California. Finally, I will discuss the newest element of the solar thermal program in the U.S., the effort to develop technologies for the solar repowering of existing power plants in the southwestern states.

SERI has recently completed an analysis of the system designs that could be used for fairly small (1-10 megawatt) solar thermal power plants (Thornton, 1979). Such sizes might be appropriate for community, shopping center, or industrial facilities. The different designs indicated in Table 2 are distinguished by choices among the options available for the design of concentrator, the process for conversion of thermal to electrical energy, the form of transport of energy, and medium of energy storage.

Seven different options for the concentrator were considered and are listed in Table 2. First is the point focus central receiver design which utilizes the heliostat concentrator described in the last lecture. In this design, a large number of independently steered heliostats concentrate light upon a single central receiving point. Thus, this is a three dimensional concentrating system with a very high concentration ratio and with the desirable characteristic that all light energy is received at one place on the site. The equivalent two dimensional design is the line focus central receiver. In this design, the heliostats track in only one dimension and direct the light from the sun to a long line focus. Thus, the receiver must run across one length of the field of collecting heliostats. Concentration ratios here will be lower than in the point focus central receiver design. Next is the point focus distributed receiver. Here the concentration is performed by independently steered paraboloidal dishes which are arrayed across the field. The sunlight is collected at individual points at the focus of each dish. Thus the term "distributed receiver" refers to the fact that the solar energy is received and converted to heat at many individual points throughout the collector field. The fixed mirror distributed focus system is a two dimensional concentrator in which the mirrors remain stationary and the absorbing receiver must move to follow the moving focus of the sunlight. The next concentrator is the line focus distributed receiver tracking collector which uses a parabolic trough to concentrate sunlight to a line. Here the heat is received in a long line at the focus of each of many parabolic troughs. Thus,

Table 2. System Options for Solar Thermal Power Plants of 1-10 MW_e Output

Concentrator Options	System Options											
	Conversion					Transport				Storage		
	Cent-Rankine	Cent-Brayton	Dist-Rankine	Dist-Brayton	Dist-Stirling	Electrical	Water	Salt	Oil	Electrical	Thermal	
											Oil	Water
Point Focus Central Receiver	●							●				●
Point Focus Central Receiver		●								●		
Line Focus Central Receiver	●							●				●
Point Focus Distributed Receiver	●							●				●
Point Focus Distributed Receiver				●		●				●		
Point Focus Distributed Receiver					●	●				●		
Fixed Mirror Distributed Focus	●							●				●
Line Focus Distributed Receiver-Tracking Collector	●								●		●	
Line Focus Distributed Receiver-Tracking Receiver	●								●		●	
Low Concentration Non-Tracking	●								●		●	
Shallow Solar Ponds			●			●	●					●

again it is a distributed receiver. As an option to such a design, the receiver might move and the mirrors remain stationary. This is the next option listed. Finally, we also considered two options without concentration; that is, the concentration ratio is one. First is a simple flat plate system and second is a shallow solar pond in which the light absorption is in a large body of water in which thermal losses are controlled by some means. It can be seen that these options span a wide range of concentration ratios and of complexities.

Each of the above concentrator options can be utilized with a number of different conversion technologies. We selected for each concentrator option one or two conversion techniques that seem to provide an appropriate match to the characteristics of the concentrator and its receiver. Thus, for example, with the point focus central receiver option, we considered both a Rankine cycle and a Brayton cycle. For the other concentrator options, we considered versions of the Rankine and Brayton cycles and also considered, in one case, a Stirling cycle.

The choice of concentrator and conversion options dictates the requirements for the energy transport system used in the facility. For the various designs considered in the study, we examined transport of energy by electrical transmission and by transport of heat in the form of hot water, steam, molten salt, or hot oil.

Finally, we selected appropriate energy storage options to complete each system design. We considered storage of energy in electrical form and thermal energy storage in oil, salt, and water.

Let us now look at how the system options are combined into complete systems in the two cases of the central receiver concentrator design. The first is a Rankine cycle in which heat is collected at a central receiver in a hot molten salt. The molten salt leaves the receiver at 590°C and is brought either to thermal storage or through a sequence of heat exchangers to produce superheated steam. The steam then drives a turbine-generator set of standard configuration. Energy storage in this system is in the form of molten salt in a reservoir. This form of storage has a number of advantages including the ability to drive the turbine from storage at the same steam temperature and pressure as when the system is operating directly from sunlight. Now consider the Brayton cycle that we might use with the same concentrator option. Here the heat is absorbed at the receiver and heats a compressed gas to high temperature. The gas expands through a turbine, is cooled, and then compressed, and sent back to the receiver. This is a closed cycle Brayton system. This system has some advantages of high efficiency but has the disadvantage that it does not readily lend itself to energy storage at the thermal end of the cycle. Thus, we store energy in this system in the form of electricity. A set of batteries with rectifier and power inverter are provided at the output of the generator. As I will discuss later in our lecture on wind energy, there are serious problems of economics of such dedicated electrical storage. A major advantage of the Rankine design over the Brayton design is its ability to use thermal storage rather than electrical storage.

The objective of the SERI analysis of these designs was to develop a relative ranking of their economics and desirability to users. That ranking resulted in the ordering shown in Table 2. We concluded that for the size range of 1 to 10 megawatts of electric output, the most economical systems would be based upon the heliostat and central receiver design. The system with the Rankine conversion cycle was slightly better than the Brayton cycle. The system designs at the bottom of the list fared very badly in our evaluation. Thus, at this time, I think it most likely that thermal electric power plants built in the next few decades will be of the central receiver type with various types of conversion cycles.

The largest single project in the United States solar thermal program over the past few years has been the design and construction of a pilot plant at Barstow, California, to prove the concept of central receiver conversion to electricity. This pilot plant was originally intended to prove concepts appropriate for large (100 megawatt or more) solar thermal facilities. However, this pilot plant now is seen also as a proving ground for technologies that might be used in much smaller sizes, such as the 1 to 10 megawatt range previously discussed. The present design calls for a pilot plant that will have an output of 10 megawatts of electricity at peak day output. It will have some storage, enough for about four hours of operation, but only at a reduced power output of 7 megawatts (Brumleve, 1977). This facility has been under design for several years, and construction is starting this fall. The present schedule calls for initial operation of the facility in late December 1981. The total project cost is estimated to be \$123M.

There are three major subsystems being developed for the Barstow facility. The collection and concentration system will utilize 1800 individual heliostats, each with about 40 square meters of reflector area. This will be by far the largest array of solar concentrators ever constructed. There is at present a competition between two companies, McDonald-Douglas and Martin-Marietta, for the design and production of these heliostats. One of the indirect benefits of the Barstow program has been the great impetus it has provided towards the development and evaluation of heliostats. These benefits may eventually exceed any we derive from the operation of the Barstow facility itself, especially if heliostats prove to be economical concentrators for other applications.

The receiver subsystem for the Barstow facility has been the subject of great controversy. Based upon what it considered valid commercialization requirements, the Department of Energy selected an external once-through steam boiler for the design of the central receiver. It was considered that this receiver would have much lower mass than the alternative cavity boilers being proposed and that, therefore, the cost of the receiver-tower combination would be significantly reduced (Brumleve, 1979). However, the selection of a once-through boiler is unusual, especially for a system with a heat flux as high as that seen in the Barstow receiver. It has been suggested that there may be problems of dynamic and static instabilities in the boiling process in this receiver. Extensive tests are underway to determine the validity of this concern. It is hoped that this design will prove adequate for the Barstow facility, even if it proves impossible to scale up this receiver design to the larger sizes once envisioned for commercial application of the Barstow type of design.

At the time of initiation of the Barstow project, the major market for solar thermal conversion to electricity was thought to

to be newly constructed stand-alone power plants. However, in the past few years, another possibility has been widely discussed and is the basis of a new direction in the solar thermal program. Many small (50-100 megawatts) oil and gas fired power plants were built in the southwest United States in the late 1950's. At the time of their construction, these plants had very low fuel costs because of the extremely low cost of oil and gas at that time. However, fuel costs have now escalated rapidly, and U.S. national policy requires a reduction in the use of oil and gas by electric utilities. Utility companies have been searching for a way to avoid the loss of their investments in these plants. One of the possibilities under examination is the conversion of these existing plants to operate from solar energy for enough hours of the year to reduce significantly their consumption of oil and gas. There is a high level of interest among utility companies in the southwest United States in this possibility.

The repowering of a power plant would occur this way. First, an appropriate plant has to be found. The appropriate plant must be in good working order, with a power output of 50-100 megawatts and with adequate land at the site or nearby for the construction of a field of heliostats and a tower and central receiver (Curto, 1978). The receiver is designed to provide steam of the same quality as that normally used by the facility when operating from oil or gas. After repowering whenever sunlight is available, the plant operates with steam from the central receiver. When adequate sunlight is not available, it operates from oil or gas. Thus, the value of the heliostats and central receiver is their fuel savings: they do not increase the total generating capacity available to the utility.

SERI was asked to analyze this repowering opportunity and determine whether or not it represented an important near-term market for heliostat-based solar thermal systems. Our analysis considered both the likely cost of heliostat-based systems (the cost of such systems is dominated by the cost of heliostats themselves) and also the value to the utility of such a system. This value is based upon the role of a repowered facility in the overall dispatch strategy of the utility. Thus, we calculated the value to the utility of a square meter of heliostat surface by estimating the fuel cost it would save. This value then can be compared to the likely costs of a square meter of heliostat to determine if this is an economically viable application.

Figure 5 shows the kind of results found in the draft report of this study (Doane, 1979). It is seen that during the early 1980's, the value to a utility of a heliostat exceeds the cost goal for production of heliostats. We now think this cost goal can be achieved. We conclude that for a period of time, these heliostats would be an economical investment for utility. However, this conclusion results from the highly non-optimum composition of the generating mix now owned by these utilities (they have far too much oil and gas fired

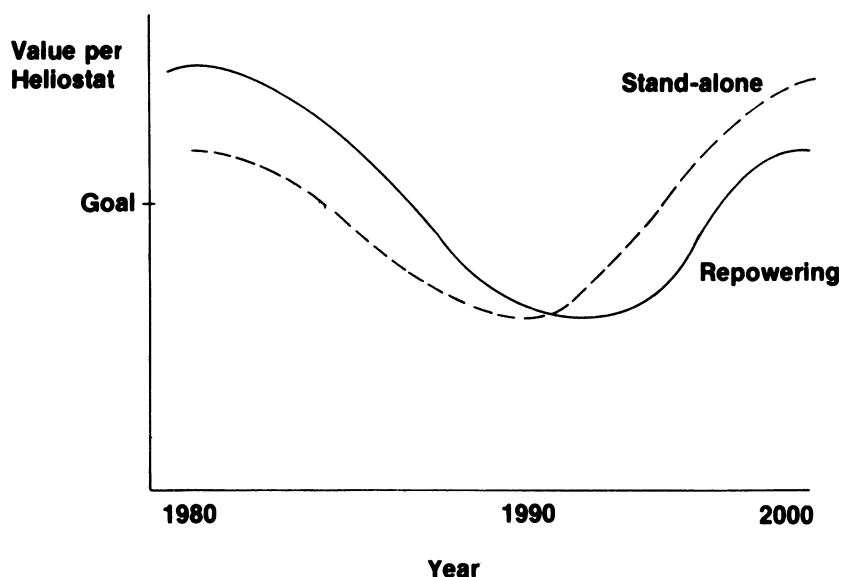


Figure 5. Value of a unit area of heliostat in a repowering application.

capacity). As these utilities add nuclear and coal base-load generating capacity during the next decade, such repowered facilities more and more often would be providing power in competition with the fuel costs of coal or uranium. The value of this fuel displacement is not adequate to justify the cost of the heliostat. Thus, we find that by the 1990's such heliostats will not return value equal to their cost. In the future, in the year 2000 and afterwards, as fuels continue to escalate in price, heliostats once again seem to have a value in excess of their cost. However, at this time, the greatest value for a heliostat is in a new stand-alone solar thermal plant, not in a repowered facility. Thus, we conclude that the repowering opportunity is not a long term significant market but is rather a temporary opportunity for demonstration of heliostat based technology. This opportunity should be used as part of the development of heliostat based technologies to be deployed in the year 2000 and afterwards.

Industrial Process Heat

In the last few years, the United States solar energy program has increasingly looked towards industrial process heat as a major

market for solar thermal technology. This would involve providing direct heat for a wide variety of industrial processes, from 50°C to 800°C from fields of concentrating collectors. It is thought these applications will generally require full backup capacity by a conventional energy system. Thus, the value of such systems to the industry that owns them is only the cost of the fuels they displace. It has been thought that the market for such systems may be very large because of the huge amounts of energy required in the United States for industrial processes. However, in market research we are conducting at SERI, we are finding that the market may not be as significant as was thought. The underlying problem seems to be that current industrial processes were not designed to be operated from solar energy. Rather, they are optimized for other energy forms, especially natural gas and oil. When one examines an industrial process in detail, it is usually found that there are very severe requirements upon the form and reliability of energy delivery for the process. It is very difficult for current solar thermal technology to meet these requirements. It may be necessary for new processes to be developed if solar energy is to contribute significantly to industrial energy requirements. These processes would be designed around utilization of solar and would be well matched to its characteristics.

The major effort in the solar industrial heat program thus far has been demonstration of systems in a number of different industries. For example, moderate temperature solar systems have been demonstrated on laundries and food processing plants. However, these demonstrations have not given us the indications of economics, performance, and reliability that we would have liked (Mills, 1978). Costs have generally been very high. The total installed cost of systems has run \$40 per square foot or higher in contrast to the cost goal of the program of about \$5 per square foot. Further, these demonstrations have not been adequately maintained and monitored to establish their operating efficiency. Data on reliability are also lacking. Thus, this demonstration program of industrial process heat has not given us the kind of information we desire from a new technology demonstration. At this time, I am not optimistic we will soon have proof of economic and reliable systems for providing solar process heat to industry. What is often considered a major market may not be of importance to the development of solar energy over the next few decades.

Energy Use in Buildings

The application of solar energy that most often comes to the mind of the general public is providing the energy requirements for residential and commercial buildings. The news constantly reports on this application, and a number of systems are now being marketed and installed. It is a major objective of energy policy in the United States to encourage the adoption of such systems. However, I

do not think the development of technology of these applications and the design of policies for their encouragement have taken adequate notice of the great changes now underway in the patterns of energy use in buildings.

The current stock of buildings was designed and constructed during periods of very low energy cost, and they are extremely wasteful of energy. The presently high level of energy use for heating of buildings can be significantly reduced by insulation, control of infiltration, and passive solar energy design. Other measures can significantly reduce the amount of energy required for cooling, hot water, and lighting (Dubin, 1978). These measures are generally both effective and economical. They have payback times as short as several months. The adoption of these energy conservation measurements will have some important consequences for the effectiveness of solar heating systems for buildings.

The total annual heating requirement for new buildings will be significantly reduced by design innovations now being developed and evaluated. A single family residence typical of the present U.S. building stock requires about 120 MBtu of space heat each year in a climate typical of the middle United States. In a building designed with measures that are now economically justifiable, this heating requirement can be cut to about 50MBtu per year. If further measures are taken to reduce the infiltration of air into the building, this heating load can be further reduced to about 30-40MBtu (Rosenfeld, 1979). At this point, the energy required for space heating has been reduced to the point that it is comparable with the energy required for the heating of domestic water. This has major implications for the sizing of solar energy systems for buildings: it now becomes just as important to design for the water heating load as it is to provide for space heat.

Table 3. Free Temperature Rise and
Neutral Point of Residential Buildings

	$\Delta T_F, ^\circ\text{C}$	$T_N, ^\circ\text{C}$
Standard Value	3.9	18
Low Energy Houses		
Arens & Carroll	9.4	11.7
Sinden	10.0	11.1
Kamney	11.1	10.0
Dumont, et al.	20.0	1.1
Robinson	16.7	*
*night set-back		

Just as the total annual space heating requirement is reduced by these design techniques, so are the dynamic characteristics of the heating load significantly altered. This has important consequences for the interaction of a solar space heating system with the thermal performance of the house. One representation of this can be seen in Table 3 (Rosenfeld, 1979). The second column shows values of the neutral temperature of houses of various designs: the temperature at which no heating is required. At and above this temperature the internal heat produced by occupants and appliances (especially refrigerators and freezers) is sufficient to maintain the interior temperature at a comfortable level. In houses of standard current construction, this neutral temperature is about 18°C. In energy conserving houses, this neutral temperature is reduced to 10°C or lower. This means that the houses no longer require heating during much of the fall and spring seasons: the parts of the year during which solar space heating systems are most effective. For these energy conserving houses, the heating requirement is concentrated in the middle months of the winter season: the part of the year during which solar energy is least available and solar systems least effective. Thus, the transition to highly energy conserving houses can have some adverse effects upon the match between solar space heating systems and the thermal performance of buildings. It is important that we design solar space heating systems appropriate to the types of construction likely in the coming decades, and not design systems (except for retrofit) for inefficient buildings that will no longer be built.

Passive Heating Systems

Over the past few years, there has been a major change in our thinking about how to include solar heating in the design of buildings. We have become much more aware of the opportunities for integration of the solar energy components with the building structure. In designs commonly referred to as passive systems, this integration is complete. The building itself serves as the solar collector and as the solar energy storage. This has economic advantages because the same components serve two roles: part of the building structure and part of the heating system. This passive design approach also has the advantage of leading the designer to a serious examination of the interaction of energy conservation measures with the performance of the solar heating system (Anderson, 1976).

I will review here five types of passive systems that are now receiving significant attention. However, this can only provide an introduction to the great variety of different designs now being developed, constructed, and evaluated (Mazria, 1979). The five types of systems I will describe are direct gain, thermal storage wall, solar greenhouse, roof pond, and convective loop. Most systems now being constructed fit into one of these categories.

The simplest of these designs to understand is the direct gain system. In a direct gain design, the windows of a house are increased in size on the south face of the building, and the design of the window and the overhang is such as to allow sunlight to enter directly into the living space during the winter months (but not during summer). Solar heat is absorbed on the interior walls and floors of the building and is stored in the mass of the building structure. There is advantage in having large masses exposed to this sunlight. Thus, one sees designs with large masonry walls or floors on the south side of the building. These often lend themselves to very attractive designs emphasizing natural building materials. The openness and airiness of direct gain designs is appealing. However, they are limited in their ability to provide heat to the building without unwanted large variations of room temperature between day and night.

In order to avoid the variations of room temperature seen in direct gain systems, many designers have adopted a thermal storage wall approach. In this design, there are large south-facing glass windows on the south side of the building just a few inches in front of a dark colored heavy wall. Sunlight is absorbed in this wall instead of being passed through to the living space. The wall is composed either of a heavy construction material, such as concrete, or of water in drums or other containers. The heat collected in this wall is then transmitted to the building space through convection and radiation from its interior surface. Because of its large mass, the wall can store heat during the day and release it at night. Such systems have been shown to provide half or more of the heating requirement of buildings in appropriate climate areas. Their disadvantage is that they require a large mass on the south side of the building, and they restrict the amount of free window space on that side. In this regard, they are aesthetically less appealing than direct gain systems, but are more efficient.

The solar greenhouse is a passive design approach of great architectural interest and attractiveness. This design is also compatible with retrofit of some existing buildings. In this design, a greenhouse is built on the south side of the building. The greenhouse is usually built with double or triple paned glass so the heat gained from the sun is not lost to the outside air. Thermal storage is provided by large masses in the greenhouse. This mass can be in the form of masonry or drums of water. Heat is brought into the building from this greenhouse by convection, which can be either natural convection or forced convection driven by fans. When properly designed, such a greenhouse can make significant contributions to the heating requirements of the house. It can also provide a pleasant additional living space for the homeowner. Many such systems have been constructed in New Mexico where sunny, cold winters make this

design especially effective. When the greenhouse is architecturally well integrated with the design of the structure, this can be a very appealing design.

The roof pond system is an approach to passive heating that also provides significant space cooling in some climates. The classic example of this approach is the house built by Harold Hay in southern California. In this design, the house has a flat roof composed of large water-filled bags or tanks. Panels of movable insulation ride in tracks above the water bags. This insulation is moved in accordance with strategies to provide heating in winter and cooling in summer. During the winter, the insulation is rolled back during the day, exposing the dark colored bags of water to the sunlight so the water is heated. During the night, the insulation is moved to cover the water bags and prevent loss of heat to the night sky. During these hours, conduction and radiation from the bags provide heat to the living space. This can be an effective heating system in mild climate zones. In summer months, the operating strategy of the movable insulation is reversed. During the night, the insulation is removed from the water bags so that black-body radiation from the bags to the cold night sky cools the water. During the day, the insulation covers the bags so that they are not warmed by the sun. During these hours, the cold water in the bags keeps the living space cool. In some climate areas, such as southern California, this system can provide almost all of the heating and cooling required by a building. Little or no backup energy is required. However, these systems cannot provide effective cooling in climates with humid summers.

The last type of passive heating system is the convective loop. This design uses natural convection to transport heat from an area of collection to a storage area. This is most commonly used for heating of domestic water in thermosyphon water heaters. This is the type of system now commonly used in Israel and commonly installed in Florida in the 1930's and 1940's. These are efficient and simple systems, but they require protection from freezing in most climates. Less common is the use of the convective loop for space heating, but a few houses of this design have been built. This design approach is somewhat cumbersome because the process of convective flow requires that the collectors be placed at a lower elevation than the storage. This can be done in a house if it is on a steeply sloping site. Then a collector area with large glass windows is built at the bottom level of the house. Air heated in this region rises through the building or through an intermediate area where a large thermal is provided (for example, a bed of rocks). These are effective systems but are limited to a few sites.

This quick tour through the types of passive designs can only begin to indicate the great variety of approaches possible. We should expect in coming years to see some of these concepts commonly applied to the design of most new buildings. The combination of

these passive design approaches and other energy conservation measures should reduce the heating energy requirements of new construction to levels far below those typical of our present building stock.

Active Heating Systems

Active heating systems are the type of solar energy systems the public hears of most often. There are now between 50,000 and 70,000 active heating systems in use in the United States, more than in any other nation. Most of these systems are used for heating swimming pools, but a good fraction, perhaps 20,000, are used for heating domestic water for residences. A smaller number, perhaps several thousand, are used for space heating of residences. We are not sure of the exact number of such systems because there is no central record kept of their construction. We have only the results of a few surveys to give us estimates of their numbers. Although there are many companies now marketing these systems and many consumers have chosen to buy them, their commercial success is not yet assured. Costs remain high and performance uncertain. While the numbers quoted above are impressive, they are small compared to the number of systems that will be necessary if active heating systems are to displace significant amounts of energy in a modern nation. That will require millions, rather than thousands, of units. The commercial prospects of active space heating systems are especially uncertain. It is yet unclear if such active space heating systems must compete with, or will be able to compete with, the passive systems described previously. At this time, it seems the passive systems may be a more economical and effective approach. After a passive system is included in the design of a house, the residual energy requirement for space heating may not be large enough or of appropriate characteristics to justify the addition of an active solar heating system.

The basis of most active heating systems is the flat plate collector (Kreider, 1977). In its most common design, this collector consists of two covers of tempered glass and an absorbing surface which often has a black chrome selective absorber coating. Water is pumped through tubes in this absorber panel to carry away the collected heat. Such collectors are used in both space heating and water heating applications, though the water heating applications are much more common. The heat from these collectors can also be used, though with great difficulty, to drive a space cooling unit. Solar driven air conditioners are expensive and relatively inefficient. We have not yet developed an adequate technology for active space cooling. The belief common a few years ago that space cooling would significantly enhance the economic viability of an active solar energy system is no longer generally accepted. Much more effort is now being directed toward the design of systems that provide only heat.

Table 4. Reports of Active Solar Energy
Collector and System Efficiencies
(National Solar Data Program)

Collector Efficiency Predicted (%)	Collector Efficiency Actual (%)	Storage Thermal Loss (%)	Solar System Efficiency (%)	Solar System COP*	Type of Installation
48.3	28.0	31.4	19.2	4.7	DHW
43.8	32.0	77.5	7.2	---	Space H & DHW
72.5	43.5	25.0	15.2	47.2	DHW, apartments
47.5	25.0	60.0	10.0	---	DHW, H, C
42.9	25.0	40.0	15.0	1.5	DHW, H, C

* COP total useful solar heat delivered to load/total electrical power for solar operations

There have been a large number of active heating systems installed in the U.S. under the auspices of the government funded demonstration program. Other systems have been installed by homeowners, some with the additional inducement of a tax credit that offsets part of the initial cost of the solar system. Such purchases support several hundred solar energy companies now active in the United States. However, many of these companies are small and are struggling to survive in a period of limited sales.

I would like to report that the systems now being installed are economical and efficient, but that is generally not the case. We have little data on the actual performance in the field of such systems, but the data we do have are discouraging. Table 4 provides data on the efficiencies of a number of systems monitored as part of the United States demonstration program (Ward, 1979). It is seen that the actual solar collector efficiency observed is much less than that predicted. In many cases, it is about half of the predicted level. Particularly disturbing are the large amounts of energy lost from storage. This is shown in the third column. With proper design, this loss should be very small. However, we see here that about half of the energy from the collectors is lost at this point. The effect of these successive losses on the overall system efficiency is shown in the fourth column. It is seen that efficiency is much lower than the 50-60% that would be estimated by the designer of the system. The last column indicates a coefficient of performance for the systems: the ratio of the useful solar heat delivered to the electrical power consumed for operation of the solar energy system (in pumps and fans). This ratio can be very high if the solar energy system is appropriately designed. However, in some cases, the electrical power consumption of the solar energy system is a significant fraction of its energy delivery. With the levels of performance actually seen in the field, active heating systems have very poor economics. The energy from the systems now being installed costs \$30-40MBtu. This is not competitive with the cost of electricity or gas in the United States. Thus, I am not as optimistic as many about the potential contribution of such systems in the next few years.

WIND ENERGY, PHOTOVOLTAIC, AND OCEAN THERMAL ENERGY CONVERSION

In this lecture I will review the technologies used for the conversion of wind energy to useful forms and review the techniques employed in assessing the value of wind energy systems. I will then give very abbreviated descriptions of activities in photovoltaic conversion and ocean thermal energy conversion.

Wind Energy Conversion

In this section, I discuss the technologies now available

and being developed for converting the energy resource of wind into useful power. This is a conversion of a flux of kinetic energy of wind into mechanical power and usually then into electrical power. I will begin with a review of the various designs available for this conversion and their efficiencies. These are shown in Figure 6. The efficiency of the conversion of the flux of kinetic energy of the wind to mechanical power output is shown for a variety of designs as a function of tip speed ratio (Wilson, 1974). The tip speed ratio is the ratio of velocity of the tip of the propeller blade to the speed of the wind blowing past the machine. Machines with higher tip speed ratios generally have higher efficiencies. Two designs are shown that operate at a very low tip speed ratio. These are important primarily because they provide high torque, not because they have good efficiency. The Savonius rotor is generally of little interest because of its very low efficiency. The American multi-blade design has been commonly used throughout the American midwest and west for water pumping. This design has advantages of moderate efficiency, very high torque, and excellent reliability. However, it is generally not considered an important candidate for production of electric power (Putnam, 1948).

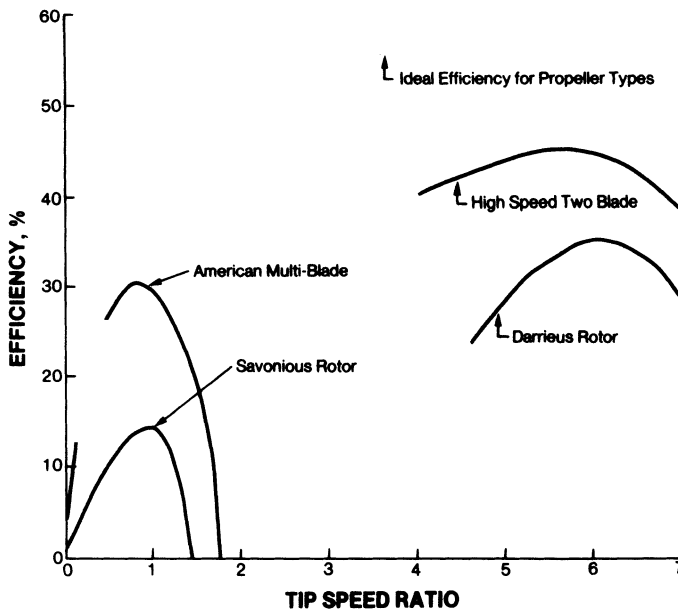


Figure 6. Efficiency of various designs of wind energy machines (Wilson, 1974).

In the conversion of wind energy to electric power, most attention is focused on the high speed, two blade design. This design has a horizontal axis of rotation. It operates with very high tip speed ratios and correspondingly good efficiencies. All very large wind machines including the recent demonstrations constructed by the Department of Energy are of this type. The Darrieus rotor is less common but has some promising characteristics. This design uses two or three blades rotating about a vertical axis and thus accepts wind from any direction. This helps make it immune to effects of wind gusts. The vertical axis of rotation also allows the generator to be mounted close to ground level, which can reduce the size and cost of the tower. Tests of this type of machine are now underway. Some proponents believe it will prove more advantageous than the horizontal axis two blade type.

There are also a number of advanced designs under development with funding from the Department of Energy. There are a great number of geometries that can be imagined for conversion of the kinetic energy of wind into useful power. Some of the geometries may have important advantages. However, the ultimate test is whether an economical machine can be built based upon the design. It is not yet clear that any of the advanced concepts will have a significant advantage over the horizontal axis two blade design or the Darrieus rotor design. In any case, the development of an advanced concept is not necessary for the commercial utilization of wind energy. The existing designs are adequate for our purposes.

It will be noted in Figure 6 that the ideal efficiency for propeller type machines approaches 60% at high tip speed ratios. It is simple to demonstrate, using only conservation of momentum and the Bernoulli equation, that the maximum efficiency possible for this type of machine is 59.3%. It is possible to design machines that approach this level of efficiency. Efficiency is not the major challenge facing the designer of a wind energy machine. The major challenge is the environment within which the machine must operate.

The operating environment of a wind machine is harsh and presents a number of hazards to the machine. One of these, mentioned earlier in the lecture on wind energy resource, is the differential in speed that exists between lower and higher elevations above ground. As the blades of a horizontal axis machine rotate, they pass from a regime of low wind speed close to the ground to a regime of much higher wind speed at the top of their rotation. This exerts strong dynamic forces on the blades, the rotor, and the tower. The machine must also withstand turbulence in the wind stream which deviates significantly from the smooth flow patterns we would desire. At times, the machine will be exposed to winds of extremely high velocity which it must somehow survive. It will also be threatened during its life by lightning, large hail stones, and ice. It must be designed to withstand all of these for a useful operating period

of twenty years or more. These requirements constitute severe challenges to the designer of a wind machine, and it is this, much more than efficiency, that concerns those now working in the development of wind energy machines. Indeed, I have heard wind energy machines described as being a material fatigue testing device which happens to provide power as a sideline.

Since I have referred a number of times to the conversion efficiency of wind machines, I should hasten to add that they are not devices of constant operating efficiency. Rather, a much more complicated specification of their performance is necessary (Golding, 1976). At a minimum, the following information must be given to define the operating properties of a wind machine. First, there is a cut-in velocity below which a machine has no power output. As the wind reaches this cut-in velocity, the machine will start to produce power. Power output will increase steadily as wind speed increases until it reaches the power rating of the generator. At this point, the blades of the wind machine are adjusted to maintain the power output constant (at the rating of the generator) if wind speed increases further. Thus, at high wind speeds, the efficiency of the machine decreases so as to keep power output constant. Finally, there is a wind cut-out velocity above which the machine cannot operate. At the cut-out velocity, the machine goes into a protective configuration (blades folded back in some way) which is intended to allow it to survive in extremely high winds. In this condition, its power output is zero. Thus, the specification of at least these parameters is necessary if one is to estimate the performance of a certain wind machine at a site: the cut-in velocity, the power rating, the velocity of wind at which the power rating is achieved, and the cut-out velocity (Justus, 1978).

Value of Wind Energy Conversion

Estimation of the value of the power from the wind energy system is a complex process that raises a number of interesting issues. I will review those issues in the context of utility connected machines. That is, I will not discuss the value of machines for remote applications where there is no connection to a utility grid. Such applications will be of little importance in contributing to the energy budget of a nation such as the United States where the grid development is already extensive. My discussion will hold both for cases in which the utility owns the machine and in which the consumer owns it and sells power back to the utility. There is no important difference between these cases for the points I will make here. It is required only that the power output of the wind machine be supplied to a utility connected application.

The value of a wind energy system derives from the total impact of the wind machine on the cost of operation of the utility. These costs include fixed charges, fuel cost, start-up cost, operation

and maintenance costs, and fuel inventory costs. Each of these items will be impacted by the addition of a wind machine to the utility grid. The impact upon the first two is most important. The impact upon the fixed charges of the utility is referred to as the capacity credit of the machine. The impact on fuel cost comes from the reduction of consumption of various fuels that is made possible by the availability of the machine to the utility in meeting its total demand for energy.

The capacity credit of wind machines has been a complex issue which is not well understood. First, let us define what constitutes capacity credit. A utility adds generating capacity to its system in order to maintain the system reliability, referred to as the loss of load probability (LOLP) at a required level (Kahn, 1979). As the demand on the utility from its consumers grows over time, the loss of load probability will increase unless the utility adds generating capacity to the system. The addition of a unit of generating capacity will reduce the loss of load probability faced by the utility, allowing it to serve a certain increase in power demand by its consumers. The capacity credit of the new unit is the increase in demand which can be met at a fixed loss of load probability. Because it is a probabilistic concept, there is a non-zero capacity credit for any unit added to the utility, no matter how unreliable it is. Thus, a wind machine will always have a capacity credit greater than zero.

Estimation of the capacity credit requires a simulation of the operation of the new unit on the utility grid. An hour-by-hour simulation of the operation of the utility over an entire year is usually necessary. Such simulations have been done for hypothetical wind energy machines operating on a number of utility grids in the United States (Marsh, 1979). From these simulations, several conclusions can be made. The capacity credit of wind machines is sometimes quite good, up to 40% of the rated power output of the wind unit. (The capacity credit of a conventional power plant is 60-70% of its rated output.) However, the capacity credit of a wind machine is often much lower than 40%. In some utilities, where there is a particularly poor match between the times of high wind speed and the times of peak demand on the utility, the capacity credit is near zero: values of a few percent may be found. These simulations also show that the first wind machine added to a utility grid has the highest capacity credit. Each subsequent machine will have a lower capacity credit. For most utilities, the capacity credit will become quite small, only a few percent, when wind machines constitute about 10% of the total generating capacity of the utility. Thus, utilities probably will not install wind machines constituting more than about 10% of their total installed generating capacity. This is an approximate upper limit upon the penetration into utility connected markets of wind machines.

The major value of a wind machine to a utility is the fuel savings it makes possible by its operation. In circumstances of correlation of high wind speeds with peak demand on the utility, these fuel savings can be significant. In most utilities, peak loads are met by inefficient units which burn oil, the highest cost fuel used by the utility. Thus, wind machines have high fuel credits in this type of utility application. In this regard, we should note the importance of utility energy storage to the value of wind machines. If the utility has adequate energy storage available to meet peak loads, then the wind machine has value only for displacing low cost fuels, such as coal or uranium. This is why wind machines will have poor value to utilities that have a high proportion of hydroelectric capacity on their grids.

This adverse effect of the availability of electrical storage on the economics of wind energy also applies to solar energy devices connected to utility grids. This represents one way in which the development of advanced storage technologies may hamper rather than aid the utilization of solar energy. This problem will occur whenever the storage is nondedicated, that is, can be recharged from any generating unit on the grid. In this case, the utility will choose to charge it from its lowest energy cost unit, probably a large coal burning plant or a nuclear reactor. If the storage is dedicated, that is, it can be charged only by the wind or solar facility, then it will increase the value of the wind or solar facility to the utility. However, nondedicated storage will almost always decrease the value of wind or solar units to the utility.

By examination of simulations of the operation of wind machines on utility grids, we can derive an estimate of the total value of the wind machine to the utility from its capacity credit, the present value of its fuel savings, and other benefits to the utility operation. There is great variance in this value. In advantageous circumstances, the value of the wind machine is as high as \$700 per rated kilowatt of output. In other circumstances, the value is near zero. It is also true that the first units installed by the utility have the highest value, and the value of each subsequent unit decreases rapidly as the amount of wind energy connected to the grid increases. It is hoped that the units now under development in the U.S. program can be produced in large quantities at a cost of \$700 per rated kilowatt. If this cost goal can be attained, then I expect that we will see these machines purchased and installed by utilities, at least up to the level of about 5% of their generating capacity. This would constitute a significant contribution to U.S. energy requirements. However, in this market, wind energy machines face stiff competition from load management, nondedicated electrical storage, and new technologies for small conversion units of low fuel cost, such as advanced coal burning plants.

Photovoltaic Conversion

I will provide only some brief comments on photovoltaic conversion because this topic is being covered so well in the lectures in this course given by Henry Ehrenreich. Indeed, I only include mention of photovoltaics because I would be uncomfortable giving a series of lectures on solar energy without including it, however briefly.

The current state-of-the-art in photovoltaic conversion is represented by the single-crystal silicon cell. Arrays built up from these cells are now sold commercially throughout the world for remote power applications. They cost about \$20-\$40 per watt of peak output, and about a megawatt of peak output is sold each year (Costello, 1978). This is a strong and viable commercial market which is growing rapidly. However, this current state-of-the-art has little relevance to the kind of technology needed if we are to have large energy contributions from photovoltaic conversion. The single-crystal silicon cell is constructed by a complicated, laborious, and expensive process. Much of the starting material is wasted in the process, and large amounts of labor and energy are consumed. This is what puts the price of these cells in the \$20-\$40 price range. As discussed by Ehrenreich in his lectures, if we are to see commercial applications of photovoltaics in the U.S., we will have to reduce the cost of arrays to about 20¢-40¢ per peak watt (Ehrenreich, 1979).

At this time, we have only vague ideas about the kind of technology that might produce photovoltaic cells at prices this low. It must be some sort of continuous, fast production system that makes efficient use of its starting material. It should have low labor and energy requirements in order to keep production costs at a minimum. With all of this, it must still produce a cell of high efficiency, since cells of very low efficiency cannot be economically used no matter how cheap they are. The most important activities in the photovoltaic program at this time are research projects working towards development of advanced cell types. We can be hopeful that within a few years, these concepts will come to fruition with designs for low cost, high efficiency cells.

In advance of the availability of that low cost technology, the Department of Energy is funding a program of application tests of photovoltaic devices. Through this program, we are gaining experience with the real world requirements for photovoltaic systems. This is an important step toward the realization of a commercial photovoltaic technology. However, we should not think that the construction of such application tests is any indication that we now have a commercially viable photovoltaic technology. The cost of these demonstrations is exceedingly high and is not justified by their power output. Rather, their value is the information

provided for guiding the photovoltaic research and development program.

During the years until we have available a low cost photovoltaic technology, the commercial photovoltaic industry will probably look to the developing nations as its major market. In nations where there is no electric power available in rural areas, photovoltaic systems can provide great benefits to the inhabitants. I expect to see a large program of installation of such systems in coming years, funded by bilateral and multilateral aid agreements. This market will probably keep photovoltaic industries viable during the years before the development of low cost technology will finally allow them to sell devices in utility-connected applications in developed nations.

Ocean Thermal Energy Conversion

This topic I will also cover briefly. This is not because it is discussed elsewhere in the course, but because I am personally somewhat pessimistic about the potential of this technology. I will review briefly the nature of the energy resource and the two generic types of technology under development: closed cycle and open cycle.

The ocean thermal energy resource is the warm water of the tropical oceans. Over about 20% of the ocean's surface, the waters average 25°C or warmer. This resource is located in a broad band extending on both sides of the equator. This is an energy resource because the deep waters at the same sites are much colder, typically 4-5°C. From this temperature difference, energy theoretically can be derived. It is the huge amount of heat in this resource that causes the great interest in its development. It also has the advantage that this resource is available day or night, summer or winter, and does not suffer the fluctuations typical of other solar energy or wind energy resources. Thus, it can provide reliable base load power. Unfortunately, the location of the resource is distant from most sites of significant electrical power demand. Thus, long distance transmission of the energy in electrical or chemical form may be necessary for significant use. A few islands, notably Puerto Rico and Hawaii, are located in areas of significant ocean thermal resource. Since these islands pay very high prices for the electricity that they generate from imported oil, they are at least potentially markets for ocean thermal energy conversion.

The type of conversion technology that is the target of most of the U.S. program is the simple closed cycle Rankine engine (DOE, 1978). This closed cycle engine would be operated between temperatures of the surface waters and the deep waters. However, because of the small temperature difference, only about 20°C, the Carnot efficiency is quite low. The overall efficiency of such an

engine would probably be about 2%. Operation of the engine requires water to be pumped from far under the surface, 600 feet or so, and also from the ocean surface around the plant. Significant energy will be required for operating these pumps. Thus, the net power output of the facility will be less than its gross power output. Indeed, until recently, we did not have demonstration that it is actually possible to operate an ocean thermal facility at a positive net power output. Within the last year, a small ocean thermal machine (called mini-OTEC) was operated off the coast of Hawaii and succeeded in demonstrating a positive net power output. This is particularly impressive because the net output was achieved on such a small machine. It is expected that the percentage of gross power appearing as net power will be much better in larger devices.

A number of serious design problems confront ocean thermal energy machines. These are all made difficult by the very low efficiency of the conversion engine. First, the devices must be very large and move massive amounts of water. Second, there must be highly efficient heat exchange between hot and cold waters and the working fluid of the engine. This means that heat exchanger surfaces must be kept quite clean for long periods of time in an ocean environment. This is not trivial. Third, the machine must survive for long periods of time in a harsh ocean environment where it is subject to storms, strong currents, and wave action. Finally, the energy produced must be transported to a site where it finally can be utilized. We do not yet know the most effective way to achieve this energy transport, though some solutions may be at hand.

As an alternative to the closed cycle design, there is some research underway on advanced concepts for ocean thermal conversion (Shelpunk, 1979). One of these is the open cycle engine. In this device, the working fluid is the sea water itself. Water vapor that evaporates (under partial vacuum) from warm ocean water passes through a large turbine to condense on the surface of colder water brought up from the depth. This design avoids the problem in the closed cycle of heat transfer between the ocean waters and the working fluid. However, it has its own problems. It requires a very large vacuum chamber and a turbine that operates efficiently with vapor at less than atmospheric pressure. The turbine in an open cycle ocean thermal plant must be sized even larger than the blades of a wind energy turbine. At this time, we must consider the open cycle concepts for ocean thermal conversion as being quite speculative.

Tests to be conducted by the Department of Energy during the next year on a floating test bed will establish some of the important design parameters for the closed cycle ocean thermal design. This will start to give us reliable engineering information that will allow careful assessment of the feasibility of this technology.

AGRICULTURE, BIOMASS CONVERSION, AND PHOTOCHEMISTRY

The primary process in production of biomass is photosynthesis. In this process, sunlight, carbon dioxide, and water are converted into energy-rich chemicals. Whether the reaction takes place in a bacterium or in a tree, the result is called biomass. For our purposes, we will distinguish between two types of biomass production. In the first, growth of the organism is assumed to have already been occurring, either as natural growth in the wild, or as part of agriculture. We then intend to divert some of this biomass (usually wastes or residues) to an energy product. In the second type of biomass production, we set out to cause plant growth that would not have otherwise occurred. This approach we will refer to as energy farming. In this case, new resources, especially land, water, and nutrients, are required.

Whether the biomass we have obtained is a residue from ongoing agriculture, or is obtained from energy farming, we have a number of options for converting the raw biomass into an energy product. Two basic categories of conversion processes exist: wet bioconversion and dry thermoconversion. The wet bioconversion processes include chemical extraction, anaerobic digestion, fermentation, and distillation. In extraction, chemical techniques are used to extract valuable hydrocarbons or other chemical forms from the plant material. An example of this is the isolation of rubber or various resins from plant stalks. In anaerobic digestion, the usual product is methane. In fermentation and distillation, the intermediate product is usually sugar with the final product usually ethanol.

Thermoconversion processes include gasification, pyrolysis, liquefaction, and combustion. Gasification can occur with air, the result being a low energy content gas, or with oxygen, the result being a medium energy content gas which can be used directly or converted to methanol or ammonia. In pyrolysis, the usual products are oils, gases, and charcoal. In liquefaction, the products are various mixtures of oils and gases. In combustion, the product is direct heat energy which might then be converted to electricity.

Table 5 tabulates by type biomass facilities in operation in the United States. This sample is taken from a recent review of biomass conversion (Klass, 1978). It should be noted that a great variety of conversion techniques (listed along the left edge) are being investigated, as are a wide variety of feedstocks (listed along the top). It should also be noted that even for each feedstock, it is not clear yet which conversion technique is best. Indeed, research on a number of conversion techniques is taking place for each possible feedstock.

The reason for the diversity of conversion approaches for each feedstock is our present uncertainty as to the most valuable form

Table 5. Examples of Biomass Pilot,
Demonstration, and Commercial Plants
in U.S.

	Municipal Solid Waste	Industrial Waste	Refuse Derived Fuel	Forest Residues, Wood, Waste Cellulose	Manures	Other
Separation	25	-	-	1	-	-
Combustion	22	1	5	8	-	3
Landfill	5	-	-	-	-	-
Anaerobic Digestion	5	1	1	-	14	3
Fermentation	1	-	-	1	-	2
Liquefaction	-	-	1	-	-	-
Pyrolysis	6	2	2	1	-	2
Partial Oxidation	6	1	5	-	-	1
Other	4	-	-	2	2	-

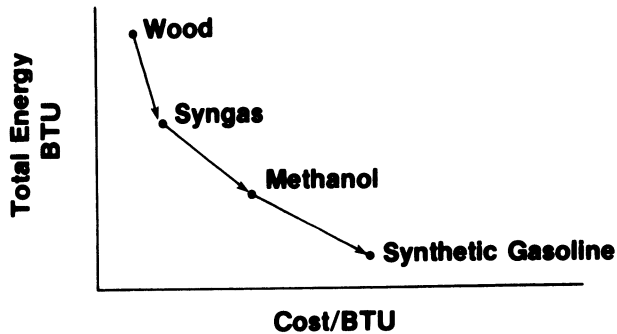


Figure 7. Sequence of steps in converting biomass to higher value fuels (Smith, 1979).

for biomass energy. Figure 7 shows the sequence of steps that may be taken in upgrading biomass to other energy forms (Smith, 1979). In this example, wood is first converted to a synthetic gas, which is then converted to methanol, which is then converted to synthetic gasoline. Each step in the process imposes a cost in equipment and operations. Further, each step in the process is less than 100% efficient. Thus, as we move along this sequence, the total energy contained in the fuel decreases and the cost per unit of energy increases. It is an open question as to which step along this conversion path has the best ratio of cost to value. It is generally true that the more processed forms (e.g., synthetic gasoline) have higher value in today's markets. However, it is costly to convert biomass into those forms. Biomass may have a greater value in future markets in its less processed forms, such as synthetic medium energy content gas.

Agriculture and Biomass Issues

The production of biomass for energy will impact agriculture in a number of ways. Most obviously, biomass production competes with agriculture for resources, especially land, water, and nutrients. However, in some circumstances, biomass production may also be complementary to agriculture and allow greater net benefit to be derived from agricultural production activities. We do not yet know to what

degree agriculture and biomass production will compete or will complement each other. However, it is clear that the development of biomass will be intimately linked to national agricultural policy. A number of important questions about this linkage come to mind (Flaim, 1979). To what extent may subsidies to agriculture (about \$5B in the United States in 1978) be redirected from limiting food production to stimulating production of energy crops? What will be the impacts of producing energy crops on the prices paid by consumers for food and fiber? What will be the consequences of a major crop failure if food and crop residues have been committed to energy production? Can crop residues be harvested for energy without depleting soils and ground water? These and other issues will certainly be debated in coming years. Research to clarify the nature of these issues is vital.

I will discuss here only one of these issues, the last question posed above about the use of crop residues. Much of the energy produced in the growth of a plant remains in the residues left in the field after the food part of the crop has been removed. The naive conclusion is that the residue is waste which is clearly available for any beneficial use such as energy production. However, such crop residues when left in the field play an important role in maintaining the quality of the soil and its ability to produce crops in future years. Thus, there is some constraint on our ability to collect crop residues for energy. Nutrient depletion and soil tilth are impacted because removing the crop residues can deprive the soil of needed potassium, nitrogen, and organic matter called tilth, which is required for good soil productivity. Water infiltration, evaporation, and soil productivity are all improved by the crop residue remaining on the ground. Finally, soil loss by water and wind erosion is reduced by the presence of crop residues on the ground.

After consideration of these factors, some analysts have concluded that very little, if any, crop residues can be converted to energy without adverse effects upon agricultural productivity. However, recent research suggests the conclusion need not be this negative. Experiments which have used good techniques for handling crop residues and for maintaining soil condition have shown that it is generally possible to take about half of the crop residues from the land without any significant adverse effects on future soil productivity (Flaim, 1979). These results, if true generally for the nation, indicate that a few percent of the nation's total energy requirements could be provided from proper use of crop residues. While this research was done on farms in the United States and is directly applicable only to U.S. agricultural practice, it is probably true that most developed nations can derive several percent of their energy requirements from crop residues.

Alcohol Fuels from Grain

A highly complex policy issue regarding the interaction of agriculture and biomass energy production is now being debated in the United States. This debate concerns the conversion of excess grain to alcohol for the operation of automobiles fueled by gasohol. Gasohol is a mixture of 90% gasoline and 10% ethanol. There is a special opportunity for production of gasohol in the U.S. because of our surplus production of grain. The conversion of this grain surplus to gasohol is being supported by farm interests in the U.S. They believe such production will help stabilize grain prices from the wild oscillations of the market.

Among the complex issues raised in the gasohol controversy are a number concerning grain exports from the U.S. Such exports provide the United States with an important flow of foreign currency. Funds gained from grain exports allow the United States to purchase large amounts of foreign commodities, including OPEC oil and other raw materials important to the U.S. economy. However, this grain is even more important to the nations that require it as a supplement to their own food production. The conversion of this food stuff into alcohol to drive American cars could become a major international issue if world-wide grain shortages develop in the future.

The economics of the fermentation process usually used for production of ethanol from grain are not very advantageous. About 2.5 gallons of ethanol can be produced from a bushel of corn. In metric units, this is about 37 liters of ethanol from 100 kilograms of corn. A byproduct known as distiller dried grain (DDG) is obtained and contains much of the biomass from the initial feedstock. Because of the low value of this byproduct, ethanol produced by this route is not competitive with the cost of gasoline in the United States at this time. However, it is possible that alternative processing techniques can be developed in which more valuable byproducts could be derived. For example, one corn processing technique would result in production of significant amounts of corn oil as well as the same amounts of ethanol as the normal fermentation approach (Hertzmark, 1979). The high value of the corn oil could significantly offset the cost of the ethanol.

Part of the debate about the gasohol production in the United States has been about the net energy or net liquid fuel balance of the program. As I noted above, about 2.5 gallons of ethanol are obtained from each bushel of corn. However, a number of analyses indicate that it generally requires more energy than this in gasoline and other petroleum products to produce that bushel of corn and convert it to ethanol. Thus, by these analyses, each gallon of gasohol produced actually imposes a net loss of liquid fuels and a net loss of energy to the United States. Some have suggested that this negative net fuel balance can be corrected if non-petroleum fuels (coal

or biomass) are used for the production and conversion of the corn. We might then have a net energy loss from the gasohol program, but a net gain in liquid fuels. Such an arrangement seems possible, but we have yet to formulate the public policy tools that will assure a net gain of liquid fuels from a gasohol program.

Given the many uncertainties, it is difficult to estimate the actual impact of a gasohol program on oil imports into the United States. One must consider the loss of foreign revenue by a decrease in grain exports, the potential value of exports of byproducts (such as a DDG) from gasohol production, and the net liquid fuels balance of the gasohol production. The debate on this issue is far from settled. However, strong political interests assure that the decision whether or not to proceed with a large gasohol program will be made on many grounds other than just the efficient production and use of biomass energy.

Digestion of Solid Wastes

Unlike the complex case of agricultural residues discussed above, there seems to be nothing but benefit to be derived from increased utilization of municipal solid wastes (garbage to most of us). The severe problems of properly disposing of these wastes provide a great inducement to finding better ways to process these materials and derive any possible benefit from the resources they contain. Much of the value of these resources is in metals and other materials. However, municipal solid wastes also represent a significant energy resource. A number of projects are now underway to demonstrate the conversion of these wastes to useful energy forms (Anderson, 1977). One of the approaches being studied is anaerobic digestion of solid wastes to produce methane, a process already widely used in Europe.

In this process, the municipal solid wastes from a community must be collected and brought to a large conversion facility. There the raw waste is finely shredded and is air-classified to separate light and heavy components. The heavy components contain valuable metals and other materials. The light fraction is largely various forms of biomass and plastics, all of it energy rich materials (Goddard, 1975). In the anaerobic digestion approach, this material, after being blended and scrubbed, is fed into a large digestion tank. Here microorganisms slowly digest the waste and produce a gas consisting primarily of carbon dioxide and methane. The methane can be separated, yielding high quality fuel gas.

If all of the municipal solid wastes from the major urban communities in the United States were converted by this process, we could produce several percent of the total U.S. consumption of natural gas. However, the value of the energy from this process will be only a fraction of the cost of the operation. Most of that

cost will have to be offset by the value of the metals and other materials derived as part of the conversion.

Anaerobic digestion is also suitable for conversion of manures from feed lots and other farm operations. Many anaerobic digesters are now being used in China, India, and other developing nations. The Department of Energy has been supporting the development and demonstration of manure anaerobic digesters for use in feed lots in the United States. These can have a significant benefit of reducing the sewer water pollution normally caused by such operations.

Gasification of Wood Wastes

Much of the biomass in a tree harvested for lumber is unused, either left in the woods or lost at the sawmill as scrap or sawdust. Some of this waste material is burned by the lumber and paper industries for production of heat and electricity for their processes. However, because of the size and ready availability of this resource, there is significant interest in other ways of using wood wastes. One of the approaches now being developed and tested by a number of firms is air gasification. In this process, chipped wood wastes are combined with a minimal quantity of air and steam to yield a pyrolysis char and a low energy content gas. The gases produced are primarily carbon monoxide, hydrogen, and nitrogen. It should be noted that biomass generally is easier to gasify than is coal. This is because of the better ratio of hydrogen to carbon in the biomass feedstock. There exists a great variety of designs for biomass gasifiers, each with certain advantages (Reed, 1979).

The crucial parameter determining the mix of products from biomass gasification is the amount of oxygen present in the gasifier. The useful parameter is the equivalence ratio: the ratio of oxygen present to the amount of oxygen that would be needed to convert all of the biomass to carbon dioxide and water. At very low equivalence ratios, the primary products of gasification at equilibrium are hydrogen and carbon monoxide, with small amounts of carbon dioxide and water. As the equivalence ratio is increased, the percentage of hydrogen in the product decreases, and the amount of carbon monoxide at first increases. At an equivalence ratio of about 20%, the carbon monoxide production is at a maximum, and the percentage of water and carbon dioxide reaches a minimum. At higher equivalence ratios, the amounts of hydrogen and carbon monoxide decrease, and the amounts of carbon dioxide and water increase. Thus, most gasifiers are operated at fairly low equivalence ratios, but the exact amount of oxygen depends upon the desired product mix.

Just as important as the equilibrium composition indicated by the oxygen content in the gasifier, are the dynamic chemical and physical processes that occur in biomass gasification. There are

many different designs of gasifiers involving updrafts or downdrafts or various types of mixing. All of these designs are intended to achieve some desirable mechanical and chemical interaction of the biomass with hot gases which leads to a maximum production of the desired components and a minimum of the undesirable components, especially tars and solid materials.

A number of large gasifiers are now being used in the forestry industries in the United States. These produce a good quality, low energy content gas which is used for on-site energy requirements. Many other types and sizes of gasifiers have been operated. One of the more interesting is the small gasifier that mounts on the back of a car and provides a gas for operation of the engine. Such small automobile gasifiers were used in Europe during World War II, and they now enjoy a new popularity.

Rapid Pyrolysis of Biomass to Gasoline

I now discuss one example of the many advanced techniques for conversion of biomass that are now being developed. These advanced processes offer potential advantages of lower cost, higher efficiency, or more desirable products, than given by the traditional conversion techniques. Researchers in China Lake, California, have been exploring an interesting and unusual process of very rapid pyrolysis of biomass for production of gasoline or gasoline-like compounds (Diebold, 1978). The process involves the very rapid heating of finely divided biomass, resulting in high yield of a synthetic gas. Subsequent treatment of this gas produces good yields of olefins which are valuable precursors to gasoline. Bench scale experiments of this process have been underway. One of the promising variants of this process would use concentrated solar radiation to provide the required rapid heating of the biomass. This heat input by solar radiation could increase the net production of liquids from the biomass feedstock.

The first step in this process is preparation of the biomass by grinding it to a fine, dry powder. It is then mixed with steam and carbon dioxide and blown through a high temperature furnace, maintained at about 800°C. Rapid pyrolysis occurs. The gases from this step are then compressed to about 50 atm pressure and enter a processor for polymerization to gasoline. The yield of liquid fuels from this process is only a fraction of the feedstock in the experiments conducted thus far. However, process improvements are hoped for.

From sources of biomass in agriculture, forestry, and municipal wastes, and with the conversion techniques I have discussed above, most developed nations could derive about 10% of their total energy requirements. However, major policy issues will arise to restrict the development of this biomass resource and affect the way

in which it is used. In developing nations, much higher percentages of energy requirements could be derived from biomass, but there will arise issues of the renewable nature of biomass production. The future may see severe policy conflicts in these nations between energy production and the protection of their natural ecosystems.

Hydrocarbon species

As an alternative to the kind of biomass production and conversion techniques described above, some researchers are investigating plant species that directly produce valuable hydrocarbons (Benedict, 1979). It has been long known that many plants produce hydrocarbons as part of their natural growth. The most familiar of these is the rubber plant. However, several other species have been grown in the United States for production of hydrocarbons. A brief effort was made during World War II to grow guayule in the southwestern United States as a substitute for the natural rubber supplies unavailable during that period. However, there has been little commercial development of hydrocarbon species since that time.

A large number of hydrocarbon-producing species have now been identified. These include guayule, rabbit bush, goldenrod, creosote bush, sassafras, euphorbia, milkweed, and jojoba. These plants contain a number of potentially valuable hydrocarbons, including waxes, fatty acids, resins, glycerol, tanins, and hydrocarbon polymers. Techniques have been developed for assaying the content of these species and measuring the presence of these useful hydrocarbons.

At present, production and demonstration plantings have been made only of jojoba and guayule. Jojoba serves as a whale oil substitute and guayule as a substitute for natural rubber. Methods for studying the hydrocarbon composition of these plants are being improved. Researchers are screening several hundred plant species to find those that show high rates of production of desirable hydrocarbons. Some of these researchers now estimate that annual production of hydrocarbons by such species can be as high as eight barrels of oil per acre per year (about 1 metric ton of oil per acre). Some argue that this production rate can be maintained only on good quality soils with high water inputs (i.e., in direct competition with agriculture). However, other researchers are optimistic that this production rate can be obtained in poor quality desert soils without additional irrigation. If true, this would mean that the deserts of the southwest United States could become a significant source of hydrocarbons. However, it should be noted that the hydrocarbons derived from such plants will probably be more valuable as petrochemical substitutes than as fuels. Thus, their impact upon our energy situation might be small.

Ocean Kelp Farming

One way to avoid a conflict between agriculture and biomass energy production is to escape to the open ocean. As mentioned in the first lecture, the natural productivity of ecosystems in the open ocean is very low. There is adequate water and sunlight, but the nutrients crucial for plant growth are lacking in surface waters. It has been suggested that we could bring up to the surface nutrients from the deep ocean waters, thus making areas of high biomass productivity. If this proves feasible, then massive biomass energy programs could be undertaken without adverse impact upon land based agriculture and natural ecosystems. Experiments on such an approach are now underway off the coast of California (Bryce, 1978).

The biomass being produced in these experiments is a seaweed, giant brown kelp. This seaweed naturally occurs in shallow waters along the California coast and has been harvested in the past as a source of iodine. It is a very fast growing seaweed when conditions are right. It requires support for its roots, good sunlight, and adequate nutrients. All but the last can easily be provided at the surface in the open ocean, but special means will be necessary to bring nutrients to the seaweed.

The conversion process being considered for the kelp is anaerobic digestion. This process would yield methane and carbon dioxide. The approach is considered by the gas industry in the United States as being potentially a major renewable source of natural gas.

A test farm based upon this concept is now operating. The mechanical structure of the test farm includes a long pipe and pump which brings up nutrient rich waters from 2,000 feet below the surface, and a series of struts and ropes to which the kelp fasten to support their growth. Divers isolate small kelp plants from their natural habitat in shallow waters and transplant them to the ropes on the test farm structure. The nutrient rich water from the deep ocean is released from a structure of pipe around the kelp, thus increasing significantly their rate of growth. Results of this work are encouraging thus far, but it is much too early to evaluate the commercial feasibility of the concept.

Options for Photochemical Conversion

The most advanced and the most speculative of all solar energy technologies is the direct photochemical conversion of sunlight to fuels. While no practical techniques for this conversion have yet been demonstrated, I consider it to be the most promising approach for the long term development of solar energy as a major energy source. We can distinguish four basic routes possible for photochemical conversion (Hall, 1979; Porter, 1976): first, biological conversion by a natural organism, usually bacteria or algae; second,

in vitro conversion by systems that incorporate elements of natural photosynthetic systems; third, photo chemical conversion by synthetic chemical systems; and fourth, photoelectrochemical conversion, which is a hybrid of photochemical and photovoltaic conversion technologies. I will describe each of these briefly.

A number of microorganisms are known to naturally produce hydrogen, though under somewhat unusual circumstances. These microorganisms include photosynthetic bacteria, green algae, and cyanobacteria. They are observed to produce hydrogen from water and sunlight in conditions in which they are protected from free oxygen. We now understand something of the chemical processes that occur in these organisms that lead to the production of hydrogen (Weaver, 1979). These processes are usually a complex arrangement of individual reactions. Several photons of light are absorbed in the conversion process, and a large number of extraneous reactions and compounds are involved. As a result, the overall efficiency of hydrogen production is very low. This low efficiency probably limits the ultimate usefulness of this approach to photochemical conversion.

To obtain efficiencies higher than those seen in the natural organisms, we can take the approach of developing in vitro conversion systems. In such a system, we would isolate the natural photosynthetic reaction centers from organisms, either plants or microorganisms, and arrange these in an engineered system to produce hydrogen. We can then avoid side reactions and direct all the energy collected toward the desired product. A problem in this arrangement is that we must protect the hydrogen-producing enzymes from free oxygen. They are rendered inactive by even small concentrations of free oxygen. Another problem is these reaction centers are very unstable: they have a very short productive life when isolated from the natural organism. We have only vague ideas as to how to stabilize these reaction centers and maintain their production of hydrogen in vitro.

We avoid the instability of natural photosynthetic systems by developing our own completely synthetic chemical system for photochemical conversion. Many photochemical reactions are known which could be coupled to hydrogen production. However, most of these reactions can be driven only by ultraviolet light. We require a system which can operate efficiently from the visible light of the solar spectrum. No appropriate photochemical system for this conversion is now known, though research on a number of promising ideas is continuing.

Another approach involves combining a semiconductor material for photovoltaic conversion with various liquid electrolytes. In

such a system, the free charges created by the photovoltaic effect are captured and converted into chemical energy. A number of such systems have been operated, though again at rather low efficiencies. Research in this area is also underway in a number of laboratories.

Thus, we see that there are a number of promising approaches to photochemical conversion being actively investigated. None of these has advanced beyond the stage of laboratory research. However, this work is of great importance because of the very desirable features possible in photochemical conversion. Theoretically, conversion efficiencies could be very high, up to 20%. This should be contrasted with the normal efficiency of plant growth, about 0.5%. With the high efficiency theoretically possible from photochemical conversion, a modern nation could derive all of its energy needs from a small fraction of its land area. Further, this could be done without significant adverse impact upon the operation of its agricultural systems or its natural ecosystems. The energy is produced in a naturally storable form, thus avoiding the complex issues of interfacing variable wind or solar energy sources to the patterns of normal energy demands. Thus, I expect photochemical conversion to be of great importance in the ultimate development of a renewable energy society.

RENEWABLE ENERGY POLICY

In the previous lectures, we have reviewed the current state-of-the-art and the directions being taken in research and development in the various solar energy technologies. But solar energy involves more than just technical issues. It has policy aspects which include complex environmental, social, and political issues. In this last lecture, I will cover a number of these issues and offer some of my own thinking on how we should approach them.

In a market economy, which in many respects the United States still is, the core policy questions can be stated: are private firms and consumers investing in renewable energy technologies at the socially optimum rate? If not, what policies can be effective in correcting the level of investment in renewable energy (Schiffel, 1978)? I think these two questions capture the important issues surrounding the development and use of solar energy. The first includes all questions of private business and consumer behavior as contrasted with behavior that gains social benefits enjoyed by the nation as a whole but not accruing to individuals in the market system. The second brings in the nasty but crucial issue of whether any government policy can be effective in correcting what might be an adverse outcome of the market system. Thus, this question expresses skepticism about the ability of government to actually make things better.

Many would not agree with the formulation of the issues as I have given them. To them, the worst possible fate that might befall solar energy is for solar technologies to be developed and marketed by the same major corporations that are seen to be responsible for many of our current social, political, and environmental ills. To these people, the development of solar energy offers a chance to make some fundamental revisions in the structure of society. While they might press for solar energy for these reasons, I see no strong connection between their political and social goals and solar energy. Those of us who find other, less political, virtues in the use of renewable energy can support its development while maintaining our own views and ways of expressing our position on social and political issues.

In this last lecture, I will not be able to address all of the important policy issues that are being debated actively in the U.S. and elsewhere concerning the development of solar energy. I will cover four areas that are central to the debate. The first has to do with the environmental costs and benefits of solar energy in comparison with conventional energy technologies. The second is the issue of the employment effects of a transition to solar energy by the evolution of industries and businesses to provide solar energy hardware and services. Third is the potential role of solar energy in aiding the current plight of the developing nations who face high imported oil costs that endanger their economic development. Finally, I will discuss various theoretical structures for thinking about the long term transition to a society based upon the use of renewable energy resources.

Environmental Costs and Benefits

Many of the issues surrounding the relative value to society of solar energy and conventional energy forms concern the externalities of these energy sources. An externality is any cost or benefit which does not accrue to the person responsible for the activity. The classic examples are environmental costs. For example, the simple smokestack of an industry allows the business to get rid of pollutants at low cost and yet subjects the surrounding residents to adverse health effects and economic costs of air pollution. There is an externality here because the business does not pay all of the costs imposed by its operation. The common understanding is that conventional energy technologies have significant externalities that should be considered in their assessment. Certainly we have made progress in recent years towards forcing an internalization of many of the environmental costs of conventional energy sources. For example, the cost of installing and operating a stack-gas scrubber on a coal power plant is an internalization of what used to be an externality. Yet, there are still many environmental costs associated with conventional energy sources. We will never be

able to internalize all of these costs. They will continue to be unpaid by those responsible for them and will continue to be an inducement to develop public policies to alter the operation of the normal market process in selection of energy forms.

It is sometimes claimed that solar energy technologies are free of external environmental costs and thus deserve a significant subsidy relative to the conventional sources with their unpaid external environmental costs. However, a moment's thought shows that solar technologies are not entirely free from external environmental effects. One must, however, in the case of solar technologies, consider the full life-cycle of the solar facility in evaluating its environmental effects. Part of the social cost of the solar facility is the environmental cost of emissions from the factories that make the solar hardware. Some of these solar technologies, for example, biomass gasification plants, will have significant environmental costs during their period of operation as well. Finally, there will be some environmental costs associated with removing, dismantling, and recycling the materials of the solar hardware after the useful life of the system.

In analyses performed at SERI, we have compared the total life-cycle emissions from various solar technologies with the corresponding total life-cycle emissions of a coal electric power plant that produces the same energy output (Lawrence, 1979). We assumed modern environmental control standards for the coal facility and either the current state-of-the-art or a direct extrapolation of present capabilities for solar technologies. Some extrapolation from present technology is necessary to develop a reasonable base for assessment of many solar technologies. However, an attempt was made to provide a conservative estimate of the total emissions due to the construction, operation, and dismantling of a solar facility. Figure 8 shows the results obtained for one of the pollutants considered, particulates. It can be seen that the worst offender among these technologies is not the coal electric plant, but the common wood stove. Almost equal to the coal electric plant in particulate emissions is a biomass steam electric plant. But generally, there are major savings in pollutant emissions of the solar technologies in comparison to the coal electric plant. This result for particulates generally holds true for all the pollutants and for the estimated impacts on human health as well (Yokell, 1979). We find major savings for the solar technologies in comparison with conventional technologies with regard to life-cycle environmental effects. This result is not supported by one analysis which has acquired a great deal of publicity recently (Inhaber, 1979; Holdren, 1979). However, I find that the works by Lawrence and Holdren a more objective and more reliable indicator of likely effects, and I agree with their general conclusions as to the environmental benefits of solar energy.

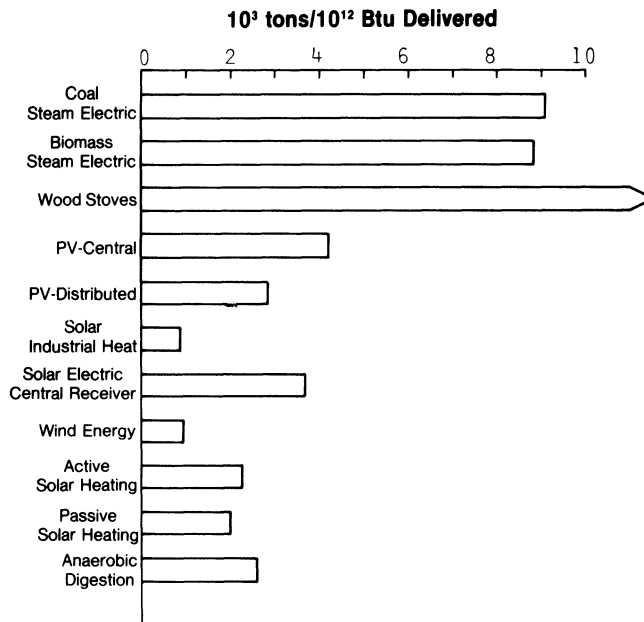


Figure 8. Total particulates released per unit of energy delivered over the life-cycle of coal-electric and solar energy technologies (Lawrence, 1979).

The analyses just discussed look at only one facility at a time and make direct life-cycle comparisons between types of facilities. However, our major interest is not in the effect of a single facility, but in the total national impact of increased use of solar technologies on a wide scale. Thus, we must sum the effects of many individual facilities to produce an estimate of national total pollutant releases. To do this, you need a scenario of the rate of solar technology deployment. In analyses done at SERI, we have analyzed a scenario that corresponds to attainment of President Carter's goal of 20% solar energy in the United States by the year 2000. We have used two different national energy-environmental models for this work. One is the large model developed by the Brookhaven National Laboratory; the other is a complex model developed by the Environmental Protection Agency called the Strategic Environmental Assessment System (SEAS). We have used these models to analyze two scenarios (Yokell, 1979). One is a base case in which the use of conventional energy sources continue to be dominant, and there is little use of solar energy by the year 2000. The other scenario we call the High Solar Scenario, and it corresponds to an accelerated schedule of development of solar energy and attainment of the 20% goal by the year 2000.

Table 6. Effects of Accelerated Use of
Solar Energy on National Pollutant Releases
in the Year 2000

Pollutant (10 ⁶ tons)	BNL Model		SEAS Model	
	Base Case	High Solar	Base Case	High Solar
Particulates	11.2	9.3(-)	10.2	10.8(+)
Sulfur Oxides	11.5	8.5(-)	26.3	23.2(-)
N Oxides	26.8	22.5(-)	23.3	21.1(-)
Hydrocarbons	5.7	5.5(-)	10.0	9.7(-)
Carbon Monoxide	15.6	15.2(-)	59.9	60.1(+)
Suspended Solids	0.2	0.1(-)	1.9	2.7(+)

Table 6 shows the total national pollutant releases in the year 2000 in these two cases as indicated by the two different models. Several things can be noted. First, the differences between the two models for the same scenario are generally larger than the differences between the two scenarios as predicted by the same model. Thus, the uncertainties in our projection techniques are very large compared to the effects we are analyzing. Second, there is no clear and unambiguous reduction in the emissions in the High Solar scenario as analyzed by the SEAS model. With the BNL model, there are reductions in all of the pollutants, but the changes are very small and are certainly within the likely uncertainties of the model.

These models lead to a conclusion that seems contrary to the comparison of life-cycle effects I discussed above. The reason for this difference is simple. In a scenario that involves rapid transition to solar energy, there is a very high rate of production of solar hardware during the first few decades. If you recall that much of the pollutant emission during the life-cycle of a solar facility comes during its production and installation, then you can realize that in the next 20 years, the High Solar scenario has high emissions exactly because a large number of solar facilities are being constructed. If we were to run these models further into the future, we would then start to see that the High Solar scenario has significantly reduced pollutant emissions relative to the Base Case scenario. However, because the environmental impacts of solar technologies come primarily at the beginning of their life-cycle, no environmental benefits are seen in the early stages of a rapid transition to solar energy. Thus, we have a paradox of sorts. Solar has great

environmental benefits, but we cannot gain those benefits immediately. To attempt to grasp them rapidly is to cause those benefits to slide forward into the 21st century.

Employment in Solar Energy

It is claimed that one of the benefits of a rapid development of solar energy is the creation of new employment opportunities. It is argued by some that solar energy can help solve the problems of unemployment that seem characteristic of modern industrial society. However, no study to date offers a comprehensive or professionally defensible analysis of solar energy employment. Some of the studies done to date have been politically motivated, and their methods and data are suspect. Some have failed to recognize the complexity of the issues involved in this area. All have suffered to some degree from unavoidable deficiencies in the current state-of-the-art of theory, data, and methods for analysis of macroeconomic and employment issues (Mason, 1978).

In a recent study by SERI, the Brookhaven National Laboratory, and Dale Jorgenson Associates, we have attempted to assess the impacts of solar energy under a variety of assumptions (Mason, 1979). Most importantly, we have considered the two cases of solar energy being cost competitive with conventional energy technologies, and not cost competitive with those conventional energy sources. In the latter case, the introduction of solar energy might be brought about either by government policy through incentives or mandate, or by willingness of consumers to pay a premium for what they perceive to be special benefits of solar energy. This study suffers, as do all others done in this field, from the inadequacies of present theory, data, and methods in conducting macroeconomic analysis. However, within the accuracy now possible, our conclusions are these: First, if solar energy is cost competitive with the conventional energy technologies it displaces, we find no significant impact on total employment. There are only a few shifts of employment between various sectors. This is true even in the case that the deployment of solar energy is rapid enough to meet President Carter's goal of 20% solar energy in the year 2000. On the other hand, if solar energy is not cost competitive with the energy technologies it displaces, we then find a slight negative impact on total employment in the economy. This consequence is a result of the movement of investment capital from other investments in the economy into an investment in solar energy systems. Thus, this conclusion depends upon the operation of a macroeconomic model which attempts to estimate the effects of investment patterns upon levels of economic activity and thus upon total employment. This conclusion must be considered very weak because of the poor state-of-the-art in macroeconomic modeling.

To see why it is so hard to estimate the employment impacts of solar energy, let us trace the chain of logic necessary (Hudson, 1979). We start with the question as to whether solar energy will require more or fewer economic inputs than the conventional technologies it displaces. Let us, for the moment, assume it requires net additional economic inputs. Then we must ask the question, does there exist excess capacity in the economy for the production of these additional inputs required for solar energy relative to conventional energy technologies? If there is indeed such excess capacity, then there is no dynamic macroeconomic impact of this activity, and there is a direct employment benefit of solar energy. However, if the answer to this last question is "no, there is no excess capacity for the inputs required," then labor and investment must be diverted from other uses in the economy in order to fabricate the solar energy systems. This then causes a chain of adverse effects in the economy with the probable results of lower productivity, slower capital growth, and slower economic growth. As a result, there may be a negative total impact upon employment. A similar chain of reasoning can be followed taking the assumption that solar energy will require fewer economic inputs than the conventional energy technologies it replaces. If there is excess capacity in the economy for the input requirements that are released, then there is no dynamic effect, and only a small decrease in employment. On the other hand, if there is not any excess capacity for these inputs, then the reduction in input requirements for solar energy relative to conventional sources allows labor and investment to be made available for other uses in the economy. This will then generally lead to higher productivity, faster capital growth, and faster economic growth. Thus, we see there is no unique answer to the question of the employment impacts of solar energy at the national level. It depends upon the relative requirements of solar energy for labor and other economic inputs, and depends upon the current situation of the economy with regard to the availability of those inputs and their uses in other areas of economic activity.

From all of this, my conclusion is that the employment impacts of solar energy on the national scale will be fairly small. Indeed, they will be small enough that we cannot predict them because of our inability to understand the processes that occur in the national economy. If one wishes to see the important employment effects of solar energy, you have to look at the microeconomic level, and see exactly what sort of skills will be required for solar energy, in which locales, and compare that to the local availability of that skill. At this micro level, you will see some positive employment effects of solar energy, but not effects significant enough to motivate policies at the national level. In my opinion, national policy must be based upon other benefits of solar energy than employment.

Solar Energy in International Development

Solar energy promises to become an important element of the international program of assistance to developing nations. Payment of high fuel prices by non-OPEC developing nations has jeopardized both future industrialization plans and the gains in quality of life made during the preceding two decades. The economies of these nations cannot long support the ever increasing economic penalty of importing OPEC oil. Among the solutions being tried is the rapid deployment of appropriate renewable energy technology, especially in rural areas of these developing nations. However, it is recognized that these nations need assistance both in gaining technical expertise and in funding of solar energy programs.

A variety of programs for international assistance in renewable energy technology are now being undertaken (Ashworth, 1979). These include multilateral donors, bilateral donors, and nongovernmental organizations. Among the multilateral donors, the most prominent are the U.N. Development Programme and the World Bank. Among the bilateral donors, the largest aid programs are those being conducted by the U.S., Canada, and major European nations. Among the nongovernmental organizations, prominent activities have been conducted by the Rockefeller Foundation and voluntary agencies of the OECD countries.

Altogether, in excess of \$200M a year is now being spent for international assistance projects in renewable energy and appropriate technologies. Eighty-six percent of this, by the estimates made by SERI, come from four nations: U.S., Sweden, Germany, and Canada. The projects include both traditional activities of international assistance that are now being directed toward renewable energy, and also some new initiatives that are special to solar energy. Among the traditional activities are these: institution building, the development of institutions for research or dissemination of information within the nation for renewable energy; manpower training, to train technicians and others to construct and maintain renewable energy systems; and resource creation and management, activities devoted primarily towards the management of ecosystems resources (i.e., biomass). In new initiatives, the following activities are underway: base line data collection, the development of information on energy requirements in rural areas and data on local energy resources; demonstration and field testing, demonstration and evaluation of technologies in the actual conditions in which they must operate (often coupled with training); technology and hardware development, the development of new technologies and hardware to meet the special requirements of these applications or to take advantage of special local resources and expertise; and creation of energy self-sufficient villages, demonstrations of complete economies for rural areas which can operate with self-independence in energy.

While solar energy will not be a magic solution to all the problems of developing nations, it does now appear that there are many circumstances in which solar energy and other appropriate technologies can significantly improve the quality of life in these nations. Efforts in this direction deserve to receive, and are now receiving, the active support of the developed nations.

Theory of Renewable Resources

As the concluding topic in these lectures, I will review various approaches to a theoretical basis for policy of renewable energy resources. The discipline of economics provides most of the terms and methods used in this area of inquiry. However, the concepts involved extend beyond those normally included in economic analysis. Ethical and moral concepts must be dealt with, either explicitly or implicitly. The question at issue can be stated this way: How should society schedule its consumption of finite resources and the adoption of renewable resource technology? The appearance of the word "should" in this question shows that we are working in the area of normative economics; that is, we are dealing with questions of what we consider to be the best choices for society according to some set of values. The ways that one assigns values to resources and their uses determines the theoretical structure and the assumptions one uses in this area of analysis.

Two major schools of thought delineate the broad range of opinions in this area. The position of the neoclassical economists is to let the market decide. That is, they make the presumption in this area, as in other questions concerning allocation of resources, that market forces will provide the optimum scheduling of a transition from a depleted resource to a new resource. At great variance with the position of the neoclassical economists is the school of thought which argues for creation of a steady-state economy. Here it is usually argued that normal market forces will fail to provide an adequate transition to a society which operates efficiently in a situation of limited resources. The gulf between these two viewpoints could hardly be wider.

I personally find much of value in both viewpoints. Each school of thought seems to have important things to say, but each analysis is valid only within a limited sphere. The question I find most provocative and interesting is how one can develop a theoretical structure that bridges these two viewpoints and deals with the issue of the optimum transition from a market economy in a period of cheap resources, to the steady state economy which has achieved a careful balance within a limited world. I know of no adequate bridging structure between these two schools of thought. I will suggest in this part of my lecture some of my personal views on how such a structure might be developed, but I'm only indicating promising ideas for future exploration.

In the literature of the neoclassical school, there is no problem of the exhaustion of finite resources that requires special social policies. The fundamental assumption is that market price gives an adequate signal to consumers and producers of any impending scarcity. Indeed, the viewpoint of this school is that government actions to restrict the operation of market forces will more often disguise and prevent adequate response to the valid signals of scarce resources. The example often given is regulation of the price of natural gas, which seems to have discouraged exploration for new fields and failed to give consumers an adequate price signal of the declining availability of natural gas.

An important part of the argument of the neoclassical economist is that increased effort for production of the resource will be stimulated by price increases. This will cause increased discoveries and availability. Thus, price will increase gradually over time, and resource availability will be assured. Many economists consider that this process can occur without limitation, that is, they do not recognize explicitly in their analyses any real physical limits to resource size or producibility. When they do recognize physical limits to resources, they then argue that the price mechanism will lead to economically more plentiful resources being substituted for less plentiful ones. However, there is little treatment in the literature of how this substitution process takes place, nor much examination of whether the transition occurs in an optimum manner.

Part of the school of thought represented here has focused on the important consequences of technological progress. It has been argued that technological progress will make it possible to keep producing ever larger volumes of extracted goods at declining real marginal costs. Thus, the view here is that technology is a much more important effect than is resource depletion. The evidence for this is said to be a declining real cost over time of goods produced from basic resources. There is some evidence in the history of long term price trends for basic resources that supports this view. In a recent review of this issue, there was found to be ambiguous evidence in most areas (Smith, 1979). It does not seem possible to conclude firmly whether there has or has not been an increase in the real price of commodities due to declining natural resources. Even in the case of petroleum, there does not seem to be clear evidence that would support the idea that the cost of petroleum has increased due to a decline in remaining natural resources. The price increases of the past years are due to accidents of ownership and location of resources in relation to users, and do not indicate any exhaustion of the resource that is leading to increases in actual production cost.

The optimism of the neoclassical school of thought is in stark contrast to the views of the steady-state economists. These two schools differ in the starting point for their analysis. The

neoclassical economist starts with the functioning of the existing market system and the historical behavior of prices and production rates. In contrast, the steady-state economist starts with the physical nature of the resource and the geological and ecological limitations to its development. The neoclassical economist assumes technological progress will continue and will be the dominant effect. The steady-state economist more often ignores completely any possibility of technical progress and assumes, perhaps implicitly, that the steady state economy has no technical advances possible within it. These two schools of thought also differ in how they approach economic analysis. The neoclassical economist is primarily positive; that is, he attempts to analyze what is occurring and project what is most likely to occur in the future. On the other hand, the steady-state economist takes a normative viewpoint: he asks not what is, but what should be? Thus, the steady-state viewpoint has an ethical content that is explicit, whereas the ethical content is only implicit in the neoclassical analyses.

The school of thought of the steady-state economist usually is built around the image of a society which is believed to represent a desirable or necessary situation (Daly, 1977). This viewpoint does not start with a description of the current state of society, but rather an ideal society: the steady-state economy, which is best defined as being one in which there is no net consumption of any finite resource. This definition does not actually require that the economy operate in a steady state. However, the term "steady-state economy" has been used frequently in the literature, and I will continue to use it even though it is somewhat inaccurate.

As an obvious conclusion of the requirement for no net consumption of any resource, all nonfuel materials must be recycled; thus copper, silver, aluminum, and other metals must be 100% recycled. However, as we know from the second law of thermodynamics, energy cannot be recycled. Thus, for this society to fit the definition given above, it must derive its only energy resources from solar energy, either directly or indirectly. It is probably useful to relax this last requirement somewhat and include in our thinking those finite resources that are so extensive that they would last long by historical times even if used at rates corresponding to the full energy requirements of a modern society. Thus, I would include both the breeder reactor and fusion energy in this category. In almost everything I say in this last part of the lecture, the term solar energy is interchangeable with these other very large, essentially infinite, energy resources.

The steady-state economy has some other important characteristics. Population must be held constant. The capital stock as measured by physical quantities must be held constant. Steady-state economists also argue that society must maintain a careful balance with the natural ecosystems of the world. To do this, the physical

throughput of materials and energy in the economy must be minimized by selection of high efficiency means of providing amenities. One consequence of this is that Gross National Product (GNP) is no longer a significant measure of economic well being. Indeed, it can be said that one objective of a steady-state economy is to minimize GNP for a given level of social welfare. However, this last rule is only useful for GNP as measured in terms of the flow of physical quantities. With other measures, GNP can grow because of the potential for technological progress in a steady-state economy.

The steady-state economists generally ignore the possibility of further technological progress: their analyses do not include it explicitly. However, I think this is an important and fundamental error. I think it quite possible, and even most likely, that a society that fits the above definitions of no net consumption of finite resources, will have significant economic progress through increasing sophistication of its technology. Thus, improvements in technology would allow yet better benefits for its population to be derived from its use of completely recycled finite resources and its use of renewable energy resources. In a measure of economic activity that represented a proper extension of Gross National Product, this would mean that economic productivity would continue to increase in a steady-state society even though the net use of physical resources does not increase.

It should be clear from the above summaries that there is little in common between the views of neoclassical economists and steady-state economists. I personally believe the neoclassical economist offers a useful, richly detailed, and pragmatic description of the current state of society, while the steady-state economist provides a useful, soundly based, and optimistic description of the long term future of humanity. The question I turn to next is how we can provide a bridge between these two viewpoints and thus start to understand how society might make the transition from our present economic system to one that is indefinitely sustainable.

In this concluding part of my lectures, I cannot offer any firm answers. All I can do is suggest some questions and some assumptions I think useful for future thinking about these issues. This viewpoint is highly personal. I offer here my own ideas as to how one should proceed in this analysis, and I am sure that many would disagree with one or more of these points. As we enter this discussion, you will see that many of the questions turn upon values and disagreements as to what the future of humanity should be like.

First, and as a fundamental point, I suggest that in this analysis, benefits to future generations should not be discounted. That is, the risk-free discount rate in this analysis should be set

to zero. Some would respond to this suggestion by saying that the discount rate represents an inevitable cost of deferring the use of money. In that view, the discount rate represents a natural part of an economic process, and we cannot ignore it. However, I would argue that discount rates used for short term analyses (i.e., comparing an investment now with one ten years from now) are not useful for analyses that compare actions centuries apart. Indeed, the straightforward application of an annual rate of discount to processes that occur over hundreds of years leads to ludicrous conclusions. For example, if one discounts the present worth of the entire North American Continent back to the time of Columbus' trip, one finds that, to Columbus, the present value of the United States could not justify the cost of his trip. Clearly, he should have stayed home. The fundamental question here is whether in an analysis of benefits to human beings occurring at greatly different times, should we discriminate systematically against one generation in favor of another? I argue we should not so discriminate. Thus, our discount rate should be zero.

I think it necessary that our analyses include explicitly physical constraints to resource use. Thus, I would not allow econometric models in which the availability of a resource depends only upon prices and in which a certain schedule of prices can lead to ever increasing levels of production. Further, we must treat in some way the nature of geological resources: as resources that are easy to withdraw are exhausted, the remaining resources will require larger investments in energy, capital, and labor to withdraw and utilize. It is, of course, extremely difficult to estimate the physical extent of resources not yet carefully explored. However, I think it far better for our purposes to include a guess as to the extent of a physical resource than it is to deny the existence of any physical constraint. Hopefully, the major conclusions of our analysis with regard to appropriate policies and strategies will not be highly sensitive to the exact size of resources.

If the only resources available to society are the finite resources discussed above, then our analysis must lead to a conclusion of ultimate disaster. We are led, therefore, to the requirement that our analysis must explicitly include the possible use of renewable resources as alternatives to finite resources. However, to be an accurate picture of the transition we face, it should also indicate that there are significant costs to renewable energy technologies, and that at the beginning point of this transition, the renewable technologies will be much more expensive than the finite resources. Our analysis must also include the fact that the development and use of renewable technology will always require investments of energy, capital, and labor. Thus, an important question for the long term future is how efficiently it is possible to use these inputs in order to derive renewable energy resources in useful forms.

In a renewable resource future, it is important that the level of the capital stock be explicitly included. This is because benefits to the population in such an economy are provided largely by the amount of the capital stock, rather than by the flow of commodities. Important questions for the analysis are how the capital stock should grow over time during the transition from finite resources to renewable resources, as well as what is the optimum level of capital stock in the steady-state situation? I expect that one of the conclusions of this part of the analysis will be that the rate of investment and saving in society is crucial to a successful transition to renewable energy. This puts the policy question at the level of the individual and his tradeoff between immediate consumption and savings. The present very low rate of personal savings in the United States is not an encouraging indicator of our readiness to proceed with the kind of transition being discussed here.

Finally, two formal points about how we should define the optimum schedule of the transition. As in normative economics, we assume that the distribution over time of benefits should be a Pareto optimum. That is, it should be impossible to alter this distribution of benefits in any way so as to further increase the benefits to one generation without reducing the benefits to another generation (Herfindahl, 1974). From this rule, we conclude that the optimum scheduling is one in which we do as well as possible for each generation up to the point at which harm is imposed on another generation. However, this rule will often not lead to a unique scheduling of the transition. Another condition may be necessary to make the schedule unique. Here I would adopt the principle used by Rawls in his development of the theory of justice (Rawls, 1971). Thus, we would attempt to make the distribution of benefits as uniform as possible, so that if people had a free choice of which generation to join, they would be indifferent as to that choice.

It may be worthwhile to look briefly at a simple model of the use of an exhaustable resource in order to see the kind of analytic structure that might be useful in pursuing the directions I have indicated above. To do this, we look at the simple model used by Koopmans to illustrate the basic issues in the use of an exhaustable and nonsubstitutable resource (Koopmans, 1973). Koopmans presents the following model. One wishes to maximize

$$U = \int_0^T e^{-rt} u(c(t)) dt$$

subject to

$$\int_0^T c(t) dt = F$$

and

$$c(t) \geq c_{\min} > 0 \quad \text{for} \quad 0 \leq t \leq T$$

Here U is the total benefit over time, that is, it is a measure of total utility. The utility derived by society at an instant from its consumption of the resource is given by u , and the rate of consumption by $c(t)$. The second equation gives the condition that the total consumption of the resource over time has a finite limit. The next condition indicates that there is a minimum level of consumption below which society cannot continue. As an inevitable consequence of these two requirements, there is a finite lifetime to society. That is, the total duration of society in this model must be less than $F/c_{\min}$. This, then, is a model of extreme pessimism. Society is living with a finite resource that inevitably will be exhausted at some time in the future. The only question is how the few generations that can survive will schedule the use of this resource before they come to an end. In this model, there is a discount rate, r , applied to the utility of consumption of the resource. With large values of r , the solution to the model given above has a high level of consumption for the early generations, declining to $c_{\min}$ rather quickly with a resulting rapid end to society. With r set equal to zero, the consumption of the resource does not change over time, and the optimum level of consumption depends upon the nature of the utility function, $u(c(t))$.

This model given above is a starting point from which we can think about how to develop an analytical structure to model the transition from finite to renewable resources. However, the model must be extended in many ways to deal with the issues I have outlined. First, benefits must derive from consumption of finite resources, from the existing capital stock, and from use of renewable resources. Second, economic production must be divided between consumption and the creation of capital stock, including the creation of stock for the development of renewable resources. At issue is how much of the finite energy resource should be consumed for immediate enjoyment, and how much should be used for building solar energy systems to provide energy in the future? Economic production should result both from depletion of finite resources and from use of renewable resources by the capital stock devoted to that purpose. The problem can then be stated as one of maximizing the integral from now to the infinite future of the instantaneous utility of the operation of the economy thus described, with the optimum constrained by the conditions of Pareto and Rawls.

This model is obviously a highly simplified vision of an economic society. It does not answer many of the questions of immediate policy importance. However, it is not intended to replace normal economic analyses for short term decisions. Rather, it

provides a structure for thinking about the far future and the kinds of transitions that must eventually occur. In this regard, it might give us some useful insight into the implications of our present patterns of behavior toward resources and how that behavior must eventually be modified.

I think we are all in agreement that renewable resources must be developed, and we are hopeful that society can succeed in making a pleasant and smooth transition to their use. In these lectures, we have seen some of the technologies now being developed which offer a means of achieving a renewable energy society. It is clear we have far to go, and yet I hope I have made it clear in these lectures that our progress to date has been impressive. We should have high hopes that this progress will be continued to the great benefit of future generations.

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Appendix I
A Partial Listing of
Solar Energy
Journals, Magazines, and Newsletters

SOLAR ENERGY TECHNOLOGY

Solar Energy (monthly). Pergamon Press, Headington Hill Hall, Oxford OX3 0BW, England. Technical journal with articles on wide variety of solar energy topics but with emphasis on solar heating and cooling. An official publication of the International Solar Energy Society.

Solar Age (monthly). Solar Vision, Inc., Church Hill, Harrisville, N.H. 03450, USA. Readable articles on good variety of solar energy topics. Emphasis is doing it yourself and solar heating. Official publication of the American Section of International Solar Energy Society.

Solar Engineering Magazine (monthly). Solar Engineering Publishers, Inc., 8435 Stemmons Freeway, Suite 880, Dallas, TX 75247, USA. Official publication of the Solar Energy Industries Association. Focuses on design, installation, and operation of solar heating and cooling systems.

Solar Energy Materials (quarterly). North-Holland Publishing Company, P.O. Box 211, 1000 AE Amsterdam, The Netherlands. New professional journal on materials science research in solar energy conversion.

Journal of Energy (bimonthly). American Institute of Aeronautics and Astronautics, Inc., 1290 Avenue of the Americas, New York, NY 10019, USA. Technical journal with frequent articles on engineering research on solar energy and wind energy conversion.

Applied Solar Energy (bimonthly). Allerton Press, Inc., 150 Fifth Avenue, New York, NY 10011. Translation of the Russian language journal *Gelioteknika*. Technical articles with emphasis on solar thermal conversion.

WIND ENERGY

Wind Power Digest (quarterly). Michael Evans, 54468 CR31, Bristol, IN 46507, USA. Easy to read magazine primarily directed toward amateur wind enthusiasts.

Wind Engineering (quarterly). Multi-Science Publishing Co., Ltd. The Old Mill, Dorset Place, London E151DJ, England. Technical articles on wind resources and conversion systems.

BIOMASS AND PHOTOCHEMICAL CONVERSION

Resource Recovery and Conservation (quarterly). Elsevier Scientific Publishing Co., P.O. Box 330, 1000 AH Amsterdam, The Netherlands. Technical journal primarily on recovery and recycling of materials, but with good articles on energy from wastes.

Forest Ecology and Management (quarterly). Elsevier, P.O. Box 330, 1000 AH Amsterdam, The Netherlands. International professional journal on management of forest ecosystems for energy and other purposes.

Journal of Photochemistry (monthly). Elsevier Sequoia S.A., P.O. Box 851, 1001 Lausanne 1, Switzerland. Technical journal which has some articles on advances in photochemical conversion of solar energy.

International Journal of Hydrogen Energy (bimonthly). Pergamon Press, Headington Hill Hall, Oxford OX3 0BW, England. Official journal of the International Association for Hydrogen Energy. Includes articles on future energy systems based on hydrogen and technical articles on production of hydrogen from solar energy (and other sources).

OCEAN THERMAL ENERGY

OTEC Liaison (monthly). Popular Products, Inc., 1303 South Michigan Avenue, Chicago, IL 60605, USA. Newsletter primarily reporting on the US OTEC program.

RENEWABLE ENERGY POLICY

Solar Energy Intelligence Report (weekly). Business Publishers, Inc., P.O. Box 1067, Silver Springs, MD 20910, USA. Emphasis is on politics of solar energy in the US, but also provides news reports on technical advances.

Solar Law Reporter (bimonthly). Solar Energy Research Institute, 1536 Cole Blvd., Golden, CO 80401, USA. Legal journal on legislation and legal cases relevant to solar and wind energy.

CoEvolution (quarterly). Point, Box 428, Sausalito, CA 94965, USA. Informative and provocative articles and reviews on appropriate technology.

People and Energy (bimonthly). Institute for Ecological Policies, 1413 K Street NW, Washington, DC, 20005, USA. News and essays representing radical views toward energy alternatives.

Technological Forecasting and Social Change (monthly). Elsevier North Holland, 52 Vanderbilt Avenue, New York, NY 10017, USA. Interdisciplinary journal reporting social science research on alternative futures.

Futurist (monthly). World Future Society, P.O. Box 30369, Bethesda Branch, Washington, D.C. 20014, USA. Imaginative and sometimes provocative articles on world futures, with increasing emphasis on energy futures.

ENERGY FROM THE SEA WAVES

A. Blandino, A. Brighenti, and P. Vielmo

Tecnomare S.p.A.

Venice, Italy

INTRODUCTION

The debate on the utilization of energy resources, becoming wider and more dramatic since 1973, presents areas of uncertainty and controversial view-points all over the world.

However, it is the general opinion that a new consciousness is growing; the scarcity of oil is irreversible and destined to influence the world-wide development rate. This consciousness is acting practically by means of the new programs that many countries have already adopted or are going to adopt. These programs contain two basic statements: first, to control, to restrain and to rationalize the consumption of energy without over compressing the development of the production rate; second, to try to satisfy partially the energy demand by means of the so called (renewable and not) alternative sources, even if oil and gas seem destined, at least for a medium term, to play a fundamental role in the world-wide balance of energy.

Among these complimentary or integrative energy sources, it is necessary to distinguish between new applications that are to be considered as an improvement of sources already available, and the utilization of new energy sources that could constitute a net increase in the global energy balance. In both fields, anyhow, the level of the research and the possibility of practical applications are conditioned by different factors, such as the technological know-how, the cost-benefit balance, the environmental impact, the safety, the available energy content, etc. Keeping this in mind, it is very difficult to evaluate the potential development of every methodology, but it is evident that efforts must be increased in

every direction through an intelligent selection of various approaches and without looking for miracles.

In this general picture the research and development activities performed by TECNOMARE in the field of sea wave energy exploitation are more comprehensible. These activities concern the following three main aspects:

- (a) Evaluation of the sea wave energy content.
- (b) Interaction between the incident wave field and the absorbing device.
- (c) Economic assessment of the wave power generator.

In the following, the main results relevant to these themes will be shown and discussed together with the computerized procedures by which they have been obtained.

WAVE POWER AVAILABLE

The exploitation of the sea wave energy content implies the knowledge of the wave characteristics as a function of the selected area, of the season, of the bathymetry, etc.

In other words, it is necessary to know a long term statistic of the above characteristics and the local bathymetry in order to have quantitative information on the wave power available.

In order to achieve this goal, TECNOMARE has developed the computer program ARDOC that furnishes the following results (see Figure no. 1):

- (a) Energy and power content of the sea waves.
- (b) Data (height, period and number of cycles) for the fatigue analysis of offshore installations.
- (c) Forecast of the working time necessary to carry out marine operations.

The program ARDOC can also work as a data bank for bare meteorological data.

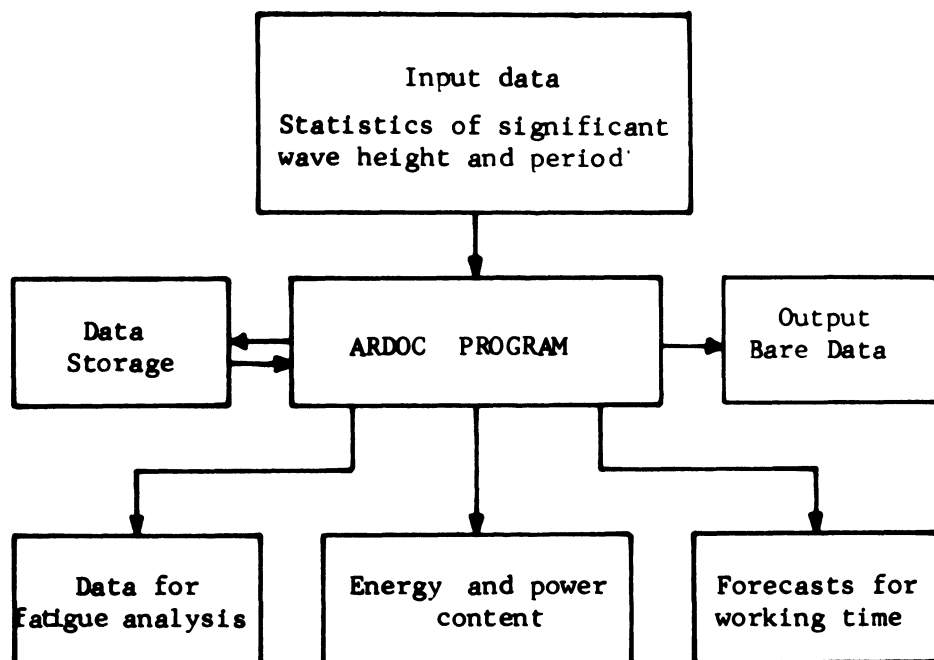


Fig. 1. Computer program "ARDOC"

The evaluation of the energy and power content of the sea waves is carried out through the following steps:

- i) Determination of the real wave height and period statistics, using as input data the significant wave height and period statistics.
- ii) Calculation, by means of the linear theory, of the mean power transferred in one period by a wave of height H and period T , through a vertical strip of unit width extending to the sea bottom.

The results relevant to the energy and power of the sea waves are:

- i) Seasonal or annual tables (as Table 1) that, for each direction, give the percentages of the time during which the power content is within preassigned power bounds.
- ii) Seasonal and directional tables (as Table 2) that give the power content in preassigned wave period and height intervals.

023-A000-REL-G001

***** TITLE : 61 NERAL-ENERGY, TARLE

***** -TFCNOMARE S.P.A.*****
***** P R O G R A M ***** JOB NO. : 623004 DATE : 10/05/77***** 081 - ARDOC-1 *****
***** ACTIVITY NO.: C704 EXT D : MP PAG. 19

AVERAGE PERCENTAGE OF OCCURRENCE FOR POWER INTERVALS

AREA: 11. NORTH SEA
DEPT: 230 FEET
SEASON: ANNUAL
LAT: 56 DEG. 32' N
LON: 3 DEG. 15' E

POWER INTERVALS (KW/M)		PERCENTAGE OF OCCURRENCE								TOTALS	
		N	NE	E	SE	S	SW	W	NW		
0	5	4.9	3.1	3.8	6.2	6.8	6.3	5.4	5.8	42.3	
5	10	1.9	1.2	1.5	2.5	2.8	2.7	2.4	2.5	17.5	
10	15	.7	.4	.5	.9	1.0	1.0	.9	.9	6.3	
15	20	.6	.3	.4	.7	.8	.8	.8	.8	5.2	
20	25	.3	.1	.2	.3	.4	.4	.4	.4	2.5	
25	30	.4	.2	.3	.5	.5	.6	.6	.5	3.6	
30	35	.3	.1	.2	.4	.4	.4	.4	.4	2.6	
35	40	.2	.1	.1	.2	.2	.3	.3	.3	1.7	
40	45	.2	.1	.2	.3	.3	.3	.3	.3	2.0	
45	50	.1	.1	.1	.2	.2	.2	.2	.2	1.3	
50	60	.2	.1	.1	.2	.2	.2	.2	.2	1.4	
60	70	.2	.1	.2	.3	.2	.3	.3	.3	1.9	
70	80	.2	.1	.1	.2	.2	.2	.2	.2	1.4	
80	90	.1	0.0	.1	.1	.1	.1	.1	.1	.7	
90	100	.1	0.0	.1	.2	.1	.2	.2	.2	1.1	
100	200	.5	.2	.4	.7	.6	.7	.8	.8	4.7	
>200		.4	.1	.4	.7	.4	.5	.6	.7	3.8	
TOTALS		11.3	6.3	8.7	14.6	15.2	15.2	14.1	14.6	100.0	

AN POWER (KW/M) : 36.
 XTIMUM POWER (KW/M) : 4983.
 TAL ENERGY (KWH/M) : 312769.

TABLE 1

ITF: -POWER AND ENERGY ARE REFERRED TO ONE METER CREST AIDTH

023-A000-REL-G001

POWER TABLE

TITLE

* -TECHNAME S.P.A.-
* P D O G R A M
* 081 - ARDOC-1

DATE : 10/05/77

EXTD : WP

ACTIVITY NO.: C704

AVERAGE POWER VALUES (KW/M) FOR HEIGHT AND PERIOD INTERVALS.

AREA: 11. NORTH SEA
DEPT: 230 FEET
SEASON: ANNUAL

LAT: 56 DEG. 32' N
LON: 3 DEG. 15' E
DIRECTION: ALL

WAVE HEIGHT INTERVALS

	0-4	4-6	6-8	PERIOD INTERVALS				15-20	20-25	25-30	>30
(METERS)				8-10	10-15						
0 1	1.	3.	6.	4.	11.	17.	22.	29.	0.	0.	0.
1 1	12.	19.	27.	37.	50.	71.	89.	93.	0.	0.	0.
2 1	36.	58.	80.	103.	138.	193.	244.	0.	0.	0.	0.
3 1	74.	119.	160.	205.	276.	377.	473.	0.	0.	0.	0.
4 1	0.	200.	260.	342.	456.	617.	756.	0.	0.	0.	0.
5 1	0.	304.	407.	515.	682.	914.	0.	0.	0.	0.	0.
6 1	0.	430.	576.	724.	949.	1255.	0.	0.	0.	0.	0.
7 1	0.	0.	781.	960.	1251.	1639.	0.	0.	0.	0.	0.
8 1	0.	0.	1017.	1240.	1587.	2104.	0.	0.	0.	0.	0.
9 1	0.	0.	1274.	1570.	1958.	0.	0.	0.	0.	0.	0.
10 1	0.	0.	1547.	1920.	2348.	0.	0.	0.	0.	0.	0.
11 1	0.	0.	1818.	2311.	2778.	0.	0.	0.	0.	0.	0.
12 1	0.	0.	0.	2736.	3241.	0.	0.	0.	0.	0.	0.
13 1	0.	0.	0.	3241.	3721.	0.	0.	0.	0.	0.	0.
14 1	0.	0.	0.	3768.	4240.	0.	0.	0.	0.	0.	0.
15 1	0.	0.	0.	0.	5253.	0.	0.	0.	0.	0.	0.
>20	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

NOTE: -POWER AND ENERGY ARE REFERRED TO 1 METER CPHST WIDTH

TABLE 2

- iii) Seasonal and directional tables (as Table 3) that give the percentage of time (occurrence) in preassigned wave period and height intervals.
- iv) Seasonal and directional tables (as Table 4) that furnish the total energy associated with waves whose period and height are within preassigned intervals.

From Table 1 the importance of the directional characteristic of the machine can be analyzed in the area considered. If the device has some minimum power level sensibility, Table 1 gives also quantitative information on the energy which cannot be recovered and on the maximum yearly power which may occur on the marine system and its supporting structure.

From Tables 3 and 4 it is possible to determine the theoretical energy which can be extracted with respect both to the frequency efficiency and to the wave height efficiency of the machine.

Following this kind of approach the usage factor can be determined. For example let's consider a marine device capable of taking up and transforming the whole energy of the waves whose periods are between $T_1=6$ sec and $T_2=15$ sec and whose heights are between $H_1=2$ m and $H_2=5$ m.

In the selected area of the North Sea we could obtain 142.400 KWh/m every year (45.5 of the total energy) with the plant working for 9.8% of the time.

INTERACTION SEA WAVES - POWER GENERATOR

The problem of extracting useful energy from sea waves involves two main items (which are interactive): the device itself and the sea.

Up to now the major effort of investigators and researchers were devoted to the design of devices capable of somehow transforming the motion of the sea into useful mechanical or hydraulic power without much knowledge of the characteristics of the sea.

The true energy content of the sea and its distribution in time has not been taken into special consideration compared with the machine itself.

Regarding the machine itself, many possible devices have been proposed, especially during this century. The present situation can be summarized in this way: great approximation in approaching the problem; a very large number of patents; many preliminary conceptual designs; and very few in-depth studies.

***** TITLE ***** OCCURRENCE POWFP TABLE *****										023-A000-REL-G001	
***** -TECHNOMAP-S.P.A.- *****											
***** P R O G R A M *****											
***** 081 - AMDOC-1 *****											
***** ACTIVITY NO.: C704 *****											
***** DATE : 10/05/77 *****											
***** EXTID : WP *****											
***** PAG. 21 *****											
***** AVERAGE PERCENTAGE OF OCCURRENCE FOR WAVE HEIGHT AND PERIOD INTERVALS *****											
***** AREA: 11. NORTH-SEA *****											
***** DEPT: 230 FEET *****											
***** SEASON: ANNUAL *****											
***** LAT: 56 DEG. 32' N *****											
***** LON: 3 DEG. 15' E *****											
***** DIRECTION: ALL *****											
WAVE HEIGHT INTERVALS										PERIOD INTERVALS	
(METERS)											

***** ENERGY TABLE *****										023-A00C-REL-G001			
* -TCNO-14MF S.P.A.- *										DATE : 10/05/77			
* P R O G R A M *										EXPTD : WP			
* 0A1 - ADOC-1 - *										PAG. 22			
***** ACTIVITY NO.: C704 *****													
***** AVERAGE ENERGY VALUES (KWH/M) FOR WAVE HEIGHT AND PERIOD INTERVALS *****													
AREA: 11. NORTH-SEA										LAT: 56 DEG. 32' N			
DEPT: 230 FEET										LON: 3 DEG. 15' E			
SEASON: ANNUAL										DIRECTION: ALL			
WAVE INTERVALS (METERS)		0-4	4-6	6-8	PERIOD INTERVALS				15-20	20-25	25-30	>30	TOTALS
0	1	1704	5680	6049	3015	2940	417	39	417	39	1	0	20765
1	2	740	8939	14144	16410	18192	3109	247	3109	247	8	0	66210
2	3				18653	26381	4844	287	4844	287	0	0	69070
3	4	76	4089	14740	14317	25013	4416	149	4416	149	0	0	54160
4	5	3	1503	8759	9842	20049	2922	51	2922	51	0	0	37961
5	6	0	440	4607	6462	14740	1537	0	1537	0	0	0	25130
6	7	0	91	2250	4152	10141	635	0	635	0	0	0	15957
7	8	0	7	1022	10141	6423	200	0	200	0	0	0	9913
8	9	0	0	427	2663	4068	27	0	27	0	0	0	5946
9	10	0	0	170	1681	4068	0	0	0	0	0	0	3491
10	11	0	0	47	1013	2431	0	0	0	0	0	0	1971
11	12	0	0	12	498	1365	0	0	0	0	0	0	1061
12	13	0	0	3	312	746	0	0	0	0	0	0	568
13	14	0	0	0	144	400	0	0	0	0	0	0	295
14	15	0	0	0	85	210	0	0	0	0	0	0	140
15	20	0	0	0	30	101	0	0	0	0	0	0	76
>20		0	0	0	0	76	0	0	0	0	0	0	0
TOTALS		2523	20749	56291	80706	133576	14107	773	14107	773	9	0	312734

NOTE: POWER AND ENERGY ARE REFERRED TO 1 METER CREST WIDTH

TABLE 4

Regarding the sea and its energy characteristics, the situation is the following: some difficulties, partly due to the mode-rate availability of useful statistical data and very few specific studies and theoretical means of analysis.

Nowadays, the highest level of development of the problem is reached when the available elements of the two main items are put together for an economic evaluation of the cost of the energy extracted (see Figure 2).

This preliminary approach is certainly very useful in early stage of development, but very approximate. In fact, the whole problem (waves and machine) must be regarded as a "system".

The assumption of neglecting the interaction between the wave activated device and the sea is unrealistic, even if necessary, in the earlier stages; the sea wave energy system cannot be divided into two (the wave activated machine with this characteristics, and the sea with its characteristics) as the two elements interact on each other. For this reason, it is necessary to seek a more organic approach as outlined in Figure 3 with a tentative block diagram.

The possible consequences of this approach are explained by the following considerations.

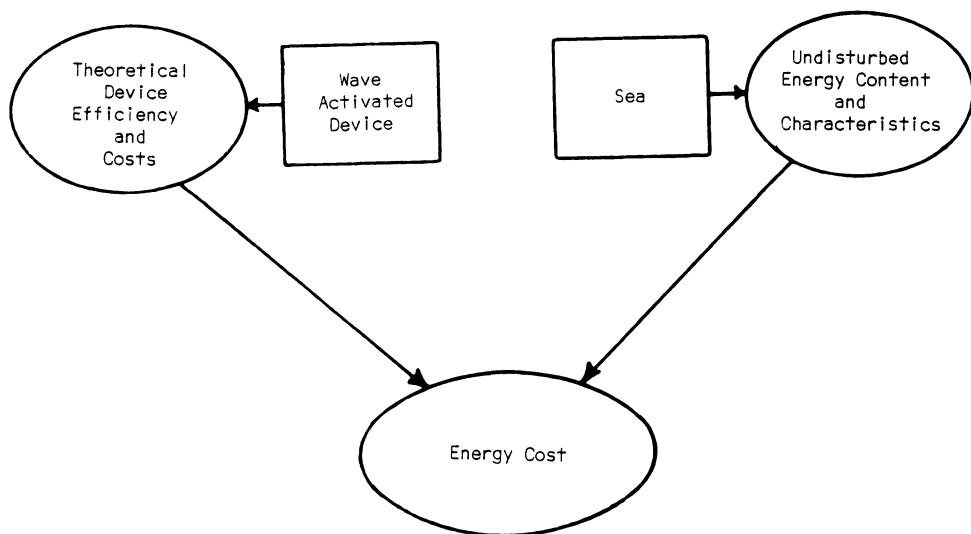


Fig. 2. Preliminary approach to the problem of wave energy conversion

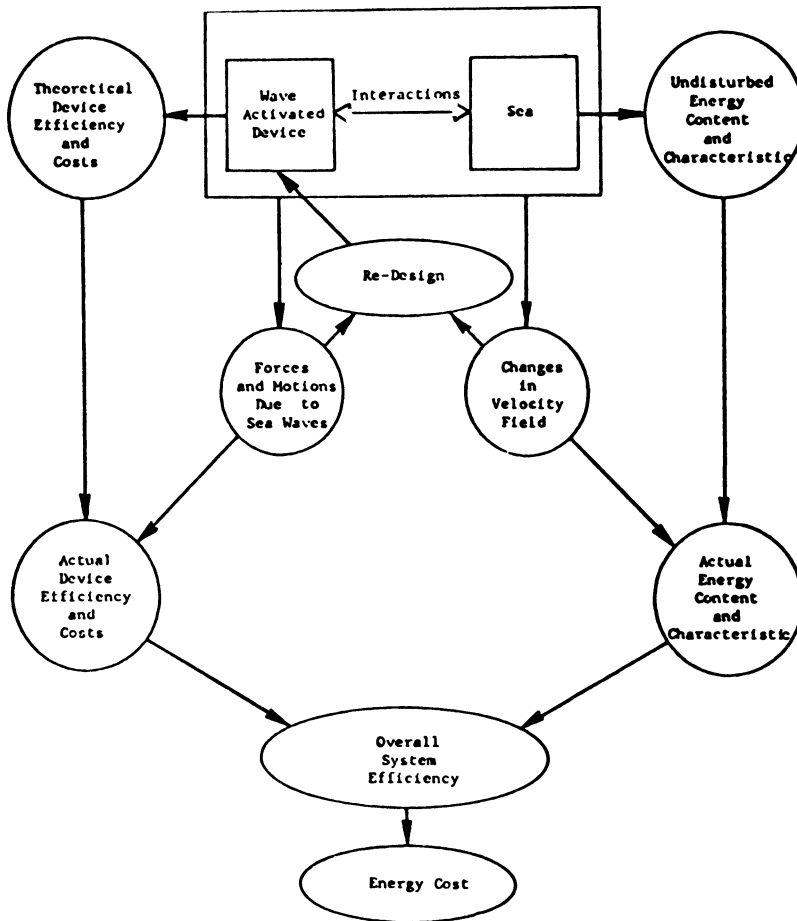


Fig. 3. Improved approach to the problem of wave energy conversion

Generally speaking, it is not completely certain that the cheapest energy from waves can be obtained from the stormiest seas and deep waters where, nevertheless, the energy contained in the sea is greater than near the shore.

In fact, very rough seas imply additional high costs for the designing of the device and a strong structure which cannot be balanced by the increase of the power output. Also, for mooring, maintenance and power transportation, deep waters imply costs which may increase more quickly than the theoretically available wave power.

Another consideration linked to the improved approach to the problem of sea wave power, is that no special attention has yet been paid to the possibility of some kind of "pre-concentration"

of wave energy by means of the interaction effects between the sea and the power absorber. This essential aspect has been developed by us during the research, presently in course, sponsored by C.N.R. (National Council of Researches).

THE POINT-ABSORBER CHOICE

The extraction of sea wave power needs a transferring process from the sea to the equipment which must be able to absorb energy from the velocity field originated by the waves, or from the pressure field or from the free surface movements. The device itself modifies the incoming wave field, perturbing considerably the wave amplitudes in the surrounding zone (diffraction effect).

Figure 4 shows the equal value lines of the ratio of the diffracted wave height over the incident one which supplies the variation of the disturbed crest elevation, at any point.

As the diffraction effects depend on the wave period the local statistic of the waves, on which the total energy evaluation is based, results modified in the sense that in some zones the energy will be more concentrated, in others more rarefied. It is obvious that the mean spatial assessment of the energy may be modified not only by the useful location of the extracting device but also by an appropriate geometric configuration, thus optimizing the mean overall efficiency of the system.

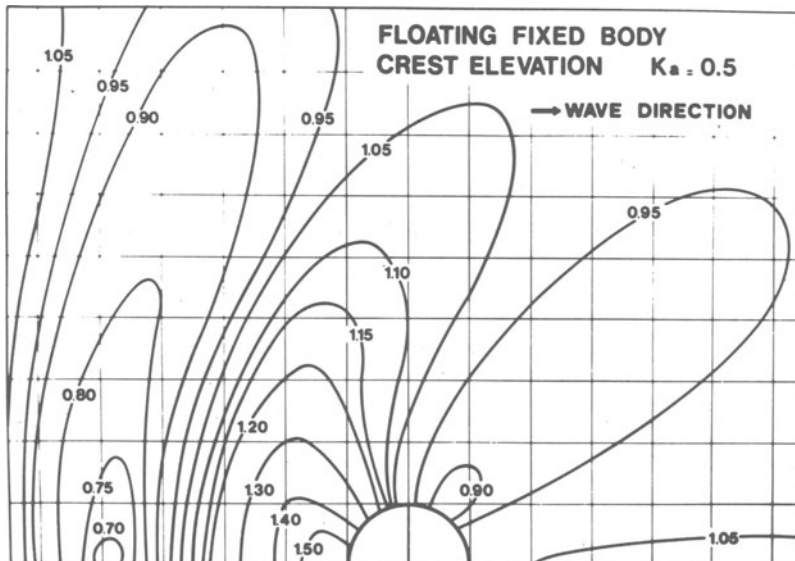


Fig. 4. Diffraction effects on the crest elevation

The system here analyzed (a vertical floating cylinder with an absorption device) is very simple but it is schematically representative of the whole family of wave energy extracting machines based on the large floating bodies' motions; they are usually called "point-absorber" devices.

The reasons for this choice are briefly summarized in the following considerations:

- As a result of the diffraction effects on the incoming wave field, caused by the extracting device, the intercepted energy is equivalent to that relevant to a crest length greater than the main dimension of the body. In other words it is possible to concentrate the energy by means of the diffraction effects.
- By means of an appropriate assessment of a given number of floating bodies it is possible to obtain a structural weight less than a continuous structure, the KWh produced being the same in both cases.
- If the main dimensions of the extracting devices are contained, the reductive effect will be analogous for the wave loads acting on the bodies.
- A high degree of modularity produces great advantages both in terms of unit cost and in terms of maintenance.
- The modularity allows a major degree of freedom during the study and the realization of the possible disposition of the extracting devices in order to achieve pre-requested resonant conditions.

The system analyzed is composed of one or more vertical floating cylinders (rigidly connected) and is representative of the whole family of the machines based on the motions of large floating bodies.

PROCEDURE FOR THE EVALUATION OF THE SYSTEM EFFICIENCY

The general procedure for the calculation of the system efficiency is shown in the block diagram of Figure 5.

For each geometric configuration, a suitable mesh having been assumed, the most important part of the procedure consists in the use of our computer program DINDIF, which calculates the dynamic frequency response of a large body of arbitrary form on the basis of the three-dimensional diffraction theory.

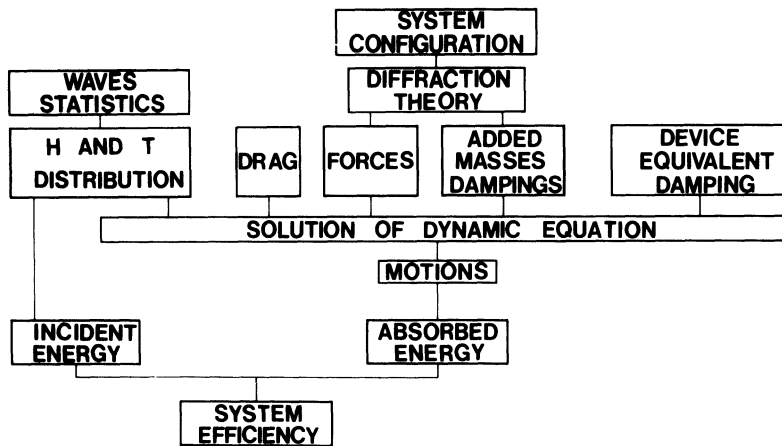


Fig. 5. Block-diagram of the procedure for system efficiency evaluation

The sink-source numerical technique is used to arrive at the solution. The results of the program include the following calculations:

- global forces and moment,
- added mass and damping matrix,
- linear motions in six degrees of freedom,
- dynamic pressure on the wet surface of the body,
- velocities, accelerations and pressures for points in the surrounding fluid.

In order to solve the linearized equation of the vertical body motion the following assumptions have been established:

- As it is necessary to consider the viscous drag resistance effects near to the resonance condition, a linearized heave damping coefficient has been added to the hydrodynamic one.
- The energy extracting device has been schematized as a linear absorber acting on the vertical motion.

In these hypotheses the total damping coefficient has been obtained as the sum of three terms:

- a) the energy irradiated by the body,
- b) the energy dissipated for viscous effects,
- c) the useful energy absorbed by the device.

EFFICIENCY OF THE EXTRACTING DEVICE

The mean power transferred by a sinusoidal wave of height H and period T through a vertical strip of unit width is:

$$P = \frac{\rho g}{16\pi} H^2 T f$$

where

$$\begin{aligned} f &= 1 \quad \text{in shallow water} \\ f &= 0.5 \quad \text{in deep water} \end{aligned}$$

The total energy (kinematic plus potential) transferred in a period T is:

$$E = PT$$

The total theoretical annual energy content in a geographical area is easily evaluated when the distribution of the number of waves (N_{jk}) into classes of H_j and T_k is obtained.

So the total annual incident energy is:

$$E_i = \frac{\rho g^2}{16} \sum_j \sum_k H_j^2 T_k^2 N_{jk} f_k$$

For each wave of characteristic H and T the energy absorbed by a machine with a linear absorber D_M is:

$$E_a = \frac{2\pi^2}{T} D_M X_3^2 \quad (\text{in one period})$$

where X_3 = vertical motion amplitude.

If the system response is evaluated for the complete distribution of the waves (H_j, T_k), we can calculate the total energy extracted annually by:

$$E_a = 2\pi^2 D_M \sum_j \sum_k \frac{N_{jk} X_3^2 (H_j, T_k)}{T_k}$$

We assume as average annual efficiency of the system the ratio:

$$\eta = \frac{E_a}{E_i} = \frac{\text{Total annual extracted energy}}{\text{Total annual incident energy}}$$

where E_i refers to a wave front equal to the dimension of the body along the crest elevation.

This efficiency is the principal parameter to perform a comparison between different systems.

RESULTS OF THE PARAMETRIC ANALYSIS

A parametric period of dynamic analysis has been developed with reference to a vertical floating cylinder connected to a device with absorption D_M relevant to the heave motion. The parameters taken into consideration are:

- radius of the cylinder (from 5 m to 40 m),
- draft of the body (from 2 m to 16 m),
- equivalent damping (D_M) of the device,
- distance between the equal components (two or more) of a system.

For all the calculations a water depth of 100 m has been assumed.

Single Body System

The calculations based on the diffraction theory have allowed us to take into account the effective forces and hydrodynamic coefficients for each body. In fact, forces, added masses and damping coefficients are variable with the body geometry and with the period (see Figures 6, 7, 8).

For each geometric configuration a parametric analysis of the efficiency in function of the linear absorbing device D_M has been performed to find the value of D_M corresponding to the maximum average annual efficiency.

The importance of a correct choice of the linear absorber D_M is confirmed by the results plotted in Figure 9. The maximum global efficiency for the system examined is 22.2% and is obtained for an adimensionalized damping value $D_M/D_0 = 0.625$.

In the plot of the efficiency versus T (see Figure 10) it can be seen that for $D_M/D_0 = 0.2$ the efficiency reaches a peak value of 39% for $T=9$ s, which is approximately the resonance period.

But, as shown in Figure 9, for the value of D_M/D_0 we have a low global efficiency (16%).

The curve of the global efficiency versus draft (see Figure 11), shows the existence of a maximum far draft = 3-4 m. Figure 12 shows also the dependence of the global efficiency on the radius.

For values of the radius greater than 20 m, the increase in the efficiency is very weak and the best zone seems to be between 20 and 30 m. Also in these curves for each value of the radius, the absorber D_M value has been optimized.

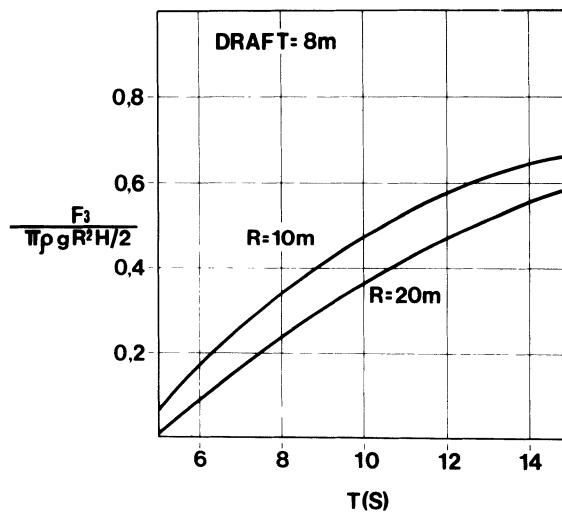


Fig. 6. Vertical force as function of wave period

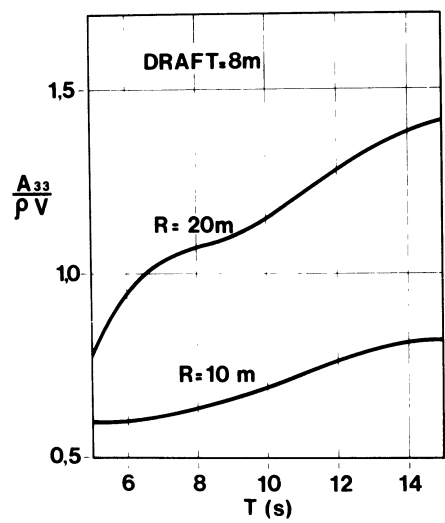


Fig. 7. Added mass as function of wave period

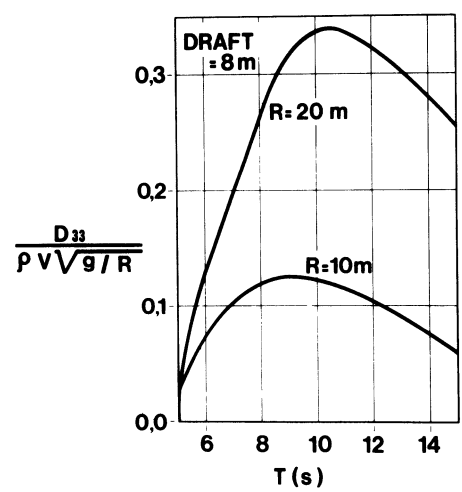


Fig. 8. Damping coefficient as function of wave period

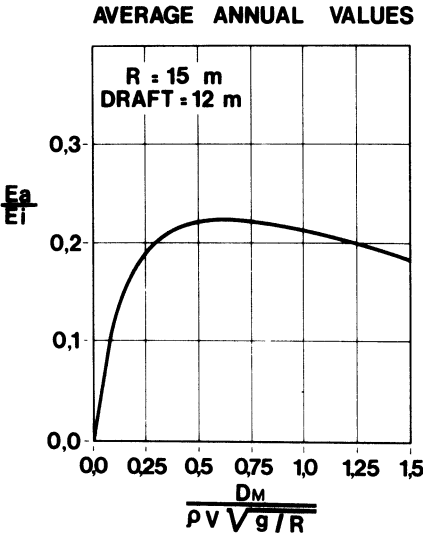


Fig. 9. System global efficiency as function of damping coefficient

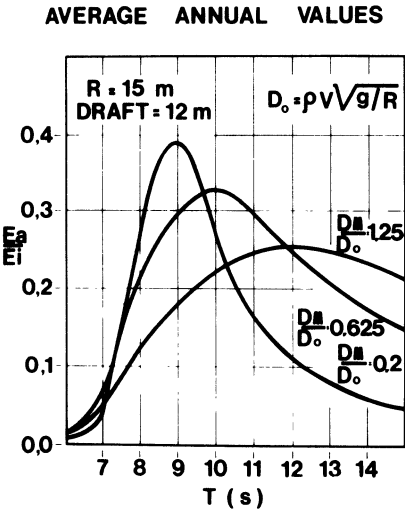


Fig. 10. System efficiency as function of wave period

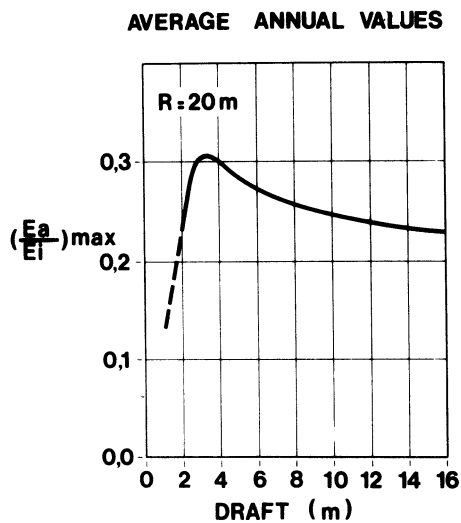


Fig. 11. Max global efficiency as function of draft

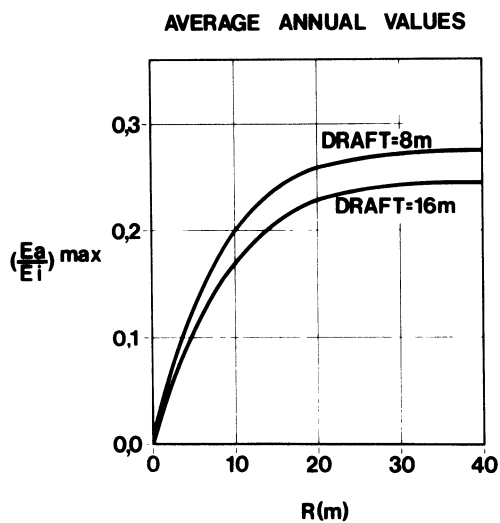


Fig. 12. Max global efficiency as function of radius

Multibody System

The results obtained for a system composed of two, three and four rigidly connected cylindrical bodies, are shown in Figures 13 and 14.

The overall efficiency is plotted as function of the mutual distance D , the maximum efficiency relevant to a single body system is also shown in order to make the comparison easier.

Figure 13 shows how the mutual interaction can increase the average global efficiency of each single component of a multi-body system; furthermore, the single body geometry being the same, an optimum number of bodies exists; in our case the maximum efficiency is obtained when the distance between the bodies is 15-25 m and for a three body configuration.

In Figure 14 the efficiency of such a system is shown as function of the ratio of the real mass M over that corresponding to the displaced volume (M_0). When the ratio is less than 1, the global efficiency decreases as the system is tuned mainly to the high frequencies where the energy content is scarce. On the contrary, when the ratio is greater than 1 we obtain the opposite effect as in low frequency bands the energy content is high.

The above results have confirmed that one of the most important problems concerning the extraction of energy from sea waves is a proper accurate parametric analysis to obtain the maximum efficiency by means of the diffraction theory. The main parameters which must be taken into account in this optimizing process are:

- typical dimensions,
- equivalent damping of the absorbing device,
- system composed of one or more components,
- number of the components,
- mechanical characteristics of the components.

The results shown in Figure 14 have demonstrated that an interesting possibility of optimizing consists in a device able to tune itself on the frequency of the incident waves. In this case it is reasonable that the global efficiency can increase to vary high values.

It is obvious that such a system will be analyzed from a technical point of view since, in order to realize a self-tuning system operating in a marine environment, it is necessary to solve a long hard series of problems concerning the reliability, the durability and the cost of the machine.

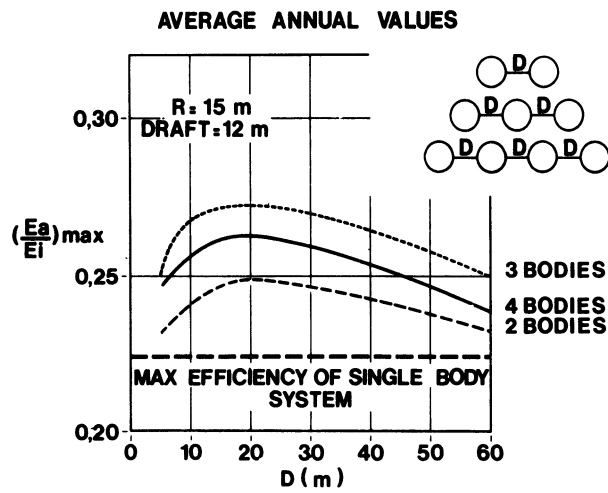


Fig. 13. Max efficiency of multi-body system as function of mutual distance

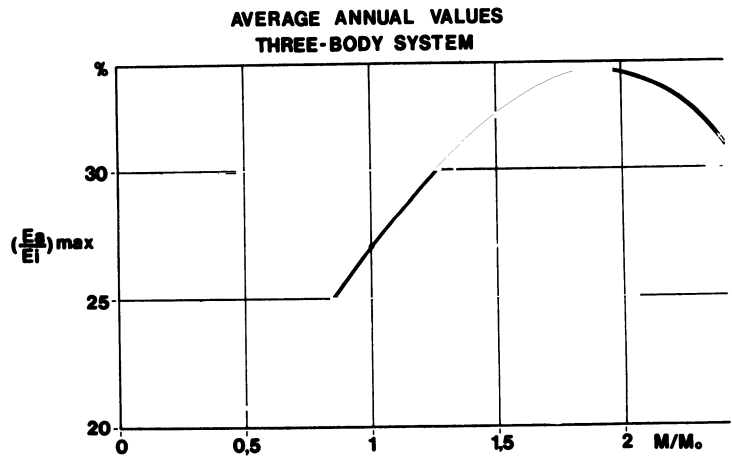


Fig. 14. Max global efficiency as function of the ratio of the real mass M over that corresponding to the displaced volume (M_0)

ECONOMIC ASPECTS OF WAVE ENERGY PRODUCTION

The cost per KWh of the power generated by various wave energy devices under given nominal conditions will be presented in the following.

Besides the cost level as such, there are some further aspects which must be considered due to the specific features of wave energy power.

Wave energy is a "low quality" energy due to its varying and uncontrolled occurrence, and often, also, its remote location. Some of the advantages and disadvantages of wave energy generated power are the following:

- The uncontrolled occurrence makes supplementary power supplies necessary.
- Adjusting the irregular output to an existing distribution grid is relatively expensive.
- The variations are too big for direct power supply to most types of offshore processing plants; hydrogen production via hydrolysis is probably the only one able to accept these variations.
- The production increased during the winter season when the demand is also higher.

Since wave energy is always of very low density, the size of any device tends to get very big and consequently, expensive in relation to the power that can be expected.

The cost of the structure will always be much higher than the cost of the power generating equipment. A device with an acceptable cost situation must thus have as little as possible static structure and essentially work on dynamic principles.

This aspect may be visualized by a simple calculation. If the energy available is 50 KW per meter crest length, and assuming 15% excess loss and 35% total efficiency, about 15 KW/m can be generated.

If the approach is taken that the device may cost as much as a typical hydro-electric plant, about 700 \$ US per mean KW, some estimates may be made of the acceptable cost of the structure. If the cost of the power generation, transmission and mooring of the device is assumed to be one third of the total cost then about 450 US \$ per KW may be spent on the structure; the structure cost per meter crest length may be $15 \times 470 = 7000$ US\$.

If the structure is built in steel at a cost of about 1800 US\$ per ton, a one-meter section of device may contain as a maximum

$$= \frac{7000}{1800} = 4 \text{ tons of steel.}$$

This obviously rules out all devices containing large pontoons or other floating devices the main dimension of which is a full wave length, if they are to remain stationary. Only devices based on the principle of moving the waves have some possibility of satisfying this weight target criterium.

Such considerations show that it is very difficult to find configurations having a sufficiently small cross section but still able to absorb the power. The studies presented here clearly show how important the weight and cost of structure are for the overall result.

For certain types of devices there may be a scale factor limiting the economic size of the device. Device buoys which, when scaled up under given wave conditions grow three-dimensionally will produce a cost increase almost in proportion to the third power of the size whereas the wave absorbing capacity increases only in proportion to the size. Moderately sized units in larger members may therefore be more feasible than very large ones.

ECONOMIC EVALUATION OF A WAVE POWER PLANT

A procedure of calculation has been utilized to evaluate the conditions of profitability of some sea wave energy plants, or better, to determine the minimum conditions for which the investment is capable of yielding an interest at least equal to the minimum acceptable net rate of return. The following hypotheses are valid as input:

- Average annual available power 36 KW/m (North Sea)
- Overall efficiency 35 %
- Operating life of the plant 10 years
- Time required by design, building, installation 2 years
- Maintenance and operative costs 10 % of the investment per year
- Over-head costs 1 % of the investment per year

The total estimated investment, per meter of wave crest, will range within 20,000 ÷ 60,000 \$/m of wave crest.

The results obtained show that the above-mentioned profitability conditions are satisfied only if the sales price of the energy at the production start-up is superior to 10.5 ¢/KWh, assuming a nominal investment of 40,000 \$/m. Table 5 shows a forecast of the cost of

solar, nuclear, and coal-burning energy (Ref. 3). The estimated costs of all these sources of energy exceed 10 ¢/KWh, should the production start in the year 2000. This allows us to assume that the sales price of KWh will reach that level by the end of this century, also making a profitable exploitation of the sea wave energy.

CONCLUSIONS

Although the principle of the wave energy conversion concept was proposed more than a century ago, many scientific, technical and economic aspects still have to be clarified before any industrial development can be seriously envisaged.

Today many ideas and projects are emerging and have been proposed in various parts of the world. However, it is necessary to emphasize that the conclusions so far reached have to be considered as provisional since this brief analysis still needs to be assessed in the proper economic and political perspectives.

From a structural/constructional point of view wave energy systems in general offer the possibility of using various steel and concrete products selected on the basis of an optimal assessment of labour, materials and energy costs. Although quite a large number of potential sites for wave energy conversion systems around Europe are mentioned in the literature, only a few sites exhibit a sufficient energy content and are located in areas suitable for possible industrial operations.

Furthermore, it is possible to identify additional potential sites that require further wave data collection and processing before any definite conclusions can be reached.

In general we have the feeling that at the present stage of development, industry and specialized societies could use their experience and competence in order to assist and to cooperate with universities during the development and fulfillment of their programmes. Such an approach would provide an opportunity of each other direct access to first-hand, practical information and of becoming involved in the already existing research and development activities.

Table 5 - Comparison of Energy Cost

	Load Factor	ENERGY COST, ¢/kWh-e			
		Capital	Other ²	O & M	Fuel ³ Total
SOLAR					
1975 START-UP	0.54	4.29	3.60	0.92	0.30 9.1
2000 START-UP ⁴	0.54	5.67	4.76	1.15	0.57 12.1
NUCLEAR					
1975 START-UP	0.55	1.08	1.17	0.23	1.17 3.7
2000 START-UP	0.70 ⁴	4.19	4.55	0.23	1.47 10.4
COAL					
1975 START-UP	0.62	0.93	0.96	0.39	2.85 5.1
2000 START-UP	0.74 ⁴	3.70	3.84	0.48	5.74 13.8

1. 1975 DOLLARS

2. OTHER INCLUDES INSURANCE, PROFIT, TAXESETC.

3. FOR SOLAR PLANTS, FUEL INCLUDES BACKUP CAPACITY AS WELL AS FOSSIL FUEL REQUIRED FOR MARGIN

4. IMPROVED LOAD FACTOR ASSUMED POSSIBLE BY AD 2000

NOMENCLATURE

A_{33}	Heave added mass for single body system
C_D	Drag coefficient
d	Draft
D	Mutual distance of two bodies in a multi-body system
D_M	Device damping system
D_{33}	Heave damping coefficient for a single body system
D_0	$\rho V \sqrt{g/R}$
E_a	Absorbed energy
E_i	Incident energy
f, f_k	Incident energy factor
g	Gravity acceleration
H, H_j	Wave height
K_a	Dimensionless wave number
M	Real body mass
M_0	Body mass, corresponding to the displaced volume
n_j	Surface generalized normal
N_{jk}	Number of waves into classes of height H_j and period T_k
R	Radius of the body
s_j	Motion amplitude ($j = 1, 6$)
T, T_k	Wave period
V	Displaced volume
η	Average annual efficiency
ρ	Mass density of water

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THE ROLE OF ELECTRIC SYSTEM IN THE DIVERSIFICATION OF ENERGY

SOURCES

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1. GENERAL REMARKS

As you know I work for a big electric utility; therefore I apologize for viewing energy problems as a specialist in electricity, which plays today in the energy system an important role of energy carrier from the source to its final uses. In opposition to those who see in electricity and the electric system a barrier to the introduction of new possible power generation and consumption models, capable of coping with the energy crisis, I see in them a fundamental tool to solve this crisis. Electricity can contribute to energy source diversification and thus exploit energy sources alternative to oil and gas. It is useless to remind the reasons why nuclear energy can be used today only by converting it into electricity. This is perhaps the major fault of electricity: to make the use of nuclear energy safe, economic and possible. But, even if our society wishes to throw away the great possibility that nuclear energy offers to solve the energy crisis, a possibility that he secured with his ability and his work, I do not see why he should throw away electricity too. On the other hand, coal, the other large alternative source, has some trouble in replacing oil and gas in the majority of current applications due to its difficult handling and combustion; therefore it must be transformed into fluid or more economically must be converted into electric energy in large power plants. Solar energy, the third alternative source, seems to be the only large source that can be used without using the electric carrier, because it is everywhere available, and can be converted into a suitable form wherever desired. The other un-transferable energy sources (like hydroelectric, high-enthalpy

geothermal, wind energy and other renewable sources) hardly ever find an immediate utilization on the spot and can thus be used only through electricity.

However, what makes the electric carrier particularly interesting with regard to source diversification, is the fact that all energy sources can be made accessible to the electric user.

This characteristic is very significant. In fact, if a variation in the policy of source utilization involves a modification in the small and numerous units using such sources, this modification would be difficult to carry out and only on a long-term basis. The reason for this is that substantial alterations in extensive service structures and, above all, a change in the habits of millions of people would be necessary.

The diffusion of electric users thus allows maximum flexibility in the policies of source differentiation, always provided, of course, that the electric user makes a proper use of this high-grade energy.

Let's go back for one moment to solar energy and to its gift of ubiquity, which makes it possible to replace oil and gas in small thermal utilizations like home heating.

Evidently, in this case, the use of an electric carrier would be neither necessary nor, especially, advantageous. In fact, the direct conversion of radiant energy into heat takes place with a good efficiency in relatively simple and economic apparatus.

Similarly, one can think of converting solar energy into electric power to supply the conventional electric power users in situ, possibly be combining generation of electric power and heat. The idea which naturally follows is an electric system which resorts to a myriad of small generators, rather than to large generators which feed a myriad of small users.

Such philosophy is feasible even when the primary source of small thermal users is not the sun but conventional fuels or, better, local fuels (like biogas, waste, etc.); in this case, small combined production of power and heat may contribute to equip our system with small distributed generations.

The interest in this type of distributed generation system is based in part on pretended large savings that could be obtained in the design of the transmission and distribution network and in its management or, even more hypothetically, in the elimination of such network.

On the other hand, an economic operation of such a distributed system requires an electric system performing some unreplaceable auxiliary functions.

These functions are:

Reserve

In order for the local electric energy units to guarantee the levels of continuous supply required today, they should have reserves which would excessively increase their costs. By making the reserves available anywhere, the electric system can enable a high utilization of such reserve and thus lower costs enormously.

Integration of Loads

Individual power requirements generally have a very irregular pattern over time and different from one another. Their integration thus allows a more regular demand thereby increasing utilization of the power-producing units and sizeably lowering their cost.

Integration of Generations

The different generation systems involved in a diversified system of energy sources can be to a greater or lesser extent restricted in their production by external conditions (astronomic and meteorologic factors of various nature for hydroelectric, wind and solar energy), heat production needs in heat productions, combined productions, etc.; or by economic conditions of better exploitation.

It is evident that through the integration of sources, it is possible to obtain enormous savings both as regards plant design and operation.

Storage

Significant efforts in energy storage are essential in a system that is based on energy sources dependent on astronomic and meteorologic events. In effect, the electric system enables one to obtain such storage in the most favorable conditions, freeing the storage systems of location constraints.

Therefore, distributed generation is a sound idea but cannot be paid by eliminating the electric system; it follows that the size and the number of generating plants is a pure matter of conversion cost.

After these general remarks on the present validity of electricity and of the electric system in the framework of energy crisis,

my lectures will be divided into three main topics.

First, I will discuss the consumption of the basic resource for the production of electric power. Then, I will deal with competitiveness comparison between energetic technologies related to electricity. Finally, I will deal with storage of mechanical and electric energy as a basic problem in energy conservation.

2. BASIC RESOURCES FOR ELECTRICITY

Introduction

The events in the last decade, referred to as environment and energy crises, produced several changes in engineering thinking habits.

One of the most evident aspects of these changes is the lack of confidence in economic optimization as a basic decision tool, capable of ensuring the best management of resources. An attempt was made to find a replacement of this decision tool in the large, universal, macro-economic models. But, because of their complexity, they risk to remain centralized tools in the hand of a cultural elite while they cannot be conveniently used by the great number of technologists, engineers and researchers for checking the solutions under study.

Today, therefore, in the energy debate somebody says that a given way of producing or consuming energy is "appropriate from the energy viewpoint" or "appropriate from the environmental viewpoint"; we are less interested in the fact that such a way of producing or consuming energy is "appropriate" in economic terms.

This is misleading, makes choices highly debatable, and generates difficulties in understanding the mutual positions; moreover, it determines a cleavage between innovative thinking and reality since our system rewards only economic choices.

Minimum Resources Utilization Criterion

To revalue economic optimization as a resource tool, we should consider that any product and any service supplied to man consumes or utilizes other products or services; but at the beginning of the chain we always find the following three basic resources (fig. 1):

- raw materials,
- labor,
- environment and land.

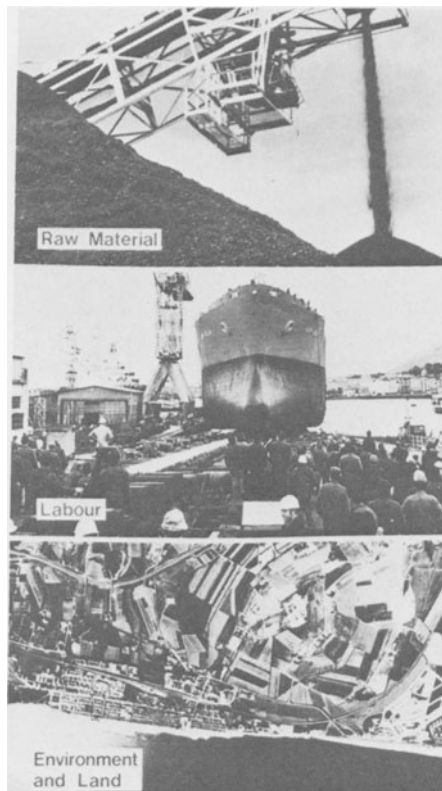


Fig. 1. The three basic resources.

As it is possible to secure the same product or service by using different combinations of these resources and since they are available in limited amounts, it is absolutely necessary to choose the approach which minimizes their use on the whole.

To get a minimum overall use of so different quantities, it is necessary to measure them with the same unit; this unit has been money for centuries and the minimum operation is called economic optimization (fig. 2).

The universal value of this logic tool is unquestionable. On the other hand, we realize that long-term choices made exclusively in current economic terms may involve big strategic errors. Indeed, the current prices of some basic resources (such as land or energy resources) may be inadequate for their value and not take into account their progressive exhaustion.

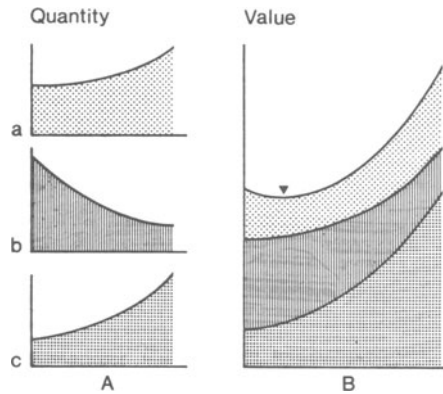


Fig. 2. Each product or service uses a different combination of the three basic resources: raw materials, labor, environment and land (a); to get a minimum overall use of these resources, they must be measured with the same unit, money (b).

While it is absolutely undesirable to neglect the economic optimization criteria, we should, in economic evaluations, give the money value a more general meaning, which does not necessarily correspond to the current price.

For instance, if we are afraid that the market value of a given resource (e.g. oil) is unsuitable in relation to the consequences of its consumption on the balance of payments, it is unwise to drop any economic assessment and to limit ourselves to energy assessments. It is preferable, once again, to make use of economic assessment assigning such resource with a fictitious strategic value accounting for the dreaded consequences.

The Gradual Penalization Approach

These criteria must be applied also to the resources which are generally considered as not quantifiable and economically appraisable.

A topical question concerns today the measure and the economic evaluation of the environmental alterations brought about by the energy conversion, transmission and utilization system.

To this aim we have to set aside present criterion of strict limits to environmental alterations and replace it with a gradual

strategic penalization corresponding to the effect brought about by each alteration.

The usual present method consists in fixing strict limits beyond which the environment is regarded as altered and below which the alteration is regarded as non-existent.

Though such simple and accessible criterion proves handy in solving possible disputes between utilities and control authorities, it is rough and unsuitable to optimize the use of limited resources available.

In effect, in some cases the possibility of reducing an alteration below the limits is disregarded, even when feasible with a modest use of other resources; in other cases a remarkable use of resources is likely to be necessary to reduce an interference even slightly, but below the conventional limit.

It is worthwhile to spend a few words to show how gradual penalization could work in the electric energy system.

Considering that the nuisance due to the polluting effluents of a power plant (or that due to the impact of a high voltage overhead line) reduces land useability for a given purpose and the extent of such reduction depends on the extent of the nuisance, we propose to associate each level of nuisance with a penalty factor which reduces the worth of the land (fig. 3).

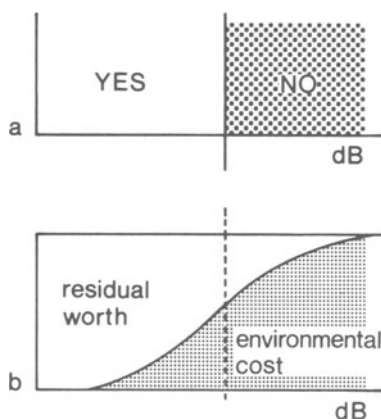


Fig. 3. Comparison between the present "strict limit" method and the "environmental cost" method: a) above the limit the environment is regarded as altered and below the limit the alteration is regarded as non-existent, b) a gradual penalization corresponds to the environmental cost.

Since the same environmental effect produced by the line has different consequences depending on land utilization, such utilization conditions the assessment of these penalty factors. It will thus be necessary to work out an appropriate classification of the land into categories.

Of course, the assessment of a gradual penalization to be assigned to a given measurable nuisance is at present highly arbitrary, but no more than the choice of a limit.

Having determined the penalty factors for the various nuisances and for each land category, they will be suitably added up to obtain an overall penalization factor that enables one to evaluate the loss of the land value brought about by the power plant or by the overhead line. It will thus be possible to determine whether a measure taken during the design stage to attenuate the disturbing effect, and which causes a certain increase in the plant cost, is offset by a lower land devaluation.

Further research and experimental work have to be done with a special emphasis on the evaluation of land (or water, air quality, etc.) worth reduction due to each environmental alteration, in order to achieve an acceptable assessment of this criterion.

Universal macroeconomic models, mentioned before, may help to set up this kind of strategic pricing.

Analysis of Basic Resources Content of Electricity

We are working in order to verify if the application of such criterion is feasible in the energy sector. For the time being, due to the lack of many data and to the difficulties in assessing environment penalizations, it is impossible to use them in making choices; anyway, along these lines, it is possible to shed light on some basic points which govern energy policies.

For instance, when we speak about energy conservation, do we realize which basic resources we want to conserve energy among raw materials, environment and labor? In fact, all actions proposed to conserve energy consume a mix of basic resources; to be able to judge among different actions we have to know the basic resource content of the various forms of energy.

In this first lecture, I will limit myself to illustrate an analysis of the basic resource content of the various forms of energy which range from crude oil to electric energy supplied to domestic users and generated in thermal power plants.

This analysis starts from a first evaluation of basic resources, based on 1977 prices, for raw materials and labor and is regardless of a direct incidence of environmental costs (even if this evaluation reflects today's environmental difficulties through some prices for raw materials).

Fig. 4 indicates the basic resource content of energy in all

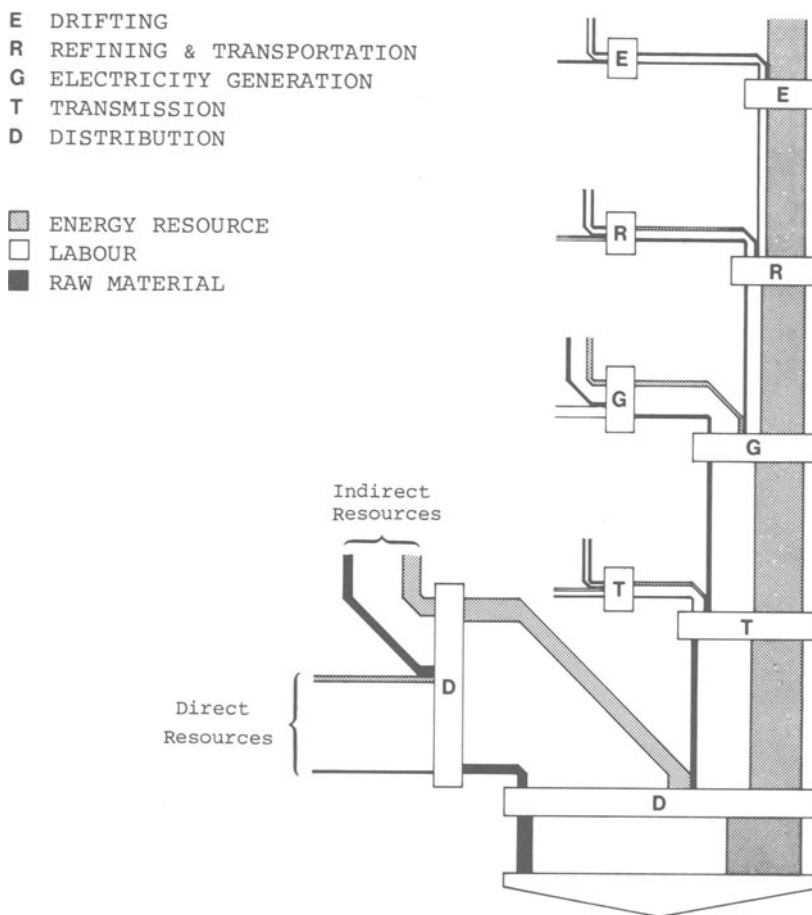


Fig. 4. Basic resources content of electricity produced from crude oil. At each stage, the upper share is referred to indirect resources, while the lower share is referred to direct resources. No environmental penalization considered.

the forms considered, i.e.:

1. crude oil
2. fuel oil
3. electric energy at the power plant
4. electric energy supplied to large industrial consumers
5. electric energy supplied to domestic users.

These energy forms are obtained through the following processes:

- extraction
- refining
- electricity generation
- electricity transmission
- electricity distribution

In this first picture, the basic resources are quoted on the base of actual market cost. Conventional environmental costs are therefore disregarded.

Since, among raw materials, the energetic raw material is of special interest, in our analysis it was particularly evidenced.

We extended the analysis of basic resources also to the numerous raw materials (steel, aluminum, cement, etc.) involved at the various stages; therefore, for instance, in fig. 4 the share of labor and energy resource used in the manufacture, transport and processing of steel used in electric transmission appears aggregated with labor and energy resources involved in the whole transmission stage, while the pure raw material share is represented by the market value of raw materials (coal, iron) used in steel manufacturing.

It is important to note, at this stage, how in this diagram we assigned a value to the energetic basic resource.

We deducted from the final crude oil market price, including royalties of the producing country and taxes of the importing country, the costs for extractions and transport to refinery, which were evidenced as consumption of labor, energy resource and non-energetic raw materials.

Since the crude oil extracted has a market value related only to quality and not to difficulty and cost of extraction, with an assessment of this type the value of the energetic raw material is lower where the extracting costs are higher.

This produces some difficulties in the parametric analysis as a function of resource value; for this analysis, we should necessarily refer to the value of extracted resources but with a given origin.

In fig. 4 we refer to an oil with a relatively high extraction cost (North Sea oil).

When dealing with economic evaluation, capital is currently considered as a basic resource; in our analysis, we take it into account by considering its influence in each process in terms of the above defined four basic resources.

At each stage of the energy conversion and transmission chain the content of resources increases; such increase is determined by an amount of resources directly consumed in the above process (lower share of the input resources at each stage; see fig. 4) while another part is consumed only indirectly (upper share). The indirected resources are those necessary for building the plant and the tools required for carrying out the processes (extracting or drifting equipment, transport means, refineries, electric power plants, lines, etc.).

Of course, it is evident that at each stage the energy process must include only a share of the resources consumed to build the relevant plant; this share financially corresponds to the depreciation charge of the plant during its lifetime.

But it is also appropriate to take into account the fact that we must penalize somehow any earlier consumption of resources in relation to the actual period of use of the energy produced; this financially corresponds to the application of an interest rate on capital.

It could be discussed about the application of this penalization and if this must be applied only to labor or even to raw materials; anyhow we applied it to the basic resources, in a manner variable but equal for all of them; in particular, in the diagram of fig. 4, it is applied at 5% per year.

The content of energetic resource in the electric energy supplied to domestic users is modest; to conserve energy at this level means to save labor rather than energy resource. Obviously, the situation of energy at fuel-oil level is quite opposite; here, indeed, any saving regards mainly the energetic raw material.

For electric power at generation or large industrial consumer level, the situation is intermediate with an almost equal share between oil and labor.

Starting from this analysis, it is possible to see what happens if we assign the energy resource a strategic value higher than the market value, so as to decrease its consumption in view of its exhaustion. Fig. 5 represents a borderline case where the price of

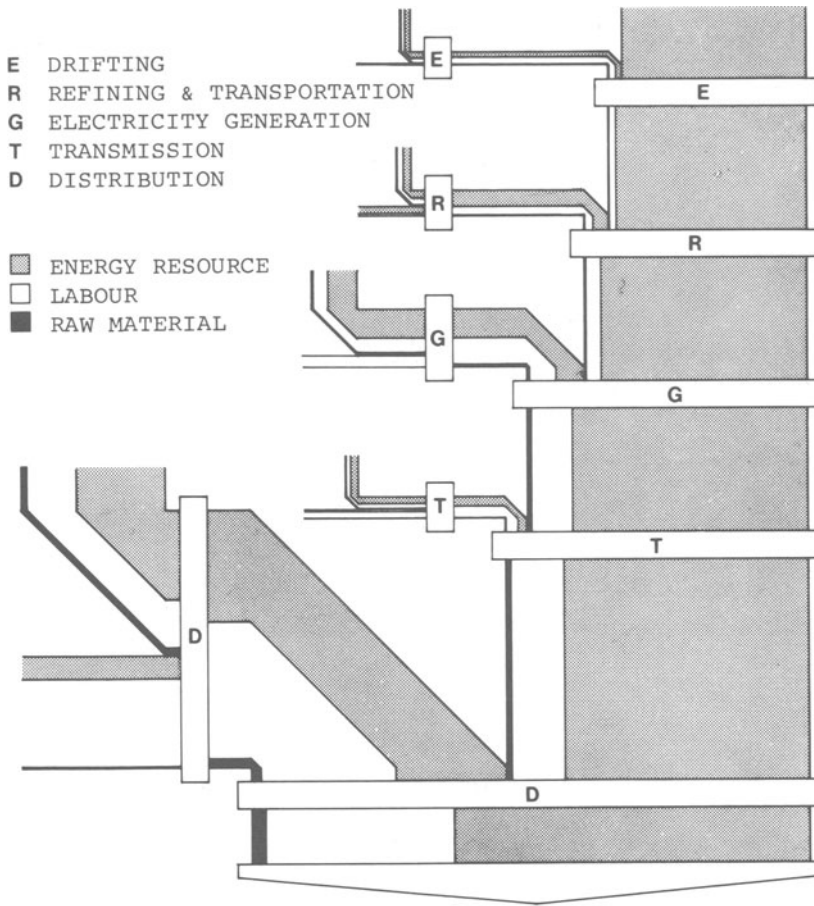


Fig. 5. Basic resources content of electricity when energetic raw material price is increased 5 times more than labor and other materials.

energy resources is increased 5 times more than labor and other raw materials. In this situation, energetic raw materials are prevalent even in electricity at domestic users.

Such an increase in energy resource value automatically entails the use of other energetic raw materials more available than crude oil, but which imply a higher use of other resources and namely

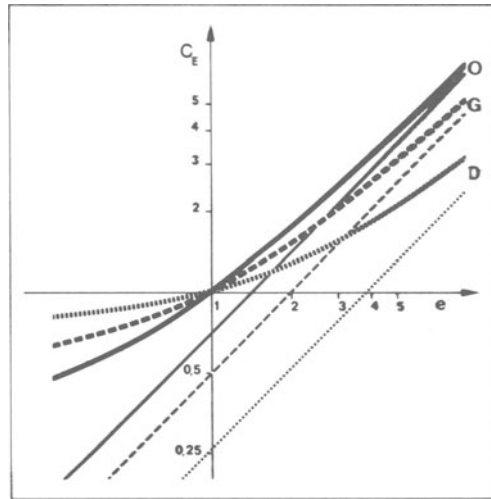


Fig. 6. Energy cost C_E at Oil, Generation and Distribution stages plotted versus e , which is the ratio of energy resource unit value to the unit value of other resources.

labor for extraction, handling, and conversion into electric energy, such as oil shale, coal or nuclear energy.

It can be concluded that as we increment the energetic raw material value, electric energy is bound to consume more and more labor resource.

This conclusion is supported by Fig. 6 where energy costs at the various stages are plotted against the ratio of the energy resource unit value to the unit value of other resources (labor and other raw materials).

The consequences of these variations are less evident when getting further from the primary source in the conversion and transport energy chain.

Electric energy at distribution level is indeed much less sensitive to the cost of energetic raw material than the fuel oil.

It is also interesting to see what happens when varying the penalization due to earlier resource consumption (interest rate).

Fig. 7 shows: a) the variation with interest rate of the percentage of total cost due to energy resource at the various levels; b) refers to the case of an increase for the energy resource five times higher than that of other resources.

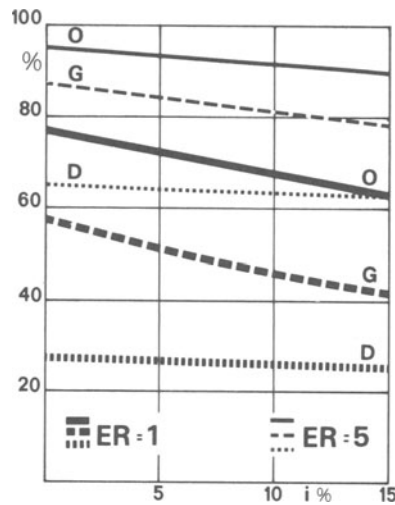


Fig. 7. Percentage of total energy cost due to energy resource at Oil, Generation and Distribution stages as function of interest rate. Thicker lines refer to the case of energetic raw material price increased 5 times.

The Assessment for a Penalization for Environmental Deterioration

All the above is independent of the environment resource; no doubt that energy consumption is seen with concern in view not only of primary energy sources exhaustion, but also of land occupation and environment deterioration, which today represent the major constraints to the development of electric power systems. And here the problem becomes much more difficult; in effect, the environment and land resource is hardly quantifiable in absolute terms. Only for complete land occupation can a useful market evaluation be resorted to.

When the environment surrounding the plant is in some way altered and quality and useability of the land resource is reduced, the assessment of an economic penalization becomes much harder; in some cases this can be done by quantifying the damage caused; in other cases evaluating the reduction in the land market value, but often it is necessary to introduce a conventional penalization.

Furthermore, when the environment disturbance has a negligible local effect but contributes, even to a minor extent, to affect the present general balance of our biosphere (like the increase of CO_2 density in the atmosphere due to combustion processes) only

conventional penalization can be used.

Similar approach applies when account must be taken of very low risks of very dangerous accidents (like the evaluations of the consequences of a serious accident in the operation of a nuclear power plant).

However, even when the choice of the environment penalization values is highly arbitrary, the penalization criterion is still valid; if we conventionally establish the penalization value we will still make choices, perhaps not the best but certainly consistent with one another, and over time, we should be able to adjust the penalization value to satisfactory levels.

It is always possible to assume the economic value of an environmental alteration as a parameter in a sensitivity analysis, so as to examine the consequences of its different evaluation in the policy choices to be undertaken.

Evaluation of Environmental Cost

In order to assess the consequences of a given alteration, we must first of all measure it; this is often very difficult, as in the case of landscape alteration, which represents the most significant nuisance brought about by overhead transmission lines.

Table 1. Measure and Penalization of Environmental Nuisance

NUISANCE	DIFFICULTY DEGREE	
	MEASURE	ECONOMIC PENALIZATION
SPACE OCCUPATION AT GROUND	*	*
SPACE OCCUPATION OVERHEAD	*	**
IMPACT ON LANDSCAPE	***	**
FALLOUT OF HARMFUL EFFLUENTS	**	**
PHYSICAL AIR & WATER ALTERNATIONS	**	***
NOISES RADIOINTERFER OTHERS	*	**
GLOBAL ALTEPNATIONS	*	***

Table I reports the various nuisances to the environment caused by electric generation, transmission and distribution systems as well the degree of difficulty in both measuring and economically penalizing each nuisance.

Space Occupation

Space occupation requirements are easily determined considering the land which, because of system operation or for safety reasons, cannot be utilized for other purpose.

Space occupation cost can be easily determined from expenses for purchase of lands and right-of-way acquisition.

Impact on Landscape

This nuisance is today considered the most difficult to quantify; even if many proposals have been put forward, we feel that most seem to lack real self confidence in their effectiveness and therefore need further discussion and improvement in order to be commonly accepted.

A measurement of such alteration which we propose is based on the geometric evaluation of the occupation of the visual field by the disturbing element, corrected with some coefficients taking into account the extraneousness of the element in the landscape and other psychological effects that can be evaluated through opinion surveys.

Then we quantified the nuisance to the landscape with criteria very arbitrary in absolute terms but very accurate in relative terms for the different components of the electric system.

To give an idea of this first-hand assessment of nuisance to landscape, you may consider that the cost of this disturbance, attributed to the power plant of figure 8, was evaluated equal to about 10 times the purchase cost of land for its construction.

Polluting Effluents

We gave particular consideration to sulphur oxides emission; for fuel oil thermal power plants we derived the measure and the costs of such emission from the evaluation of the damages due to combustion processes over all the national territory and the definition of the share to be attributed to thermal power plants.

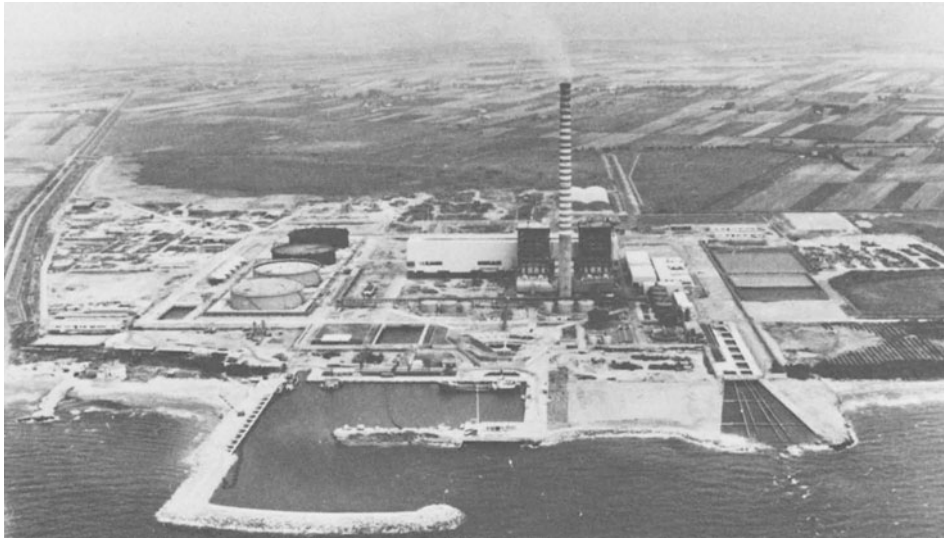


Fig. 8. Thermal power plant of Piombino (Tuscany) under construction.

Air and Water Alteration

Concerning environmental alterations introduced by cooling systems, we imagined that thermal power plants were water-cooled. As it happens, today nearly all of them in Italy are water-cooled, and consequently, there are no alterations in the physical conditions of the atmosphere. Further, we considered that in water-cooled power plants local effects of the water temperature alteration are today reduced to such levels that they do not cause damage to the aquatic environment. On the other hand, the availability of cooling waters highly restricts the possibilities of power plant siting; that implies the use of valuable land like the banks of large rivers and seacoasts which are often densely populated or exploited as touristic resort areas and when these areas happen to be completely wild for this very reason are likely to be protected as a natural wildlife sanctuary.

In other words this implies the use of more and more valuable land, that is more expensive environmental resource, which was taken into account in our assessment. Additionally, while on the seacoasts the availability of cooling water is practically unlimited, this does not occur on the rivers. Therefore, we deemed it right to quantify this type of resource in such a way as to make equivalent the cost of plant installation on the rivers near the load, and the

plant installation on the sea, far from the load: this was achieved by adding to river plant production cost the extra costs for energy transmission, from the closest seacoast, as a compensation cost for engaging the cooling water resource.

Minor disturbances like noise and radiointerference due to overhead lines were for the moment disregarded.

Global Alteration: The Problem of CO₂

As possible source of global alterations, at least CO₂ emission should be considered, since it appears the most controversial topic in the debate over the global balance of our biosphere.

The consequences of an excessive CO₂ concentration in the atmosphere are questionable and questioned; anyway, a conventional penalization per ton of CO₂ discharged into the atmosphere might be a tool for rationally limiting such discharge.

In our first approach analysis, however, we overlook CO₂ penalization.

The Influence of Environmental Cost

In fig. 9 the previously examined diagram is completed by taking into account environmental cost. We added to environmental costs relevant to electricity generation, transmission, and distribution, the costs to be charged to emissions in fuel refining. Also, the environmental damages linked with extraction and transport of crude oil should be considered. Unfortunately, at the present stage of our study we did not have sufficient elements for an evaluation, though conventional, of such costs.

Anyhow, the addition of environmental costs does not substantially alter the diagram, which seems to show a poor environmental component in the electric energy cost, quite disproportionate in view of the actual difficulties encountered in electric power plant siting.

Sulfur Oxide Emission

In order to check the validity of our approach, we report in fig. 10a the trend of the environmental cost assessment for sulphur oxide emission.

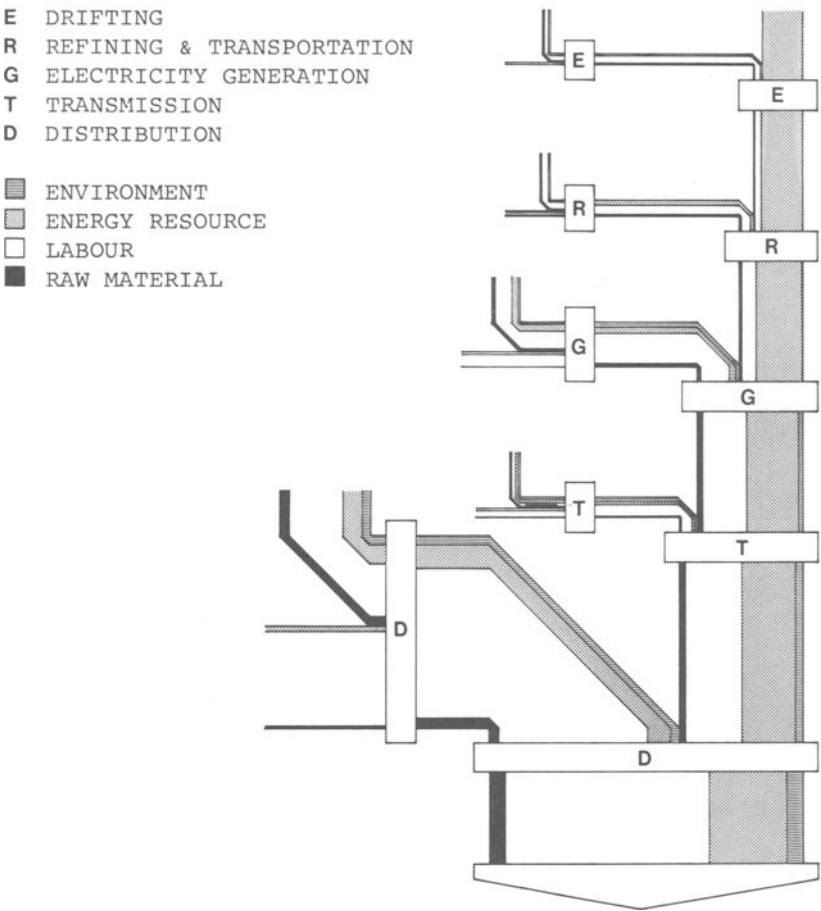


Fig. 9. Basic resources content of electricity with environmental cost.

The graph exhibits the cost of pollution control and the cost of environmental damage, assessed with the criteria so far proposed, as a function of the degree of SO_x pollution at ground. The total of the two costs with its minimum determines the most appropriate compromise between pollution control cost and environment deterioration. The pollution degree x has been adopted in the economic

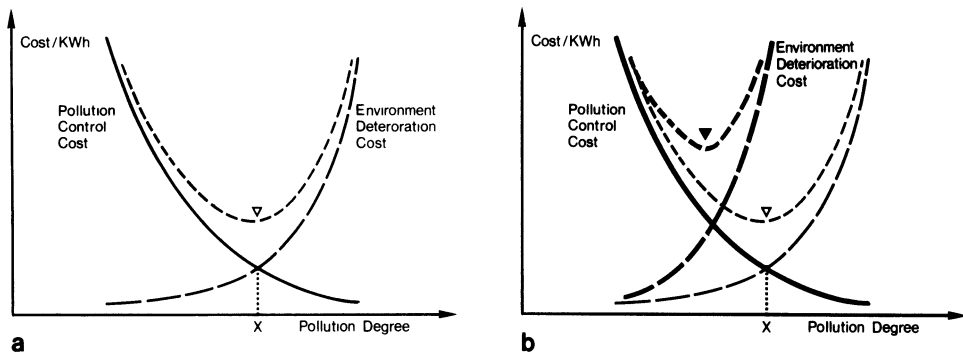


Fig. 10.

calculations of fig. 9. This pollution degree is considered as acceptable by the present Italian laws and the relevant environmental cost approximately corresponds to the above mentioned minimum of the total of the two costs.

Now, let's suppose that the cost (for kWh produced) which the community must bear for sulphur oxide pollution is in fact, due to a reasonable mistake in its assessment, five times higher. In this case (fig. 10b), the optimum pollution degree decreases to lower values. This implies more expensive control measures which would engage after all more labor and raw materials rather than environment.

Visual Nuisance

The choice of economic value of landscape nuisance is much more questionable. A significant increase of such values does not seem to correspond to present requirements. Indeed, the impression that the penalization is insufficient derives from a poor correspondence between the difficulties in building plants, namely power plants, and the penalization of environmental disturbances. An increase in environmental penalizations would affect more overhead lines than the power plant; on the contrary the major difficulties are concentrated on power plant siting.

On the other hand, no doubt that the most evident element of the power plant is the stack. Our evaluation criterion assigns to the stack about three quarters of the total power plant visual impact.

A reduction in stack height would drastically reduce the impact on the landscape, but increase effluents pollution. Now, stacks tend to increase rather than diminish in height and this could not occur if today the nuisance to the landscape were considered as extremely disturbing.

We could, therefore, think that a significant contribution to environment cost derives from factors which we neglected, i.e. from the environmental damages originating from extraction and handling of oil, or, but this is less credible, from CO₂ emission.

At any rate, we wanted to plot the diagram of resource mix also for an environmental unit cost increased 5 times (fig. 11).

We are thus in an extreme situation, at least by present standards, for considering the environment resources. Despite this fact, the environment resource used is still modest if compared with other resources and does not seem to represent the fundamental cost for electric power production from fuel oil.

This is strangely in contrast with the opposition of the public opinion which actually conditions the development of power plants and which largely aggravate the energy crisis. This leads us to think that this opposition, which is not so strong against other more evident and irreversible land uses is more linked with social relation problems than with actual land optimization ones.

At any rate, this type of analysis can serve, in my opinion, to clarify the aspects of this problem so important for our society.

At this stage, it would be interesting to effect the same analysis for different energy sources and to assess the advantages and disadvantages of the use of different energy sources, or of different ways of using energy, in view of different unit costs for environment and energy resources.

We do not yet have sufficient elements to do this, particularly as regards the environment resource.

In the next lecture, we will explore this topic with reference only to the cost of the energy resource, neglecting the problems related to the consumption of the environment resource.

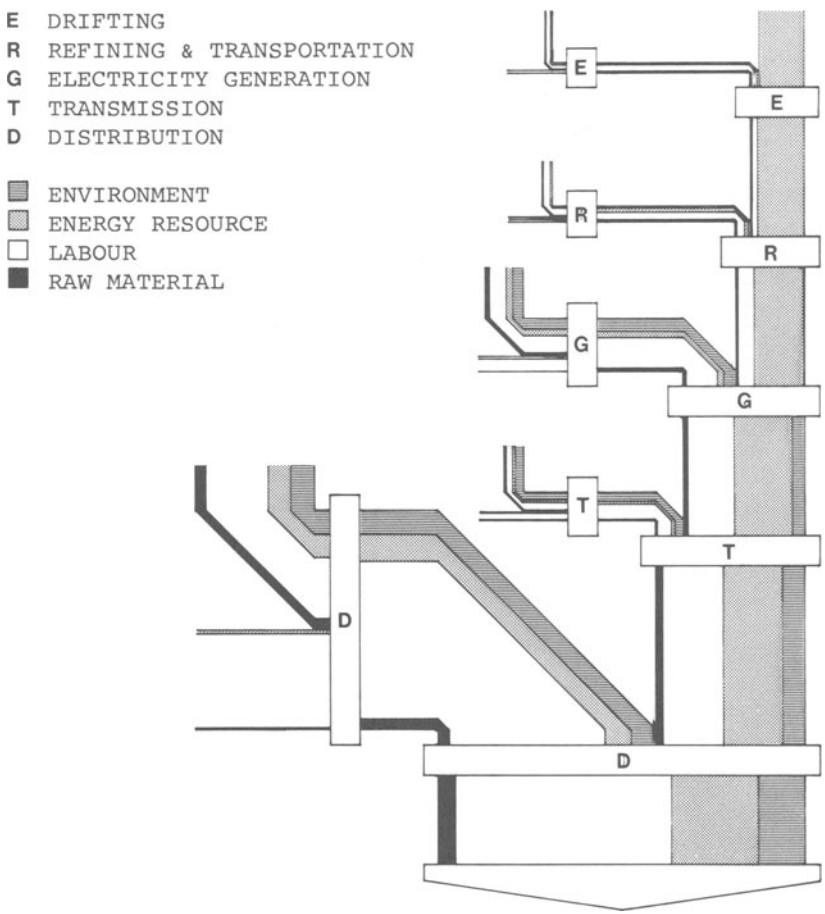


Fig. 11. Basic resources content of electricity with environmental cost 5 times higher.

3. COMPETITIVENESS COMPARISONS AMONG ENERGY TECHNOLOGIES RELATED TO ELECTRICITY

Introduction

In the previous lecture, we made some considerations about the validity of economic comparisons in energy choices. In particular, we recognized the need for making such choices by assigning to the resources a conventional money value which also accounts for the price these resources may reach in relation to their gradual exhaustion.

We described the difficulties of an integral application of the above mentioned method and we supplied numerical data above all with a view to envisaging results we would obtain by the application of the methodology under study. The aim of this lecture is, on the contrary, to give the results, strictly expressed in quantitative terms, of some evaluations made, in an extremely simplified way, on the basis of the above mentioned method.

The economic convenience of employing new technologies in the energy field is analyzed by supposing that fuel oil is still at the base of the energy economy and assuming as a variable the market price of fuel oil, expressed in actual goods (i.e. in constant monetary terms).

In particular, we aim at stressing the weight of the energy consumed for the construction of power plants, namely we aim at analyzing the phenomenon called "energy cannibalism."

In order to simplify this analysis, my exposition will be lacking in contents.

Moreover, I thought this study could give a contribution, even if a modest one, to the formation of a set of actual reference data, which are today so necessary to the economic assessments of new technologies.

The main cost items considered in competitiveness comparisons are listed in opposite tables, in order to give more weight to their reference value. All costs are referred to 1975.

The competitiveness comparisons will be made as a function of a parameter "e" representing the unit price of fuel oil¹ in constant monetary terms, using the 1975 average price as the unit. In other

¹Including the value of both the resource (crude oil), as defined in the previous lecture, and all the resources necessary to oil extraction, transportation, and refining.

words, "e" = 2 means that the price of fuel oil expressed in actual goods is twice that of 1975.

Today (September 1979) the value of "e" is equal to approx. 1.2, while at the beginning of 1973, prior to the energy crisis, it was worth about 0.25 (fig. 1). The analysis considers "e" values up to 10, even if an economy based on such high-cost primary sources would probably be too different from the present one for the extrapolations to be considered as valid. In fact, the average share of primary sources in the costs of the unit of product would be in the order of 40% (for "e" = 1 such share is in the range of 7% and for "e" = 0.25 less than 2%).

Figure 2 shows the trend, as a function of "e," of the cost of the basic kWh² produced through thermal power plants, using as unit the cost of the kWh corresponding to "e" = 1 (1975 prices). This trend takes into account the fact that not only fuel costs (curve a) vary with "e," but even capital costs do (curve b represents the total cost of the kWh). In effect, the power plant cost increases as the cost of the energy needed to build it increases (for "e" = 10 the power plant costs approximately 40% more than for "e" = 1). Nonetheless, the capital cost share becomes smaller and smaller as "e" increases, dropping from about 30% for "e" = 1 to about 4% for "e" = 10.

It could also be advisable to measure the competitiveness of auxiliary sources with nuclear production facilities.

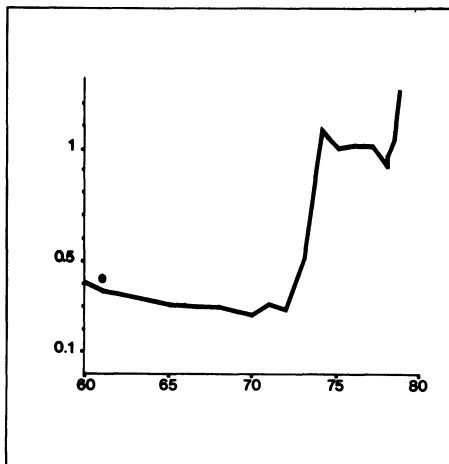


Fig. 1.

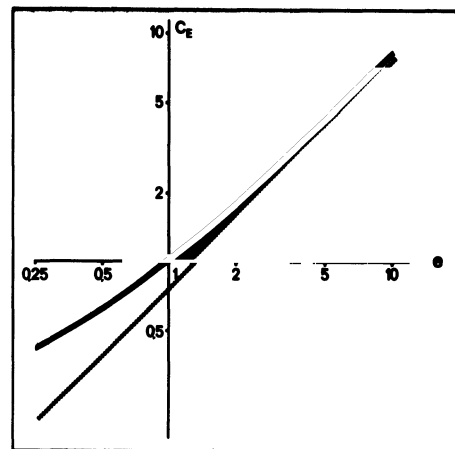


Fig. 2.

²Utilization duration 6,000 hrs./year.

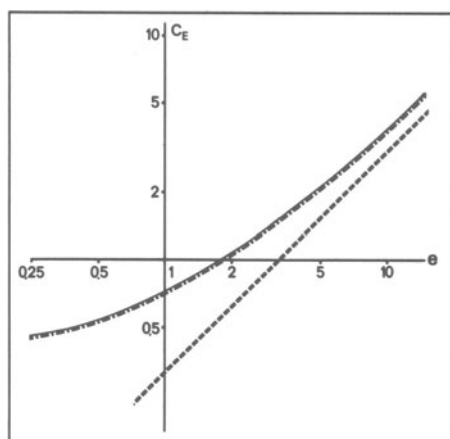


Fig. 3.

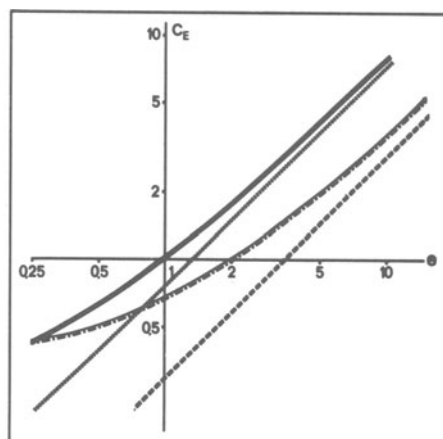


Fig. 4.

Figure 3 illustrates the cost trend of the kWh produced with lightwater nuclear power plants as a function of parameter " e_n ," i.e. of the nuclear fuel cost expressed in actual goods and relative terms.

Curve c represents the share of the nuclear fuel cost and curve d the total cost; hypothesizing that the nuclear fuel cost remains proportionate to the oil cost, $e = e_n$ and the two diagrams of Figures 2 and 3 are superimposable and costs comparable (fig. 4).

All following assessments are aimed at providing indications on the competitiveness of the techniques being studied.

Cost of Electric Power from Geothermal Power Plants

The geothermal power derived from vapor-dominated hydrothermal systems is already useable today in economic terms. Instead, the economic exploitation of water-dominated hydrothermal systems, which are much more frequent in nature, is highly conditioned by the salt content of the fluids found, which may make their utilization difficult and effluent disposal problematic.

Since a significant share of the cost of geothermal power derives from exploration and harnessing activities, whose cost is highly aleatory, it is possible to express the costs of electric power from geothermal power plants only with a wide range of values.

In the calculation of the cost of the geothermal kWh, capital costs will be considered as the sum of two components, one of which

includes the installation costs of the plant proper and the other the installation costs of the geothermal field (soundings, drillings, preparation of wells and pipelines to the power plant).

The installation costs of the geothermal field will be different according to the geological peculiarities of the geothermal system, depths and diameters of wells, characteristics of fluids, logistic situation, and several other factors.

In Table 1 there are indicated the extreme values expected in Italy and utilized to assess the cost of the geothermal kWh.

Fig. 5 indicates production cost estimates of geothermal energy that can still be found in Italy by means of traditional techniques and at average depths (not exceeding 3000 m).

As can be seen, geothermal electric power is competitive with thermal power plants when value of "e" is between 0.8 and 2.2.

The increase, which the cost of the kWh from geothermal power plants undergoes as "e" increases, is due to the fact that energy

TABLE 1: INSTALLATION COST OF THE GEOTHERMAL FIELD

INSTALLATION COST	300 $\frac{\$ (75)}{\text{kW}}$	1400 $\frac{\$ (75)}{\text{kW}}$
SURFACE EXPLORATION COST	18 $\frac{\$ (75)}{\text{kW}}$	18 $\frac{\$ (75)}{\text{kW}}$
WELL DEPTH	1000 m	2500 m
DEEP EXPLORATION COST (DRILLING)	280 $\frac{\$ (75)}{\text{kW}}$	500 $\frac{\$ (75)}{\text{kW}}$
RESERVOIR ENGINEERING COST	18 $\frac{\$ (75)}{\text{kW}}$	18 $\frac{\$ (75)}{\text{kW}}$
AVERAGE CAPACITY OF A WELL	2 MW	2 MW
STEAM PIPELINES COST	180 $\frac{\$ (75)}{\text{m}}$	180 $\frac{\$ (75)}{\text{m}}$
OTHER COSTS (STEAM SEPARATORS SCRUBBERS SILENCERS, ETC.)	—	11 $\frac{\$ (75)}{\text{kW}}$
REINJECTION WELLS	—	1 WELL FOR TWO PRODUCING WELLS
SUCCESS RATIO	0.7	0.6

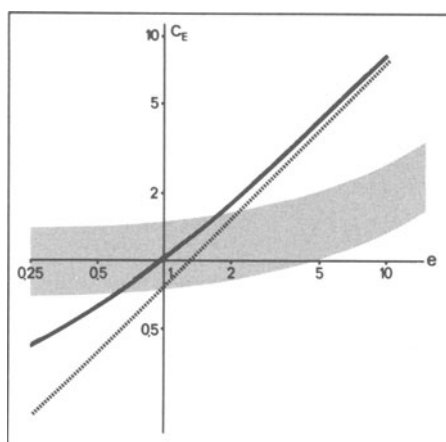


Fig. 5.

must be consumed to build and maintain the power plant. As a result, the costs increase as the cost of the primary source increases.

It is necessary to stress that, in these evaluations, we did not assign any value to the resource, as if it were inexhaustible or in any case a renewable resource. Actually, geothermal energy is not inexhaustible and it is a renewable resource only for a small part; in view of this fact, we should in effect assign it a given value. This would imply raising competitiveness toward a higher value of "e."

Cost of Electric Power from Solar Thermal Central Receiver Power Plants

As is known within the framework of thermodynamic conversion of solar energy for the production of electricity, central receiver power plants are among the plants which lend themselves best to offer significant capacities thanks also to the relatively high concentrations which can be achieved and to the possible scale economies in a mass production of heliostats.

In our calculations, we will refer to a power plant having a capacity of 10 MW connected to the network and therefore without storage units. In Table 2, there are indicated the main elements we considered to assess the cost of the kWh produced by such a plant. In particular, we considered a mirror field composed of 31 m² heliostats whose cost on site was estimated about 3800 \$ (75), corresponding to a specific cost of 570 \$ $\frac{(75)}{\text{kW}}$. This cost can be obtained only in mass production.

TABLE 2: INSTALLATION COST OF A SOLAR THERMAL
CENTRAL RECEIVER POWER PLANT

$$\text{INSTALLATION COST} = 1470 \frac{\$ (75)}{\text{kW}}$$

HELIOSTAT SURFACE	$4.6 \frac{\text{m}^2 \text{ OF HEL}}{\text{KW}}$	31 m^2 PER HELIOSTAT
LAND USE	$2.6 \frac{\text{m}^2 \text{ OF LAND}}{\text{KW}}$	$172 \text{ m}^2 \text{ OF LAND}$ PER HELIOSTAT
LAND SETTLEMENT AND CIVIL WORKS COST	$8 \frac{\$ (75)}{\text{m}^2 \text{ OF LAND}}$	$1400 \$ (75)$ PER HELIOSTAT
HELIOSTAT COST (INCLUDING SUPPORT AND CONTROL SYSTEM)	$125 \frac{\$ (75)}{\text{m}^2 \text{ OF HEL}}$ $570 \frac{\$ (75)}{\text{kW}}$	$3800 \$ (75)$ PER HELIOSTAT
RECEIVER AND CONCRETE TOWER COST	$170 \frac{\$ (75)}{\text{kW}}$	_____
ENERGY CONVERSION COST (MECHANICAL AND ELECTRIC MACHINERY, COOLING AND AUXILIARIES)	$450 \frac{\$ (75)}{\text{kW}}$	_____

Fig. 6 shows the costs of electric power produced with plants of this type provided that the amounts of electric power generated be such as to enable large-scale implementation of heliostats. Also in this case, costs increase with "e" as a result of "power" consumption needed to build the power plant.

To account for approximations in estimating the costs of the solar power plant components, a belt of values was considered, which is included between the value found (which is still regarded as a not easily achievable target) and a 30% higher value.

It can be noted that solar power plants are competitive with thermal plants only when oil costs are 5-7 times higher (in terms relative to other goods) than the 1975 costs.

As a consequence, solar power plants of this type, at least in our climates, belong to an energy scenario very different from the present one. In such a scenario a lot of other new technologies for facing fuel oil shortage would already have been more conveniently applied.

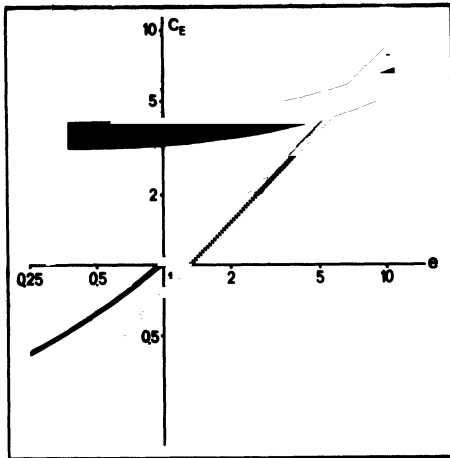


Fig. 6.

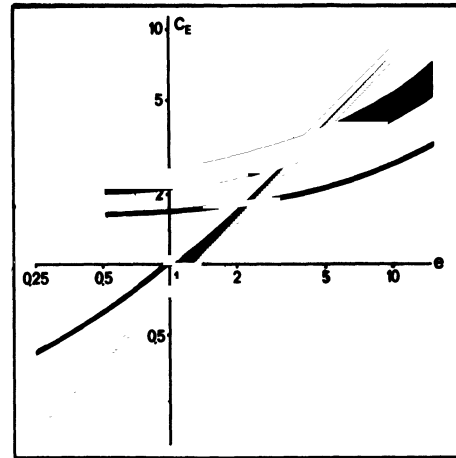


Fig. 7.

On the other hand, since no industrial country renounces to study the thermodynamic conversion of solar energy, energy scenarios of this type are believed possible sooner or later.

Cost of Electric Power from Photovoltaic Power Plants

In a preliminary study effected by ENEL within the framework of Progetto Finalizzato Energetica (Energy targeted project of CNR), the cost was assessed for a 10 MW photovoltaic power plant with mono-crystalline silicon cells ($\eta = 11\%$) without concentrators.

Table 3 summarizes the main elements we considered to carry out this study, for which we did not take into account the cost of photovoltaic cells.

To assess the costs of photovoltaic cell module, reference was made to the goals set by the U.S. Department of Energy for 1985 and 1990.

Fig. 7 displays the trend of the values determined above, which represent a belt of possible costs, as a function of "e."

As regards photovoltaic power plants, we have to consider that important conventional structures (such as structures supporting photovoltaic modules, wiring, power conditioning, etc.) are necessary and cannot be eliminated. At present, their cost is a considerable share of the overall photovoltaic power plant cost.

TABLE 3: INSTALLATION COST OF A PHOTOVOLTAIC POWER PLANT

INSTALLATION COST	1170 $\frac{\$ (75)}{\text{kW}_p}$	for 500 $\frac{\$ (75)}{\text{kW}_p}$	GOAL
	920 $\frac{\$ (75)}{\text{kW}_p}$	for 250 $\frac{\$ (75)}{\text{kW}_p}$	GOAL

MODULE (310 kW _p) SURFACE	10m ² OF MODULE kW _p	3.1m ² PER MODULE
LAND USE	35m ² OF LAND kW _p	11m ² PER MODULE
LAND SETTLEMENT AND CIVIL WORKS COST	4.5 $\frac{\$ (75)}{\text{m}^2 \text{ OF LAND}}$	50 $\$ (75)$ PER MODULE
SUPPORT AND SETTING UP OF MODULES COST	360 $\frac{\$ (75)}{\text{kW}_p}$	110 $\$ (75)$ PER MODULE
OVERHEAD CONNECTIONS COST	100 $\frac{\$ (75)}{\text{kW}_p}$	31 $\$ (75)$ PER MODULE
CONTROL APPARATUS COST	50 $\frac{\$ (75)}{\text{kW}_p}$	15.5 $\$ (75)$ PER MODULE
PHOTOVOLTAIC CELLS COST (DOE GOALS)	-500 $\frac{\$ (75)}{\text{kW}_p}$ -250 $\frac{\$ (75)}{\text{kW}_p}$	-155 $\$ (75)$ - 77 $\$ (75)$

To have an idea of how much the photovoltaic power plant without photovoltaic cells costs, the curve is also shown relevant to a nil cost of solar modules.

Cost of Electric Power from Wind Power Plants

We will carry out our assessments with reference to a mean-capacity wind generator having the characteristics shown in Table 4. To assess the cost of the kWh produced by wind power plants, we will refer to the available wind characteristics for some Sardinian areas where anemometric stations are located, assuming that sites are found for installation of power plants having corresponding characteristics.

TABLE 4: INSTALLATION COST OF A WIND POWER PLANT

INSTALLATION COST 940 $\frac{\$ (75)}{\text{kW}}$

RATED CAPACITY	875 kW	_____
RATED WIND SPEED	12.5 m/s	_____
ROTOR DIAMETER	65 m	_____
COST OF WIND GENERATOR	820 $\frac{\$ (75)}{\text{kW}}$	717,500 \$ (75) PER WIND GEN.
COST OF SWEEPED AREA	0.3 $\frac{\$ (75)}{\text{m}^2}$	

TABLE 5: DISTRICT HEATING (CHIVASSO)

INSTALLATION COST (Distribution network, heat exchangers, etc.)	253 · 10 ⁶
MAINTENANCE COST	583,000 $\frac{\$ (75)}{\text{year}}$
CAPITAL AND MAINTENANCE COST OF CONVENTIONAL BOILERS	543,000 $\frac{\$ (75)}{\text{year}}$
FUEL CONSUMPTION OF CONVENTIONAL BOILERS	18,000 $\frac{\text{ton}}{\text{year}}$
UTILIZATION DURATION	2,000 $\frac{\text{hours}}{\text{year}}$

Fig. 8 evidences the trends of the values determined above, which represent a wide range of possible costs, as a function of "e." As can be seen, the great variability of these costs is closely linked to the wind characteristics of the site, which determined the machine utilization.

The cost of the energy produced by wind generators should be compared with the cost of the fuel only (dashed line) required to produce electric power with thermal power plants. Indeed, the significant wind irregularity does not allow one to rely on wind generator capacity; as a result, they should be considered as "fuel savers."

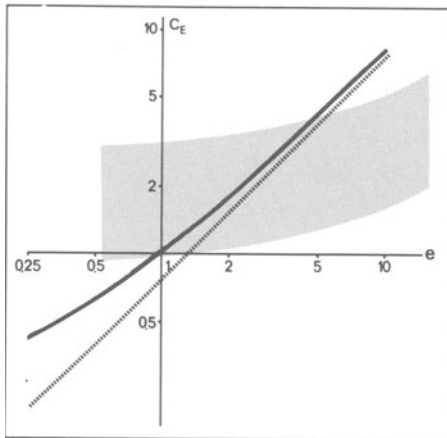


Fig. 8.

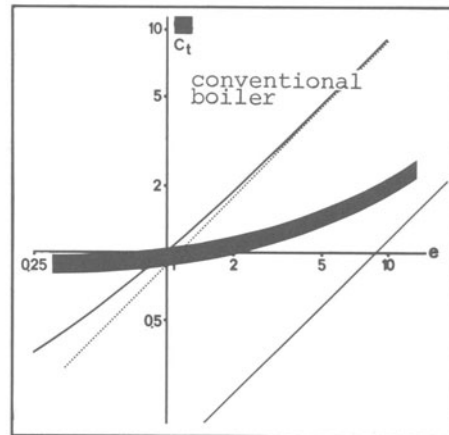


Fig. 9.

Co-Generation for District Heating from Large Power Stations Near Towns

In principle, the obtainable energy savings with co-generation are considerable; but the economic advantages are conditioned by numerous local variables, such as location of thermal loads with respect to the power plant, heating periods, heat demand, in addition, obviously, to the price trend of primary energy sources.

As an example, we will describe a typical case with the climate of North Italy and with power plants near consumption centers.

It is a study conducted for ENEL by a specialized firm (jointly with the Regione Piemonte and Comune di Chivasso authorities). This study aimed at evaluating a system for heating one part of the town of Chivasso. For this system, we supposed to use steam bled from a 320 MW unit of the existing power plant. Table 5 exhibits the data used in the study.

Fig. 9 shows, as a function of "e," the cost of the kcal supplied to the consumer as against the cost of the kcal supplied by conventional boilers.

From the figure, you can realize how under the Italian conditions (at least under the conditions similar to those given in the example), district heating before the energy crisis was not economically convenient in comparison with conventional boilers, and this is why it was not largely employed.

Co-Generation in Small Total Energy Systems

In addition to co-generation for district heating, the attention has been recently focused on co-generation in small total-energy systems. These systems can be mass-produced and, therefore, can allow significant savings in capital costs, especially in costs relevant to engines if we resort to a series production.

One well-known project in this field is the Totem system for combined production of power and heat, developed by FIAT.

This is a limited capacity module (15 kW, 33,000 kcal/hr), consisting of an engine from the 127 motor car, fueled by gas and a synchronous generator connected to it. A group of heat exchangers recover the heat from the heat engine, exhaust gases, and generator.

Based on the data contained in Table 6, the cost of the kWh produced by the Totem system was assessed as a function of "e" (fig. 10).

Transmission from Remote Energy Sources

In today's search for new energy sources, which are often very expensive, important hydroelectric resources far from consumption centers (or resources which are not easily transferable) are disregarded as they are considered not convenient because of their considerable transmission costs. On the other hand, considering our great efforts towards energy conservation, transmission is to be

TABLE 6: TOTEM

INSTALLATION COST OF TOTEM	5,100\$ 75
MAINTENANCE COST OF TOTEM	24.5 $\frac{\text{€ (75)}}{\text{h}}$
INSTALLATION COST OF BOILER	1000 \$ (75)
MAINTENANCE COST OF BOILER	5.1 $\frac{\text{€ (75)}}{\text{h}}$
FUEL CONSUMPTION (TOTEM)	6 $\frac{\text{N m}^3}{\text{h}}$
NATURAL GAS COST	8.8 $\frac{\text{€ (75)}}{\text{m}^3}$
UTILIZATION DURATION	2000 $\frac{\text{hrs}}{\text{year}}$

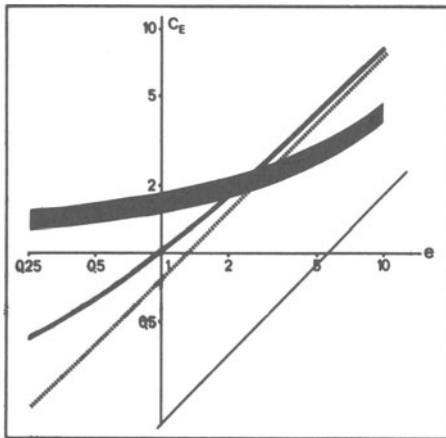


Fig. 10.

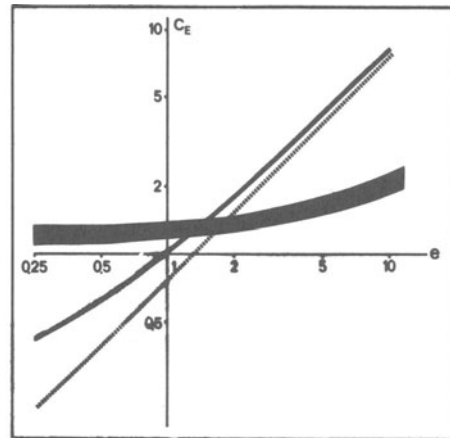


Fig. 11.

looked at as a means to recover these sources, that is it may be regarded as an alternative source of energy. In this connection, assumptions should be made on the cost of electric energy produced by a remote source. We will assume as a remote source a hydroelectric power plant producing electric energy at a cost equal to that of electric energy produced by a thermal power plant (near consumption centers) in the case of $e = 1$.

Fig. 11 shows the variation, as a function of "e," in the cost of the kWh produced by a hydroelectric power plant, evaluated at the end of a transmission line with a length of 1,000-3,000 km.

We can observe how this particular resource becomes competitive before other energy sources which are today considered as alternative.

Synthesis of Competitiveness Comparisons

The figure 12 summarizes the results of the competitiveness comparisons carried out in the previous paragraphs.

For each of the new technologies, the range of values of "e" is given, starting from which the technology under consideration becomes competitive.

New Utilizations

The method followed so far for competitiveness comparisons among the various energy forms may also be applied to evaluate the

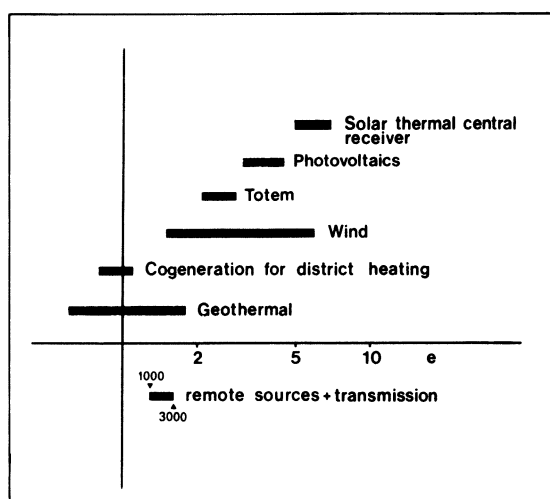


Fig. 12.

benefits deriving from new utilizations substituting the conventional ones consuming oil. Firstly, we will take into account the sector of road transport.

Electric energy is above all qualified to make mechanical work available. Almost all the needs of such mechanical work are covered today by electric power, except for transport in independent vehicles, where only hydrocarbons are used. In particular, road vehicles rank extremely high among oil consumers. It is thus logical that priority be given, in the sector of users, to the "electric road vehicle."

Today, the diffusion of the electric vehicle is essentially conditioned by the problem of power storage. The storage capacity per unit of weight and volume of present batteries limits the range of such vehicle significantly, narrowing its use to urban traffic alone (range 70-100 km).

On the basis of the data supplied in Table 7 we have obtained figure 13. By referring to this figure, one gets an idea of the competitiveness of the electric vehicle as compared to the combustion one (provided that the electric vehicle be produced in a number comparable to the corresponding thermal vehicle), even supposing that the electric power is produced with fuel oil, namely that the power comes from the same primary source. This figure indicates the ratio between the cost of electric power for an electric vehicle and that of fuel for an internal combustion one.

If the annual capital and maintenance costs for the two vehicles are considered to be equal, when such ratio reaches 1, it represents

TABLE 7: COMPARISON BETWEEN ELECTRIC
AND COMBUSTION VEHICLES

	COMBUSTION VEHICLE (Diesel)	ELECTRIC VEHICLE
PAYLOAD	1.500 kg	
ANNUAL MILEAGE	20.000 km	
CONSUMPTION	0.2 $\frac{\text{litres}}{\text{km}}$	0.6 $\frac{\text{kWh}}{\text{km}}$

the economic limit of the combustion vehicle. The equality of fixed annual costs can be an achievable goal, in that the electric vehicle should have a longer life and lower maintenance costs, to offset the high costs of batteries.

Belt "a" corresponds to the case in which day electric power is used to recharge batteries, belt "b" to the case where the batteries are recharged using to a good extent night electric power.

It can be observed that the electric vehicle is already competitive today in case "b," whereas in case "a" it becomes competitive when "e" = 2. At any rate, the advantage of the electric vehicle increases as the value of "e" increases.

ENEL has carried out tests on vehicle prototypes to be used for the urban network maintenance services for the distribution of electric energy. Two vans, derived from the 850 T, built by FIAT, have been equipped and tested on the road by ENEL for the last three years.

The result of this common effort is a type of van which, produced on a small scale, is used in a demonstration fleet which is now used in routing jobs at the ENEL division of Milan.

Another demonstration fleet of 3-5 passenger vehicles is now operating at ENEL for use in ten Italian towns for management services.

Outside the sector of transport, the only other important new users of electric power are found in the field of thermal uses. In

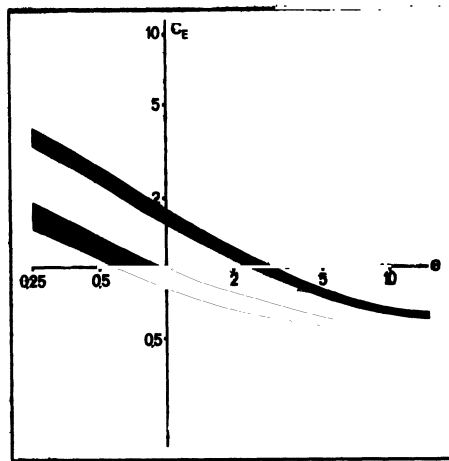


Fig. 13.

this case, equipment must be used which enables use of electric power, taking full advantage of its high-grade power characteristics. In this sector, we are now considering an organic plan of demonstration activities with regard to the sector of "heat pumps."

At present, a study is being carried on as to the possibility of using a heat pump in combination with solar energy for home heating. Demonstration will be made using a number of demonstration systems for the heating of ENEL personnel homes at the thermal power plant of Rosano Calabro.

4. ENERGY STORAGE IN THE ELECTRIC SYSTEM

Introduction

In introducing the subject of storage, I think it is interesting to call your attention to the definition of energy. The concept of energy can be expressed in many different ways, but out of all of them I choose the following one: energy is "stored mechanical work." Though slightly embarrassing to talk about storing something which, if not stored, doesn't exist, this definition immediately evidences the close relationship between energy and storage.

At any rate, overlooking the misleading definitions, it is true that energy is usually considered as goods and as such it is produced, transformed, transferred, and also stored. Storage, therefore, is one of the fundamental aspects of energy handling in energetic systems.

In the following pages, I will not talk about fuels which, as actual commodities, do not raise particular storage problems. I will, instead, talk about energy storage under other forms.

As long as energy was cheap, the role of storage was limited; today, like all problems concerning energy conservation, it is a topical subject.

Within this general context old ideas are being reconsidered which now, however, can be effectively carried through thanks to the development of new technologies.

In view of the broadness of the subject, a number of limitations must be set. Consequently, I will leave out the problem of heat storage in addition to that of fuel storage, and only examine the problems posed by the storage of energies of highest value, such as electric energy and mechanical energy, which are perhaps the most difficult to store.

The end uses of these energies are mainly mechanical work, electricity for information, processes and light; rarely, we find heat as an end use of these energies. Electricity and light are mainly supplied by the electric system. The users of mechanical work can be divided into two categories: self-powered means of transport which do not use electricity and those which, instead, use such carrier and therefore are fed by the electric power system.

Therefore, we will talk about the storage of energy in the electric energy system and in the self-powered means of transport; namely, in the means which can cover distances not being bound by special continuous supply systems.

Reasons for Energy Storage

Storage fulfills the main purpose of lessening the constraints between the energy demand and availability at production level. Since it allows one to store energy when availability exceeds the need and then redistribute it in case of need, storage features numerous technical and economic advantages. We will examine the reasons for storage as a means for energy conservation, which at present is that receiving the most attention.

Now, in terms of energy conservation, four reasons can be singled out for storage, three of which stem from the fundamental consideration that still today fuels, whether fossil or nuclear, are by far the main source of energy. Thus, to transform such energy into mechanical and electrical work, we must use thermal prime movers.

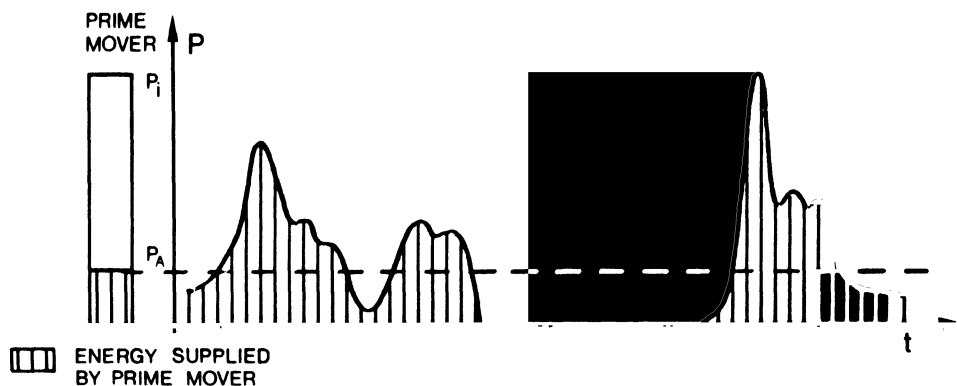


Fig. 1.

Let's consider a possible time distribution of the power requested versus time of our prime mover (load diagram)(fig. 1).

A thermal prime mover must be designed for the peak power requested. Notice that the average value of the power supplied, P_A , is much lower than the installed power, P_i , and thus if the prime mover is designed for the peak power its utilization is modest.

Now let's consider that there is a wide variety of thermal prime movers which are competitive with each other: engines with high efficiency featuring low operating costs but with a high installation cost and, vice versa, engines with low installation cost and thus with low efficiency and high operating cost.

The high efficiency engines are more competitive for long-duration utilization while the others are preferred for short-duration utilizations. In the electric system, for instance, we find a large variety of prime movers ranging from those with a high operating cost and low installation cost, such as the turbogas units, which are used to cover peaks with utilizations below 1000 hours, up to nuclear ones with low operating costs and high installation cost. The same occurs in motor vehicles: if the engine is not utilized so much, a gasoline-fueled engine is used; if it is much utilized, a diesel engine is resorted to.

Coming back to our case, we are inclined to use an engine with low efficiency with a consequent energy waste in order to reduce installation costs. The situation can be improved by using a storage system. The prime mover is thus designed for average power while the peaks are covered by the storage system which stores the energy available during low demand periods (see fig. 2). A small prime mover, having a very high efficiency, can then be used, providing considerable energetic advantages.

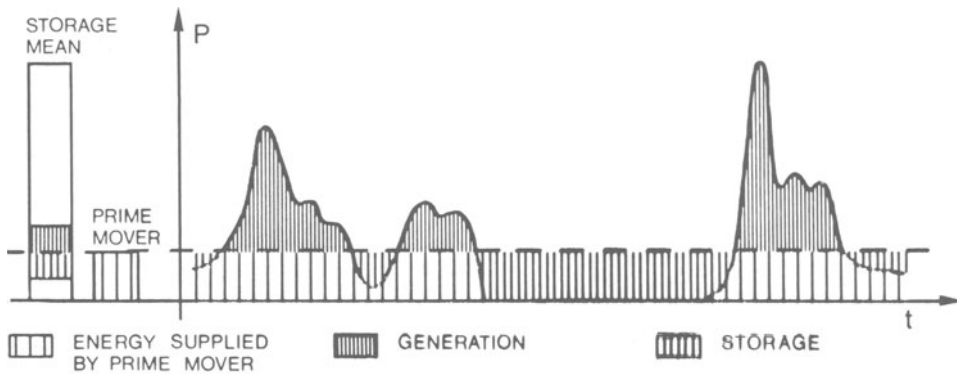


Fig. 2.

One of the fundamental applications of this principle is the hybrid car, that is to say a car with a small engine of limited power which produces energy that is stored in batteries (or in a flywheel, as we will see later on) and this stored energy covers the service peaks.

Let's analyze the second point. If we use the prime mover designed for the peak power demand and it is not utilized much, we have energy called marginal energy which remains available and which actually is cheap since its conversion is performed by a prime mover already paid for (fig. 3). In this case, we are inclined to use this energy also for improper uses.

This occurs in particular in the electric system where the marginal electric energy is made available at a reduced rate (in general at night) and is thus often used for heating purposes, an improper energetic utilization.

The pumped storage system, vice versa, allows one to upgrade the energy of off-peak hours, thus drastically reducing the availability of marginal energies.

The third point is as follows: the load diagram which was entirely positive in the previous cases, may also be negative. This means that the system may need braking (see fig. 4). This energy is generally dissipated as heat.

In such case, if we have a pumped storage system, we can store energy during the braking, thus reducing the average energy produced and gaining part of the energy that can be produced by the prime mover (fig. 5).

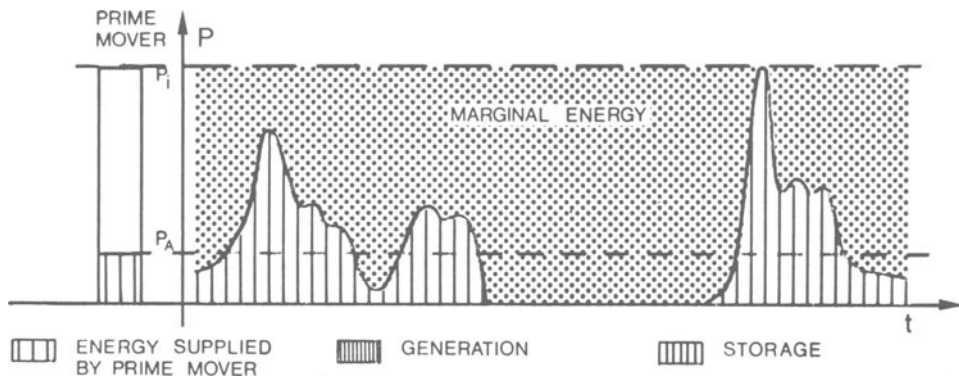


Fig. 3.

The third point is, therefore, the recovery of braking; recovery of the energy which otherwise would be wasted.

So far, we have always talked about a thermal prime mover, namely energy derived from fuels. When, instead, the energy is directly derived from available mechanical energy, such as hydroelectric energy or wind energy, the problem is set under slightly different terms.

Let's consider this relatively regular load diagram (fig. 6) of a group of electric users and the diagram which shows the availability of the primary source; this diagram is very irregular because of the

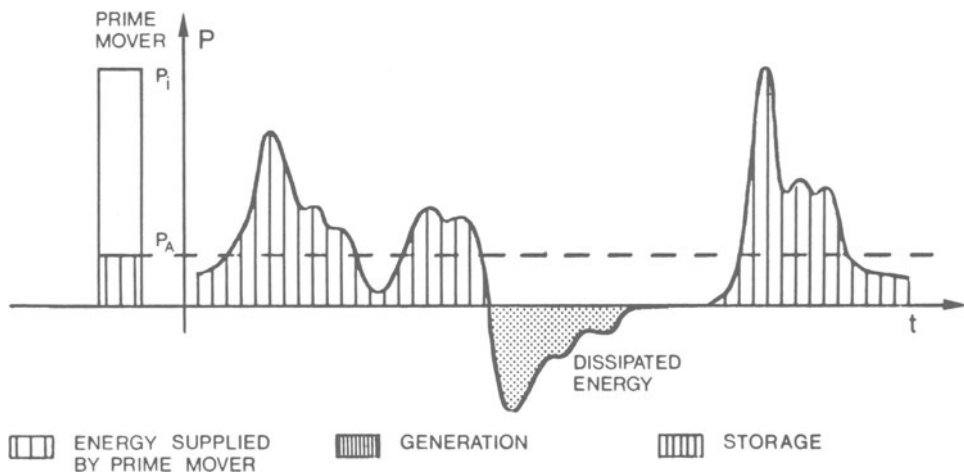


Fig. 4.

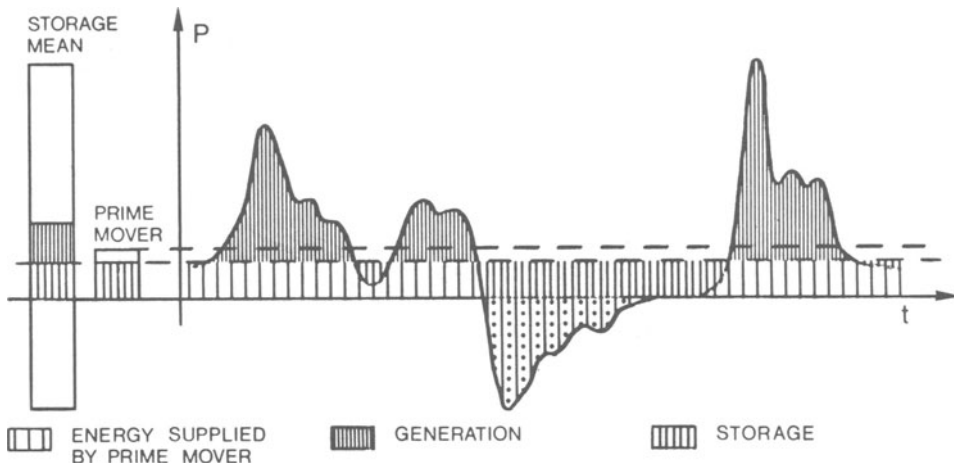


Fig. 5.

nature of the primary source.

The power availability depends on water flow (the peak may be a flood) if hydroelectric energy is involved and on wind speed in the case of wind energy. Even if the prime mover is designed to cover the peak load (see Fig. 7) but a storage system is not provided, not only is it impossible to always cover the load, but a lot of energy available ends up being wasted. By contrast, with the storage, energy is stored instead of being wasted and is released during power shortages. In this case, however, the prime mover should be designed for the availability peaks (fig. 8).

This actually occurs only when using the wind source, because wind energy cannot be directly stored but must be converted by means of a prime mover large enough to use such energy and then inserted in an electric system featuring an adequate storage capacity.

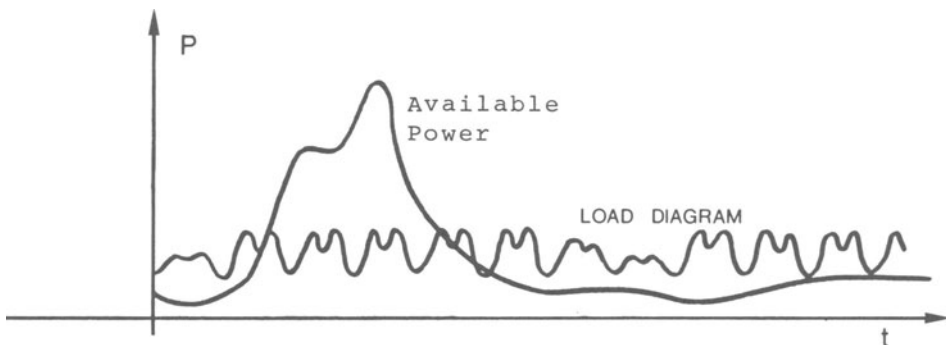


Fig. 6.

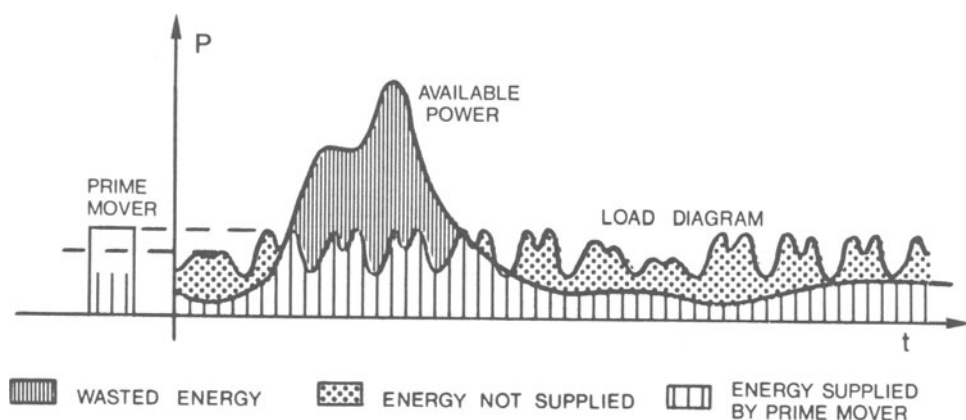


Fig. 7.

Hydraulic energy, instead, can be directly stored before its conversion. This makes it possible to use a small prime mover. This explains why the first large storage systems were of hydroelectric energy.

Based on the above, four reasons for storage can be established as far as energy conversion is concerned: 1) improvement in thermal conversion efficiency (namely of the prime mover efficiency), 2) upgrading marginal energy, 3) recovery of braking, and 4) utilization of the discontinuous primary source.

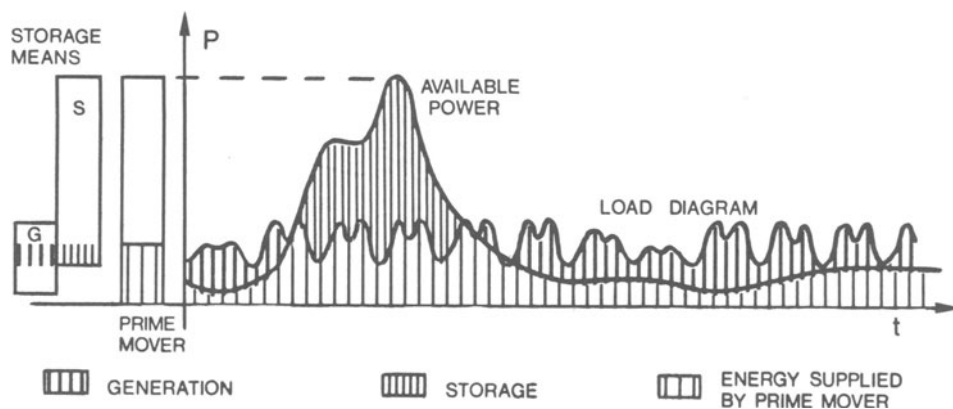


Fig. 8.

Applications of Storage in the Electric System and in Traction

In the electric system (Table 1), conventional storage is a hydroelectric power plant fed by a reservoir acting as a flow regulator. This type of storage, used since the beginning of electric systems, has been fundamentally used for utilization of discontinuous primary sources; today it is used also to improve the thermal conversion efficiency. In effect, if stored energy is used in the hydraulic form to cover the peak loads, low-efficiency prime movers like the turbogas units can be eliminated and prime movers with a higher efficiency can be better used. These functions are peculiar of pumped storage plants, that is hydroelectric plants which during off-peak hours take water from a lower basin through a system of pumps and fill the upper reservoir. The two main purposes of storage plants today are the improvement of thermal conversion and the upgrading of marginal energy.

These storage plants can be also used to improve the utilization of the discontinuous primary sources and in particular play an important role in the development of alternative sources.

In traction (Table 1), the two main applications of storage are in the electric vehicle and in the hybrid vehicle.

The hybrid vehicle, already mentioned, enables to improve thermal conversion efficiency and to allow braking recovery.

The electric vehicle, which at the beginning of the car development was greatly considered, has over the past few years become an important possible utilization, because of both environmental and energy crisis, receiving extremely widespread consent from both the technical circles concerned and public opinion. The electric vehicle

TABLE 1. ROLE OF ENERGY STORAGE

Reasons For Storage in Energy Conservation	Application in			
	Electric System		Traction	
	Reservoir Plant	Pumped Storage	Hybrid Car	Electric Car
Improvement of Thermal Conversion Efficiency	○	●	●	●
Recovery of Excess Energy		●		●
Recovery of Braking			●	●
Utilization of Discontinuous Energy Sources	●	○		

is fully fed by energy stored (generally in batteries but the fly-wheel is also proposed) during the rest periods of the vehicle and thus mainly at night. Consequently, storage in the electric vehicle allows us to reach the following goals: improvement in thermal conversion efficiency, valuable recovery of excess energy, and lastly, braking recovery.

I would like to draw your attention to these three goals since I feel that, in the present energy situation, they justify the renewed interest in the electric vehicle and may be the impetus to overcome the major obstacles to their diffusion. The most important of such obstacles is the excessive weight of the batteries per unit of energy that can be stored, which drastically limits the energy storage capacity and thus the range of such a vehicle.

Storage Units and State of the Art of their Application

The types of qualified energy which are stored are essentially two: mechanical energy and electrical energy (Table 2).

Mechanical energy can be kinetic, elastic and due to the force of gravity. These forms of energy storage have been used by man for a long time: the mechanical energy due to the force of gravity and the mechanical energy of the elastic type were used to run clocks (e.g. weight-driver or spring-loaded clocks), while kinetic and elastic energy represented the first instruments of man. In effect, if you think of the club, it merely stored kinetic energy and released it shortly after when used in hitting. The club then evolved into the hammer and into other percussion tools and then into more complex machines, such as the eccentric press, which is one of the applications of energy storage in the kinetic form of the flywheel.

TABLE 2. MAIN APPLICATIONS OF STORAGE

Energy Type		Storage Unit	Electric System	Traction
Mechanical Energy	Due to Gravity	Hydro Reservoir	●	
	Kinetic	Fly Wheel	▲	■
	Elastic	Compressed Air Reservoir	■	
Electric Energy	Electro Chemical	Battery	■	●
	Electro Magnetic	Superconducting Magnet	▲	

● Operating

■ Experimental

▲ Under Study

The first application of storage of elastic deformation energy was certainly the bow.

All these applications exploit a capability typical of kinetic energy storage, i.e. the possibility of making the energy stored available in the very short time, i.e. of providing considerable capacity peaks.

Electric energy can be divided into electrochemical and electromagnetic energy. The electromagnetic storage of considerable amounts of energy has been considered only since the development of the technology of the superconductors. These allow one to obtain very intense magnetic fields practically with very low losses. The electrostatic storage, on the contrary, is not feasible, since the material with super-insulating properties has not yet been invented.

Let's examine now how the different forms of storage are applied in the electric system and in traction.

Fig. 9 shows the general arrangement of Lake Delio pumped storage hydroelectric plant in Northern Italy. It uses a head of 700 meters between the upper reservoir of Lake Delio and the lower basin of Lake Maggiore. Generation power is about 1,000 MW with around 16 million kWh of annual energy output. This plant, in operation since 1974, has been the first major project in the extensive pumped storage program which ENEL, taking advantage of Italy's favorable orography, is implementing (8,000 MW capacity plants are at present under construction) so as to achieve an in-depth regulation of electric power supply on the Italian network. Fig. 10 shows a view of Brasimone pumped storage plant, a 300 MW plant in operation since 1977.



Fig. 9. Artist's view of pumped storage plant of Lake Delio. On the left lower corner is the underground powerhouse.

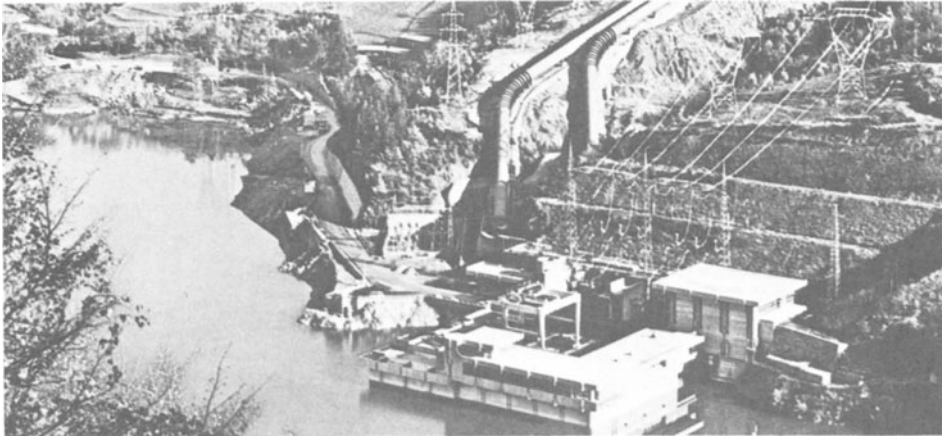


Fig. 10. Brasimone-Suviana pumped storage plant. Powerhouse is underwater to a depth of 45 m.

Extensive programs of research, development, and demonstration are underway in the field of battery-powered vehicles, as the widespread use of electric vehicles (fig. 11) should have a positive effect both as far as energy sources diversification and pollution reduction are concerned. Moreover, overnight battery recharging would contribute to the levelling of the electric load profile.

As for storage means presently under test for traction, we must quote the flywheel, which thanks to the progress in material



Fig. 11. FIAT-ENEL 900 T Electric Van belonging to an experimental fleet used for activities connected with construction and maintenance of urban distribution networks: maximum speed is 55 km/hr, urban range of 50 km.

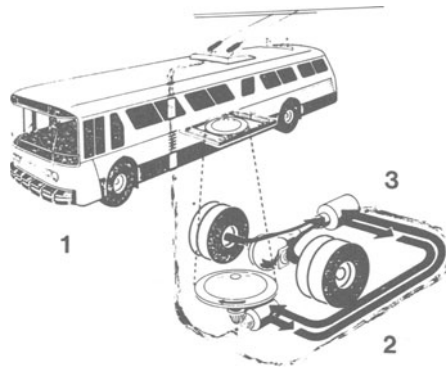


Fig. 12. Design of S. Francisco electric trolley-bus:

- (1) Trolley draws current from overhead lines to run both the flywheel motor and the drive motor.
- (2) With trolley retracted, spinning flywheel's stored energy generates current to run drive motor.
- (3) Going downhill with trolley retracted, drive motor becomes generator driven by wheels, providing current to increase flywheel spin.

technology features a density of storable energy higher than batteries. Since the storable energy is directly proportional to the strength of the flywheel, the task is to succeed in finding extra light, reliable materials with a high strength so as to realize the so-called super-flywheels. Some new plastic fibers have the same density as aluminum and an extremely high strength, much higher than steel. These fibers will allow manufacture of flywheels with extremely high storage amounts per unit weight. The flywheel has thus wide prospects in traction. Fig. 12 shows a trolley bus designed some years ago in San Francisco. This bus stores energy by means of the flywheel during the route section where it is fed by an overhead line; then by utilizing the energy stored, it can cross downtown areas, without needing to contact lines, for a range of 10-15 km.

In the electric system, the reservoir for compressed air storage is being tested. Turbogas units are being developed, which have a compressor separated from the engine; at night, air is compressed and injected into the turbogas unit (fig. 13) which does not drive the compressor and, therefore, has a much higher power and provides a greater amount of energy. The compressed air storage plant of Huntorf (West Germany) utilizes a reservoir excavated in salt caverns, while a similar Italian project will utilize the empty geothermal reservoir near Sesta (Tuscany). The empty reservoir of Sesta has a volume of about 3 million cubic meters, filled with CO_2 at 20

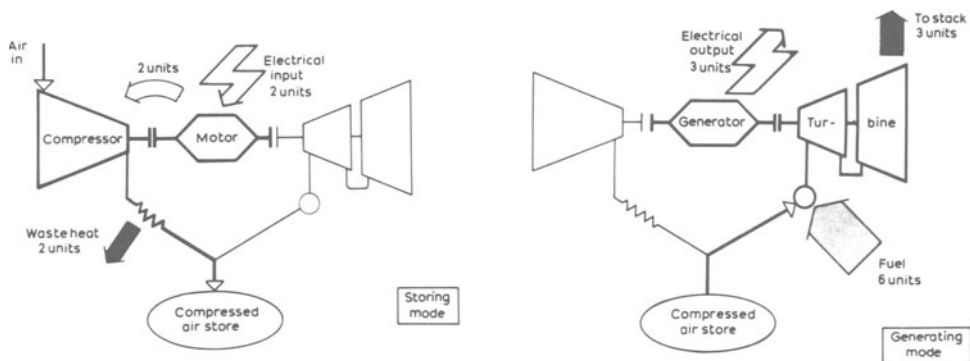


Fig. 13. Schematic flowsheet of a compressed air storage system for electric utility load leveling. The compressor is driven by nighttime, off-peak electricity and the air is cooled before being stored in an underground cavern (left). On release, the compressed air allows fuel to be burnt twice as effectively as in the simple turbo generator powering its own compressor.

atmosphere pressure. Feasibility studies are underway, while the experimental plant, to be built in 1982, shall feature 40 MW of output power.

Finally, even in the electric system operation there is a tendency to resort to batteries as storage units. For applications of this type, batteries are required which have a cost (here weight is no longer important) sufficiently low to replace the pumped storage plant. Since, contrary to what happens for pumped storage plants, the overall power of a battery storage system can be fractionated in many units of reduced power, the single storage units can be located at the high voltage transformer rooms. In this case, the batteries can even serve as "reserve standby" for the entire primary transmission and distribution system. Fig. 14 displays an artist's view of a battery system which Westinghouse expects to market in a couple of years at prices even more competitive than the pumped storage plant.

Still for the electric system, studies are underway on the flywheel and on the supermagnets, i.e. superconductive magnets to be located underground. Fig. 15 shows a flywheel system for energy storage; the rotating mass is buried underground for safety reasons, even if the adoption of fiber composites minimize the problem of fragment containment in case of wheel failure. Tests were conducted to study the behavior of fibers in case of failure and it was seen that when fiber composites are excessively stressed, they crumble

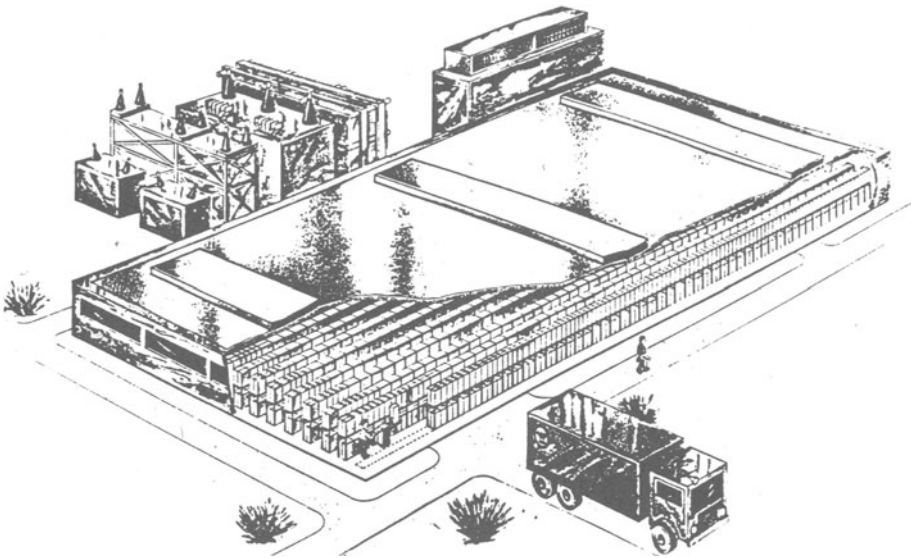


Fig. 14. Electric storage through battery system according to a Westinghouse project.

or pulverize, instead of breaking into large pieces, as happens with steel flywheels.

Superconducting magnetic energy storage systems (SMES) store electric energy in a magnetic field produced by circulating current in the winding of a magnet. In principle, d.c. current induced in a superconducting winding will flow without electrical losses until energy stored is returned to the network.

For a utility size SMES, feasibility studies performed until now mainly in the U.S. consider plants located several hundred feet below ground in solid bedrock (fig. 16). This large magnet, made with several superconducting coils is contained in a cryogenic envelope with vacuum insulation. A liquid helium flow at 4.2 k, or even better a superfluid helium flow at 1.8 k, at low pressure will keep coils in the superconducting state.

Typical evaluated dimensions of an underground tunnel housing a 10,000 MWh SMES plant are about 7 m wide, 100 m in height and 150 m in radius. Magnetic forces on coils would be transmitted to the surrounding rocks through solid thermal insulators. Some U.S. reports on this field conclude that these systems should be feasible even with present-day technology. Declared technical maximum efficiency is about 90%, although optimization studies show that lowest annual

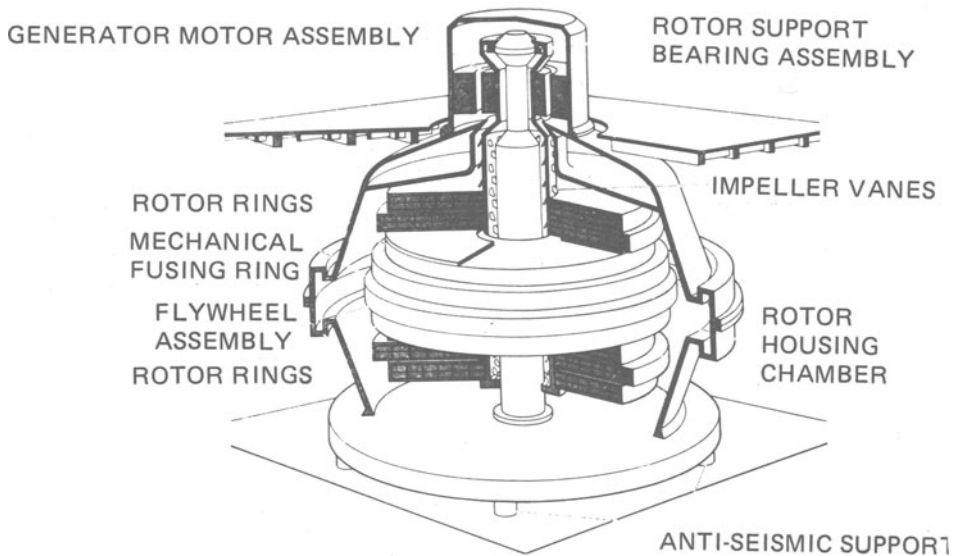


Fig. 15. Design of superflywheel for the coverage of electrical peak load (from Scientific American, December, 1973).

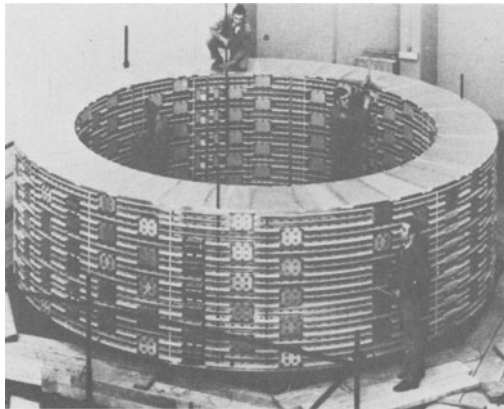


Fig. 16. One of the poles of the superconducting magnet designed for the 3.7 m European bubble chamber at CERN. Operating at liquid helium temperatures, the magnet stores less than one quarter of a megawatt-hour. Much larger magnets would be necessary to provide bulk electrical storage at economic cost.

owning and operating cost should be got for efficiencies of the order of 80-85%.

Storage System Design

Now, I would like to dwell on the criteria which should be followed in designing storage systems.

First of all, let's analyze the characteristics to be designed in a storage system and, to this effect, we refer to the two diagrams of Fig. 17. The first plots the power required and shows the capacities which the system should offer in terms both of pumping and generation; the second plots the integral indicating the energy stored in the reservoir and shows the size of reservoir E. With reference to a pumped storage system as a typical storage plant, we define as pumping capacity the maximum capacity with which the energy to be stored is consumed and as generating capacity the maximum capacity with which the energy is released by the storage system and as reservoir the part of the system where energy is actually stored (e.g. flywheel, battery, etc.). As you can see in the two diagrams, energy in the reservoir decreases when the system supplies energy and increases when pumped storage operates. Therefore, the characteristics to be designed in the plant are: the generating capacity, the pumping capacity, and the size of the reservoir. Fig. 18 shows in the upper diagram the effects deriving from an insufficient designing of generating capacity: the power demand is not entirely covered at peak-time. Fig. 18 in the lower diagram shows the effect of an insufficient reservoir size: the power demand is not covered at the time when the reservoir becomes empty. The effects of an insufficient designing of the pumping capacity is indicated in the diagram with the drop in capacity shown in black in Fig. 19: the slope of the recovery curve becomes lower with consequences similar to those of an insufficient designing of the reservoir: impossibility to meet the demand due to emptying of the reservoir.

Consequently, we can have two types of outages: one due to lack of power and one due to lack of energy in the reservoir. A generation deficit brings about a deficit due to lack of power, while both an insufficient reservoir capacity and an insufficient pumping capacity bring about an outage due to lack of energy.

The problem of designing would be simple if the load diagram were defined in a deterministic way; actually these diagrams have always a high random component. Just think of the load diagram of an engine driving a vehicle which strictly depends on route and traffic conditions. As a result, we cannot eliminate in an absolute way either the lack of power or the lack of energy; we should content ourselves with reducing the risk that these events occur to reasonable levels.

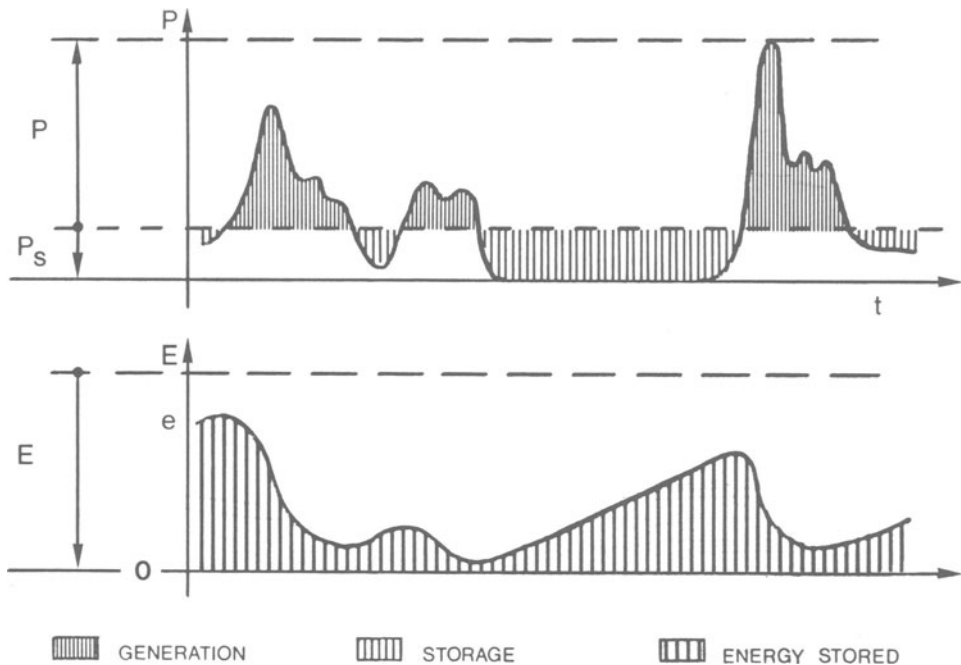


Fig. 17.

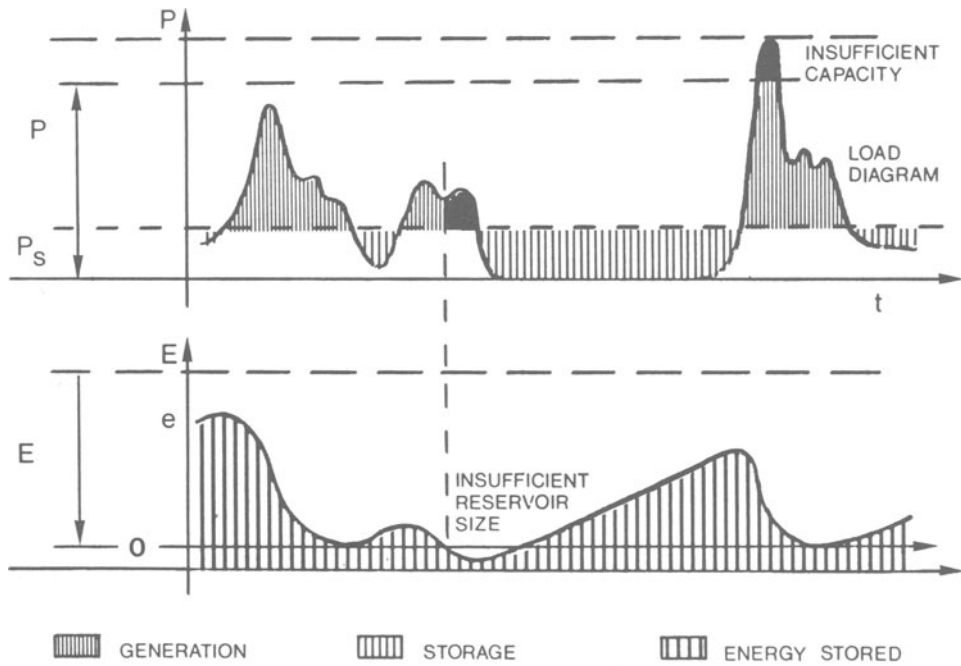


Fig. 18.

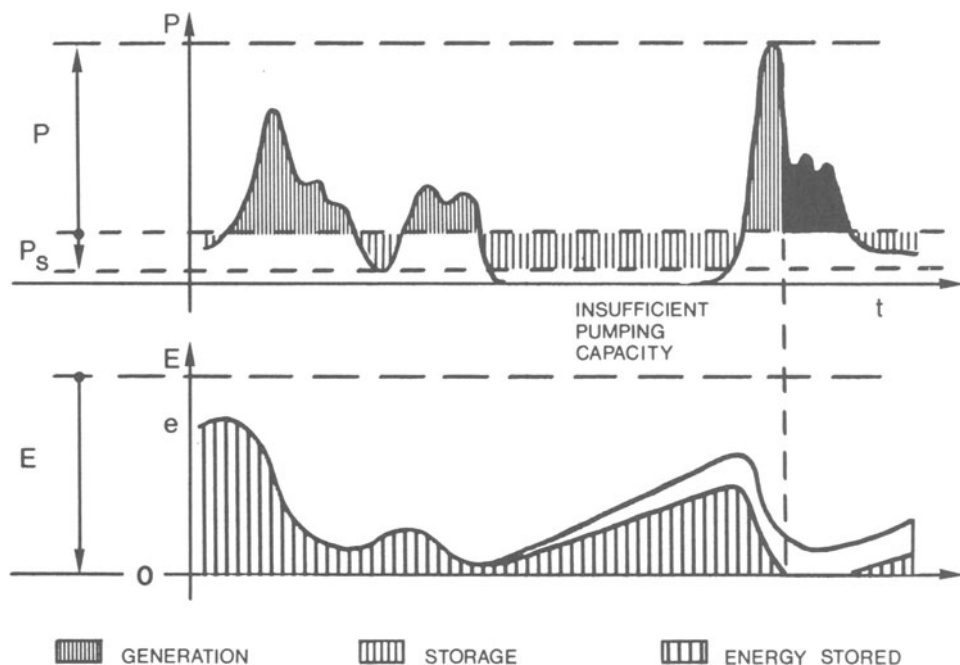


Fig. 19.

The three basic dimensions, generating capacity, storage capacity, storable energy, can be expressed in relative terms for the sake of simplicity. Assuming the generating capacity as 1, we identify the pumping capacity expressed in p.u. of the generating capacity with π and the ratio between storable energy and generating capacity with h (see Table III).

We will thus have the relative magnitudes π , restoring ratio and h , which represents the number of hours when the power plant can operate at full capacity starting from the full reservoir state and reaching the empty reservoir one.

I will deal in particular with designing of the reservoir, i.e. of the choice of the optimum value of h .

As we already observed, there is always the risk of not being able to meet the demand due to lack of stored energy; the greater the reservoir, the smaller the risk. If we manage to quantify the risk (and, as we will see, this possibility exists), we will obtain a curve. This curve indicates that the risk decreases when the reservoir size (see fig. 20) increases. But, the reservoir cannot be enlarged indefinitely for evident cost reasons. Indeed, the installation cost of the plant grows with the reservoir size; therefore,

TABLE 3. BASIC DIMENSIONS OF A STORAGE PLANT

		Per Unit of Generating Capacity
Generating Capacity	P	1
Storing Capacity	P_s	$\pi = \frac{P_s}{P}$
Storage Energy	E	$h = \frac{E}{P}$
π Restoring Ratio	h Generating Hours at Full Capacity	

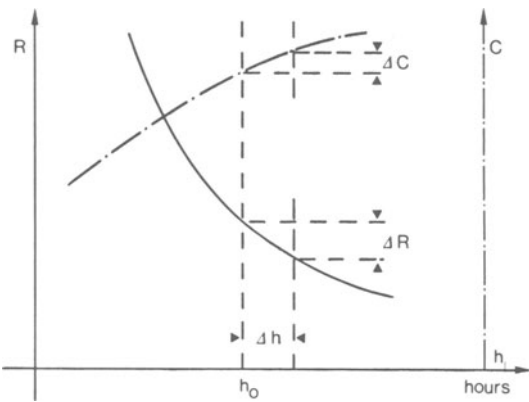


Fig. 20.

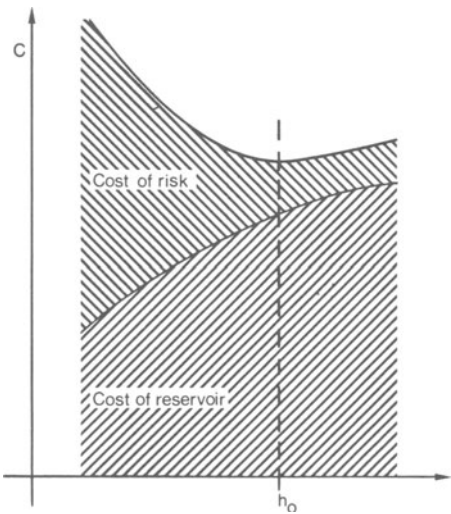


Fig. 21.

designing h , is a matter of compromise between risk and cost. We will then say the value of h is optimum when by increasing it by a given quantity h , the resulting risk reduction R might, in our opinion, justify the corresponding cost increment. This implicitly introduces the notion of "risk cost," that is the economic assessment of an aleatory event; this is currently made and represents the insurance premium required for remunerating a random event.

This notion becomes so necessary that it should be explicitly introduced by economically penalizing the risk. In this case, the compromise between cost and risk can be obtained in the most objective and reliable way, as an economic optimum, by summing up the risk cost (see fig. 21) and the installation cost, and minimizing this sum.

We will limit ourselves to risk evaluation in the case of a storage plant which is part of an electric system. In this instance, we should bear in mind that the load can be known and forecasted with sufficient reliability, so much so that aleatory components can be neglected.

By contrast, in a system prevalently made up by a highly forced unavailability rate, the total available capacity is highly aleatory.

Fig. 22(a) shows the load diagram of a work day from 6 to 6 of the following morning and a possible mix of the generating units meant to cover this load; the total capacity of the generating units is greater than the peak load of a certain quantity called reserve; this mainly is meant to cover forced or planned unavailabilities of the various units.

Now, let's imagine that on the day considered, the availability is not total. For reasons of operating cost, we will use all nuclear

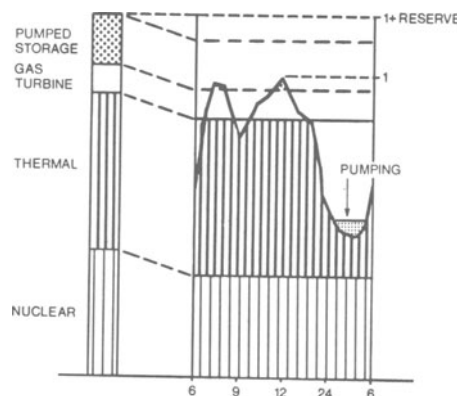


Fig. 22(a)

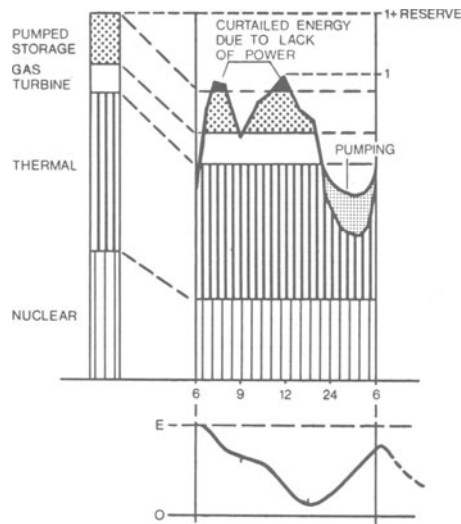


Fig. 22(b)

power plants, then all thermal power plants and, if necessary, the turbogas units and the storage plants as illustrated in this figure. In this case, only part of the storage plants are required to cover the load.

Certainly, this system is a most reliable one since, with a short duration utilization of storage plants, it avoids the risk of reservoir emptying. But, it is not necessarily the most economical one. Indeed, in spite of the relatively low efficiency of the storage plant (approximately 70%), the energy produced by the turbogas units may cost more than the off-peak energy used to pump water into the upper reservoir.

Therefore, it could be useful sometimes to revert the position of turbogas units and of pumped storage units; pumped storage units are used in a more extensive way, while the turbogas units are limited to peak-load (consequently, all of them are used as reserve). In this case, the storage performs the function of energy transfer from hours of low marginal cost to hours of high marginal cost, which allows fuel and thus energy savings.

From the standpoint of availability, there may be good days, like the ones considered so far, and critical days (see fig. 22(b)) when the available capacity is not sufficient to cover the load. In this case, part of the power demand will not be covered due to lack of power (blackened areas in the figure).

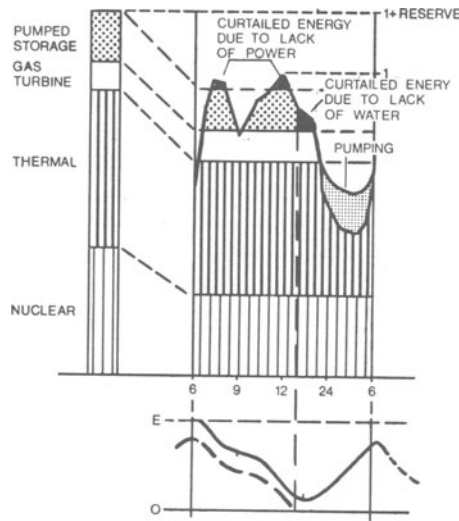


Fig. 22(c)

As concerns storage plants, it is necessary, in such critical situations, to work in such a way as to obtain the maximum reliability, i.e. maximum utilization of turbogas units (possibly even to pump) before resorting to storage plants. In this way, the risk of reservoir emptying, and thus of not covering the demand due to lack of power is avoided.

In effect, the behavior of the reservoir level indicated in the lower part of Fig. 22(b) shows that the reservoir did not become empty. But, if the critical situation continues even on the following day (fig. 22(c), the storage plant will have the reservoir empty before finishing its service (dotted line in the reservoir level curve). Consequently, it will be unable to supply energy to the load due to lack of stored energy.

If we simulate several times the operation of the system for the entire year we are interested in, and each time we take note of the energy not supplied due to lack of power and of the energy not supplied due to lack of energy, and we determine their averages, we obtain values which tend to stabilize and give an indication of the system capability to perform the service required.

This simulation can be made with an appropriate computer program which, for each hour of the year, based on stochastic models of power plant availability, determines which power plants will be out of

service at that time and how long they will remain out of service, and then assess, at the same time, the available capacity. Then the program examines if and to what extent it is necessary to resort to the storage power plants to cover the load or if, vice-versa, it is possible to store energy and how much. In this way, it will be possible to know, starting from data known at the beginning of the hour, the energy stored in the reservoir of the storage plant at the end of the hour. Proceeding in this way, we succeed in simulating the behavior of the energy stored in the reservoir during the year and particularly when the energy in the reservoir is short at the time when it is demanded.

Obviously, such simulation should be repeated for a considerable number of years, so as to achieve average results which are as close as possible to the expected values. The diagram of fig. 23 illustrates the sequence of the energy not supplied due to lack of available capacity and to lack of stored energy, values obtained in about one hundred simulations of the same operation. It is worthwhile to underline the different natures of the two phenomena: while the lack of power determines relatively modest crises almost every year, the lack of stored energy determines much rarer but more severe crises.

In this connection, it is interesting to compare two random samples of this set of values (see fig. 23(b)). The two samples might well represent the experience of two operators, A and B, who

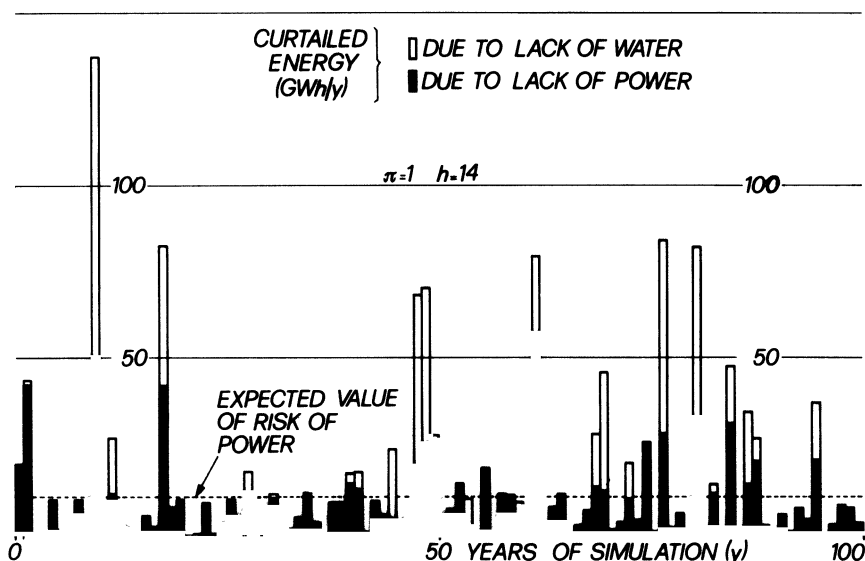


Fig. 23.

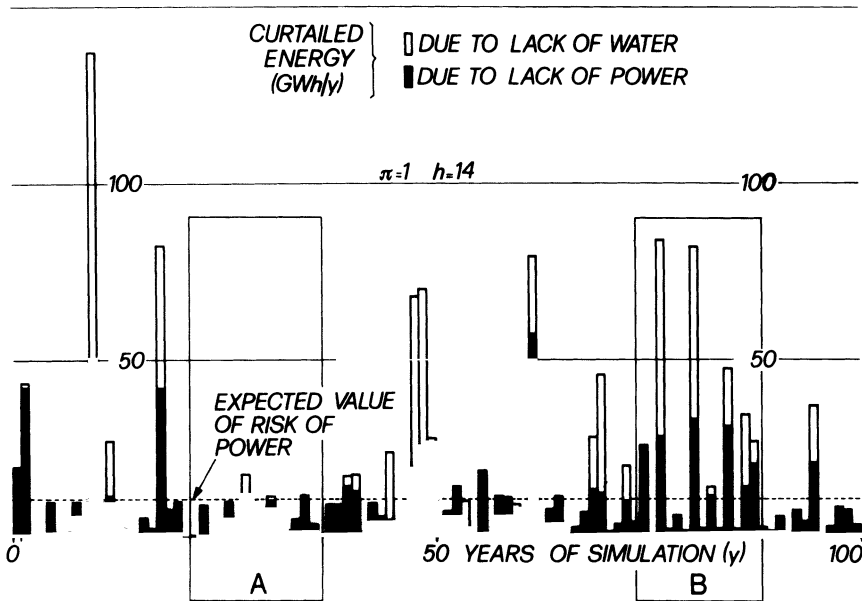


Fig. 23(b).

have managed the same system for about 15 years; their different experience would be due to purely random facts. If the two operators met after this experience, operator A might state that outages from lack of stored energy are not a problem, while operator B, severely hit, will assure that the reservoir of his pumped storage plants are entirely insufficient.

This proves that when random facts dominate, the operating experience, even if long, cannot be considered as a design rule without a thorough interpretation, based on simulation tools.

The average value of energies not supplied, obtained from a very high simulation number represents instead a very valid index.

Fig. 24(a) displays the behavior of the two indices concerning outages due to lack of power and to lack of energy as a function of the value of h (generation hours at full capacity). For $h = 5$ hours, the ratio between energy not supplied and energy supplied is about $5 \cdot 10^{-4}$, as if for one hour every year all the capacity of the system were not supplied. Sometimes, speaking about storage plants, a discrimination is made between 5-hour "daily" plants and 13-hour "weekly" ones (points d and w of fig. 24).

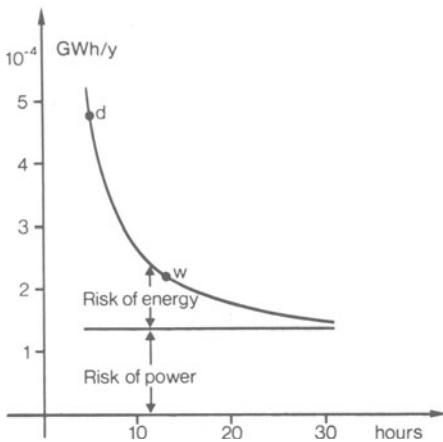


Fig. 24(a)

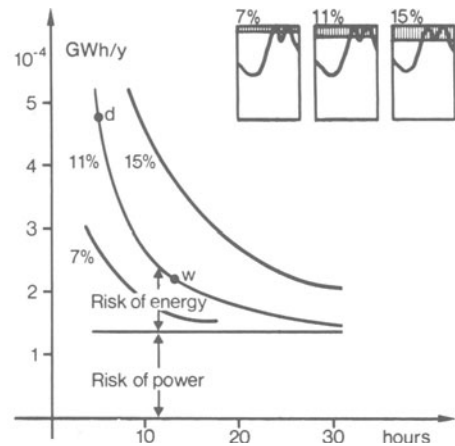


Fig. 24(b)

Obviously, this discrimination is absurd; designing of the reservoir is not related to the cycle duration but to the entire designing of the generating mix and to the risk of outage due to lack of water which we are willing to accept.

Fig. 24(b) shows that this risk depends also on how many pumped storage plants we want to introduce into the generating mix; indeed, with reference to a generating mix including 11% storage units, larger reservoirs are required to have the same risk in a generating mix with 15% storage units. If we want to equip the generating mix with 7% storage units, the reservoirs can be smaller. This is evident, since if we decrease the percentage of pumped storage plants, we affect less and less significant parts of the load diagram. But, the optimum size of the reservoir clearly depends also on the cost of the storage plant and, in particular, on the cost of the reservoir. In other terms, the unit cost of a pumped storage plant can be expressed as a function of the reservoir size h . Fig. 25(a) exhibits the cost functions of three storage plants with different characteristics: a high-head pumped storage plant, a mean-head pumped storage plant, and an electric battery system.

As regards pumped storage plants, the power cost depends on the water supply system cost, whereas the energy cost depends on the two upper and lower reservoirs and, in particular, on their size.

In high-head plants, the expense for the two reservoirs is generally modest with respect to the cost of water supply systems and, as a result, the overall plant cost slightly increases with increase in relative reservoir size.

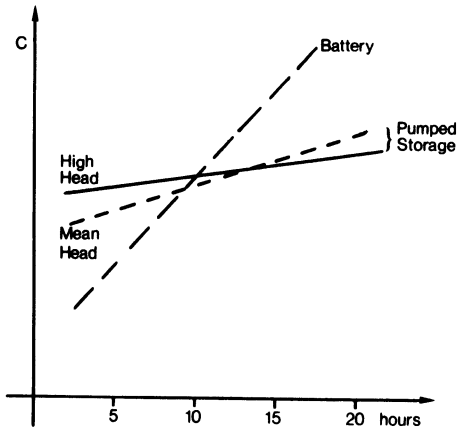


Fig. 25(a)

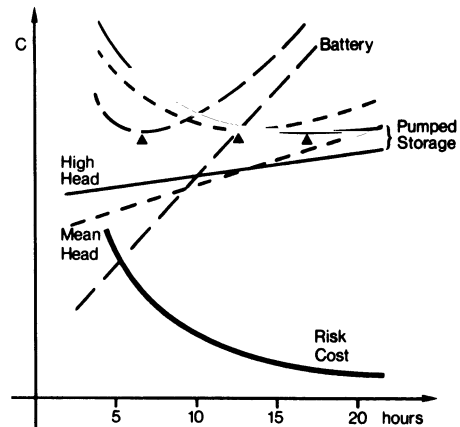


Fig. 25(b)

Instead, in mean-head plants, the reservoir cost represents a significant share of the overall plant cost; in effect, the reservoirs are generally larger (often there is the need to create reservoirs of the concrete-coated type), while the water supply plants cost definitely less than the high-head plants. As a consequence, the overall cost of a mean-head plant grows significantly with a growing number of hours, i.e. a growing reservoir volume.

In case of batteries, the power is clearly negligible with respect to the energy cost, because what affects the overall cost is the number of batteries, which rises in direct proportion to the number of operating hours required.

Obviously, the calculation of the battery cost took into account the economic advantages that batteries have in transmission and distribution systems, because they can be installed very close to the loads.

To assess the competitiveness between high and mean-head pumped storage plants and batteries, we make an economic calculation.

In fig. 25(b), if we sum up the risk cost (curve in the lower part of the figure) and the mean-head plant cost, we obtain a curve which shows that the optimum value of h is approximately 12 hours. These data correspond rather well to an electric system of the ENEL type, which was planned assuming a storage unit incidence of about 11-12% and requires reservoirs with a capacity sufficient to ensure about 12 hours of production with mean-head plants.

Naturally, if we repeat the economic calculations to define the most advantageous number of hours in case of high-head plants or batteries, we find different values of h : for high-head, the optimum value of h is 16 hours, while for the battery, it is 5-6 hours.

For these values of h , mean-head plants and the battery are competitive because they have really the same cost.

Of course, there are not only high-head plants, mean-head plants, and batteries. In fact, a mix of the three systems is generally required. To have an optimum mix, we will take a value of h greater than h_0 in case of high-head plants and a value of h smaller than h_0 in the case of batteries.

Also for this reason, it is important that our plants have large reservoirs, because if tomorrow we want to add batteries to such plants, we might do it at relatively modest costs.

Services Performed by a Pumped Storage Plant

So far we dealt with only one of the services that a storage plant can perform, i.e. the power service, which consists in making available the installed capacity whenever it is necessary to meet the demand.

To see whether the storage plant is competitive with turbogas, it is necessary to examine also the other services. To this purpose, we recall that the services that a storage plant can perform within the framework of an electric power production system are not only the static services, i.e. those dependent on the static characteristics of the system (on steady-state operations), i.e. on P , π , and h , but also the dynamic services. The static services include the power service, already mentioned, which serves to ensure the power, and the energy transfer service, which transfers energy from hours when thermal production takes place at lower marginal cost to those where it would take place at higher cost and which results in an operating cost saving. The dynamic services are: The ramp services, consisting in meeting rapid load variations which cannot be covered with conventional thermal power plants (e.g., when in the morning the load rises very rapidly, an entirely thermal system may not follow the rising load). Then, it is necessary to intervene with units which can be rapidly brought to maximum capacity (the pumped storage plant of Vianden prevalently carries out a service of this type). The spinning reserve service consists of meeting unexpected generation disconnections, reducing the consequent outage. And, the frequency control service, which is similar to the previous one and includes, in part, the spinning reserve service.

UNITED STATES NUCLEAR ENERGY AND NON-PROLIFERATION POLICY

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I believe that U.S. nuclear energy and non-proliferation policy is not well understood, and I hope to be able to clarify where the U.S. Government stands on a number of very complex issues. I shall speak first about the role of nuclear energy within the context of overall energy policy, then about the development of nuclear energy, and finally about nuclear non-proliferation. A general discussion will follow this talk.

Let me start by emphasizing that the Carter Administration views nuclear energy as a part of the overall energy picture. No one, today, can afford to project a completely or even predominantly nuclear future, as was once popular. In the United States, our first priority in the near term is energy conservation. We must make the transition from an era of cheap oil and gas to an era, still largely in the future, of expensive oil and gas. By the year 2000, we can expect to be using at most not more than 70 percent of the total energy resources that we would have used in the absence of price increases, and we may well be using much less.

We shall, nevertheless, be using a good deal more energy in the year 2000 than we are using today, and many projections indicate that an increasing proportion of this energy will be in the form of electricity. Nuclear energy is one of our options for meeting this increased electrical demand. Our other option is coal. Oil and gas are not considered viable fuels for newly constructed electrical capacity in the United States, except for "peaking" purposes. Solar energy, although increasingly seen as an important source of heat for building and industry, will not make a major contribution to meeting electrical demand before the year 2000.

The United States does, however, have a choice between coal and nuclear power, and in this respect we clearly face a different situation from many of our Allies, including Italy. Our domestic coal reserves are enormous; our capacity to utilize them is limited largely by infrastructural requirements, especially railroads, and by environmental considerations.

I am personally convinced that the total health and environmental impact of producing a given amount of electricity with nuclear power is substantially lower in the United States, than the impact of producing that same electricity with coal. In fact, until coming to Rome, I worked at Brookhaven National Laboratory with a research group devoted in large part to quantifying health and environmental impacts of various fuel cycles, and we repeatedly came to the conclusion that coal could be expected to do more harm than nuclear power, even when the best future available pollution control technology was used. I believe that this conclusion is generally accepted in knowledgeable circles within the United States.

Why, you may then ask, are orders for nuclear power plants so slow, and coal much more popular? This question goes to the heart of the matter: the federal government does not directly decide how many power plants of each type will be built in the United States. Unlike the Italian Parliament, the American Congress has never decided on a specific number of nuclear power plants. The government clearly contributes to the atmosphere in which such decisions are made, but it is the publicly regulated electrical utilities--privately or publicly owned--that actually order power plants.

Perhaps the strongest reason for ordering coal rather than nuclear power in recent years has been uncertainty: uncertainty about the regulations that will have to be met in building a nuclear power plant, and about public acceptance of nuclear power in general and of particular sites. These uncertainties have meant delay, and delay in a one-billion-dollar project means added costs. The Carter Administration, following closely on policies already developed under President Ford, has attempted to reduce these uncertainties in two ways: first, by streamlining the licensing procedures; second, by meeting public concerns. I shall only mention briefly the effort to streamline licensing; so far, it has failed to attract significant Congressional support.

The effort to meet public concerns has, I believe, been more successful. Nuclear power is very carefully regulated in the United States, and the public has many opportunities to be involved directly in the procedures of the Nuclear Regulatory Commission. The Commission maintains more than 130 rooms throughout the United States where its documents can be read by the general public.

"Abnormal occurrences" at nuclear power plants that may affect public health and safety are routinely announced to the public. The public can intervene in many stages of the licensing process, and citizens can request NRC documents of many types with no justification required.

Of course, public participation often leads to uncertainty and delay, but within limits we are convinced that the price is a reasonable one. If there is something wrong with the present provisions for public participation, it lies largely in our failure to create similar procedures for coal-fired power plants, which are made more competitive by the relative simplicity of their licensing procedure. In any case, public acceptance of nuclear power in the United States is much more extensive than is generally believed in Europe: many referenda have been held at the State level, and nuclear power has never lost.

One of the intense public concerns in recent years has been the issue of nuclear proliferation. These concerns arise, in part, from an exaggerated picture of the role of nuclear power. It was only a few years ago that nuclear proponents were talking of many hundreds of power plants and dozens of reprocessing facilities spread throughout the world. The "plutonium economy," in this view, was to be a relatively free-trade economy, with each country doing as it liked under the fairly loose reign of the IAEA Safeguards. The Carter Administration has confirmed the Ford Administration's rejection of this plutonium free-trade economy. It has done so not in order to hurt nuclear power, but rather to make nuclear power acceptable. And it has done so not for commercial advantage, but rather at substantial cost to the American economy.

Let us turn back to April 1977, when President Carter announced his non-proliferation policy, and review the points he made then.

First, the President emphasized at that time his commitment to light water reactors without reprocessing. He reiterated this commitment at the Bonn summit in July 1978: "the further development of nuclear energy is indispensable, and the slippage in the execution of nuclear energy is indispensable, and the slippage in the execution of nuclear power programs must be reversed." Clearly, the Carter Administration is not against nuclear power.

Second, the President deferred indefinitely commercial reprocessing of plutonium in the United States and urged other countries to do likewise. The cost of this measure to American industry was substantial, as symbolized in the still unused Barnwell reprocessing plant. This deferral of reprocessing still stands, and I expect it to continue for two reasons: our experience with commercial reprocessing, from both an economic and an environmental point of view, has been bad; and reprocessing offers only the

slightest advantages in terms of reducing fuel demand in the next 25 years. If reprocessing and plutonium utilization in light water reactors are used when they are clearly justifiable on an economic basis, we believe that they will be very little used for several decades.

Third, the President reshaped the U.S. program for breeder reactors by cancelling the planned plutonium liquid metal fast breeder at Clinch River and increasing funding for more proliferation-resistant technologies. Here one must not be trapped into misreading U.S. policy. While we are against reprocessing for recycle of plutonium into light water reactors, we have not yet reached a conclusion on the issue of the use of plutonium in breeders. As a result, we maintain by far the largest breeder reactor development program in the world (\$370 million in fiscal year 1980), and we have every intention of remaining in the forefront of this technology. Here the charge that we are seeking commercial advantage might seem viable, although the American nuclear industry has bitterly contested the cancellation of the Clinch River reactor. Nevertheless, U.S. industry may some day benefit from sales of a more proliferation-resistant breeder technology that the technology under development elsewhere. If this comes about, however, it will be because there is a genuine demand for such technology, a prospect we can hardly be banking on given the present response to U.S. non-proliferation policy.

We are sure that less non-proliferation-resistant technology will prove more popular if the non-proliferation regime is strengthened. The President also announced in April 1977 a series of measures to increase non-proliferation incentives: limited American spent fuel storage for fuel from abroad; nuclear fuel assurances; application of full-scope safeguards as a condition of U.S. exports; U.S. veto rights over reprocessing of U.S.-supplied fuel or fuel irradiated in a U.S.-supplied reactor; and restraints on U.S. export of sensitive technology. None of these measures significantly improved the commercial position of American companies, and a number of them are thought to have hurt the position of American industry as well as the nuclear export market as a whole. The fact of the matter is that these measures had a security goal, not a commercial one: we want to slow the proliferation of nuclear weapons, and we are willing to pay a substantial price to do so.

What of the future of American non-proliferation policy: Where is it headed? The answer to this question depends heavily on the outcome of INFCE, the International Nuclear Fuel Cycle Evaluation. INFCE is a joint effort of 50 countries to re-examine the role of nuclear power. We believe that five basic norms for a stable non-proliferation regime are emerging from INFCE, norms that Joe Nye has already spoken about at the Uranium Institute

as well as during his visit to Italy. First is the application of full-scope safeguards, that is the application of safeguards to all facilities in a given country as a condition of nuclear exports by one of the nuclear suppliers. Second, avoidance of sensitive facilities like reprocessing plants and enrichment plants where they are not economically justifiable. Third, use of more proliferation-resistant technology. Fourth, joint multi-national control of sensitive facilities. And fifth, stronger assurance that needed fuel, enrichment capacity and spent fuel storage will be available.

These norms certainly forebode a future for nuclear power quite different from the one its strongest advocates once projected. Plutonium, if it flows at all, will flow in very restricted and well-watched channels. Light water reactors will not be built as rapidly as we once imagined: in the European community, projections of electricity produced in 1985 by nuclear reactors declined by 40 percent between 1974 and 1978, and even the 1978 projections are likely to be far too high. We in the U.S. government very much want such delays to be reversed, but it is no wonder that when we look at the hard data we feel less urgency about reprocessing and the commercialization of breeder reactors. As George Rathjens, an M.I.T. professor who now runs the INFCE staff of the State Department, said when he was in Italy, "a technology can be developed too early, and the costs of doing so are very substantial." Light water reactors are clearly useful today on an economically justifiable, commercial basis; those who believe the same will be true in the near term of reprocessing and breeders are entitled to their view, but I think they stand to lose a bundle. They should not blame us if they do.

This, in summary, is how the Carter Administration views nuclear power and non-proliferation for the next two decades: slower than expected, but substantial, growth in the use of light water reactors, very limited reprocessing, continued development of plutonium and other breeders. At the same time we expect much tighter bilateral and multilateral controls over the entire fuel cycle, very little commercial reprocessing for thermal recycle purposes, and a considerably delayed decision on commercialization of breeder reactors. This is a future different from the one prevalent in the days when enrichment and reprocessing technologies were being sold to countries before reactors were built, but it is a future in which the spread of nuclear weapons is likely to be a good deal slower.

UNITED STATES ENERGY POLICY

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There is no greater challenge to the Western world today than the energy crisis. And during the past year what has seemed to many to be a difficult but distant problem has come perilously close to upsetting the world's political, economic and military balances. I need only mention in passing the revolution in Iran, the importance to the West of Saudi Arabia, the fall of the dollar and the risk in gold prices, the current conflict over the Camp David peace agreements, and the occasional strains in the U.S.-European relationship over the oil market for us all to realize the gravity of our energy situation and its repercussions throughout the world.

All of these events are symptoms of a single disease: the Western world is importing too much oil. The United States bears a large portion of the responsibility. We are now importing 7.7 million barrels per day (MMBD) or 15 percent of total non-Communist world consumption. Even with recent increases, American energy prices are still low by European standards. We are widely, and with some justice, regarded as profligate users of energy. We consume nearly twice as much energy per capita as countries like Germany, which has approximately the same standard of living. We consume more than three times as much energy per capita as Italy.

These are, however, international comparisons, which count for little in domestic American politics. It is difficult for Europeans to imagine the extent to which ordinary Americans are insulated from international affairs and foreign policy. Until recently, surveys consistently showed 50 percent of Americans unaware of the fact that the U.S. imports oil. To the man in the street, the energy crisis has meant only long lines for gasoline

and sharply higher prices. Even the declining dollar and OPEC wealth are hardly noticeable to the average American consumer, who wants fuel at reasonable prices.

True as all this is, it is a mistake to conclude that the situation is hopeless. Quite to the contrary, the United States in recent years has moved decisively in the direction of limiting oil imports. The Carter Administration knows only too well how impossible it is to fulfill the American consumer's dream. The era of abundant and cheap oil supplies is gone forever, in the United States as well as elsewhere. It is hardly surprising that the President who has brought this message home to Americans finds himself criticized sharply. The question to be faced in the United States is no longer whether energy prices will rise or whether oil imports will be limited, but rather how and when we shall make the transition to a new, more energy-conservative regime.

On these issues, the President has spoken decisively for the near-term. While it is generally known that the Congress turned down the President's effort in 1977 and 1978 to raise domestic American oil prices to world levels using a tax, it is less generally recognized that since then the President has decided to exercise his executive powers to achieve the same goal by decontrolling domestic oil prices. This decision does not require Congressional approval.

As of June 1 of this year, newly discovered American crude oil, as well as oil produced with advanced recovery techniques, is being sold at world prices. Beginning January 1, 1980, presently controlled crude oil prices will rise gradually to world levels. Decontrol will be completed by September 30, 1981.

In addition to oil price decontrol, the President has announced that American oil imports will not be permitted between now and 1985 to rise above 8.5 MMBD, the level reached in 1977. The very sharp increase in American oil imports that has caused so much difficulty in the 1970s is at an end. If necessary, the President will use his executive powers to impose quotas limiting the amount of oil entering the United States.

This basic constraint on oil imports still leaves us with a good deal of freedom in the longer term. Indeed, the great challenge posed to the West by the energy crisis is the challenge of long-term projections and planning. What fuels will we be using in the year 2000 and beyond? How much of these fuels can be displaced by solar energy and by a greater commitment to energy conservation? How will nuclear power develop?

Let me turn to this longer-term transition, first by taking a closer look at American energy consumption in an economic context

and then by reviewing the very extensive legislation--both in effect and proposed--that we believe will make an orderly transition possible.

While it is true that per capita American energy consumption is very high, some of this energy consumption is due to the high productivity of our economy. Americans consume more energy partly because they produce more goods and services per capita. Despite our high per capita energy consumption, our energy consumption per dollar of gross domestic product is actually lower than that of the United Kingdom, and only 25 percent higher than that of Italy.

Moreover, we have in the last few years been able to reduce significantly the amount of fuel we need to produce a dollar of economic output. The rate of increase of our energy consumption was only 1.8 percent in 1978, down from 2.5 percent in 1977 and 5.3 percent in 1976, all years of economic growth. In the years 1962-72, when real energy prices in the U.S. declined by 1.4 percent per year, economic growth in the U.S. brought a more or less proportional increase in energy usage. This is no longer true, largely because real energy prices from 1973 to 1978 have increased at a rate of 12.5 percent per year. This year, American energy prices have already increased 29.8 percent in the first nine months of 1979. Our oil consumption in the first half of 1979 actually declined by one percent, and our gasoline consumption has declined by 3.4 percent. For every one percent increase in GNP, we now have much less than a one percent increase in energy consumption: an increase of only .5 percent appears to be sustainable, although in fact recent increases have been even lower.

In many countries of Western Europe, economic growth and energy use are still more or less proportional. Thus per capita U.S. energy consumption is likely to remain high. But consumption per dollar of GNP may well approach the level of Western Europe in the longer term.

To summarize, we regard continued economic growth as critical in the long term. We have no intention of saving energy by reducing growth. The social impact would be primarily on the poor, and we need growth in order to invest in the capital required for our longer-term energy transition. However, we believe that growth in energy consumption can be much less than it has been in the past, and we plan to use both price and non-price mechanisms to limit the energy effects of economic growth.

Looking beyond oil price decontrol, the key to these mechanisms, we find a very complex set of legislation. Some of it has been approved by the Congress and signed into law by the President. Other items are still Presidential proposals, and their fate in

the Congress is, of course, uncertain. Let me review this legislation for you.

After a year-and-a-half of Congressional discussion, the President signed five bills into law in November 1978:

1. The National Energy Conservation Policy Act;
2. The Power Plant and Industrial Fuel Use Act, essentially a "concoal" conversion law;
3. The Public Utilities Regulatory Policy Act;
4. The Natural Gas Policy Act; and
5. The Energy Tax Act.

The only essential proposal the President made in April 1977 that failed to pass the Congress entirely was a tax on domestically produced oil to raise its price to the world price, a goal that he has now implemented by decontrolling oil prices.

Let me offer an overview of these five acts already in effect in the U.S.

ENERGY CONSERVATION

This Act offers standards and subsidies for conservation, with a strong bias toward grants and loans for conservation to lower-income families as well as conservation and solar energy in public buildings.

COAL CONVERSION

This Act prohibits new oil and gas boilers for electrical or industrial use and restricts use of oil and gas as a fuel in existing boilers, thus making coal the boiler fuel of choice for the future. Exemptions in special circumstances can be made.

PUBLIC UTILITY REGULATORY POLICIES

This Act encourages adoption by gas and electrical utilities of more energy-conservative rate structures, requires utilities to buy and sell power to industrial cogenerators, encourages grid interconnections, and provides loans for the development of small hydroelectric projects.

NATURAL GAS PRICING

This Act provides for the decontrol of most newly-discovered gas by 1985, but gas from old wells will remain under control.

ENERGY TAXES

This Act offers income-tax credits to individuals:

a) for residential conservation, the credit is \$300 or 15% of the first \$2000 expended;

b) for residential solar or wind devices, the maximum credit is \$2200 for up to \$10,000 of expenditure.

The Act also severely taxes "gas guzzling" cars and exempts "gasohol," gasoline mixed with alcohol produced from agricultural residues, from the Federal Excise Tax on gasoline.

The estimated 1985 savings of imported oil as a result of this legislation already in force, is as follows:

Conservation	.7 million barrels/day
Utility rates	.2
Coal conversion	.3
Taxes	.4
Natural gas pricing	<u>1.0</u>
TOTAL	2.5

These are quite substantial savings, amounting as they do to 32 percent of our current oil imports.

These are large savings, but they are far from sufficient. Even adding the 1.5 million barrels per day that we estimate to be the savings by 1990 from oil price decontrol plus further measures to encourage solar energy, we would still be only managing to keep our oil imports at more or less current levels rather than actually reducing them. The President has therefore proposed a series of additional measures, funded by a tax on the additional oil company profits due to the decontrol of oil prices. This tax, if enacted by Congress, will provide at least \$146,000 million between 1980 and 1990.

As proposed by the President, this fund would be split in two big pieces. The smaller piece, about \$50,000 million would be spent by 1990 primarily on further support for energy conservation and solar energy, including a solar energy bank to provide low-cost loans to home-owners who want to install solar devices and substantial assistance to people with low incomes as well as to mass public transportation. While the President's proposals may be changed by the Congress, I think there is relatively little controversy about the wisdom of using a substantial portion of the so-called "windfall" profits tax for energy conservation and solar energy.

The larger part of the proceeds, about \$90,000 million, would be spent by 1990 on producing synthetic and unconventional fuels. Here there is more controversy. The Administration has already accepted Congressional initiatives that would slow down the initial proposal, in essence making the Administration's goal of 2.5 MMBD effective for the year 2000 rather than 1990. The essence of the proposal would remain the President's: a government-owned Energy Security Corporation would use public funds to offer price guarantees, to create a synthetic fuels industry. These fuels would include liquids and gases made from coal, oil from oil shale, gas from agricultural products and waste, and gas from so-called "tight" sands."

Why undertake such a large, government-sponsored program for synthetic fuels? And is 2.5 MMBD in the year 2000 worth the expenditure of \$90,000 million in public funds, plus much more in private investments?

There are, I think, several good reasons for this new program. First, America's energy problems are largely problems of liquid fuels. We have already prohibited the use of oil in new industrial and utility boilers, and the President will soon send proposals to the Congress for early retirement of existing oil-fired boilers. In order to make further headway on liquid fuels, we are virtually forced to use coal, shale, biogas, and other unconventional gases to substitute for oil in transportation and in heating buildings.

Second, the government must act because private industry, given current oil prices, cannot justify major unsubsidized investments in synthetic fuels. Oil shale will cost \$28-\$35 per barrel and gas and oil from coal will cost \$35-\$40 per barrel. Current world prices are \$20-\$22 per barrel, and controlled American prices still substantially lower, but we know full well that both American and world prices will rise. Public intervention is necessary if we are to move ahead with synthetic fuels as insurance against these price increases.

And finally, we must, I think, begin to move now rather than waiting. Predictions of oil prices are impossible. We know, however, that, even in the best of all possible worlds, with Iranian production fully restored and no further surprises, that the mid-1980's to mid-1990's will be a period of great strain in the oil market, with supply at current prices falling short of demand. To invest \$90,000 million of public funds to produce 2.5 million barrels of oil per day in 1990 or 2000 would not in itself be worthwhile. If, however, one believes that by the 1990's the synthetic fuel plants will be operating on an economic basis, then this massive public investment looks very reasonable indeed.

Let me turn back to the big picture and look at overall American energy supply in the year 2000. One can, I think, offer a projection based on the Carter Administration's energy initiatives. Total American energy use is likely to grow much more slowly than in the past, averaging about one percent per year. Coal use will double, making it by far our greatest single energy source in the year 2000. Gas and oil supplies will barely manage to hold their present levels. Nuclear energy will grow substantially to about 14 percent of total energy supply, both because we shall finish the 130 nuclear plants now under construction (70 are already operating) and because we hope to see orders resume again before the mid-1980's. And solar energy, which includes in our definition wind, hydroelectric power and biomass fuels as well as the more obvious solar technologies, will increase at a somewhat slower but substantial rate.

Last, but by far not least, we hope to cut American oil imports to four MMBD by the year 2000, half the current figure. This compares with projections, in the absence of vigorous measures to promote conservation and alternative energy sources, as much as four times higher.

We cannot afford to let any more time slip by. I am convinced that the United States has begun the long and difficult process of conserving energy and limiting its oil imports. We cannot even hope for energy independence, as once we thought possible. But with our domestic house now at least partly in order, we need to turn to our Allies and friends to form an even stronger coalition of oil consuming countries. As our Secretary of Energy said at the Paris conference of Energy Ministers: "We share a collective responsibility for the orderly and timely development of a stable and secure energy market. I am confident that we have the means and the political will to meet this responsibility."

ENERGY SCENARIOS FOR THE U.S.

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RECENT U.S. ENERGY HISTORY

In this lecture I will talk about the U.S. only and this is both a strength and a weakness. It is a strength because the U.S. maintains good statistical records and a weakness because international issues pay an increasingly important part in the energy policy of the Western countries.

In order to explain the usefulness of constructing scenarios, let me first describe the usual way of proceeding before 1970. We plotted the logarithm of the energy use against time as shown in the sketch:

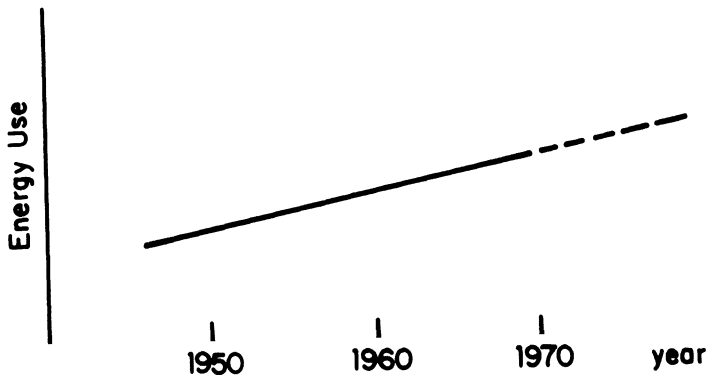


Figure 1. Energy use versus time before 1970.

and extrapolated into the future. From 1950 to 1970 such a plot demonstrated increases as follows:

economy as a whole	3.2%/year
energy	3.4%/year
electricity consumption	9.0%/year

The close link between the economy and energy was in many circles regarded as fixed. Two figures illustrate this: one a relation between GNP of a country and its energy use (Figure 2) and the next (Figure 3) a differential graph showing how changes in energy use and changes in GNP have been highly correlated in a short time scale.

However, the correlation is not complete, as a plot of the ratio of energy use to GNP in different countries (Figure 4) shows. The question is posed: can we reduce the historical ratio for the U.S. to the European ratio without lowering the quality of life?

Of the increase in energy use, about 2%/year was due to population increase; the switch toward electricity was regarded as a trend toward more convenience and less environmental pollution. The population increase has now slowed down and we now regard

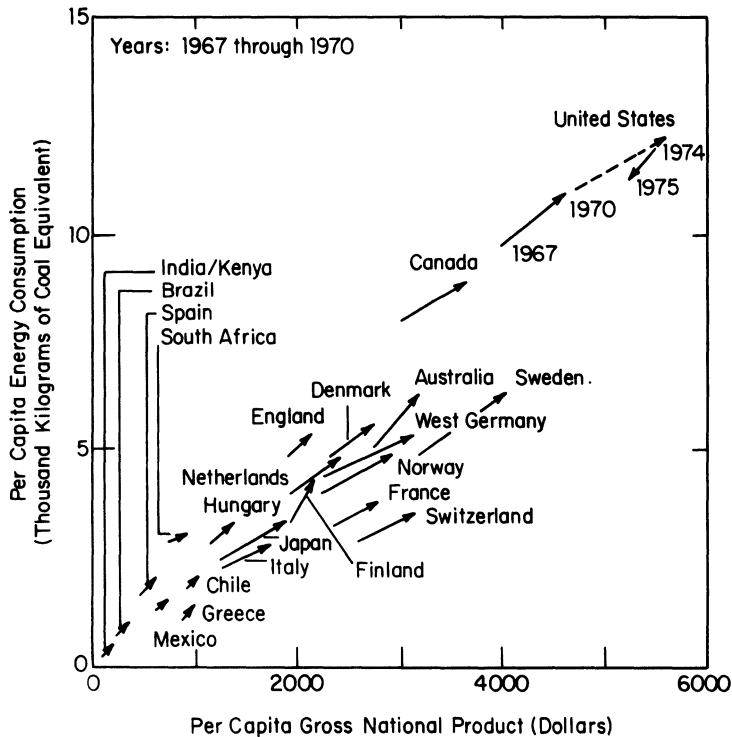


Figure 2. Per capita energy consumption versus gross national product for a number of countries.

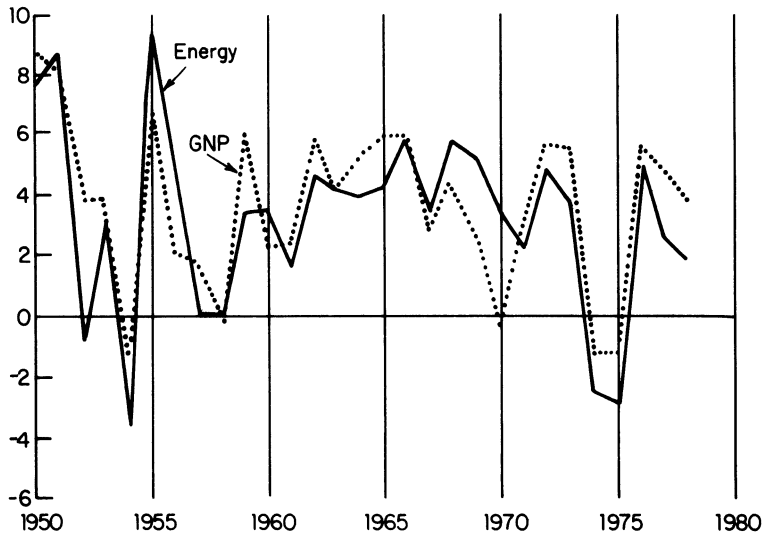


Figure 3. Changes in Primary Energy and GNP, 1950-1978.

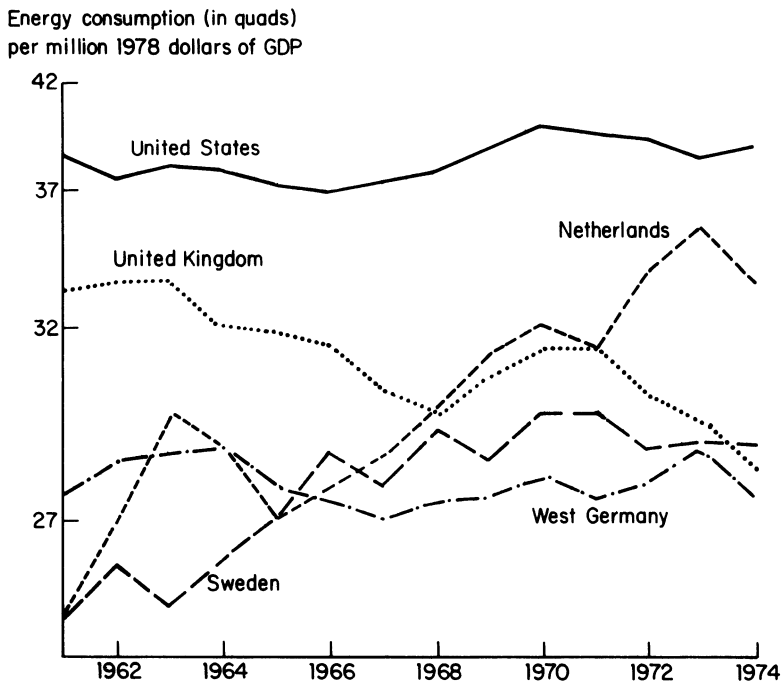


Figure 4. Energy/Output Ratios for Five Selected Countries, 1961-1974.

any further switch toward electricity, if it occurs, as a change in the source of fuel.

These projections were already beginning to become erroneous before 1973 when the dramatic increase in oil prices came. However, there were people in the U.S. who did have farsighted plans. It is useful to remember what they were, and why the plans have been rejected or modified.

The trend toward electricity use was taken very seriously. The price of electricity had, in real terms, been steadily falling, and electrical home heating was becoming a reality, particularly for apartment dwellers, where the ease of individual control outweighs cost disadvantages.

There was overoptimism about nuclear fission and fusion electric power. One careless remark--"electricity will be too cheap to meter"--has often been quoted. Some of the technical optimism was misplaced, but much more serious was optimism about public acceptance.

The Connecticut Yankee Atomic Power plant was put into service in 1967 and has been a very successful plant. In 1970 it was producing electricity at 0.55 cents per kilowatt hour including interest and amortization of capital and fuel costs. (It is now less than 1.5 cents/kwh). This was competitive with the fuel cost alone of an oil fired generating plant, given 40% efficiency and the cost of oil at \$3.75 a barrel. Residual oil was being bought at \$1.75 a barrel on the East Coast of the U.S., but prices were expected to increase.

It was therefore confidently expected that nuclear power would replace most oil for electricity generating just as soon as it could be built. Plans in my area, New England, (the Zinder report), anticipated that by 1990, 80% of all electricity would be generated by nuclear power; plans were also being made to produce process steam by nuclear power in large industrial areas--such as Midland, Michigan.

In areas with coal fields, coal was expected to keep competitive with nuclear power--since in these areas the cost of transportation (which doubles the cost of coal in New England and quadruples it in Japan) is small.

It is common now to state categorically that these pre-1970 plans and projections were wrong and ignorant. I think this shows a lack of understanding of the energy situation.

Society has made the following new demands on a nuclear power station:

1. Increased attention to environmental matters since the National Environmental Policy Act of 1969, often termed the most important energy legislation of the century. No longer can power stations have simple once-through cooling. They now must have cooling towers, or cooling water discharges 2 miles out in the ocean.

2. Radioactivity release in normal operation has been reduced ten-fold.

3. Increased public participation makes public hearings last 5 years instead of 1 day.

4. Antinuclear groups, for a variety of reasons, have instituted deliberate delaying tactics. For example, a delay of 18 months in the awarding of an operating license to Vermont Yankee Nuclear Power Plant meant that the plant was idle for this time, while banks and lawyers continued to be paid. This probably increased the capital cost 25%.

5. Somewhat associated with 4, greater regulatory requirements by the Nuclear Regulatory Commission, some associated with safety, but some not.

6. Increased cost and declining productivity of U.S. construction labor.

7. Increases due to the rising costs of materials (inflation) and rising interest rates which are an expression of the expectation of further inflation. Sometimes these are included as costs of delay, but they are really separate.

At a very rough guess I would put increased costs at the following:

Table 1

Environmental	x 1.3
Delays caused by increased public participation and opposition	x 1.3
Increased regulatory requirements	x 1.2
Increased labor costs relative to the rest of the economy	x 1.2
Inflation and expectation of inflation	<u>x 1.8</u>
Overall capital cost increase	x 4.4

In our discussions we should logically try to separate out inflation and expectation of inflation--but this is hard to do and is rarely done consistently.

It is not my purpose here to argue that any one of these causes of price increase are wrong in any absolute sense. I supported improved environmental controls. But they have occurred and to a very large extent they were deliberate decisions made by the American public.

Since 1973 cost increases have been great all over the Western world. I now go to a paper by my colleague, Prof. William Hogan of the Kennedy School of Government at Harvard.¹ Hogan first notes that reactions to increased energy costs will depend on net energy costs delivered not on primary energy costs. In the U.S. there has historically been a marked difference between the two which is illustrated in Figure 5. As the primary cost rises and the delivery cost stays the same, the difference has been going down. (These prices are corrected for inflation to 1978 dollars.)

The important point is that by 1979, the increase in delivered cost was only 20%; this is not enough to stimulate much reduction in energy demand.

However, we can see this broken down by sector in the next table. Here I show delivered energy prices for each of 3 primary sources--solid (coal), oil, and gas--and for electricity in industry, transportation and residential for 3 years. In the accompanying Table 3 we see the energy actually used.

We see at once that energy prices, as delivered to industry, rose rapidly after 1973 and that industry responded rapidly by reducing demand. On the other hand the delivered prices in the domestic sector had a smaller fractional rise, and the demand barely changed. The switch away from gas, toward oil, in industrial use was in response to a government directive. Noteworthy is a doubling of domestic electricity use in this decade. Yet it is in this sector that we hear cries for reducing energy demand and electricity demand in particular.

Similar tables for the U.K. are shown in Tables 4 and 5; note the increased use of gas in the U.K. due to inexpensive North Sea (subsidized) gas.

Now I turn to scenarios for the future, particularly those suggested by the CONAES study. In this talk I will not refer to this study directly, but to a published summary.² The change which is forced by the inability of domestic oil supply to meet demand, with the trend to foreign oil and a high price, suggests a re-examination of the whole energy system and its impact on society.

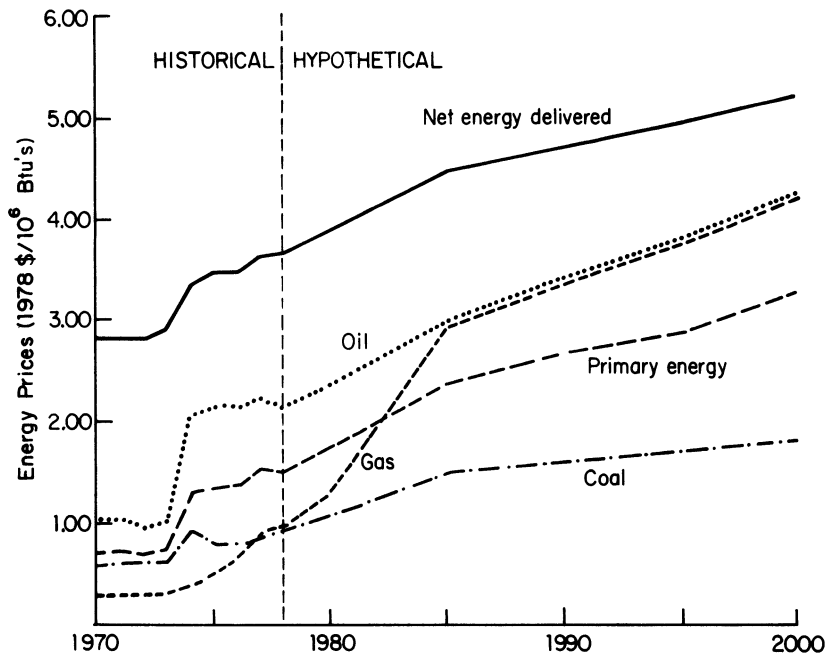


Figure 5. Illustration of Relation between Primary-Energy Prices and Net-Energy Delivered Prices

TABLE 2

Prices by Fuel and Sector, United States*

Year	<u>Industry</u>			
	Solid Fuels	Oil	Gas	Electricity
1968	0.399	0.619	0.478	4.840
1969	0.394	0.585	0.462	4.671
1970	0.423	0.644	0.464	4.623
1971	0.467	0.858	0.475	4.797
1972	0.481	0.920	0.490	4.911
1973	0.488	1.099	0.523	4.990
1974	0.705	2.351	0.677	6.015
1975	0.814	2.136	0.930	6.805
1976	0.795	2.025	1.199	6.954
1977	0.821	2.129	1.441	7.438
1978	0.881	1.945	1.489	7.541

Year	<u>Transportation</u>			
	Solid Fuels	Oil	Gas	Electricity
1968	0.000	5.155	0.000	0.000
1969	0.000	5.087	0.000	0.000
1970	0.000	4.940	0.000	0.000
1971	0.000	4.825	0.000	0.000
1972	0.000	4.630	0.000	0.000
1973	0.000	4.709	0.000	0.000
1974	0.000	5.785	0.000	0.000
1975	0.000	5.714	0.000	0.000
1976	0.000	5.665	0.000	0.000
1977	0.000	5.744	0.000	0.000
1978	0.000	5.817	0.000	0.000

Year	<u>Residential/Commercial</u>			
	Solid Fuels	Oil	Gas	Electricity
1968	3.302	2.284	1.528	11.312
1969	3.240	2.239	1.486	10.694
1970	3.079	2.206	1.480	10.208
1971	2.999	2.256	1.528	10.246
1972	2.967	2.541	1.572	10.413
1973	2.880	3.811	1.560	10.361
1974	3.276	3.723	1.633	11.018
1975	3.108	3.358	1.844	11.408
1976	3.096	3.389	2.097	11.586
1977	3.156	3.696	2.440	12.160
1978	3.216	3.686	2.572	12.263

*All prices are \$1978/MMBTU

TABLE 3

Consumption by Sector and Fuel, United States*

<u>Industry</u>					
Energy Demand (Delivered) in Quads					
Year	Solid Fuels	Oil	Gas	Electricity	Total
1968	3.92	5.16	9.66	2.58	21.32
1969	3.91	5.24	10.33	2.76	22.24
1970	3.78	5.59	10.69	2.90	22.96
1971	3.45	5.69	11.02	3.01	23.16
1972	3.83	6.00	11.14	3.19	24.17
1973	4.14	6.21	10.78	3.35	24.48
1974	3.82	5.67	10.90	3.31	23.69
1975	3.44	5.53	9.34	3.20	21.50
1976	3.49	5.68	9.20	3.47	21.83
1977	3.32	6.00	8.91	3.63	21.86
1978	3.14	6.26	8.37	3.74	21.51

<u>Transportation</u>					
Energy Demand (Delivered) in Quads					
Year	Solid Fuels	Oil	Gas	Electricity	Total
1968	0.02	13.51	0.00	0.02	13.55
1969	0.02	14.06	0.00	0.02	14.09
1970	0.02	14.53	0.00	0.01	14.56
1971	0.01	15.20	0.00	0.01	15.23
1972	0.00	16.16	0.00	0.01	16.18
1973	0.00	16.87	0.00	0.01	16.88
1974	0.00	16.69	0.00	0.01	16.71
1975	0.00	17.21	0.00	0.01	17.22
1976	0.00	17.78	0.00	0.01	17.79
1977	0.00	18.29	0.00	0.00	18.29
1978	0.00	19.07	0.00	0.00	19.07

*Continued on following page.

TABLE 3 (continued)

<u>Residential/Commercial</u>					
Year	Solid Fuels	Oil	Gas	Electricity	Total
1968	0.50	5.56	6.54	2.13	14.74
1969	0.42	6.23	7.00	2.34	15.99
1970	0.40	6.54	7.63	2.48	17.05
1971	0.38	6.55	7.72	2.65	17.29
1972	0.34	6.98	7.93	2.94	18.19
1973	0.31	6.42	8.32	3.16	18.21
1974	0.28	5.99	7.62	3.37	17.26
1975	0.27	5.22	7.72	3.60	16.81
1976	0.27	6.75	8.27	3.76	19.05
1977	0.27	7.15	8.01	3.98	19.40
1978	0.30	7.43	8.77	4.19	20.69

Total Energy Demand (Delivered) in Quads, by Fuel Type

Year	Solid Fuels	Oil	Gas	Electricity	Total
1968	4.44	24.23	16.21	4.73	49.61
1969	4.35	25.53	17.32	5.12	52.32
1970	4.20	26.66	18.31	5.40	54.57
1971	3.84	27.44	18.73	5.67	55.68
1972	4.18	29.14	19.08	6.15	58.54
1973	4.45	29.50	19.10	6.53	59.57
1974	4.10	28.35	18.52	6.69	57.65
1975	3.71	27.96	17.05	6.81	55.53
1976	3.75	30.21	17.47	7.24	58.67
1977	3.59	31.43	16.92	7.61	59.55
1978	3.44	32.76	17.14	7.93	61.27

TABLE 4

Prices by Fuel and Sector, United Kingdom*

Year	<u>Industry</u>			
	Solid Fuels	Oil	Gas	Electricity
1968	1.211	1.461	3.999	11.314
1969	1.106	1.385	3.323	10.719
1970	1.050	1.079	2.393	10.145
1971	1.152	1.567	1.588	10.261
1972	1.273	1.528	1.330	9.692
1973	1.268	1.313	1.652	9.049
1974	1.178	1.633	1.289	11.042
1975	1.846	4.053	1.368	12.353
1976	2.148	3.870	1.539	13.315

Year	<u>Transportation</u>			
	Solid Fuels	Oil	Gas	Electricity
1968	0.000	10.837	0.000	0.000
1969	0.000	11.647	0.000	0.000
1970	0.000	11.193	0.000	0.000
1971	0.000	10.674	0.000	0.000
1972	0.000	10.027	0.000	0.000
1973	0.000	9.539	0.000	0.000
1974	0.000	10.178	0.000	0.000
1975	0.000	18.307	0.000	0.000
1976	0.000	16.068	0.000	0.000

Year	<u>Residential/Commercial</u>			
	Solid Fuels	Oil	Gas	Electricity
1968	2.918	3.073	6.471	15.370
1969	2.778	2.866	5.992	14.080
1970	2.813	2.657	5.601	12.999
1971	2.944	2.949	4.927	12.891
1972	3.180	3.131	5.106	12.815
1973	3.193	3.624	5.458	11.947
1974	2.796	3.384	5.089	12.377
1975	2.706	5.424	4.596	12.536
1976	3.015	5.916	4.599	14.687

*All prices are \$1978/MMBTU

TABLE 5

Consumption by Sector and Fuel, United Kingdom*

Industry

Energy Demand (Delivered) in Quads

Year	Solid Fuels	Oil	Gas	Electricity	Total
1968	1.16	1.57	0.16	0.36	3.26
1969	1.15	1.71	0.20	0.39	3.43
1970	1.08	1.80	0.26	0.40	3.53
1971	0.94	1.84	0.36	0.40	3.54
1972	0.80	1.92	0.51	0.40	3.64
1973	0.79	2.00	0.59	0.44	3.82
1974	0.71	1.80	0.61	0.41	3.54
1975	0.66	1.52	0.60	0.41	3.20
1976	0.65	1.57	0.64	0.43	3.29

Transportation

Energy Demand (Delivered) in Quads

Year	Solid Fuels	Oil	Gas	Electricity	Total
1968	0.00	1.03	0.00	0.00	1.03
1969	0.00	1.07	0.00	0.00	1.07
1970	0.00	1.12	0.00	0.00	1.12
1971	0.00	1.16	0.00	0.00	1.16
1972	0.00	1.31	0.00	0.00	1.21
1973	0.00	1.29	0.00	0.00	1.29
1974	0.00	1.24	0.00	0.00	1.24
1975	0.00	1.23	0.00	0.00	1.23
1976	0.00	1.27	0.00	0.00	1.27

*Continued on following page.

TABLE 5 (continued)

Residential/Commercial

Energy Demand (Delivered) in Quads

Year	Solid Fuels	Oil	Gas	Electricity	Total
1968	1.03	0.41	0.35	0.32	2.11
1969	0.97	0.46	0.39	0.35	2.17
1970	0.89	0.49	0.43	0.37	2.18
1971	0.74	0.50	0.48	0.38	2.10
1972	0.65	0.53	0.55	0.41	2.14
1973	0.63	0.55	0.59	0.43	2.21
1974	0.60	0.48	0.67	0.43	2.18
1975	0.51	0.48	0.73	0.42	2.14
1976	0.47	0.49	0.78	0.42	2.15

Total Energy Demand (Delivered) in Quads, by Fuel Type

Year	Solid Fuels	Oil	Gas	Electricity	Total
1968	2.19	3.02	0.51	0.69	6.40
1969	2.12	3.23	0.59	0.73	6.67
1970	1.96	3.41	0.69	0.76	6.83
1971	1.68	3.50	0.84	0.79	6.81
1972	1.45	3.66	1.06	0.81	6.99
1973	1.43	3.84	1.18	0.87	7.31
1974	1.31	3.53	1.28	0.84	6.96
1975	1.17	3.23	1.33	0.84	6.56
1976	1.12	3.33	1.41	0.85	6.71

On the one hand, as we planned before 1970, we could again choose a rapid but smooth transition to nuclear energy or coal for all uses of energy in stationary devices--electricity generation, industrial heat and home heat--leaving oil for transportation. On the other hand, we could try to reduce demand and develop alternative sources of supply so that both nuclear power, with the problems it raises, and coal, with its health and environmental effects can be avoided. The CONAES report studies some of these scenarios as listed in Table 6.

Table 6

Scenario	GNP growth rate (aver. ann.%)	Energy price ratio 2010/1975(aver.)	Energy conservation policy
I ₂	2	4	Very aggressive, deliberately arrived at reduced demand requiring some lifestyle changes
I ₃	3		
II ₂	2	4	Aggressive; aimed at maximum efficiency plus minor lifestyle changes
II ₃	3		
III ₂	2	2	Slowly incorporates more measures to increase efficiency
III ₃	3		
IV ₂	2	1	Present policies unchanged
IV ₃	3		

Firstly, we have to decide what we would like our equilibrium energy position to be--choosing from among realistic alternative strategies. Secondly, we have to decide how to get there from here. In discussing this, CONAES make several assumptions. Among these is that it is politically impossible to return to the pre-1970 forecasts of costs and expansion capability of nuclear power and coal. The delays and additions caused by the need to protect the environment, and even more important to satisfy the public that the environment is protected, have increased costs much higher than inflation.

Thirdly, we have to decide that a completely free market in energy is politically impossible now, even if it existed or were possible at one time.

Fourthly, we have to decide that energy costs in "constant" dollars will double in 20 years; this is very likely for oil and gas which we are running out of, but it is also assumed for the capital construction of a nuclear or coal plant. The basis for this assumption is the experience of the last 8 years that I outlined earlier, but it can be questioned; do we now have enough safety or enough stack gas purification?

Fifthly, CONAES assume the principal political method for influencing demand will be price adjustment. If the price goes up, demand will go down. Price can be raised higher than cost, either by taxes or by profits.

I show in Figure 6 from the CONAES study how to achieve the various energy scenarios.

For scenarios II_a, II_b it is assumed that energy prices rise a factor of 4 in attempts to reduce the demand. For scenarios I_a, I_b, it is assumed in addition that aggressive laws and regulations are used to force lower energy demand. We already saw that energy prices in the U.S. are only about 70% of those in Europe, so this corresponds to a price risk to 2 1/2 times the European levels.

I note from Figure 2 it is possible to have self consistent energy scenarios with GNP growth rates of 2% or 3% per year.

I would, in line with my earlier discussion, include a scenario V₃: a return to the 1970 plan with more nuclear power, less constraints and therefore lower price (0.8). This is the 1970 projection with delays. I would do this to emphasize what we have already decided to give up.

The point of this part of the CONAES study is that the choice between the desired outcomes is a political one and the means that are taken now to influence the outcome are political decisions.

The next table (7) shows the breakdown by energy sources for several scenarios. It is worth commenting on the ways in which the explicit, and hidden, assumptions enter into the different results.

In none of the scenarios is there an abolition of oil imports. Yet other countries regard this as the biggest single action which the U.S. can take. Continued oil imports keep up the world price and make oil unavailable for less developed countries. International policies demand that this attention to oil imports be a prime policy statement for the U.S. government. In Tokyo, the French President, Mr. Giscard D'Estaing and the Prime Minister of France urged this very strongly on President Carter. Although I believe this is a very important point, the main new feature of CONAES--a serious discussion of our energy scenarios--is unaltered by such

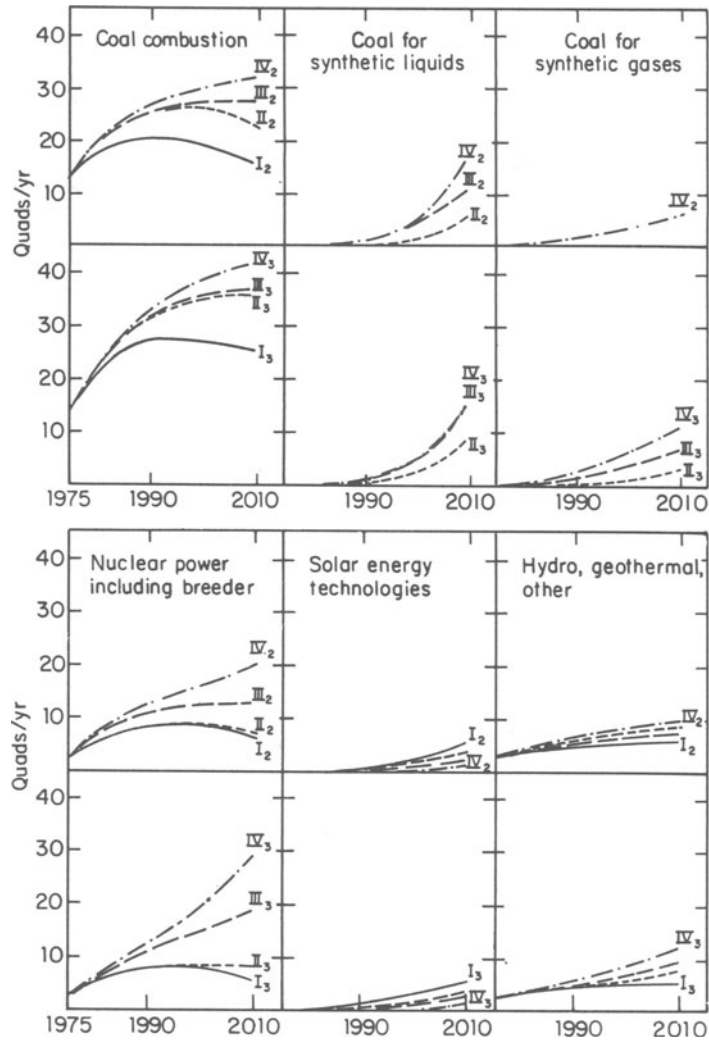


Figure 6. Trends in U.S. fuel production and imports, adopted for the CONAES scenarios.

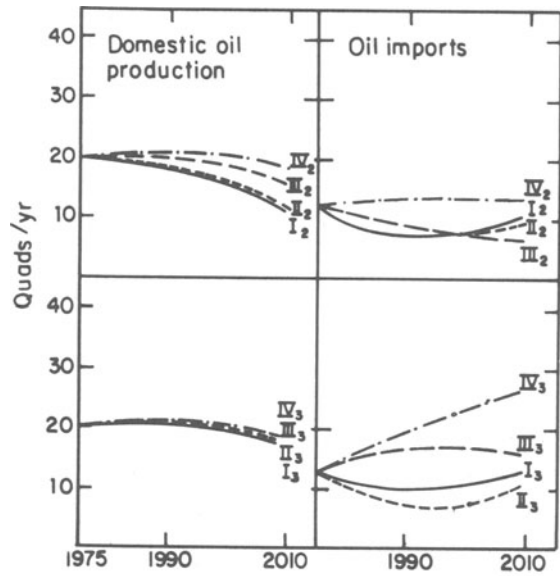


Figure 6 (continued)

TABLE 7
CONAES Scenario I (fuel mix in quads/year)

Scenario	1975	1990	2010
<u>I₂: 2% GNP growth</u>			
Oil			
domestic	20	18	11
imported	13	5	12
shale	0	0	0
Gas			
domestic	19	13	8
imported	1	0	0
Coal			
combustion	13	20	15
conversion to synthetic liquid	0	0	0
conversion to synthetic gas	0	0	0
Nuclear	2	8	6
Solar	0	1	6
Other (hydro, geothermal, etc.)			
Total	71	70	64
Liquid Fuels ^a	33	23	23
Gaseous Fuels ^a	20	13	8
Electricity ^b	20	25	17
<u>II₂: 2% GNP growth</u>			
Oil			
domestic	20	18	11
imported	13	5	10
shale	0	0	1
Gas			
domestic	19	13	10
imported	1	0	3
Coal			
combustion	13	25	22
conversion to synthetic liquid	0	0	6
conversion to synthetic gas	0	0	0
Nuclear	2	8	7
Solar	0	1	4
Other (hydro, geothermal, etc.)			
Total	71	76	83
Liquid Fuels ^a	33	23	26
Gaseous Fuels ^a	20	13	13
Electricity ^b	20	31	29

^aIncludes losses in production and distribution, but not conversion for synthetic fuels derived from coal.

^bIncludes conversion losses.

TABLE 7 (continued)

Scenario	1975	1990	2010
<u>III₃: 3% GNP growth</u>			
Oil			
domestic	20	21	18
imported	13	16	14
shale	0	0	2
Gas			
domestic	19	14	14
imported	1	1	1
Coal			
combustion	13	29	34
conversion to synthetic liquid	0	2	19
conversion to synthetic gas	0	1	7
Nuclear	2	11	18
Solar	3	5	10
Other (hydro, geothermal, etc.)			
Total	71	101	140
Liquid Fuels ^a	33	38	47
Gaseous Fuels ^a	20	16	20
Electricity ^b	20	38	48
<u>IV₃: 3% GNP growth</u>			
Oil			
domestic	20	21	18
imported	13	20	27
shale	0	0	3
Gas			
domestic	19	18	16
imported	1	0	6
Coal			
combustion	13	31	42
conversion to synthetic liquid	0	1	19
conversion to synthetic gas	0	3	12
Nuclear	2	12	30
Solar	0	0	2
Other (hydro, geothermal, etc.)			
Total	71	113	188
Liquid Fuels ^a	33	42	61
Gaseous Fuels ^a	20	20	30
Electricity ^b	20	45	71

^aIncludes losses in production and distribution, but not conversion for synthetic fuels derived from coal.

^bIncludes conversion losses.

an adjustment.

A hidden assumption of scenarios I_2 and I_3 is that nuclear power is undesirable. Indeed, it seems that a major motivation of those urging these scenarios is a desire to avoid completely the use of nuclear electric power. We see in I_2 , therefore, a reduction in nuclear electric power by the year 2010. We could, if we choose, modify scenarios I_2 or I_3 , increase nuclear electric power and reduce oil consumption somewhat more. Then we can completely avoid oil imports.

Economically, the assumption that the costs of nuclear power will rise faster than inflation--and as fast as oil prices--tends to lead us to this dependence on oil. However, if nuclear power costs rise no faster than inflation, economic considerations will lead to more nuclear power.

I have talked privately to many of the persons who have been vocal and effective in public discussions of alternatives to nuclear power. They all privately agree that their proposals imply this increase of fuel price by a factor of 4, although for tactical reasons they do not always say it in public.

I want, therefore, to discuss some aspects of this factor of 4 price increase. This will not all be a cost increase, and therefore for purposes of calculating the change in gross national product, all of this factor is not involved.

The most important conclusion of the CONAES study is that moderation of energy demand is of the highest importance. I list in order the following conclusions in this regard:

1. Very substantial moderation in energy demand growth is realizable over a 20-30 year period as a result mainly of technical efficiency improvements in the use of energy without adverse effects on economic growth or employment.

2. Even at present energy prices, there are many opportunities for investments in energy-use efficiency that cost less per unit of energy saved than the investment cost of increasing energy supply by the same amount.

3. The potential for cost-effective energy conserving investment increases with increasing energy prices. Conservation could therefore be stimulated by energy taxes.

4. If the economically optimal response to energy price changes is to be realized in practice, especially by individual consumers and households, it will probably have to be encouraged by mandatory performance standards for durable goods, including housing.

5. A wide range of future growth rates in energy consumption is technically feasible and compatible with continued high economic growth and little change in consumption patterns in the nonenergy sectors. Which path should be followed is primarily a question for political and social choice. Political difficulties tend to increase at both the high and low end of the energy growth possibilities.

6. Sustained and predictable price and regulatory trends are necessary to the realization of any of the projected growth paths without social and economic disruption.

7. Continued research on the economic and distributional consequences of various tax, pricing, and regulatory practices and policies is necessary to improve the basis for energy conservation policy.

It is interesting to discuss what the effect would be on GNP of a reduction of energy use. The pre-1970 conventional wisdom would imply a proportionate reduction in GNP. One important change in perception is that the historical energy/GNP ratio might be halved by technical efficiency improvements.³ This is discussed in detail in a paper by Jorgenson and Hudson.

The point is that the increase in total costs is in not just the direct use of energy, but also the indirect use of energy. Jorgenson uses an input/output analysis to trace energy and capital flows through the economy. In Table 8 I show the assumptions of the 4 policies studied and in Figure 7 I show the way in which the calculation proceeded.

Finally, in the Table 9 I show some results of their calculations. They list alternative procedures by which they suggest that energy consumption be reduced. The base case is the 1979 set of laws and regulations, and the output is listed as percentage changes resulting from these laws. Let us look at Jorgenson's proposal 4.

This is designed to bring the U.S. energy consumption down to 70 Q (10^{16} Btu per year), which is about the level of the CONAES scenario I. They agree with CONAES that energy prices have to increase a factor of 3 1/2. Relative to cost of capital (set as 1.0) the labor costs drop to 0.9 of the base case value; this is a reflection of an assumption that less skilled (and more) labor is used for energy conserving devices than for energy production devices.

Energy costs account for about 5% of the U.S. gross national product. Scenario I of CONAES suggests an increase of a factor of 4 in energy costs. Jorgenson and Hudson consider the effect of an increase of a factor of 3 1/2 (not 4). Naively one might

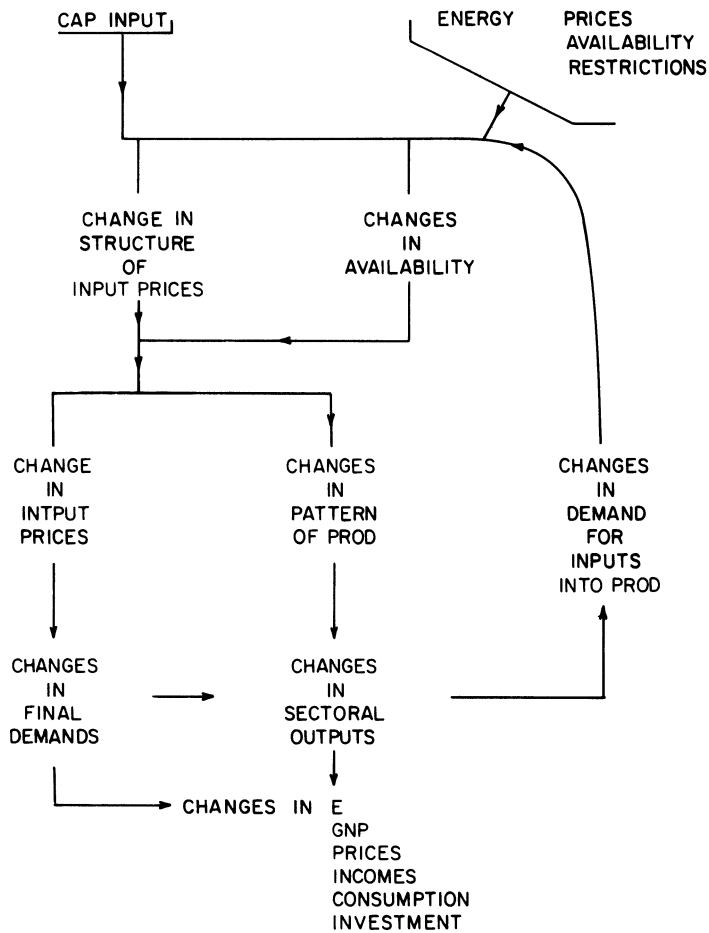


Figure 7. Flow chart of the Jorgenson Calculation

TABLE 8
Jorgenson Calculation

Base Case	1979 (June)
Policy 1	Taxes on domestic oil to world energy prices Energy conservation taxes and subsidies Oil and gas conversion to coal
Policy 2	+ tax on oil to \$4.50/BBL in 1985 \$7.00/BBL in 2000
Policy 3	Tax to reduce to 90Q
Policy 4	Tax to reduce to 70Q

TABLE 9

Percentage Change From Base Case Policy

	1	2	3	4
Input Prices				
Capital	-	-	-	-
Labor	-0.68	-2	-5	-10
Energy	16	30	108	217
Output Prices				
Agriculture and Construction	1	1.3	2	5
Manufacturing	0.08	0	1	6
Transportation	3	4	8	13
Services	-0.3	-1	0.6	2
Energy				
Actual	0.2	11	88	187
Effective	16	30	108	217

imagine it is an effect on GNP of a reduction of $(3 \frac{1}{2} - 1) \times 5 = 12 \frac{1}{2}\%$. But there will also be a reduction of investment and according to Jorgenson and Hudson's calculations, there will be a reduction of GNP by 27% relative to no increase in fuel prices.

These considerations and scenarios may all be irrelevant to the rest of the world. In all the scenarios nuclear power can be replaced by coal--to the extent it can be produced fast enough--and the cost increase is not great. But for other countries this is not true. Japan, for example, has little coal, and the transportation would quadruple the price relative to the Montana price, and perhaps double the delivered energy cost.

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FAST BREEDER REACTORS - LECTURE 1

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INTRODUCTION

The subject of these lectures will be the Fast Breeder Reactor. At the outset let us make some statements which will serve to illustrate the importance of this subject.

- (a) The world's thermal energy reserves from fossil fuels are about 83×10^{21} thermal joules according to King Hubbert.
- (b) The world's uranium reserves are about 10^7 tonnes and in thermal reactors this would yield about 4×10^{21} J of heat.
- (c) Fast breeder reactors could extract about 2×10^{23} J of heat (i.e. greater than that from the total fossil reserves) from this 10^7 tonnes of uranium.

Thus fast breeder reactors can make a significant contribution to the world's future energy requirements.

In these lectures we will describe the development and construction of fast breeder reactors, their safety, the fuel cycle and the economics of the system. Lastly, we will consider the concerns that have been expressed with regard to the introduction of fast breeder reactors on a commercial scale.

FAST REACTOR

It is not our intention to delve into the physics of fast breeder reactors. If you wish to pursue this aspect then an appropriate reference (Ref. 1) has been provided in the lecture notes. However it is worth including some comments because part of the terminology is derived from it.

At this stage it is worth reminding ourselves that the term "fast reactor" does not in itself define a specific style of design any more than does the term "thermal reactor". It just means that the reactor is constructed without a moderator and consequently that the average neutron velocity is very much higher than in the thermal reactor. Typically, in a fast reactor, the most numerous population of neutrons will be in the energy range 0.2 to 0.8 MeV. In a thermal reactor, the neutron population will be roughly equally divided above and below about 1 eV. (See Figure 1).

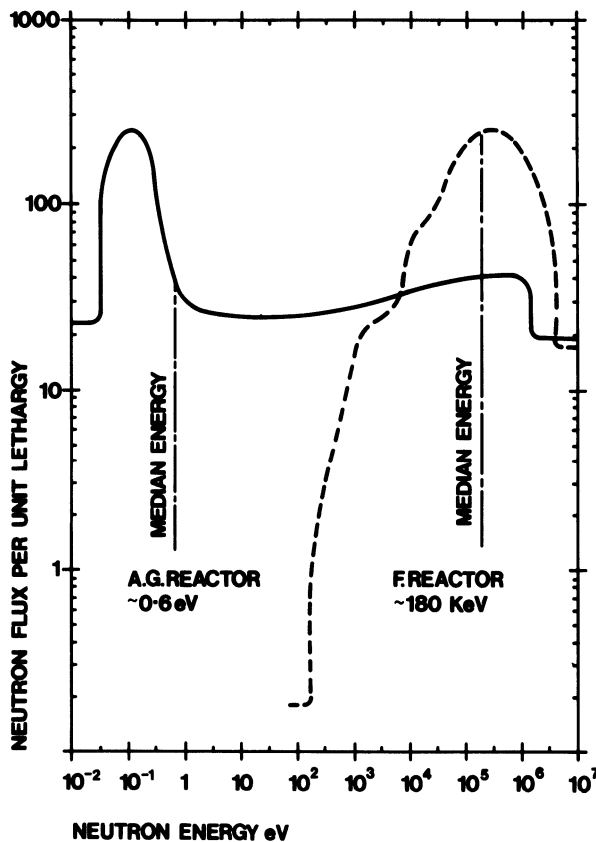


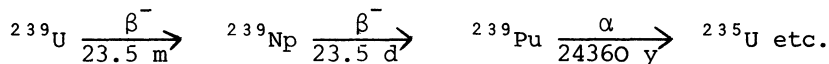
Fig. 1. Neutron flux per unit lethargy plotted against neutron energy for a "thermal" reactor and a "fast" reactor

When the fission of uranium nuclei had been discovered, and it had been observed that a fission caused by one neutron generated two or three new ones, the possibility of a chain reaction generating power was apparent.

There was difficulty in achieving a chain reaction. Of the two main isotopes present in naturally occurring uranium, the "fissile" one, ^{235}U , in which fission can be caused by neutrons of any energy, is very rare. The other, ^{238}U , can be fissioned only by high energy, or "fast" neutrons, above about 1 MeV, but it "absorbs" neutrons of all but the lowest energies, (below about 0.1 MeV).

Therefore, for a chain reaction, the energy of the fission neutrons has to be round about thermal levels, in which case natural uranium can be used, or the proportion of ^{235}U or some other fissile isotope has to be increased substantially. Both of these routes were followed from the early days; the first led to the development of "thermal" reactors, and the second to "fast" reactors.

Let us now consider what happens to neutrons captured in ^{238}U . The ^{239}U nucleus formed decays as follows:



The times are the half-lives of the decay processes. As far as reactor operation is concerned, ^{239}Pu is the end product of the chain.

The nuclear properties of ^{239}Pu are similar to those of ^{235}U , and in particular it is "fissile". So we have a way of converting the "fertile" isotope ^{238}U into "fissile" material. The quantity of fissile material which can be potentially generated depends on the material in which the fissions take place and the energy of the neutrons causing them. The important parameter is η , the number of fission neutrons generated per neutron absorbed. Figure 2 shows the variation of η with energy for two fissile isotopes. Of these η neutrons, one is needed to maintain the chain reaction. Some of the rest are lost because they diffuse out of the reactor or are absorbed in other materials such as structure or coolant. The remainder are available for capture in fertile material to turn it into fissile. If L neutrons are lost and C captured in fertile material, we have therefore, roughly

$$C \approx \eta - 1 - L$$

If $C > 1$, more fissile atoms are created than are consumed. C is known as the "Breeding Ratio", and the reactor is a "Breeder" reactor. If $C < 1$, as it is in most thermal reactors, it is called the "Conversion Ratio".

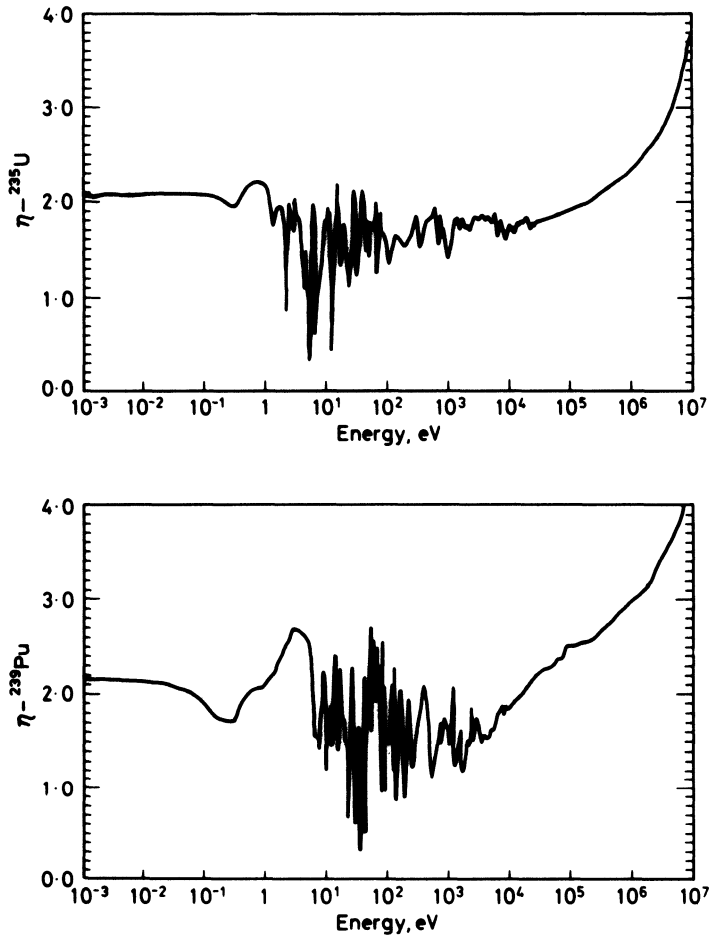


Fig. 2. Neutron yield (η) per neutron absorbed for ^{235}U and ^{239}Pu (REF. 1)

In practice, L cannot be reduced below 0.2, so breeding is possible only for $\eta > 2.2$. Figure 2 shows how this can be brought about. A fast reactor using either of the two fissile materials will breed only if the neutron energy is above 1 MeV or so. In both cases the higher the neutron energy, the higher the breeding ratio.

Thermal reactors using ^{235}U have "conversion ratios" in the range 0.6 (LWRs) to 0.8 (heavy water and gas-cooled reactors).

If N atoms of ^{235}U are fissioned in a reactor with breeding or conversion ratio C , then CN ^{239}Pu atoms are generated. If these in turn are fissioned in a similar reactor C^2N ^{239}Pu atoms are formed (assuming for illustration that C is unchanged) and so on. The total number of atoms which can be fissioned in this way is $N(1 + C + C^2 + \dots)$. If $C < 1$, the series converges to $N/(1 - C)$. If the fuel is natural uranium, N is 0.7% of the total number of uranium atoms supplied, and the maximum number of atoms which can be fissioned in a thermal reactor with $C = 0.7$ is, $0.7/(1 - 0.7) \approx 2\%$ of the uranium supplied. For the PWR the value is 0.6% because so much of the ^{235}U is rejected in the initial enrichment.

For a breeder reactor with $C > 1$ the series diverges and, in principle, all the uranium supplied can be fissioned, the ^{235}U directly and the ^{238}U by converting it into ^{239}Pu . In practice, some ^{239}Pu is not immediately recoverable during fuel reprocessing, and some by conversion to higher isotopes, and the limit is about 50% of the total uranium feed which can be fissioned. Thus, in round numbers, breeder reactors can extract about 80 times as much energy from uranium as pressurized water reactors.

So, breeding is basically the conversion of ^{238}U into ^{239}Pu by neutron capture, but there are complications. ^{239}Pu is the beginning, not the end of a chain. It in turn, undergoes neutron capture and is converted into ^{240}Pu . This is a fertile isotope with properties rather like ^{238}U ; it is fissile to fast neutrons, but captures neutrons of all energies. When it captures a neutron it is converted into ^{241}Pu , which is fissile like ^{239}Pu , except that it has a higher fission cross-section, especially for neutrons with energy below 0.1 MeV. ^{241}Pu may in turn capture a neutron to become ^{242}Pu , which again is fissile only to fast neutrons. ^{242}Pu also captures neutrons, and the resulting ^{243}Pu undergoes β -decay to ^{243}Am . Still higher isotopes are formed, but the quantities are small and they can be neglected for the purposes of this lecture.

DESCRIPTION OF FAST REACTOR

In this section we will describe the fast breeder reactor in outline and we will show that a variety of designs is possible.

The core of the reactor contains fuel sufficiently enriched to achieve a chain reaction. This core is surrounded by a "blanket" of fertile ^{238}U which can capture neutrons escaping from the core. In the operation of such a reactor the inventory of fissile material decreases in the core and increases in the blanket; overall it falls. The fission product inventory increases.

The core fuel is removed after a period of operation to:

- (i) Remove the fission products accumulated in the fuel. They absorb neutrons and reduce the breeding ratio of the reactor.
- (ii) Adjust the fissile loading to maintain the chain reaction.
- (iii) Reconstitute the fuel into new fuel because there is an irradiation limit to the operation of the fuel.

At longer intervals the blanket elements are also reprocessed to remove fission products and to separate out the plutonium for use in fabricating new core fuel. New blanket elements are made from purified ^{238}U and from new ^{238}U feed material.

Since the reactor can produce more plutonium than it consumes, this excess can be accumulated until it is sufficient to fuel a second fast reactor. Alternatively, if no system expansion is required, the ^{238}U blanket could be reduced until only enough plutonium is generated to replace that which is consumed in the core. More probably the breeding could be adjusted so that the speed with which the fuel is cycled could be relaxed so that the system as a whole is "self-sustaining" rather than "breeding".

When system expansion is required the obvious approach is to minimize the quantity of plutonium involved in the whole reactor and processing system; in that way it takes less time to accumulate enough plutonium to start up a second one.

We have already indicated that a number of variations are possible in the design of a fast breeder reactor with respect to:

- (i) the size of the 'specific plutonium inventory' - the amount of fissile material needed for a reactor to produce a given power output at a given load factor. This inventory comprises two parts - fissile material present within the reactor itself and fissile material outside the reactor in the fuel processing cycle. The former part depends, particularly, on the fuel rating and enrichment. The latter amount is dependent on the rate at which fuel passes through the reactor (i.e. burn-up and rating) and also the time taken in storage before reprocessing the fuel, the

reprocessing time itself and the time to fabricate fresh fuel and to transport it into the reactor.

- (ii) Its 'breeding gain' (i.e. its excess plutonium production) and hence its 'linear doubling time' (the time taken for a fast reactor to produce enough plutonium to provide the total, i.e., in-pile and out-of-pile, inventory required by a new reactor. It is proportional to total plutonium inventory and inversely proportional to its net plutonium production, the latter depending on breeding gain, the amount of plutonium not immediately recovered from process residues and load factor).

In addition to these two major factors are the practical considerations arising directly from reactor design.

Since the reactor has a liquid metal coolant the core must be small (a few cubic metres); neutron leakage from the core into the blanket is therefore relatively high. It follows that for neutronic reasons a high concentration of fissile material is required for criticality to be achieved. Thus a fast reactor requires fuel with a high content fissile component - and such fuel is expensive besides being a scarce resource. To produce electricity costing about the same as that produced by thermal reactors means that the 'specific power' (in MW/t of heavy atoms) of the fast reactor must be at least an order of magnitude greater than thermal reactors to offset the increased fuel costs. That in turn makes it necessary to maximize the heat transfer area of the fuel. Because the fuel is usually in the form of cylindrical rods ('pins') an increase in heat transfer area leads to reducing the diameter of fuel, thereby implying an increase in length or number of fuel pins. The cost of manufacture considerably increases as the diameter decreases. All this demands an optimization of reactor design to give best performance within the technical restrictions we shall be discussing later. Depending upon circumstances that optimization process can lead to a wide variety of design parameters. There is therefore no unique "fast reactor design".

The criteria applied to the choice of coolant are:

- (i) It must be chemically compatible with the core and heat exchanger materials.
- (ii) It must be commercially available.
- (iii) The pumping power required to remove the heat must be a minimum.
- (iv) It must be acceptable in terms of reactor safety.

Table 1. Variation of Design Parameters for Fast Reactors

	DESIGN 1	DESIGN 2	DESIGN 3 Reference	DESIGN 4	DESIGN 5	DESIGN 6
PLUTONIUM INVENTORIES kg Pu E 239/GWe						
In-pile inventory at equilibrium	2940	2350	2230	2230	2060	2640
Fuel cycle inventory at 75% load factor	2334	1228	1184	1042	1628	1368
Total inventory	5274	3578	3414	3272	3688	4008
PLUTONIUM FLOWS kg Pu E 239/GWe yr						
Input	1921	2050	1936	1739	2735	2160
Core	-174	-254	-231	-306	-282	-99
Blanket	+347	+404	+421	+434	+460	+405
Output	2094	2200	2126	1867	2913	2466
Net production	+173	+150	+190	+128	+178	+306
After reprocessing (Allows for some Pu held in process plant residues)	+131	+107	+147	+91	+120	+293
Equilibrium doubling time at 75% load factor years	53.4	44.8	30.9	47.9	41.2	18.2

DESIGN 1 assumes 18 months out-of-pile time, 2 fuel cycle batches, a core height of 1.2m and a mass rating of 229 MW (t) tonnes of heavy atoms

DESIGN 2 includes an increase in the number of fuel cycle batches, a decrease in the time the plutonium spends in the cycle and a decrease in fuel pellet diameter compared with Design 1

DESIGN 3 is Design 2 with decreased core height

DESIGN 4 is Design 3 with decreased core fuel density and increased core burnup

DESIGN 5 is Design 3 with decreased core fuel density and decreased core burnup

DESIGN 6 is Design 5 with decreased mass rating, decreased can thickness, increased axial breeder height and reduced plutonium held in residues

- (v) It must be suitable to reactor core conditions (i.e. not a neutron moderator).

Sodium is used because it allows the use of higher power density reactors with less pumping power. It also has the advantage of requiring no circuit pressurisation. As sodium becomes slightly radioactive in the primary circuit it is prudent to interpose an additional sodium circuit and this, in turn, exchanges heat with water. This additional circuit and the capital cost penalties consequent on the use of sodium carry the immediate implication that the capital cost of the fast breeder reactor will be higher than that of a thermal reactor even though there are capital gains from the smaller core and the use of a low pressure primary system. However, overall, the capital cost will be higher.

Fuel and core temperatures are high - leading to enhanced damage to the fuel during operation. However, high burn-up of the fuel is necessary to minimize inventory losses. Metallic fuel has achieved high burn-up but is metallurgically unstable, particularly at high plutonium contents, so ceramic fuel (usually oxide) is universally preferred. However the introduction of oxygen into the fuel increases the degree of moderation which leads to reduced breeding gain. It is possible that carbide fuels would be better than either but not enough is known about them to plan on their early use.

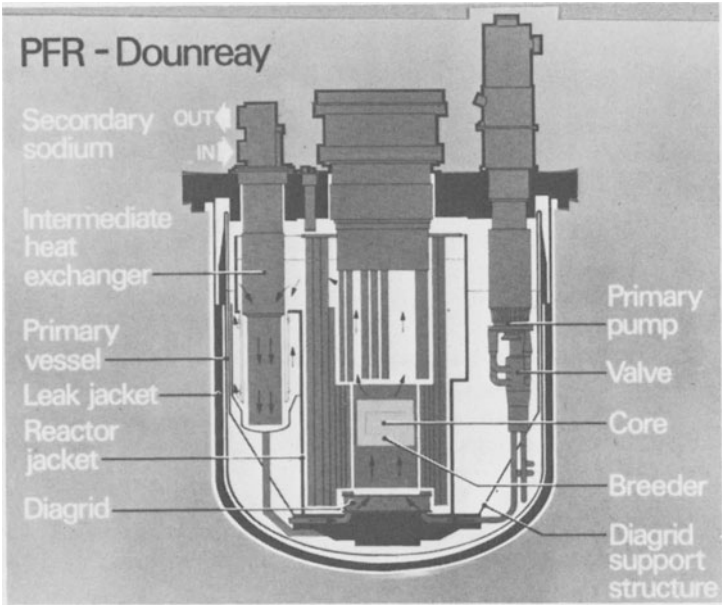


Fig. 3. Schematic illustration of the 'internals' of a fast breeder core region

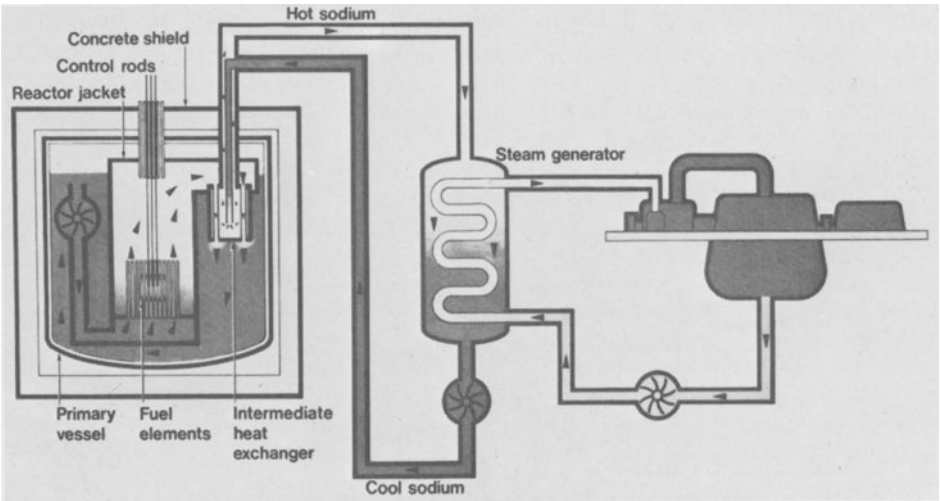


Fig. 4. Schematic illustration of the general arrangement of a fast breeder reactor

Because the fuel releases fission products it has to be 'clad' in a 'can'. The cladding material chosen has not only to be compatible with the fuel and coolant but also has to withstand the rigours of service - neutron irradiation and stress. However such materials, usually steels, are neutron absorbers so the thickness of the cladding has to be minimized but still be able to withstand rigorous service.

The effect of variations in design parameters on the plutonium inventories, plutonium flows and doubling time are shown in Table 1, where it can be seen that variation in core and blanket design leads to variations in both plutonium production and in doubling time.

Figure 3 shows, schematically, the core region of a typical fast breeder reactor. The fuel elements are made of mixed plutonium and uranium oxide clad in stainless steel. The core is surrounded by a region called the "breeder or blanket", which is filled with ^{235}U , clad in stainless steel.

Figure 4 shows, schematically, the general arrangement of a typical fast breeder reactor. The heat generated from the fission process is carried away from the core by molten sodium. The hot sodium is pumped through heat exchangers so that its heat is exchanged with the sodium in the secondary circuit and this, in turn, exchanges heat with water in the secondary heat exchangers which produce steam to drive the turbines to produce electricity.

DEVELOPMENT OF FAST BREEDER REACTORS

Before about 1960 a high breeding ratio was thought to be the most important quality of a fast reactor. This meant that the mean neutron energy had to be kept high, so extraneous materials, especially moderators, had to be excluded from the core. As a result the early reactors had metal fuel.

The cores of these reactors were small; for high power operation they had to be cooled with high density coolants. Water was precluded because it is a moderator, so liquid metals - either sodium or sodium potassium alloy - were used. Many neutrons leaked from the small cores, and they were captured in surrounding regions of the natural uranium known variously as breeders or blankets.

Low power experimental reactors of this type were built in the late 1940s and early 1950s. EBR-I (USA) was the first step towards power reactors. It produced 1.2 MW and was the first nuclear reactor of any type to generate electricity.

For full scale power production the core had to be enlarged to include more fuel to permit extra power generation and to allow

for the extra coolant flow. The result was EBR-II and EFFBR in the USA and DFR in the UK. When they were constructed these were seen as prototype power station reactors and EBR-II and DFR were used mainly to test oxide fuel for the next generation of reactors.

About 1960 it became clear that there was more to a fast reactor than good breeding. The cost of the fuel itself, and of fabricating it and reprocessing it after irradiation to remove the fission products and replenishing the fissile material in the core, is significant. The longer the fuel can stay in the reactor before it has to be reprocessed, the lower the cost.

The extent of irradiation that fuel undergoes can be defined in terms of the fraction of all the uranium and plutonium atoms (i.e. all the heavy atoms) which are fissioned. This is called the "burn-up". It became clear that metal fuel could only withstand modest burn-ups before the fuel-clad reaction was excessive so that it had to be reprocessed. The fuel costs associated with such frequent reprocessing were excessive, so an alternative was found in the form of oxides, either UO_2 or PuO_2 or a mixture of the two. Oxide fuel can stand 10% burn-up or more, and so has lower reprocessing costs.

Oxide fuel has other advantages over metal, mainly that it can be operated at high temperatures. The main disadvantage is that the introduction of oxygen into the core reduces the mean neutron energy, and therefore reduces the breeding ratio.

Carbide fuel (UC and PuC) should be better than oxide in many respects, but suffers the disadvantage that it is not so well understood as oxide, which is widely used in thermal reactors as well as fast. The need for reliability often dictates a conservative approach, so oxide fuel is currently used almost universally. In the future, however, it is quite possible that carbide will be preferred.

Mixed oxide fuel, a stainless steel structure, and a liquid sodium coolant have become accepted widely as the route for the development of fast breeder reactors. The use of these materials restricts the design so that all current reactors, from whatever country, show marked similarities. These are all prototypes to be followed by production reactors for the commercial generation of electricity. The developments in countries having major breeder programmes are shown in Figure 5. It is anticipated that the start-up of the first commercial size demonstration fast breeder reactor will be in France in 1982.

FAST BREEDER REACTORS - LECTURE 2

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INTRODUCTION

While various possibilities for the design of the fast breeder reactor exist, you will remember that the main development of the technology has been along the line of mixed oxide fuel, steel cladding and liquid metal coolants. We will restrict ourselves to the consideration of the design of this sort of reactor in this lecture, where we will describe some of the features in some detail. The performance of the fast breeder reactor can be varied with respect to the size of its specific plutonium inventory (the amount of fissile material required for the cycle of operation) and also the breeding gain (i.e. its excess plutonium production) and hence its doubling time, by altering some of the basic core parameters.

In general, specific inventory decreases with:

- (i) Increasing fuel burn-up (mainly due to decreasing the ratio of the out-of-pile time to the in-pile time).
- (ii) Increasing mass rating (MW/tonne heavy atoms) - by either decreasing pin diameter at constant linear rating or by increasing linear rating at constant pin diameter.
- (iii) Decreasing core height.
- (iv) Decreasing axial breeder height.
- (v) Increasing the number of batches in the fuel cycle.
- (vi) Decreasing fuel density.
- (vii) Decreasing out-of-pile processing time.

(viii) Decreasing fuel pin can thickness.

In general, breeding gain increases with:

- (i) Decreasing burn-up.
- (ii) Decreasing mass rating.
- (iii) Decreasing core height.
- (iv) Increasing axial breeder height.
- (v) Increasing the number of batches in the fuel cycle.
- (vi) Increasing fuel density.
- (vii) Decreasing fuel pin can thickness.

We can add that nett plutonium production, which depends upon breeding gain, increases with decreasing amounts of plutonium not immediately recoverable from the fuel cycle during fabrication and reprocessing. In addition, the specific inventory and breeding gain decrease with decreasing load factor (i.e. availability of plant).

It is also worth remembering that because a decrease in specific inventory and an increase in breeding gain both lead to

Table 2. Typical core parameters for an early 1250 MW(e) commercial reactor

Number of batches in fuel cycle	-	6
Fuel pellet diameter	mm	5
Can thickness/pellet diameter	-	0.075
Linear rating	W/mm	50
Mean mass rating	MW/tha	291
Max core burnup	% ha	10
Fuel density	% theoretical	80
Core height	m	1
Core diameter	m	2.66
Axial breeder height	m	2X0.4
Radial breeder thickness	m	0.4
Total sodium area/total core area	-	.410
Fuel feed enrichment	% PuE239	17.0
In-pile inventory at equilibrium	tPuE239/GWe	2.23
Out-of-pile inventory at 75% load factor and nine months Pu out-of-pile time	tPuE239/GWe	1.18
Breeding gain	-	0.209
Nett plutonium production with 2% Pu in residues	tPuE239/GWey	0.147
Equilibrium linear doubling time at 75% LF	y	30.9

a reduction in doubling time the search for an optimum value of doubling time involves a balance of core parameters that often work in opposite directions. Overshadowing the optimisation of the reactor core itself are the adverse effects of long plutonium hold-up times and plutonium retained in residues from the reprocessing plants. As a result of optimisation studies, typical core parameters for an early 1250 MW(e) commercial reactor are listed in Table 2.

These optimised values have an immediate implication on the requirements of the fast breeder reactor system, both in terms of design and its operation. We will examine some of these features in the following sections.

HEAT TRANSFER

The specific inventory consists of two parts - the fissile material in the reactor and that outside the reactor in the reprocessing cycle. The amount of fissile material present within the reactor itself depends on the heat rating and burn-up achieved in the fuel in the reactor. Thus the higher the rating of the fuel, the lower the specific inventory. So there is an incentive to maximise the fuel rating.

However, there are two limitations on the design of the core. In the first instance, the cladding must not exceed 700°C to ensure the cladding will remain intact because of a general loss of strength and, secondly the maximum temperature for the fuel is set at about the melting point of the fuel (2800°C).

The centre temperature of the fuel during operation is related to the linear heat rating of the fuel pin. Thus to avoid melting of the fuel a maximum limit is set for the linear heat rating, and the value is usually about 50 kWm^{-1} . Because there are axial and radial variations, the average value for linear heat rating for the fuel is about 30 kWm^{-1} . Thus a 2500 MW(t) fast breeder reactor requires $8 \times 10^4 \text{ m}$ total fuel element length.

To reduce the investment in fuel there is therefore an incentive to make the diameter of the fuel elements as small as possible. However, the route for manufacturing fuel elements is complex and also the cost increases with smaller diameters and a compromise of about 6 mm is chosen. A fuel pin diameter of 6 mm implies a total of 28 tonnes of fuel in the core of a 2500 MW(t) fast reactor.

The high heat flux can be transferred with only a small temperature difference between cladding and the sodium coolant.

To allow for small variations in power density, temperature variations etc., the maximum coolant temperature is controlled at less than 600°C , which then meets the mechanical properties requirements of components.

Because the maximum coolant temperature has been "fixed" and because the high temperature differences increase stresses in the structure, the resulting design is a compromise. A typical 2500 MW (thermal) reactor would have a coolant temperature rise of about $150 - 170^{\circ}\text{C}$, a mass flow rate of 1200 Kgs^{-1} at a maximum speed of 10 ms^{-1} , and a core about 1 m high and 2.2 m in diameter.

FUEL

The fuel is usually in the form of a mixture of uranium and plutonium dioxides. Oxide is used because it is stable at high temperatures, is compatible with the stainless steel cladding, and consequently it is the fuel that has been most widely studied for use in fast breeder reactor systems. There is a possibility that the carbide form of uranium and plutonium could be used in the future because it has a higher thermal conductivity, higher density and a lower moderating effect on the neutrons.

The fuel element is a stainless steel tube which contains the fuel. Usually the fuel is in the form of sintered pellets which are made from UO_2 and PuO_2 powders, which are mixed in the correct ratio with a binder, formed into shape, sintered and ground to size. There are variations in the manufacturing of the fuel. One alternative to using sintered pellets is to fill the tube with sintered particles of oxide and then to vibrate the tube until the fuel is compacted. To obtain a high packing fraction, particles of various sizes are used. This "vibro-compacted" fuel is attractive because of its simplicity and possible cheapness of manufacture. There are other variations being considered.

On irradiation the appearance of the fuel is completely changed. Figure 6 shows a polished and etched cross-section of fuel after irradiation. You will observe that a hole has developed in the centre which is surrounded by a high density region of fuel of long "columnar" grains lying along the radii of the cylinder. This is surrounded by a region where the grains are larger than in the original material, but arranged at random and only in the outermost region is the original structure preserved.

This restructuring takes place because at intermediate temperatures in the range $1250 - 1700^{\circ}\text{C}$ the sintering process started during manufacture, continues and grains coalesce and

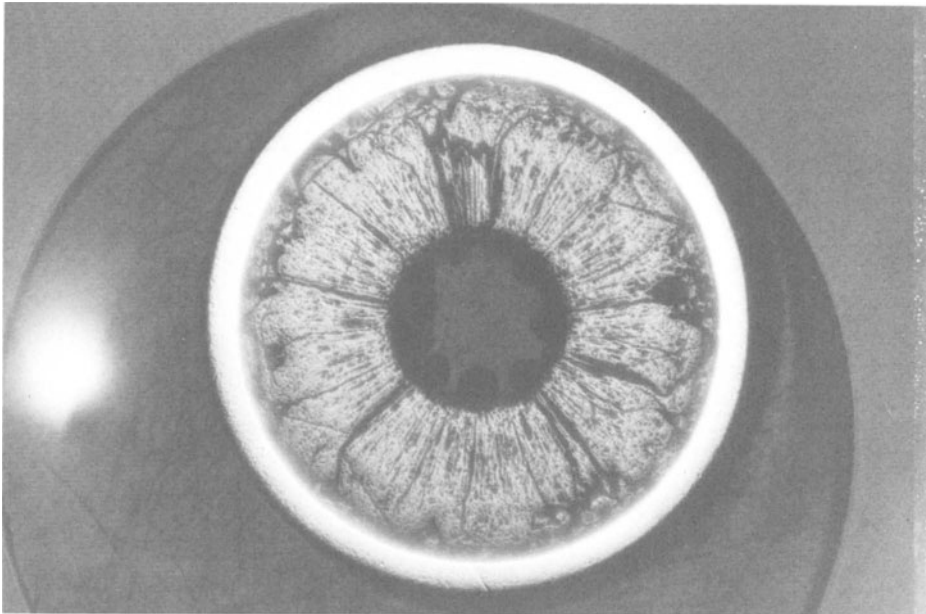


Fig. 6. Cross-section of irradiated fast reactor fuel showing central hole, macroscopic cracks, columnar and equiaxed grain region

grow. At higher temperatures the pores migrate up the temperature gradient because fuel atoms move from the hot to the cold side. The pores move to the centre where they form a hole, while the fuel recrystallises in the wake of a pore as the single crystal or columnar grain. The columnar region is being recrystallised as first the original pores and later bubbles of fission product gas migrate to the central void. In figure 6 you will also see cracks which were not present when the reactor was operating. When the fuel is at temperature, the centre expands more than the circumference because it is hotter, and the cracks, tapering towards the centre, are formed. In the central region these soon heal as the fuel is recrystallised. When the reactor is shut down the central fuel contracts and new cracks, tapering towards the circumference, are formed. These cracks heal on reoperation of the fuel under the irradiation conditions.

Fission in the fuel itself causes swelling of the fuel because one fissile atom is replaced by two fission product atoms. Some of the fission products are lost so that the actual volume increases about 0.8 times the burn-up of the fuel. If this swelling were accommodated entirely by straining the cladding, it would cause about 3% linear strain at 10% burn-up.

Of the fission products that are produced in the fuel, about 12% are gaseous. These are Xenon and Krypton. As their solubility in the fuel is very low, they tend to be precipitated in the form of small bubbles which eventually link up at grain boundaries to form channels by which most of the gas is released. The quantity is very large. At 400°C and 1 atmosphere pressure the gas generated by 10% burn-up of fuel with a density of 10^4 kgm^{-3} occupies 53 times the fuel volume. This gas is accommodated in an empty volume or "plenum" at one end of the fuel element.

It is possible to make the fuel more porous so that this swelling can be accommodated by the elimination of pores. Another possibility is that the pellets can be made with a central hole for the same purpose.

A wide range of elements are produced as fission products, forming a very complex chemical system in the fuel. Also the temperature difference that exists between the surface and the centre of the fuel further complicates the chemical system formed. Probably the dominant chemical factor is the oxygen potential of the fuel which changes as the fissile atoms are replaced by fission product atoms.

The purpose of the cladding is to maintain the configuration of the fuel and to prevent radioactive materials getting into the coolant. A small amount of the cladding is removed by the coolant and a fraction of the corrosion products will become radioactive but the amount is tolerable. We have already seen that as the fuel swells, it releases fission product gases and some of the fission products tend to corrode the cladding. The fuel and cladding interact mechanically and this is a very complex process. The fuel swells and presses onto the cladding at the start of irradiation but the stresses are limited by creep deformation. The cladding itself swells under fast neutron bombardment (an effect not observed in thermal reactors) and this swelling may at some stage exceed the fuel swelling rate, so that the gap between them increases. We will return to this later.

As we have mentioned before, the various mechanisms occurring during irradiation of the fuel interact in a very complex way, so that the main guarantee of fuel behaviour for the design of a fast breeder reactor is provided by extensive irradiation testing of such fuels. For such evaluation there is the requirement for test facilities - both for irradiation and post irradiation examination.

The fuel is in the form of sintered pellets. Above and below the core fuel are axial breeder regions consisting of natural or depleted UO_2 . The volume of the fission product gas plenum is about equal to that of the fuel so that the pressure in the fuel

element at the end of life is some 5 or 6 MPa.

CLADDING AND STRUCTURAL MATERIALS

Let us now say something about the effect of neutron irradiation on the cladding and structural material.

It has been calculated that each and every atom in the iron and steel structure is displaced from its lattice site about 70 times on average during neutron irradiation to full lifetime in the fast breeder reactor. This neutron irradiation has an effect on the properties of these materials. The main effects are swelling, creep deformation, embrittlement and hardening.

Each neutron scattering event produces a cloud of interstitial atoms and vacancies. These diffuse through the material and normally would recombine in due course. In addition, the irradiation produces helium atoms by (n,α) reactions. As they diffuse, the vacancies tend to form clusters around helium nuclei while interstitials accumulate at grain boundaries.

The clusters of vacancies form minute voids, and these grow causing the material to swell. The swelling depends strongly on temperature and varies widely for different materials. In extreme cases, volume increases of about 10% are possible. (See Figures 7 and 8).

Creep deformation is enhanced by neutron irradiation and this is important. In sub-assembly deformation the hexagonal wrapper tries to become a cylinder.

The defects produced by neutron irradiation reduce the mobility of dislocations in the material and so inhibit plastic strain. This results in an increase of the yield stress. At higher irradiation temperatures however the defects tend to be annealed out by a mutual annihilation of interstitials and vacancies. So that the mechanical properties are closer to those of the unirradiated material.

At even higher irradiation temperatures (above about 700°C) the helium tends to diffuse to grain boundaries where it collects as small bubbles and these cause a loss of cohesion so that the grains can be torn apart more readily. The result is a loss of high temperature ductility.

Sodium has a slightly corrosive effect on the austenitic stainless steels which are used for the canning materials, where it tends to preferentially remove chromium and nickel. However, the removal rates are quite low. But it is dependent upon the

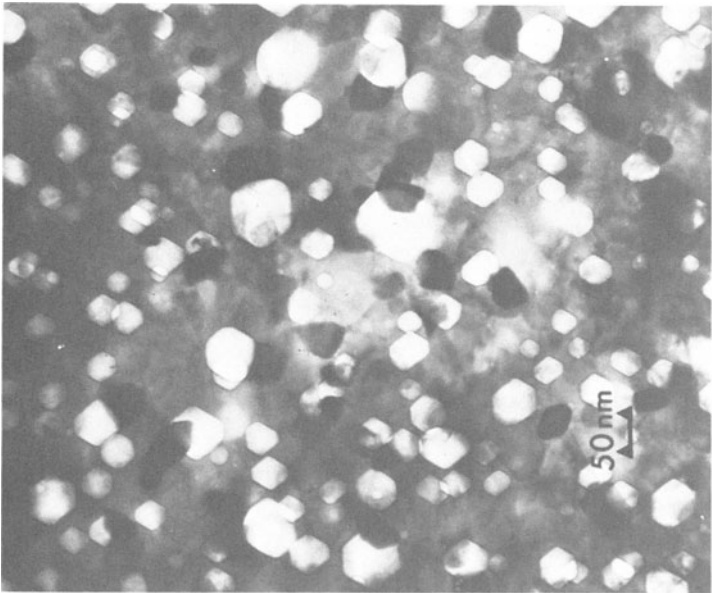


Fig. 7. Voids in 316 steel (after D. Mazey)

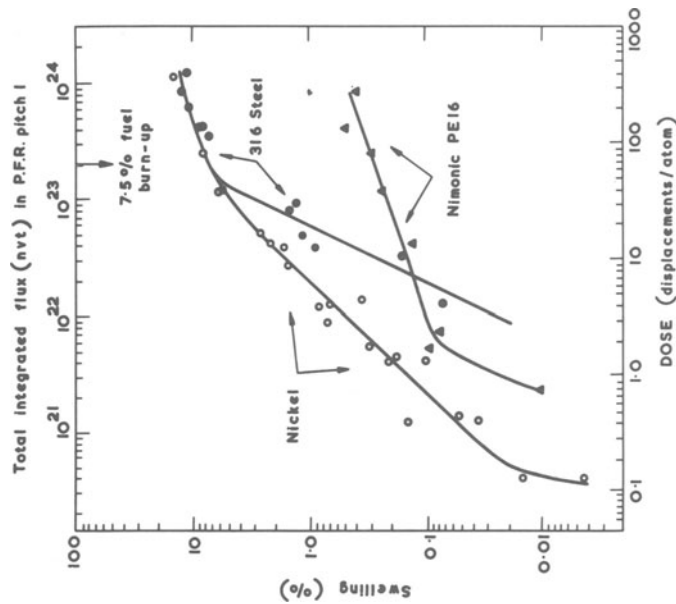


Fig. 8. Void swelling plotted against displacement dose for a variety of materials (after J. Hudson et al., Conference on Foids, BNES, 1971)

oxygen content of the sodium, the higher the oxygen content, the greater the corrosion. For example, at 500°C, 316 type steel is corroded at about 2 μm per year by sodium with 10 ppm of oxygen, and at 10 μm per year with 30 ppm of oxygen.

Carbon can be transported between the different components exposed to sodium at a rate which depends on the carbon activity in the sodium. Depending on temperature carbon tends to be lost from ferritic material with high carbon activity, causing it to lose strength, and to be gained by austenitic steel, reducing its ductility.

Sodium tends to cause very high thermal stresses on structural components because it transfers heat so readily. Temperature variations or fluctuations in the coolant are transmitted to the structure and induce high surface stresses, which may cause fatigue damage.

The steels available to meet these demanding requirements fall into three classes; austenitic stainless steels, nickel alloys and ferritic alloys. Austenitic steels have relatively low yield strength but high ductility, and they resist corrosion if the oxygen content from the sodium is controlled. They suffer, however, from irradiation embrittlement, are susceptible to thermal shock and irradiation swelling. Cold work of austenitic steels tends to reduce, but does not eliminate, the swelling during fast neutron irradiation.

High nickel alloys are stronger and more resistant to irradiation swelling. The higher neutron absorption in nickel than iron is offset by the greater strength, allowing less material to be used. Alloys with a high nickel content such as Nimonic 80A (75% nickel) corrode too fast in sodium. Ferritic steels have rarely been used in reactor primary circuits because of the loss of strength and decarburisation that occurs.

CORE STRUCTURE

It will be remembered that the fuel elements are stainless steel tubes about 6 mm in diameter and 2.5 to 3 m long, containing a 1 m section of core fuel. About 80,000 of these go to make up the core of a 2500 MW (thermal) reactor, and obviously they cannot be handled one by one. They are made up into "sub-assemblies", each consisting of 200 - 300 elements in a hexagonal steel tube or wrapper. This arrangement allows the coolant flow to each sub-assembly to be regulated by means of adjustable restrictors at the inlet so that the outlet temperature is approximately uniform across the core, in spite of the variation of power density. The fuel elements are located in the sub-assemblies

either by transverse grids or by wires run helically round each element.

Irradiation swelling leads to distortion of the sub-assemblies. The neutron flux is higher at the centre of the core than the outside so each sub-assembly experiences a greater fluence and therefore greater swelling on the side towards the core centre. As a result it tends to become curved with the convex side inwards. The extent of bowing depends on the dimensions as well as the fluence and temperature, but if unrestrained it could result in displacements of about 10 to 50 mm of the tops of the sub-assemblies.

Besides using void swelling resistant material the distortion can be avoided by rotating the sub-assemblies from time to time to equalise the swelling, but it is more usual to prevent it. This can be done either by a passive restraint structure, which surrounds the core and resists any outward movement after clearances between the assemblies have been taken up, or by an active restraint mechanism consisting of clamps which can be tightened up after the core has been assembled and slackened to allow fuel to be changed. The restraint structure can be prevented from swelling by keeping it cool and in a region of low neutron flux.

The fuel in the outer part of the core has a higher concentration of plutonium than the inner to compensate for the lower neutron flux and make the power density more uniform across the core. There may be two or more enrichment zones of this type. The control rods occupy sub-assembly positions in the core. They consist of neutron absorbers, usually boron carbide inserted and withdrawn by mechanisms above the core. The core is surrounded by the breeder, the elements of which are contained in similar sub-assemblies or may be a separate structure. The core rests on a support structure called the Diagrid, which serves also to distribute coolant to the sub-assemblies.

PRIMARY COOLANT CIRCUIT

The primary coolant circuit consists of the reactor core, intermediate heat exchangers and circulating pumps. One variation in the design is whether the pumps should be in the same vessel as the reactor core (a pool reactor) or in separate vessels (a loop reactor) (see Figure 9). The pool layout has the advantages that all the primary circuit is contained within a vessel of simple form which has no penetration, which minimizes stresses and is exposed only to cool sodium. The large diameter may make handling of irradiated fuel easier because there may be room within the reactor vessel to store it for a period to allow the fission product heat generation to decay. The pool reactor

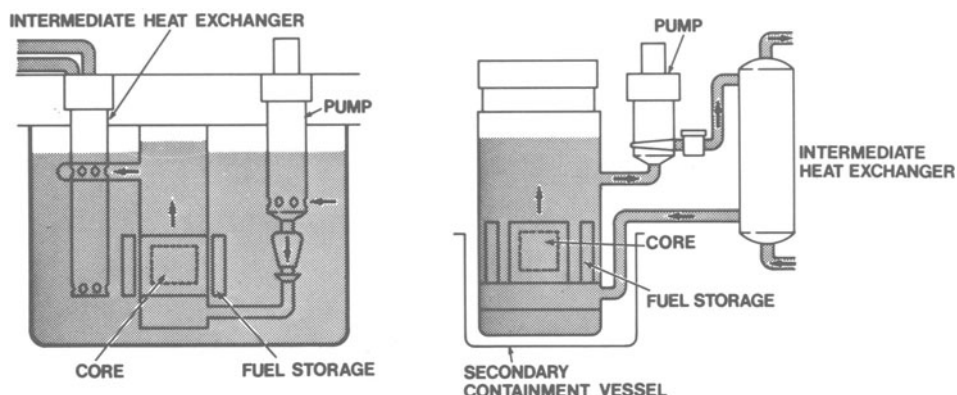


Fig. 9. Schematic arrangement of 'Pool' and 'Loop' type fast breeder reactors

roof is however large (possible 15 m in diameter) and highly stressed because it carries the weight of the core, neutron shield, primary pumps and motors and the intermediate heat exchangers. It has to be a complex and expensive structure compared with the roof of a loop reactor vessel.

A loop reactor vessel is smaller, part of it and of the connecting pipework is exposed to hot sodium and part to cool, so there are thermal stresses, and the complex shape of the vessel may lead to stress concentrations. However, the vessel and pipework can be inspected more easily than the stressed members within a pool vessel. A loop reactor is more prone to damage due to thermal shock if either the reactor or a steam generator shuts down suddenly because of an accident.

The sodium coolant which flows through the core becomes radioactive. It is usually thought too dangerous to use highly radioactive sodium to raise steam, because a leak in the sodium/water heat exchanger would allow a violent chemical reaction which might cause enough damage to release radioactivity to the environment. It is normal therefore to incorporate a secondary sodium circuit which receives heat from the radioactive primary sodium but is protected by a neutron shield from becoming radioactive itself.

The coolant is usually circulated by pumps at the bottom of long vertical shafts. The surface of the sodium is covered with an atmosphere of argon at a pressure slightly above atmospheric. The reactor vessel and pipework have therefore to withstand only modest pressures of a few hundred kPa. They are made of welded stainless steel and the external boundary of the primary circuit is double-walled, the space between the walls being monitored to detect leaks.

STEAM PLANT

The secondary sodium coolant is used to generate steam that can be used in a turbine to drive an alternator and generate electricity. The steam cycle is very similar to that in a conventional power station so we will not dwell on that aspect.

Because of the severity of the chemical reaction between sodium and water, great care has to be taken that leaks are very unlikely in the steam plant and that, if a leak should occur, the resulting damage can be controlled. The welded joints between the tubes and tube plate have to be made to the highest standards and subjected to rigorous inspections.

If a large leak in the heat exchanger should develop suddenly the rest of the plant has to be protected by bursting discs or by some other means of relieving pressure rapidly. If there is a small leak, say due to a crack in the weld, the remedial action has to be taken before it grows or spreads to adjacent welds or tubes. Fortunately, a small leak can be detected by monitoring for the presence of hydrogen which is released from the sodium water/steam reaction. Once hydrogen is observed the heat exchanger unit concerned can be isolated and drained and the leak repaired.

If heat is transferred to the primary coolant at the rate of 2500 MW(t), the nett work output of the steam plant is 1060 MW(e) giving a thermal efficiency of 42%.

FAST BREEDER REACTORS - LECTURE 3

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INTRODUCTION

In this lecture we will discuss two areas associated with fast breeder reactors. The first is safety and the second is the fuel cycle.

SAFETY

The risk caused by nuclear reactors is that the radioactive materials they contain may escape and injure members of the public in the course of an accident. Although we realise we are in the wake of the Three Mile Island incident, let us state that such reactor accidents are improbable events. It is much more likely that the events leading to such accidents will be detected and that the reactor will be safely shut down without damage. There is always the risk that multiple faults or errors will result in inappropriate corrective action being taken and that the reactor plant will be severely damaged. In a fast breeder reactor the most likely outcome of such an accident would be that the containment system would prevent significant leakage of radioactive material into the environment. Only if all the various containment systems failed in a catastrophic and sudden manner would there be a serious release of radioactive materials.

We will not be considering the consequence of releases of radioactivity in the event of these remote accidents in this lecture. However, we have included some references at the end

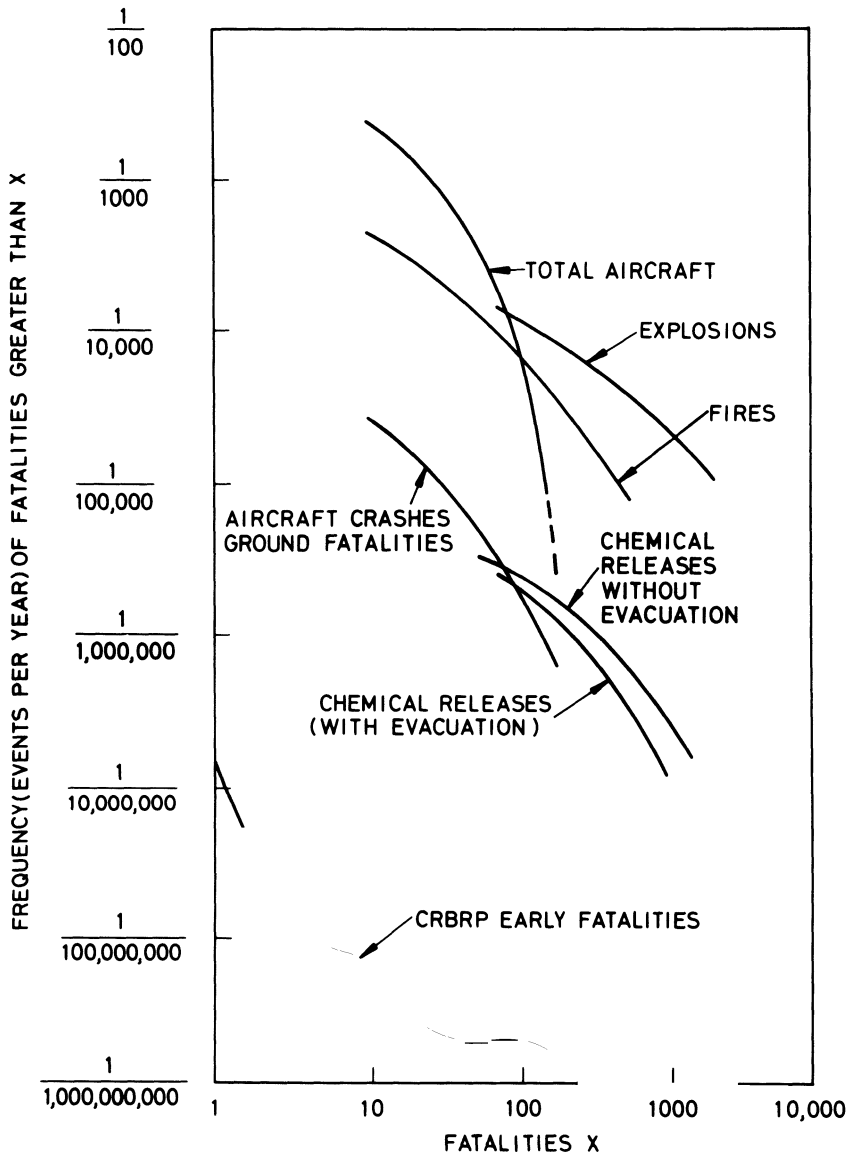


Fig. 10. Frequency of fatalities due to man-caused events occurring within ten miles of the CRBRP site (from CRBRP-PMC 78-01)

of these lecture notes for those who wish to pursue these aspects further.

Much attention is given to the assessment and understanding of hypothetical accidents. Such studies identify those areas of design and operation to which attention should be paid. So that when a fast breeder reactor (or any other reactor for that matter) is properly designed, properly built and properly operated the release of radioactive materials is very unlikely indeed.

This point is illustrated in Figure 10, where the probability per year of fatalities is plotted against the number of early fatalities in accidents for the cases of dam failures, aircraft accidents, thermal reactors and the Clinch River Breeder Reactor.

Let us now say something about the safety features of fast breeder reactors.

The radioactive materials present in the fast breeder reactor include the fuel, the fission products generated in the fuel as burn-up proceeds, and the activation products (mainly the radioactive sodium and the products of clad corrosion).

One of the inherent safety features of the fast breeder reactor is that there are several barriers between the radioactive materials and the external environment. There are usually three barriers; there is the fuel element cladding, the primary coolant containment, and the reactor building. (These are shown schematically in Figure 11). For radioactivity to be released, these three barriers (two in the case of ^{24}Na) have to be breached.

The second inherent safety feature of a sodium-cooled fast breeder reactor is that the coolant pressure is low, so that the coolant containment is lowly stressed and unlikely to fail. However, even if this failed, it can be seen that it is quite easy to design the system so that the core can still be cooled. (This can be done by surrounding the reactor vessel in a hole in the ground, so that even if the vessel and leak jacket fail, the primary coolant still covers the reactor core and the intermediate heat exchangers). So there are two main advantages of the low pressure coolant; it is unlikely to fracture the containment and even if it does, it is quite easy to remove the fission product decay heat and thus prevent the fuel and its cladding from becoming too hot. This feature is in contrast with the gas and water cooled reactors where the coolant pressure is high and the concern is providing adequate cooling in the event of coolant containment failure.

The third inherent safety feature of the fast breeder reactor is the large thermal inertia of the primary coolant which

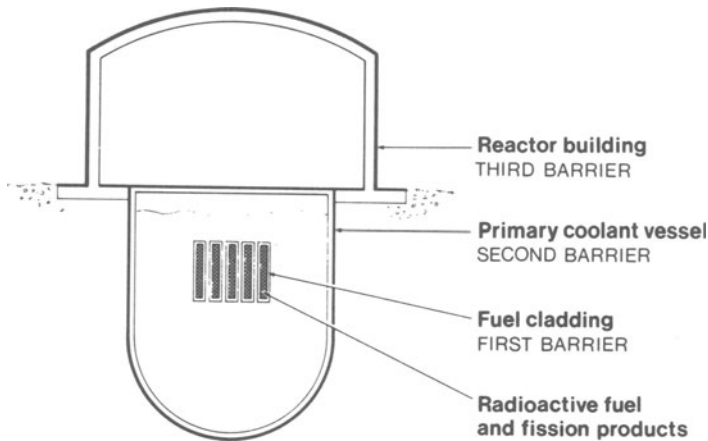


Fig. 11. Barriers to the release of fuel and fission products in the event of an accident

tends to prevent overheating of the fuel and its cladding. You will remember that the fuel cladding is more stressed at the end of its life in the reactor because of the accumulation of fission product gas. It will remain intact provided it is kept cool. (Failure temperature will depend on the details of the burn-up achieved, the design of the fuel pin, and the time at temperature during such an excursion). These effects are illustrated in Figure 12, which shows the rate at which the primary coolant temperature rises when the reactor is shut down, assuming a complete failure of the secondary cooling. You can see that provided the primary coolant continues to circulate, the timescale for overheating is quite long. However, there is the requirement for an emergency cooling system to remove the "decay heat". But the timescales involved in its operation are quite long.

The fourth inherent safety feature is what is known as the Doppler effect, which reduces the rate of fission in the fuel as the temperature increases. It provides a reliable prompt negative reactivity feed back. So that if the fast breeder reactor is subjected to a reactivity increase for some reason, the Doppler effect acts to limit the consequent power rise.

Besides these inherent safety features, there are safety disadvantages in a fast breeder reactor compared with a thermal

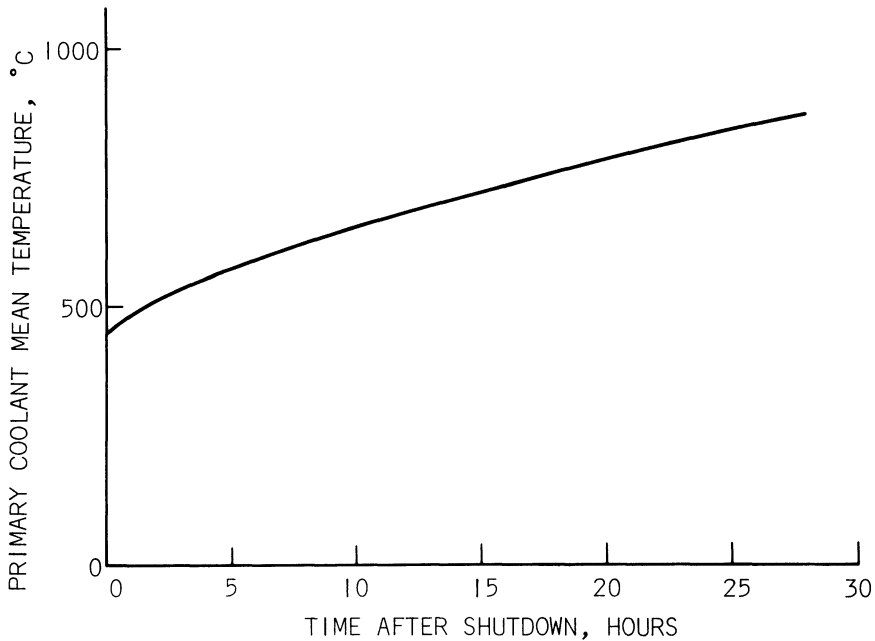


Fig. 12. Rate of primary coolant temperature rise in a 'Pool' type fast reactor, assuming complete failure of secondary cooling

power reactor. The fuel temperature is higher, there is a higher power density, and there is the possibility of an accidental increase in reactivity.

The higher fuel temperature in the presence of the sodium coolant implies the risk of rapid vaporisation of the coolant. If some molten metals are mixed with water the vaporisation is sometimes violent, giving rise to the phenomenon called a "steam explosion". Significant sodium vapour-molten oxide fuel explosions have not been produced under realistic experimental conditions and may be impossible, but until this is proved the possibility has to be taken into account.

The high power density means that if the fuel is uncooled, its temperature rises very rapidly. If the reactor is not shut down, and for example, if a central fuel element heats up, its mean temperature could rise at some 600 K s^{-1} .

The risk of increasing reactivity arises partly from the possibility of moving control rods accidentally, but also because the fuel in a fast reactor is not in its most reactive configuration. For example, if it were rearranged into a more compact shape, the reactivity would increase. However, the probability of such an event occurring is very low.

THE FUEL CYCLE

There are several fuel cycles which involve uranium and plutonium. Each have their own characteristics and it is important that these should be clearly understood and distinguished one from the other. We shall distinguish four fuel cycles and these are described in Figure 13 in an outline form.

The first fuel cycle shown in Figure 13, the once-through fuel cycle, is that which most countries in the world are now operating. The uranium fuel is put through a thermal reactor and is then stored, together with its plutonium content, without reprocessing. This is done either because reprocessing capacity is not available or, in the case of the United States and Canada, because it is judged to be premature and unnecessary. The situation in the UK is different from the rest of the world because our thermal reactors are gas-cooled and the spent fuel from a gas-cooled reactor is not easily stored for long periods of time. In our case, therefore the fuel must be reprocessed for environmental reasons to separate out the plutonium, the uranium and the fission products.

The second fuel cycle is that where the fuel is reprocessed, the plutonium is extracted and is refabricated into fuel for the thermal reactor. This is called thermal recycle of plutonium. It is the fuel cycle which a number of countries are planning to operate in the near future. The exceptions are the United Kingdom and France, which believe it to be both unnecessary and an inefficient use of plutonium, and the United States which considers it to be a proliferation risk. The economic attraction of recycling plutonium into thermal reactors is very simply stated. It replaces the need for some fresh uranium fuel and could be applied at a relatively early date because thermal reactors are already available.

The third fuel cycle is that to launch the fast reactor and uses the plutonium made in thermal reactors. In this fuel cycle the spent fuel from a thermal reactor is reprocessed and the plutonium is stored until it is needed. Notice that, in these three fuel cycles, there is no urgency to get the plutonium fabricated into fresh reactor fuel because in the once-through fuel cycle, the plutonium is not used at all, in the case of thermal recycle of plutonium, the value is marginal unless the cost of uranium increases substantially and, in the third case, fast reactors are simply not yet available to use the plutonium.

The fourth fuel cycle is that used to maintain fast reactors in operation. That fuel cycle contains three main parts:

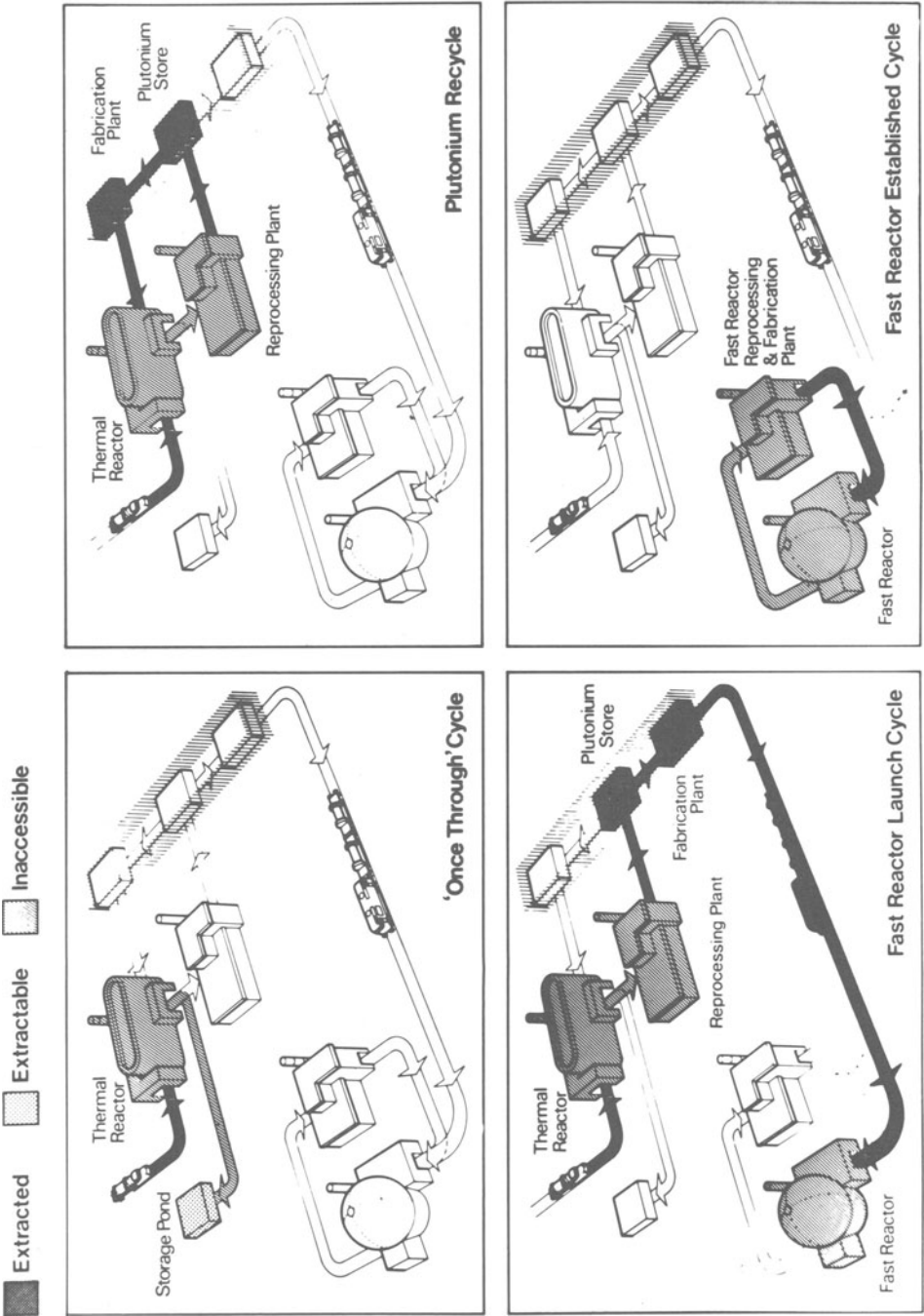


Fig. 13. Various fuel cycles

- (i) The reprocessing of the core and breeder elements to extract the fission products from them and recover a mixture of uranium and plutonium oxides in the correct proportions to make up a fresh charge of fuel for the fast reactor core.
- (ii) The fabrication of fresh fast reactor fuel elements from this recycled material.
- (iii) The disposal of the fission products (and actinides) as high level waste.

The waste disposal process is very similar to that used for thermal reactors so we shall say nothing about it in this lecture. However, it is important to recognise that the reprocessing of the core and breeder fuel and the refabrication into fresh fuel is very intimately linked to the operation of the system as a whole because it is essential, for good economic operation, for the plutonium to be extracted from the spent fuel and returned to the reactor within a period of say, two years, to keep the total plutonium inventory at a reasonable level. Typically, therefore, fast reactor fuel will be reprocessed, at the latest, about 12 months after it comes out of the reactor. This is in contrast to the reprocessing of fuel from water-cooled thermal reactor systems where, typically, the fuel will have been allowed to cool for five to ten years before reprocessing.

In addition to these differences of emphasis, the fast reactor reprocessing plant itself is significantly different from the reprocessing plant for thermal reactors. The percentage of plutonium in the material going through the plant is much higher than it is in thermal reactors but the total bulk of material is lower in quantity. These plants are designed with such a geometry that a criticality accident is impossible. Therefore, the overall size of a fast reactor reprocessing plant is smaller, the pipes are of a narrower diameter and the various components have a different geometry compared to a reprocessing plant for thermal reactor fuel. These differences are not of a fundamental kind but they need to be defined and the process needs to be demonstrated and fully proven.

Reprocessing of spent fast breeder reactor fuel consists of the following major operations:

- (i) Dismantling, shearing and dissolution.
- (ii) Separation by extraction of uranium and plutonium from fission products and trans-plutonium elements.

- (iii) Transformation of the recovered uranium and plutonium into useable solids.
- (iv) Conditioning of the wastes.

Because of the complex structure of the fast breeder reactor fuel bundle, significant quantities of metallic sodium may be trapped in the structural parts of the fuel bundle or in defective fuel pins. This sodium must be completely removed before the fuel is transferred into water or nitric acid. The residual sodium can be removed by melting or by steam or humid CO_2 treatment. Any residual sodium can be neutralised by oxidation after the shearing stage.

The fuel bundles are then dismantled, the end pieces are cut off and, depending on the structural assembly, the shroud is removed by mechanical or laser cutting.

Pulverisation of the sheared fuel prior to dissolution has been considered as an optional step. In the voloxidation process, the sheared fuel segments are dropped into a rotating calciner, possibly equipped with crushing balls. For mixed oxides containing less than about 25% PuO_2 , heating of the fuel in air or oxygen at a nominal temperature of 450°C transforms UO_2 into U_3O_8 ; the resulting expansion of the lattice structure breaks up the fuel grains releasing the tritium and a high proportion of the fission gases.

In general, there are two stages of dissolution in concentrated nitric acid:

- (i) The major part of the fuel dissolves rapidly.
- (ii) A residual part, enriched in plutonium and noble metal fission products, dissolves slowly.

Generally, there remains an insoluble part consisting mainly of noble metals, fission product refractory compounds, and, in some cases, undissolved fuel particles. If the amount of plutonium in the insoluble residue exceeds a certain value, its recovery can be achieved by the addition of HF in a separate dissolver.

In the feed preparation for plutonium extraction the insolubles are removed by filtration or by centrifuging. The total quantity of insolubles to be handled is about 1% of the initial amount of fuel and the heat released from these insolubles is of the order of 1 W/gm. The uranium and plutonium extraction flow sheet is shown in Figure 14. In principle, the process and equipment used for the extraction of uranium and plutonium from fast breeder reactor fuel are similar to those used in thermal

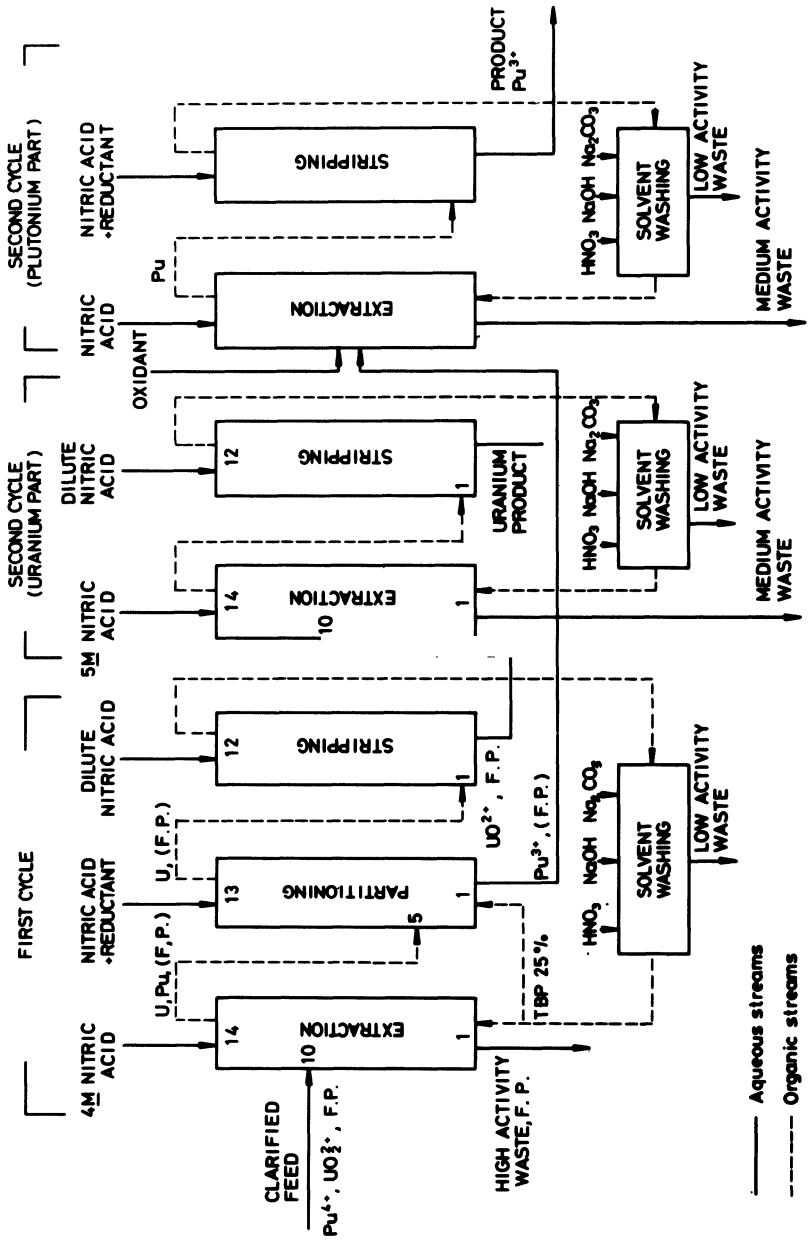


Fig. 14. Purex Flow Sheet

reactor fuel reprocessing.

The separation of uranium and plutonium is based on the chemical reduction of the tetravalent to trivalent plutonium, this higher plutonium concentration requires the use of larger amounts of reducing chemicals, such as U^{4+} , Fe^{2+} , and $NH_2OH-N_2H_4$.

This in turn, leads to a near doubling of the volume of the solution and of the wastes. As an alternative, electrolytic reduction seems most promising but may not be sufficiently reliable for use in radioactive areas.

The method for purification of separated uranium is essentially the same as that used for LWR fuel reprocessing. The purification of plutonium differs because of the larger amount of plutonium involved and the necessity to keep the plutonium content of the wastes as low as possible.

The conversion of uranium and plutonium into oxides is the same as that for thermal reactor fuel reprocessing.

The fuel fabrication process starts with the mechanical mixing of the UO_2 and PuO_2 powders. The conventional fabrication process includes the following steps:

- (i) Pressing green pellets.
- (ii) Sintering the green pellets into finished pellets.
- (iii) Grinding to size (optional).
- (iv) Drying sintered pellets.
- (v) Assembling sintered pellets into stacks.
- (vi) Adding axial blanket pellets to the stack, together with other devices.
- (vii) Inserting the pellet stacks into one-end welded tubes.
- (viii) Establishing the proper inert atmosphere inside the fuel pin.
- (ix) Closing the pin.
- (x) Non-destructive examination of the pin.
- (xi) Acceptance and final identification of the pin.
- (xii) Storage prior to assembling into bundles.
- (xiii) Bundle assembly and inspection.
- (xiv) Bundle loading into the wrapper tube.
- (xv) Head and foot assembly.

- (xvi) Acceptance and final identification of fuel assembly.
- (xvii) Storage until shipment.

Pelletizing and pin loading operations must be carried out in glove boxes or their equivalent, in contrast to the production of uranium LWR fuel, because all plutonium oxide dust must be contained down to very low levels. Therefore, operations are cumbersome and physical inventory checks, either approximate or highly accurate, can be made only at temporary storage stations which exist to allow time for process control and production interruptions. Control of the fissile content of the finished pins is essentially a routine operation.

Shielding must be provided against gamma-rays and neutrons owing to the presence of many plutonium isotopes and their radioactive daughter products. In addition, forced draught cooling is required because of radiation heat generated in concentrated storage areas. Shielding must not only protect the body but also the hands and arms of operators or maintenance crews. In storage areas, separation shields must be provided to prevent neutronic interaction between fissile masses.

Tracing plutonium through the fabrication plant, along the production line as well as along the line of plutonium recovery from scrap and the measuring of plutonium left in final waste requires a variety of measuring methods and devices.

Plutonium fuel development laboratories have now operated for two decades, while plutonium fabrication plants have operated for one decade.

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FAST BREEDER REACTORS - LECTURE 4

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INTRODUCTION

So far in these lectures we have looked at some fundamental points concerning fast reactors, we have reviewed the technological problems in developing them and we have examined the fuel cycle which is required to maintain them. We shall now turn to the more difficult task of discussing the economics of fast reactors. This discussion must be of a different kind from that we have given so far for a number of reasons which can be summarised as follows:

- (i) It is notoriously difficult to predict the cost of new technological innovations in advance of their introduction on a true industrial scale. This is especially true for large complex projects and, as we have seen, the fast reactor is a more complex reactor than a thermal reactor and thermal reactors themselves are more complex than conventional power stations. The very high energy density in the core, the novel use of sodium as a coolant, the necessity to exchange heat between sodium and water, the unique safety features of the fast reactor and the intimate integration of the fuel cycle for the fast reactor operation all pose areas of major uncertainty. Furthermore, only three prototype fast reactors are operating in the world today - in the USSR, in France and in the UK. Even when the first reactor of full commercial size is built, that will not by itself give an estimate of future costs because a first full size demonstration reactor must necessarily cost more than

one produced as part of a programme of power station production.

- (ii) So far as the cost of the reactor itself is concerned, it is probably fair to judge now that the performance of the core will be satisfactory and the major areas for development in the future concern the development of components like the sodium water steam generators. That involves considerations of production engineering and routine production of components in a style which we have only previously seen for light water reactors. The emphasis of that work must switch from nuclear R & D to practical production in industry.
- (iii) On the fuel cycle, each individual step has been demonstrated on either a laboratory or prototype scale but a complete and dedicated prototype fast reactor fuel cycle plant has not yet operated anywhere in the world and, obviously, that makes the prediction of the ultimate fuel cycle costs when performed on an industrial scale that much more difficult.
- (iv) The absolute economics of fast reactors do not themselves determine when fast reactors should be installed because the use of sodium and the addition of an extra intermediate circuit suggests that electricity produced by fast reactors will be more expensive than electricity produced by thermal reactors of the present day. The real attraction of fast reactors as we have seen in the earlier lectures is that, once launched, they require no fresh uranium ore. The economic installation of fast reactors, therefore, depends not only on the economic factors we have reviewed but upon the way in which the price of uranium ore varies. This is itself difficult to predict because it depends upon the law of supply and demand and both the future supply of and demand for uranium ore cannot be predicted with any certainty.

Despite these difficulties, we must find a method of discussing the economics of fast reactors in the future. Most discussions published so far have begun with a set of assumptions about world demand for electricity and world supply of uranium and have then attempted to deduce the variation of uranium ore price with time and hence the "breakeven" point for fast reactor technology. The difficulty with all those discussions is that it is unclear how much the final conclusions are dependent upon the initial assumptions. In this lecture, we shall therefore adopt a different approach which has been found useful in recent international discussions to summarise and incorporate a wide range of technical views upon the points we have discussed earlier.

The approach we will set out in the remainder of this lecture

may seem complicated or over-elaborate at first sight but we have chosen to give it here because, in practice, it has been found useful and the ideas are generally applicable to the introduction of any new technology whether it be fast reactors, coal, solar power, etc.

The factors which influence the economics of nuclear power may be set out as follows:

Macro-economic Factors

Gross National Product (GNP).

Balance of payments (imports/exports).

Resource utilisation

- capital intensiveness
- level of innovation/risk/development and lead times
- job intensiveness
- level of qualified manpower required
- job satisfaction.

Infrastructure and environment

- infrastructure required (services/transport etc)
- impact on environment
- influence of ecological and non-proliferation considerations, and the sociological environment
- availability of fuel cycle services.

Micro-economic Factors

Availability and price of uranium ore.

Cost of reprocessing and waste disposal.

Cost of fabricating plutonium-bearing fuel relative to that for uranium-bearing fuel.

Enrichment costs.

Capital cost of breeder reactors and of fuel cycles necessary to sustain them.

Relative costs of spent fuel storage, conditioning and ultimate disposal.

The two factors which must influence the relative evaluation of thermal reactors and fast reactors are the cost and availability of uranium ore to an individual country on one hand, and the capital cost of fast breeder reactors and the fuel cycle needed to service them on the other hand. We shall consider both these

factors as unknown parameters and we shall permit both to vary with time. We expect the cost and availability of uranium ore to go up with time as the uranium reserves of the world become exhausted and we expect the capital cost of the reactor and fuel cycle plants for fast reactors to start at an initial high value and decrease with the benefits of scale as time progresses. We shall use these two parameters to establish a phase diagram of the type shown in Figures 15, 16, 17, 18, 19 and 20. In these diagrams the horizontal axis is "the uranium (U_3O_8) price in \$/lb" and the vertical axis is "the premium over the LWR once-through fuel cycle" which is defined as "the cost of electricity in \$/kW(e) total present worth, relative to the cost of electricity in the same units computed for an LWR operating on the once-through cycle with uranium priced (arbitrarily) at \$25/lb".

Because we are concerned with the relative economics of thermal and fast reactors, we must look at both the cost of maintaining fast reactors in operation and the cost of launching them. This drives us to consider the cost of reprocessing thermal reactor fuel to get the initial plutonium inventory which is required and that in turn obliges us to look at the alternative uses of plutonium, namely for recycle back into thermal reactors. In brief, therefore, we cannot examine the economics of fast reactors without looking at the full range of options for the use of plutonium. We shall discover, therefore, that the phase diagrams describe, in a simple form, the main features of the "plutonium economy" and we shall find that this is helpful for our discussion of economics in this lecture and our discussion of proliferation questions in the last lecture.

We cannot, however, discuss everything in our relative assessment and we shall look only at light water reactors as examples of thermal reactors. This means that we look at:

- (i) The once-through cycle using light water reactors.
- (ii) Reprocessing with uranium cycle into light water reactors and plutonium storage.
- (iii) Reprocessing with both uranium and plutonium recycle to light water reactors.
- (iv) The launching of fast breeder reactors.
- (v) The maintenance of fast breeder reactors once launched.

ALGEBRAIC DEFINITIONS

The algebra set out below may be performed in any of three main sets of units, viz:

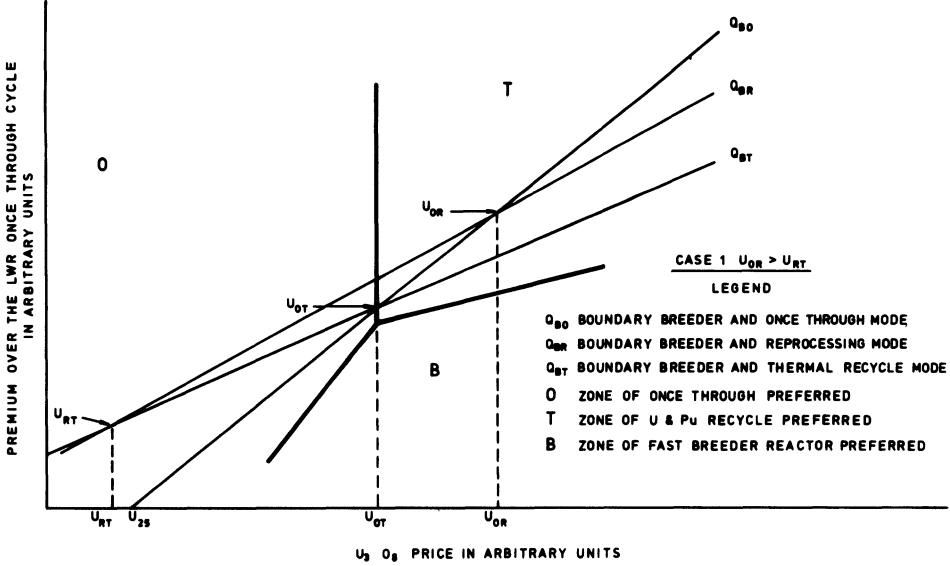


Fig. 15.

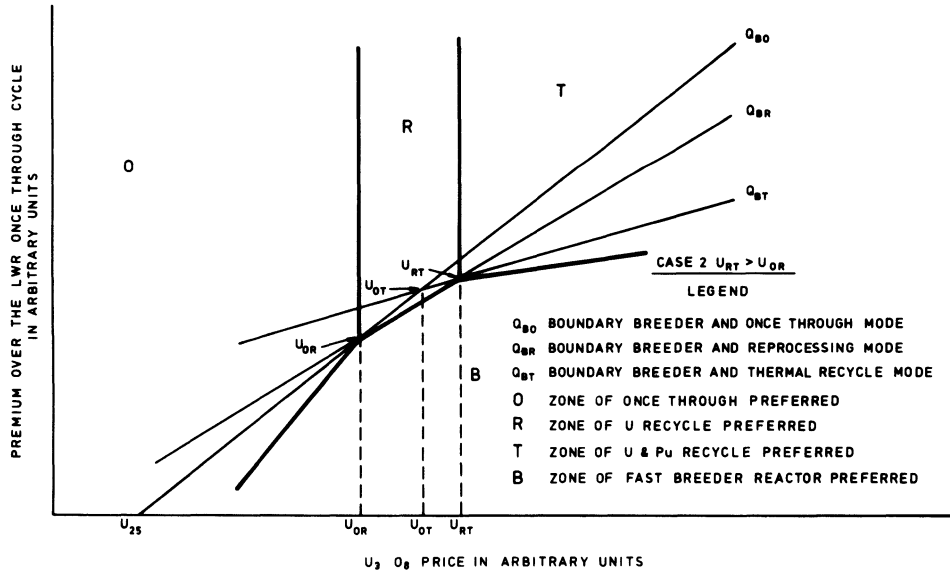


Fig. 16.

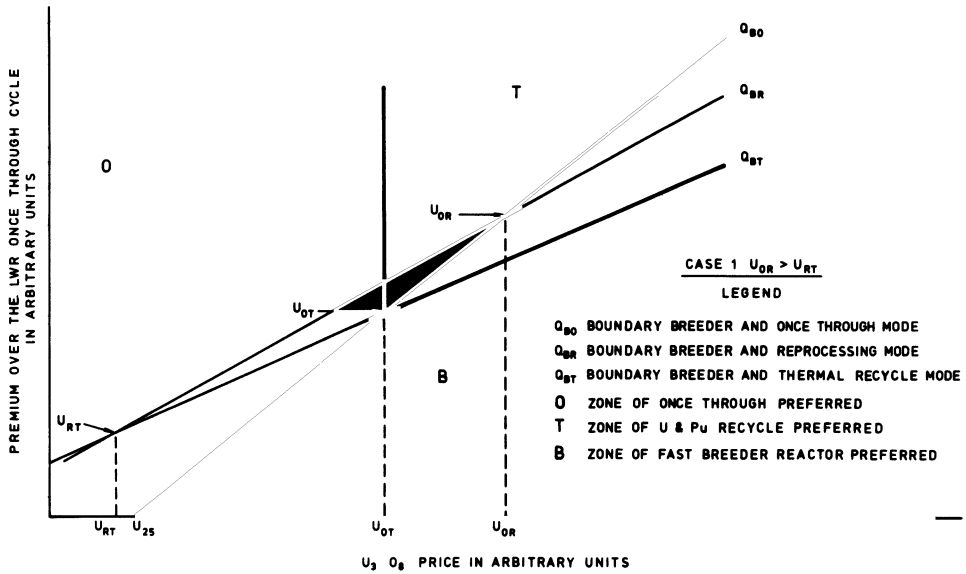


Fig. 17.

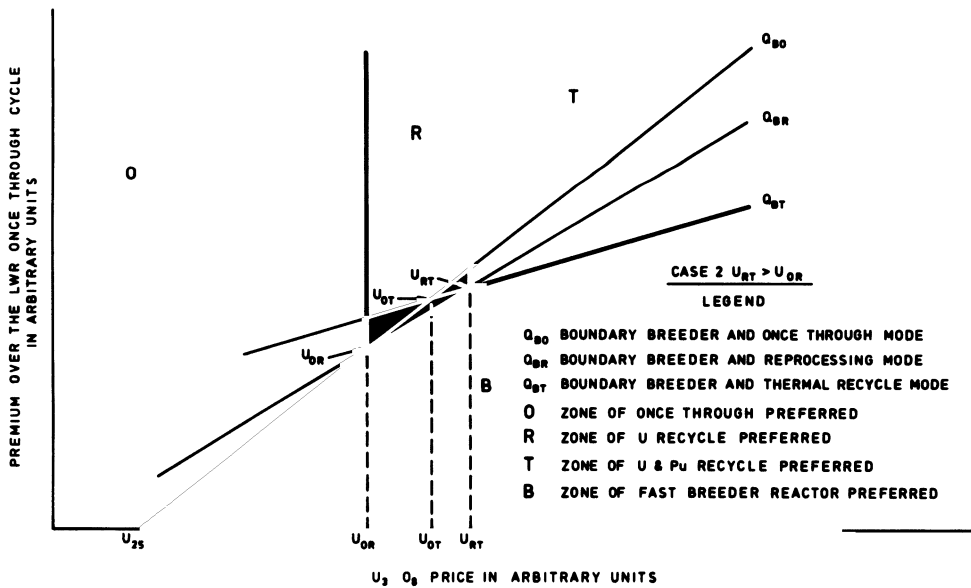


Fig. 18.

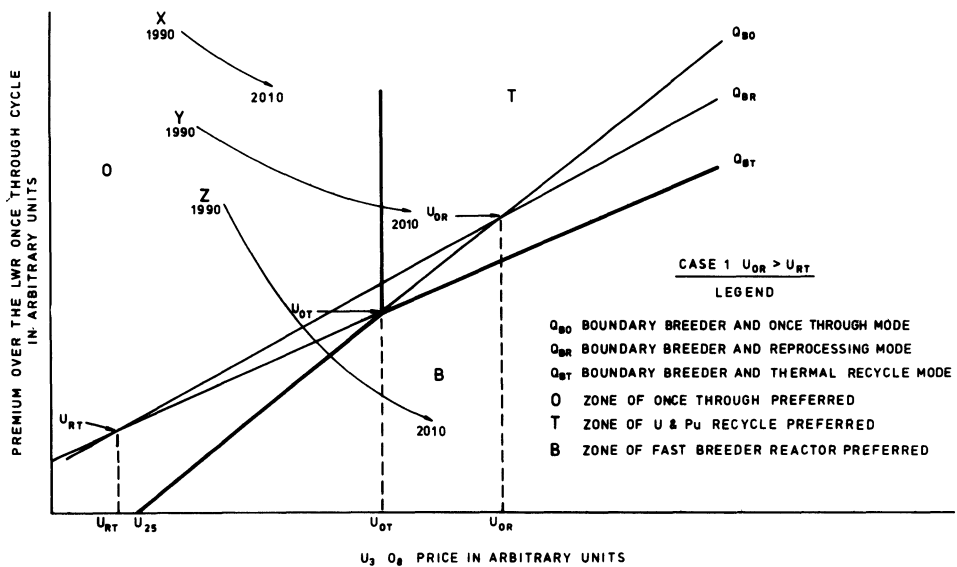


Fig. 19.

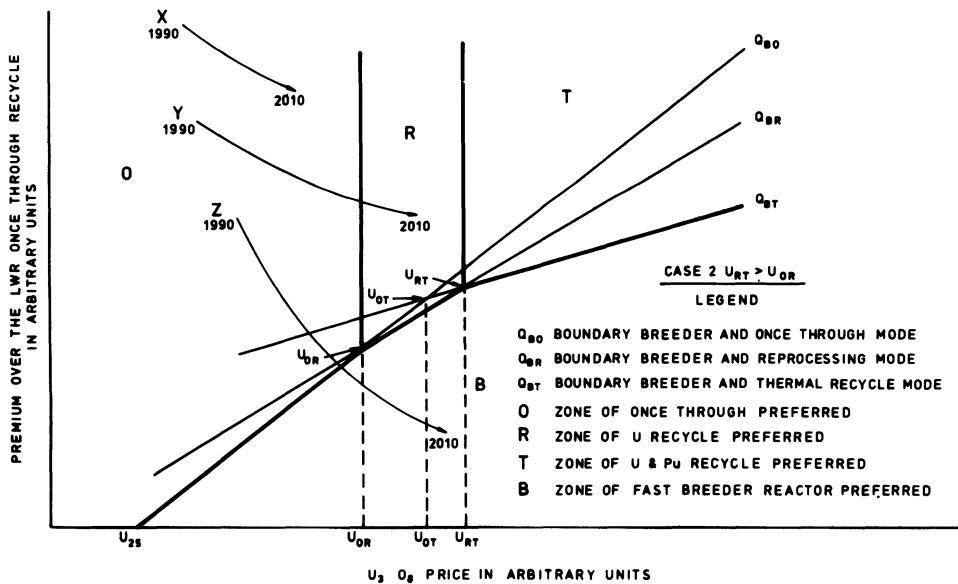


Fig. 20.

- (i) \$/kW total present worth at the assumed lifetime, discount factor and load factor.
- (ii) \$/y per kW installed capacity, related to \$/kW present worth by the annuity factor A derived from the assumed lifetime and discount rate (say, for illustration, 30 years and 10% per annum respectively when $A = 0.10608$) or
- (iii) mills/kWh related to \$/y by the assumed load factor (say 70% i.e. 6132 full power hours per year) and 1000 mills = \$1.

For the relationship between these units see Table 3.

The units \$/y per kW installed capacity will be used below. It will, where appropriate, e.g. for the uranium component, include the separate parts relating to the initial fuel loading, the replacement fuel and the last charge of fuel and the relevant lead and lag times.

Using the financial rules outlined above define the annual cost of electricity produced in an LWR in the once-through mode to be:

$$\{O\} = C + U + E + F + S + M \quad (1)$$

where $\{O\}$ = total cost of electricity produced at a fixed load factor

C = component due to capital cost of reactor including interest during construction, owners' costs, levy for decommissioning at end of life, etc

U = uranium cost component of fuel cycle embracing initial, final and replacement quantities

E = component of fuel cycle cost covering enrichment of the uranium

F = fabrication cost component of fuel cycle for uranium oxide fuel

S = storage charge and final disposal of irradiated fuel component of fuel cycle

M = operation and maintenance cost.

Using the same financial ground rules, the cost of electricity produced in an LWR with reprocessing, recycling uranium and sending plutonium to storage for future use is:

$$\{R\} = C + U(1-x) + E(1-x') + F + R + W + M + H \quad (2)$$

COST COMPONENT	\$/kwe PRESENT WORTH	\$/y PER INSTALLED kwe AT CAPACITY FACTOR Fe	MILLS/kweh
\$/kwe present worth	1	$\frac{I}{1 - (1 + I)^{-L}}$	$\frac{I}{8.76 \cdot Fe} \frac{1}{1 - (1 + I)^{-L}}$
\$/y per installed kwe at capacity factor Fe	$\frac{1 - (1 + I)^{-L}}{I}$	1	$\frac{1}{8.76 \cdot Fe}$
mills/kweh	$8.76 \cdot Fe \frac{1 - (1 + I)^{-L}}{I}$	$8.76 \cdot Fe$	1

Table 3. Conversion factors for different generating cost representations

where x and x' represent the fractional savings in uranium and separative work due to recycling uranium

R = reprocessing and interim waste storage component of the fuel cycle

W = waste treatment and storage component of the fuel cycle

H = plutonium storage component of the fuel cycle (note: if plutonium is separated but not used for environmental or proliferation reasons its treatment and disposal would be included in W).

Using the same financial ground rules, the cost of electricity generated in an LWR recycling both uranium and plutonium is:

$$\{T\} = C + U(1-y) + E(1-y') + fP + (1-f)F + R(1+r) + W + M \quad (3)$$

where y and y' represent the fractional savings in uranium and separative work due to recycling both uranium and plutonium

P = fabrication cost component of fuel cycle for MOX fuel

f = the fraction of fuel to which P applies after making due allowances for the initial uranium charge

r = fractional change in reprocessing cost due to reprocessing MOX fuel and to any slight change in Pu recycle reactor fuel logistics.

Finally using the same financial ground rules, define the cost of electricity produced by a FBR to be:

$$\{B\} = C' + P_c + P_{rb} + R' + W' + M' \quad (4)$$

where C' = the capital cost of the breeder reactor, IDC, etc

P_c = core fuel fabrication component of fuel cycle

P_{rb} = radial breeder fuel component of fuel cycle

R' = average (core and blankets) fuel reprocessing and interim waste storage component of fuel cycle

W' = waste treatment and storage component of fuel cycle

M' = operation and maintenance component of fuel cycle

The fast reactor premium is now defined as the difference in the cost of electricity produced from the breeder and the cost of electricity produced from the once-through LWR where U is calculated at some arbitrary choice for the value of uranium - say \$25/lb U_3O_8 .

If this premium is called Q , then:

$$Q = C' + P_c + P_{rb} + R' + W' + M' - C + U_{25} + E + F + S + M \quad (5)$$

Using the above definitions it can be seen that the boundary between the once-through and U recycle cases occurs at the uranium value where $\{R\} = \{O\}$, i.e.

$$U(1-x) + E(1-x') + R + W + H = U + E + S$$

$$\text{i.e. } U_{OR} = \frac{R + W + H - S - Ex'}{x} \quad (6)$$

(Note U_{OR} = uranium component at the particular U_3O_8 value)

Similarly, the boundary between the U recycle and U and Pu recycle cases occurs at the uranium value where $\{R\} = \{T\}$, i.e.

$$U(1-x) + E(1-x') + F + R + H = U(1-y) + E(1-y') + fp \\ + (1-f)F + R(1+r)$$

$$\text{i.e. } U_{RT} = \frac{f(P-F) + rR - H - E(y'-x')}{y-x} \quad (7)$$

and the boundary between the once-through and U and Pu recycle cases occurs at the uranium value where $\{T\} = \{O\}$, i.e.

$$U(1-y) + E(1-y') + fP + (1-f)F + R(1+r) + W = U + E + F + S$$

$$\text{i.e. } U_{OT} = \frac{f(P-F) + R(1+r) + W - S - y'E}{y} \quad (8)$$

Similarly it can be concluded that the boundary between the breeder and the once-through phase occurs along the line:

$$Q_{BO} = U - U_{25} \quad (9)$$

and the boundary between the breeder and reprocessing mode occurs along the line

$$Q_{BR} = U(1-x) - U_{25} - Ex' + R + W + H - S$$

$$\text{i.e. } Q_{BR} = U - U_{25} - x(U - U_{OR}) \quad (10)$$

and finally, the boundary between the breeder and thermal recycle phase occurs along the line:

$$Q_{BT} = U(1-y) - U_{25} - y'E + f(P-F) + R(1+r) + W - S$$

$$\text{i.e. } Q_{BT} = U - U_{25} - y(U - U_{OT}) \quad (11)$$

It is known from simple algebra that, providing x and $(y-x)$ are both positive, the quantity U_{OT} must, in numerical value, lie between the two quantities U_{OR} and U_{RT} , whatever the relative values of those two numbers are, because from equations (6), (7) and (8) the following algebraic relationship applies:

$$yU_{OT} = xU_{OR} + (y-x)U_{RT} \quad (12)$$

Two possible cases are now distinguished.

Case 1

$$U_{RT} < U_{OR}$$

$$\text{i.e. } \frac{f(P-F) + Rr - H - E(y'-x')}{y-x} < \frac{R + W + H - S - Ex'}{x} \quad (13)$$

Alternatively, Case 2 where this inequality is reversed.

Case 2

$$U_{OR} < U_{RT}$$

$$\text{i.e. } \frac{R + W + H - S - Ex'}{x} < \frac{f(P-F) + Rr - H - E(y'-x')}{y-x} \quad (14)$$

Case 1 corresponds to the circumstances that probably apply in most countries. Roughly speaking, it corresponds to the assumption that the costs of reprocessing and waste management/disposal are more important factors than the subsequent cost of fabricating plutonium-bearing fuel.

Case 2 corresponds to the opposite assumption and under current economic conditions and using the expected range of fuel cycle component costs, it is unlikely that Case 2 will occur in practice. However, under certain circumstances, it is conceivable that reprocessing with uranium-only recycle could be economic. Such circumstances would entail high transport, storage and disposal costs for irradiated fuel in the once-through mode, low plutonium storage costs in the uranium-only recycle mode and high fabrication costs for MOX fuel assemblies (for instance, for the mixed island concept) in the plutonium recycle mode. A reduction in the

interest/discount rate would favour this situation also.

Phase diagrams corresponding to these two cases are shown in Figures 15 and 16 respectively. In both these diagrams the various lines are labelled according to the notation of the equations just given. A glance at these diagrams shows that for any chosen values of our main parameters, one of the four main technology options will be preferred. The position of the boundaries between the various phases depends upon the parameters used in the above equations and, of course, the values of those parameters depend on technical or industrial judgements. However, nothing we have done so far is dependent on future markets, either for electricity or uranium ore. In practice, many discussions, particularly international discussions, are able to agree on technical or industrial facts but are unable to agree upon supply and demand considerations. The main value of this approach is, therefore, that we are able to reach a broad consensus on the appearance of the phase diagrams and this more clearly identifies where different countries are making different judgements because of their views of the market situation.

Nevertheless, it is stressed that within any particular country the uncertainties in the economic data and the variations in reactor parameters would change the sharp lines into broad band-widths but, for simplicity of presentation, only the lines are shown in these diagrams. Furthermore, it should be stressed that technical judgements vary substantially from one country to another and the economic ground rules vary sufficiently from one country to another so that, quite properly, different countries will show the boundaries between the various thermal reactor phases at somewhat different positions.

So far in all the above equations and phase diagrams, the value of plutonium has been assumed to be zero. We now must consider how the analysis is changed when plutonium has become a valuable commodity, i.e. when fast reactors have been launched or when thermal recycle of plutonium is being practised. Clearly, there is no change in the cost of electricity produced by the once-through mode because, in this mode, the plutonium is not separated from spent fuel. However, a nation or utility which sends fuel for reprocessing may decide to sell its plutonium after storing it for a while and, in this case, equation (2) becomes modified to the following:

$$\{R'\} = C + U(1-x) + E(1-x') + F + R + W + M + H - V \quad (2')$$

where V is the value received for the plutonium produced per year per kW installed capacity.

The value of plutonium in the case of thermal recycle is

already implied by the use of equation (3) but equation (4) needs an important modification. In addition to the capital cost needed initially to build a fast reactor, we also need to take account of the initial cost of acquiring the plutonium needed to launch it. Suppose that the initial plutonium inventory of the fast reactor requires the operation of a thermal reactor for t years then we have the additional launching cost of tV and an additional term tVI has to be added to equation (4). However, that is not the only modification which needs to be made because we also need to note that if the fast reactor is breeding then we need give it credit for the excess plutonium which is produced. This credit produces an additional term in (4) which is tV/τ , where τ is the doubling time. In total, therefore, in place of (4) we get

$$\{B'\} = C' + P_c + P_{rb} + R' + W' + M' + tV\left\{I\frac{1}{\tau}\right\} \quad (4')$$

We now know that V takes on different values in different parts of the phase diagram. Along the boundary between the once-through and breeder phases, the appropriate value of V to be used in (4') is the cost of obtaining the plutonium. This is simply:

$$V = \{R\} - \{O\} = x(U_{OR} - U) \quad (15)$$

Along the boundary between the reprocessing mode and the fast reactor mode, we have the formula:

$$V = 0 \quad (16)$$

and along the boundary between thermal and fast reactors the value of V which must be used is the opportunity cost of using the plutonium to launch fast reactors instead of using it in thermal recycle. Hence we get the formula:

$$V = R - T = (y-x)(U - U_{RT}) \quad (17)$$

Inserting these three values into equation (4') modifies the phase diagrams as shown in Figures 17 and 18 and, in the remainder of this discussion, we shall refer to those two figures.

So far we have determined the value of plutonium only along the boundary lines between the various phases. We can extend the analysis to give a value for plutonium inside any particular area of the phase diagram only if we make some assumptions of the terms under which plutonium will be traded. For the sake of simplicity, let us assume that it is traded at a free market value. Then a utility can gain value from its plutonium either by using it itself or by selling it to other utilities. We can therefore determine the value of V by simply equating $\{R'\}$ either to $\{O\}$,

{R}, {T}, or {B'}. This tells us that the cost of obtaining a unit of plutonium (either real cost or lost opportunity cost) is either (15), (16) or (17) in the {O}, {R} and {T} phases respectively. Within the breeder phase, equating (2') to (4') gives us the simple result:

$$V = \frac{\{R\} - \{B\}}{1 + tI - t/\tau} \quad (18)$$

DISCUSSION

Let us now use this algebraic background to represent the various views which have been expressed by various nations about the cost of fast breeder reactors and their associated fuel cycle services, the timescale by which they might be available and the simultaneous variations in the price of uranium. Various views expressed by groups in different countries can be superimposed on the phase diagram and three illustrative trajectories marked X, Y, and Z are shown on Figures 19 and 20.

In these trajectories, time increases along the line and in general uranium prices move upwards and the fast reactor premium moves downwards as the benefits of R & D, replication and economies of scale take effect.

The line marked X illustrates the view of a country which expects neither a rapid reduction in fast reactor generating costs nor a rapid increase in the price of uranium, so that the once-through cycle or thermal recycle will be the cheapest option for many years ahead.

The line marked Y illustrates the view of a country which expects somewhat lower fast reactor generating costs, but a substantial increase in the price of uranium, such that uranium or uranium and plutonium recycle become the most attractive option.

The line marked Z illustrates the view of a country which has developed fast reactor technology early and expects fast reactor generating costs to decrease rapidly with time accompanied by an increase in the price of uranium (particularly in a world with few or no fast reactors) so that the fast reactor fuel cycle will become the most economic choice at an early date.

Actual presentations made by individual countries in recent discussions serve to verify the general nature of this discussion and a detailed examination of the various views which have been expressed brings out two points very strongly. First, if nuclear power is to make a long term contribution to the needs of the

world, the introduction of fast breeder reactors is both essential and necessary. At first sight, views may appear to differ about the economic viability of fast reactors but in the end those disagreements merely result in slightly different assessments of when they will be important on a large scale. Some countries judge that this time will be as early as 1995 and others judge it will be postponed until 2025. A difference of only 30 years is trivial measured against the lifetime of mankind. This simple thought has been expressed in various ways many times and is easily seen from the phase diagrams. If we move far enough to the right, the breeder reactor must be favoured. Most published discussions about the economics of fast reactors spend a great deal of time on this point and necessarily involve uncertain judgements about the variation of uranium ore price with time.

However, trajectories shown in Figures 19 and 20 demonstrate another factor of equal or more importance. It is that, as the scale of fast reactor use increases, the cost of electricity produced by fast reactors will decrease dramatically. Therefore, an essential feature of the nuclear strategy of any country must be its industrial strategy for decreasing the capital cost of fast reactors and fast reactor fuel cycle centres. It is, therefore, very important with fast reactors to make the correct judgement of when to introduce large scale industrialisation. This in turn means the economics of fast reactors will be very significant to individual countries and very dependent upon their industrial capability and their manufacturing expertise.

Generally speaking, in many discussions concerning fast reactors this last point is not given the weight it deserves. There is nothing very surprising about this. It is freely acknowledged over a wide variety of endeavour that people doing research and development to introduce new technologies always underestimate the difficulty of converting their technology to a routine production basis and they underestimate the difficulty of penetrating the market place with that new technology. The formalism of these phase diagrams simply obliges us to acknowledge those points specifically and give some estimate of them.

FAST BREEDER REACTORS - LECTURE 5

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INTRODUCTION

We now turn to the most difficult lecture of this series concerning fast breeder reactors because we are now going to discuss questions which are not scientific, not technical nor even economic; we are going to discuss a range of issues which, in recent years, have alarmed some members of the general public about the use of fast reactors. In short, we shall consider the emotional question of the "plutonium economy". Opponents to fast reactors do not always make their points clear but so far as we are able to understand them, the "social" objections to the fast reactor fall into one or all of six areas.

- (i) Fast reactors are too expensive.
- (ii) Fast reactors produce nuclear waste which in some way, it is suggested, will be worse than waste produced by thermal reactors.
- (iii) The use of plutonium introduces "the plutonium economy" and that opens the possibility of terrorist groups stealing the plutonium and using it for blackmail purposes.
- (iv) The difficult security measures needed to protect the plutonium from being stolen will themselves limit our civil liberties in some fundamental way.
- (v) The use of plutonium in a worldwide way will assist the proliferation of nuclear weapons.

- (vi) Fast reactors are such sophisticated machines that they cannot provide energy for developing countries because the latter would not have the expertise either to operate or build them.

We have discussed the question of fast reactor economics in the previous lecture. The other points are not technical and many of our scientific colleagues tend to dismiss them as insubstantial or irrelevant. However, that in our opinion is not a satisfactory way of dealing with legitimate concerns and, therefore, although these points are neither quantitative nor easy to discuss, we shall now do our best to discuss each of these in turn.

NUCLEAR WASTE

We have lost count of the number of times when, in general conversation with members of the public in the UK, they have commented that the fast reactor produces a more difficult waste problem than a thermal reactor. We do not know where this view has come from and neither do we know if it is specific to the UK, but nevertheless, let us first address ourselves to this question.

Both thermal and fast reactors produce heat and thereby produce electricity by the controlled use of the fission process. In the case of thermal reactors, the main fission process is that involving ^{235}U , whereas in fast reactors the main fission process involves ^{239}Pu . The fission process automatically produces fission products, i.e. two nuclei each roughly half the mass of a uranium or plutonium nucleus. Those fission products are highly radioactive and produce the most dangerous part of the nuclear waste from either type of reactor. However, the nature of the fission process is such that it cannot significantly differ between uranium and plutonium and there can, therefore, be no significant differences between the fission product waste produced by either type of reactor. Any slight differences that do exist are second-order effects which can be ignored at this level of discussion and in practice. There is, therefore, no reason in principle or in practice why fission product waste should differ significantly from one case to the other.

However, the fission process is not the only one we need to consider. In addition to that, nuclei can simply absorb a neutron to produce what are called transuranium elements, i.e. nuclei which weigh more than uranium. The most important transuranium element to be produced is simply ^{239}Pu . This is the plutonium isotope we have discussed throughout this lecture course and its production is inevitable because all nuclear fuel contains ^{238}U , all ^{238}U absorbs neutrons and that neutron absorption process converts ^{238}U to ^{239}Pu .

In addition to that, ^{239}Pu can itself absorb a neutron to become ^{240}Pu and that in turn can absorb a further neutron to become ^{241}Pu which becomes ^{241}Am , etc. The production of these actinides can vary from one reactor to another because the neutron absorption process depends upon the energy of the neutrons which are present and the successive incineration of these actinides also depends upon the way in which the reactor is operated. For example if fuel is put into a reactor and taken out of it after a relatively short period then a certain amount of ^{238}U will have been converted to ^{239}Pu but there would have been no time for that ^{239}Pu itself to be converted to ^{240}Pu . The production of actinides can, therefore, vary between fast reactors and thermal reactors but, for all practical purposes, this production of actinides always starts with the simple conversion of ^{239}Pu . In all cases, therefore, the dominant actinide which is produced is ^{239}Pu . We have seen in the earlier lectures that that is produced in thermal reactors and can be incinerated efficiently in fast reactors. If that ^{239}Pu is not incinerated then it is a waste product. In other words, if there are no fast reactors and no incineration of ^{239}Pu , then the quantity must increase indefinitely. In short, therefore, if we do not have fast reactors then the plutonium produced by a thermal reactor must be classified as a waste product. By that judgement, it is clear that fast reactors must produce less waste products than thermal reactors alone. It follows from this that there is no corresponding ecological argument which can be produced against the fast reactor as compared to thermal reactors. Indeed, the argument we have just given underplays the advantage of the fast reactor by a large margin because, on a worldwide basis, the single largest detriment to the environment produced by nuclear power is almost certainly the release of radioactivity from the mining of uranium. Since the introduction of the fast reactor avoids new mining operations as far as possible, it follows therefore that the introduction of fast reactors has actually a positive effect on the ecology of the world relative to the use of thermal reactors.

TERRORISTS AND PLUTONIUM

This concerns the fear that plutonium will be stolen or hijacked by terrorists or sub-national groups which would hold the civilised world to ransom. It is unfortunately true that we must give attention to that possibility and it is sad to reflect that the growth of violence throughout the world has brought us to that acknowledgement. It is, however, not the only place where we are obliged to adopt measures which are intrinsically distasteful. Air travel nowadays is made unpleasant by the necessity for luggage and body searches because of these terrorists and sub-national groups. Nowadays national leaders in almost all

countries have to be guarded night and day from attempts at assassination or kidnapping. We find this one of the most miserable features of the modern world. It does, however, have more to do with the existence of terrorists than the existence of plutonium and although this distasteful subject must be treated with the seriousness it deserves, it does not seem to us that the existence of this danger should determine the whole future course of civilisation. Furthermore, the danger is, in our opinion, exaggerated. The GESMO study in the United States concluded that if the use of plutonium was introduced on a large scale in the United States then it could be guarded to a satisfactory level without undue difficulty. This is a conclusion which is likely to be generally valid. It does give special difficulties for a country like our own where we have a long standing tradition that for normal civil activities we do not arm our police. We have no doubt that this well known tradition encourages criminals in the UK not to carry firearms, but most international terrorist groups intent on stealing plutonium would almost certainly use firearms. It follows, therefore, that the steps taken to ensure physical protection of significant quantities of plutonium, whether in store or in transit must include not only physical isolation but also suitably armed policemen. This is an uncomfortable conclusion to come to in the UK, but in other countries of the world, where police are normally armed, it does not raise new questions of principle. Therefore, in our judgement and in the judgement of many responsible people who have studied this matter worldwide, this is not an adequate reason for avoiding the use of fast reactors.

The necessity to guard plutonium which we have just discussed should not, however, mislead people to the idea that the contruction of a nuclear weapon using plutonium is an easy matter. It is a misconception to suppose that a small number of people who obtain plutonium could convert it into a weapon. The task of doing so is actually very complicated and difficult. We have seen a number of ideas produced by "amateur bomb designers" and, in our judgement, none of them would explode. For obvious reasons we do not want to discuss this subject in public but it is worth making a few comments to put the problem in perspective. These comments are all based on information which is freely available in the open literature.

If we cast our minds back to 1945 when the Manhattan Project had been operating for a few years and had prepared its first few weapons, then we know that they had prepared two types: one based on ^{235}U and one based on military grade plutonium. The project had assembled the very best scientific brains and engineering expertise at Los Alamos and made two decisions. They were entirely satisfied that the uranium weapon would explode and there was no need to test it but they were not confident that

the plutonium weapon would explode and they therefore felt that a test of that was essential. The test in New Mexico desert was actually successful and, therefore, one uranium weapon and one plutonium weapon were used at Hiroshima and Nagasaki respectively. However, the point of the story lies in the fact that, all that assembled expertise of the most brilliant scientists in the USA, Canada and the UK thought that the design of the plutonium weapon was sufficiently difficult that they were not confident in advance that it would detonate. It is fair to deduce from this that the characteristics of a plutonium weapon, which necessarily must remain classified, are more difficult and more complex than that of a uranium weapon. It is our judgement, therefore, that if a group of terrorists attempted to make a crude weapon from plutonium then, almost certainly, all they would do is produce a "fizzle". It is for this reason that we believe the risks coming from plutonium diversion are generally exaggerated in the popular literature.

CIVIL LIBERTIES

It has been argued in our own country and to some extent in others that the security measures which are required to protect plutonium will lead to an abuse of civil liberties in some fundamental way.

This concern is best answered by the reply given by Mr. Benn (the then Secretary of State for Energy) in 1977 to such questions and is quoted below:

"As will be seen from the replies given to earlier questions, it is not considered that the development of a large nuclear programme would give rise to security arrangements materially different from those at present. The level of the national security commitment would not however be dictated only by the size of the nuclear programme or the extent to which it employed plutonium, but by the scale, the nature and the intensity of terrorism and other violent criminal activity. It cannot be assumed that such terrorist activity would necessarily be directed against nuclear plant and material, or that, if the latter did not exist, terrorism and other violent crimes would disappear. And although the general situation in this country and in the world in the first half of the next century is not of course one which can be predicted with exactness and confidence, no democratic Government would want to take precautions against terrorism and violent crime that would be more derogatory of individual liberties than the actual situation demanded."

PROLIFERATION

Proliferation involves the acquisition of nuclear weapons by governments and the possibility of this is a real and genuine question which must be discussed carefully and responsibly. Because fast reactors produce and use plutonium, it follows that they could be abused to produce nuclear weapons. However, it does not follow that the problem would be better if we abolished the use of fast reactors. Let us now discuss this matter as carefully as we can by reviewing all the arguments that have been produced in recent years on this issue, trying to put them in perspective one to another.

The first point to make is that a decision by a government to construct nuclear weapons is a political decision motivated by political considerations. Whether a government has nuclear materials immediately available to it or not is almost irrelevant. The connection between civil nuclear power and nuclear weapons proliferation must, therefore, necessarily be a marginal matter. It is nevertheless sufficiently important that we cannot dismiss it.

It should be remembered that a dedicated nuclear weapons programme is cheaper and quicker than an approach to nuclear weapons which first sets up civil nuclear power facilities. No country with weapons ambitions would, therefore, normally choose to start off with a civil programme. Nevertheless, the existence of a civil nuclear programme has, by its very nature, produced training know-how and skills which could be diverted to a weapons programme. However, it seems impossible to argue for that reason alone that civil nuclear power should be discouraged. One could just as well argue that any form of higher education of a technical kind could be abused by a government into a weapons programme. Yet we do not argue that the use of universities should be abolished throughout the world because of that reason. There is, therefore, no definitive argument of this kind which can be made.

Next we should point out that the diversion of plutonium is not the only way in which nuclear weapons could be constructed. Easier enrichment techniques for ^{235}U are becoming more widely appreciated and we should remember that the difficult step in isotope enrichment of uranium is to do it on a large scale at a suitably cheap cost. To do it on a small scale is nowhere near as difficult and many people who have thought about this subject believe that the use of enrichment techniques to separate ^{235}U presents a greater proliferation risk than the use of plutonium. There is indeed a real danger that, by concentrating on the plutonium issue, other routes towards nuclear weapons will not be inhibited as thoroughly as they should be.

Turning, however, to the diversion of plutonium to produce weapons, we should first recognise that the production of plutonium is an inevitable consequence of nuclear power. As soon as uranium of any isotopic composition is put into a reactor, ^{238}U is irradiated and creates ^{239}Pu , indeed about half of all nuclear power comes from plutonium fissions. Many arguments which have been orientated against the fast reactor on these grounds are, in our opinion, misdirected. The plutonium is created in the first place in thermal reactors and if we are to have nuclear power at all, we are obliged to accept that that is a fact.

Some people have argued that the once-through cycle in which spent thermal reactor fuel is not reprocessed is a desirable technology because the plutonium does not exist in separated chemical form but remains within the spent fuel element. It is therefore intimately mixed with fission products of high radioactivity, which act as a self-protecting "policeman" to prevent plutonium diversion. In our judgement, however, this argument does not survive careful examination. It is not possible for spent fuel elements to be highly radioactive indefinitely. Indeed the radioactivity of a PWR spent fuel element falls off as shown in Figure 21 and, after a suitable interval of time, the fission product activity is not an automatic protection for the plutonium. Eventually, therefore, the plutonium produced in a thermal reactor becomes "accessible" and, from a proliferation

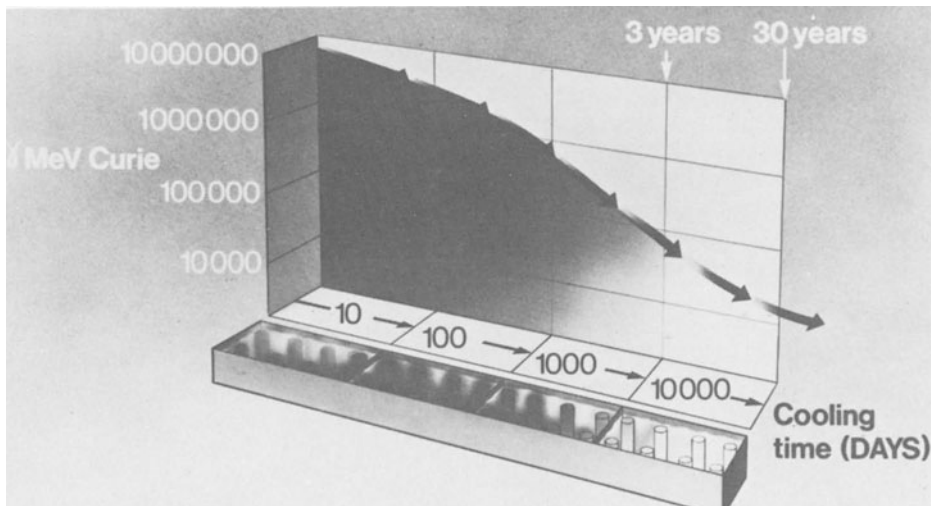


Fig. 21. Gamma activity of a spent PWR fuel element with time after removal from reactor

point of view, we do not believe it is wise to advocate the indefinite and widespread use of the once-through cycle.

Furthermore, we should recognise that the once-through cycle produces more plutonium in the world than either thermal recycle or fast reactors. The reason for this is self-evident. In either thermal recycle or in fast reactors the intent is that plutonium is incinerated to produce heat and then electricity. Going back to Lecture 1, you will recall that the production of plutonium from a fast reactor was in the range of 170-250 kgs per GW year. The corresponding figure for light water reactors is 330 kgs per GW year. The introduction of fast reactors, therefore, reduces the amount of plutonium in the world. It is remarkable how many times the opposite statement is made in public discussions.

However, of course, it is true that a country operating fast reactors is handling plutonium or perhaps mixed uranium/plutonium oxide in a readily accessible form and it is true that that is easier to convert to a weapon than the plutonium contained in a spent fuel element. However, we have already remarked that the radioactivity of a spent fuel element decays with time and, therefore, the distinction between plutonium in these two forms becomes less sharp as time progresses. Furthermore, a nation which has the ability to build, or even just operate, fast reactors is a nation of a high technological standard. For a nation of that standard the form of plutonium, whether it is accompanied by radioactivity or not, is a trivial and unimportant question. In contrast to that, if the government of any particular state found the form of "accessibility" of the plutonium to be a suitable inhibition to a weapons programme, then that state would not anyway be at an advanced enough level to have a fast reactor in the first place and, therefore, the question does not arise. This last point illustrates the point that many published arguments concerning the proliferation questions are highly theoretical and academic in their approach. We should not actually be comparing proliferation risks of fast reactors in use now with thermal reactors in use now because it is a hypothetical comparison. Fast reactors will not be in use on a wide scale until well into the next century. We should, therefore, be comparing and discussing the proliferation risks of the fast reactors as used then and the once-through cycle as used then and, at that point in time, an "accessible" form of plutonium will be that contained in old spent thermal reactor fuel elements.

To sum all this up, we surely must conclude that any nation which could successfully develop and introduce a nuclear power programme has the ability to undertake successfully the much easier task of having a nuclear weapons programme. We return, therefore, to the first point we made. The proliferation of nuclear weapons is primarily a political issue and the true

answer to any proliferation question is the motivation and the determination of any individual national government and the consensus view amongst governments that the widespread proliferation of nuclear weapons should be avoided.

FAST REACTORS AND DEVELOPING COUNTRIES

This is the last item we shall discuss in these lectures. In the first lecture, we stressed the ability of fast reactors to meet the energy demands of the world community. However, the later lectures have probably satisfied you that fast reactors are quite difficult to build and are complex machines which depend not only on high quality fabrication of the reactor and highly trained operators to run them, but also require an elaborate fuel cycle to sustain them. It is, therefore sometimes argued that the development of fast reactors is totally irrelevant to the needs of developing countries. In our own country, some people go on to argue that, for this reason, research and development activities effort should be put into other simpler technologies. In our opinion, this argument does not stand up to examination. Let us examine why this is the case.

In the previous lecture we discussed the economics of fast reactors using phase diagrams and we described various industrial strategies which might be adopted by advanced countries to introduce them. Suppose now that the most advanced countries take policy decisions to introduce fast reactors then, as each advanced country switches to fast reactors, it becomes removed from the world uranium market and the normal laws of supply and demand will then lead to a stabilisation of uranium ore prices. That immediately produces a benefit to other countries, presumably developing countries, which have acquired enough expertise to operate thermal reactors, but cannot yet contemplate introducing fast reactors. They are then able to purchase their uranium ore at a more reasonable cost than would otherwise be the case. (This is not such a good point for those developing countries which also happen to be uranium exporters, but they are a special case).

However, this is not the only benefit produced for the developing country. Going back to the results of the first lecture, we must remember that the plutonium inventory to launch a fast reactor is large and the rate of breeding additional plutonium is actually slow. Therefore, for a wide range of figures for the economic growth rate of the advanced countries, the introduction of fast reactors is limited by the availability of plutonium. In that situation, plutonium acquires an international market value for the production of electricity. This in turn means that spent thermal reactor fuel acquires a market

value. We therefore, have reached a situation where the advanced countries who want to build more fast reactors need plutonium to do so whereas developing countries who have thermal reactors are producing plutonium they have no use for. The obvious thing to do in those circumstances is trade in plutonium and the simple diagram of Figure 22 shows that, in a free market model, the benefits of that plutonium trade fall to both the advanced and the developing countries. Indeed the simple algebra of the previous lecture and illustrated in diagrammatic form in Figure 22 shows that the developing country has the full benefit of fast reactors without having fast reactors at all! In this way we can conclude that fast reactors do in fact benefit developing countries provided we can, in practice, ensure that this trade in plutonium comes about in the way outlined by this discussion. Looking back to equation (18) of the previous lecture, we see that the essential conditions for these circumstances to arise are the following:

- (i) The cost of producing electricity from the breeder {B} must be less than {R}. This can be the case provided the cost of uranium has drifted up far enough and the benefits of scale have been fully effective in launching the fast breeder programme.

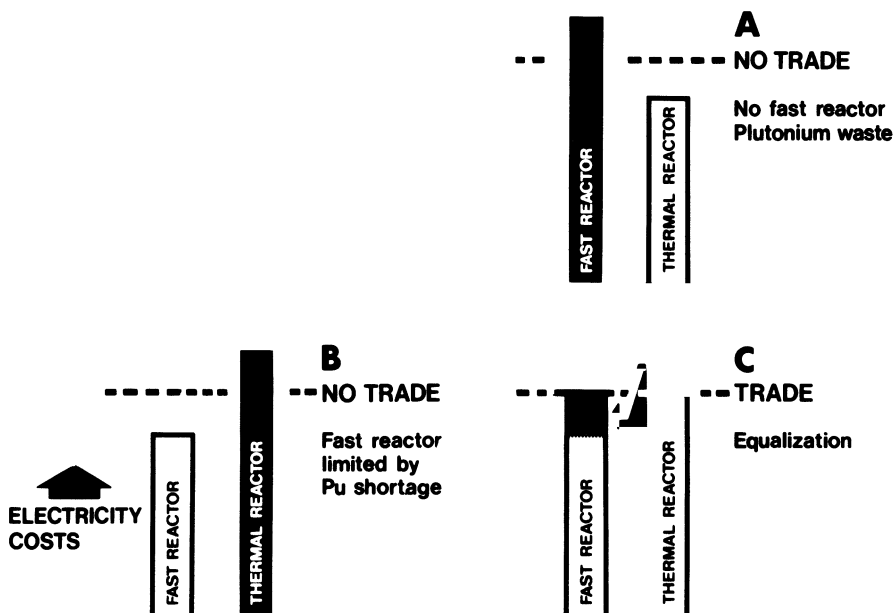


Fig. 22. Equalisation of electricity costs by world trade in plutonium

- (ii) The economy of the advanced country must be expanding so that it needs more electricity. If this were not the case, it would not need to build more fast reactors and, therefore, the incentive for trade would disappear.
- (iii) The doubling time must not get too short. On present design of fast reactors using oxide fuel, this does not seem much of a risk. Doubling times are frequently estimated to be in the 20-40 year range and a long doubling time obliges advanced countries to rely upon a source of plutonium from thermal reactors to expand its electrical generation capacity.

However, as we mentioned earlier, it is possible to design fast reactors with short doubling times. This certainly would be the case if we introduced carbide fuels. If that were done too early, there is a risk that it would produce a glut of plutonium and the argument we have just reviewed would collapse.

It follows from this argument that the intelligent use of fast reactors can benefit both advanced and developing countries. However, this can only be the case if they are introduced by the advanced countries in such a way that they encourage interdependence between nations of the world. There is, therefore, no guarantee that fast reactors will help developing countries and this discussion has simply served to point out that the opportunity exists. Whether that opportunity is taken or not will depend upon governments and not upon scientists.

ACKNOWLEDGEMENTS

We are indebted to Mr A M Judd and Mr A A Farmer, together with many others in the UKAEA, for their contributions and comments which have helped in the preparation of these lecture notes.

HOW REACTOR SAFETY IS ASSURED IN THE UNITED STATES

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This is the first of four lectures* that I will give in this School. The main goal of this talk will be a description of the present system in the United States for assuring the safety of large nuclear power reactors. The second talk will cover risk assessment and its use in reactor safety and regulation. The last two talks will discuss the recent accident at Three Mile Island. This talk will begin with a description of the underlying safety philosophy, including which institutions have the various responsibilities. I will then proceed to discuss how the safety assurance system is implemented, how oversight is accomplished outside of the system itself, and how feedback occurs to improve the system. Finally, some issues and problems with the system will be discussed.

I shall not be covering the broader question of whether nuclear electric power plants are an appropriate, or best, choice for generating electric power in our country or any other country. I feel that this basic policy issue requires much more input than that which I have chosen to discuss here today. However, some of the points I shall be making can be of guidance to any country that chooses to undertake a nuclear power program, or that has already made that decision. This is because many of the institutional issues raised have broad generic implications that extend beyond the borders of the United States, with its own particular political arrangement.

Also, I must emphasize at the outset that the opinions expressed here are my own and do not necessarily represent policies of the U.S. Nuclear Regulatory Commission. I shall attempt to be candid with you concerning both the strengths and weaknesses of our present safety regulatory system, as I see them myself.

*Only the first two lectures are included in this volume.

The talk will focus on the American system mainly because that is the system with which I am most familiar. Other countries' safety and regulatory systems will not be treated, although many important lessons useful in other countries can be easily transferred from the American experience. Also, because the large commercial reactors in the United States are mainly PWRs (pressurized water reactors) and BWRs (boiling water reactors), these will be the focus of attention. The remarks may not be fully applicable to the gas reactors prevalent in the United Kingdom, to the heavy water reactors built by our Canadian neighbors, or to the fast metal-cooled reactors now under intensive development in many countries.

The emphasis will be on safety through regulation. I will thus give less attention to issues as they might be presented by a reactor vendor, an architect/engineering firm, or a utility/owner. I hope that this admittedly biased approach will nevertheless be of interest to the attendees at this School.

The main design concept under which power reactors have been built and operated in the U.S. is known as the "defense-in depth" concept. This concept has three elements. The first is the philosophy that the designer should contemplate all important accidents that he thinks have significant probability of occurring, and should design against them. The designer should use intrinsically safe designs wherever possible, and engineered systems elsewhere. The concept of an intrinsically safe design implies reliance where feasible on fundamental physical laws for protection. A good example of this is the fact that the water in the reactor coolant system also serves as the moderator in U.S. power reactors, and its loss automatically shuts down the chain reaction. This is an intrinsic feature that does not require specific engineered equipment to carry out its function. Of course, not all elements of the design can rely on such physical phenomena for protection against accidents.

The second element in "defense-in-depth" is the assumption that, despite best efforts in design, accidents will happen anyway, because they cannot be all designed against absolutely (either intrinsically or through engineered features), and therefore significant redundancy must be built into the designs to cope with equipment failures. Also, for many important types of accidents there is a need for engineered safety systems to cope with events that occur. Examples of these systems include the well-known ECCS (emergency core cooling system), the auxiliary feedwater system, seismic restraint systems, and redundant/diverse systems to terminate the chain reaction.

The third element in "defense-in-depth" is reactor design and siting to mitigate consequences of accidents if they occur despite the best efforts of the first two approaches. Included in this part of the philosophy are the large reactor containment building, built to contain radioactive releases if they occur from the reactor itself;

the use of sites remote from large populations, so as to reduce the doses that potentially might be delivered to nearby residents in the event of a radioactive release; and the filtering of airborne releases to reduce their magnitude.

One of the key design features of our reactors is the multiple barriers against the release of radioactive materials from the fuel. There are four barriers between the fission products in the fuel and the broader environment. The first is the fuel matrix itself, which is a ceramic-like material that immobilizes or significantly retards the various fission products. The second is the fuel cladding, designed to retain within itself the fission products that do migrate from the fuel matrix. The third is the reactor primary pressure vessel system, designed to keep fission products which might escape from the fuel cladding from going outside the reactor; and the fourth is the containment building mentioned earlier. Each of these barriers will contain or retard radioactive releases, and their effectiveness is a major element in safe reactor design and operation.

There are three crucial considerations in putting together a safe design for a reactor, and careful attention must be paid to each. The first is the ability to shut down the chain reaction and keep it shut down; this "scram" mechanism must be reliable and effective. The second is maintaining structural integrity of the fuel, the core structure, the primary coolant boundary of vessel and piping, and the larger building and its equipment. Especially when one considers seismic or hurricane forces, but also in considering forces generated internally to the reactor, this structural design problem is a very difficult one. The third is the absolutely crucial need for residual heat removal after reactor scram. Unlike fossil-fired power plants whose fuel can be fully extinguished, nuclear plants cannot fully extinguish the heat generated in the chain reaction; there remains a very large body of fission products within the fuel after scram, and these produce large amounts of heat as they themselves undergo radioactive decay. This "decay heat," amounting to several percent of the initial heat energy just after scram, and as much as 2 percent a day later, must be removed or the entire reactor core will ultimately (indeed, rapidly) rise in temperature to the point where fuel damage will release the encapsulated radioactivity. This need for maintaining a long-range heat sink is recognized as one of the most vital issues in recovery from accidents large or small.

Finally, there is the issue of reliance on automatic features and its complement, reliance on the human operator. Reactor designs recognize that many safety-related functions are best made automatic. Examples include the automatic actuation of the several ECCS systems when various pressure set-points are crossed, and automatic actuation of auxiliary feedwater pumps when the main feedwater pumps fail. Despite using such automatic systems, reactor designers

recognize that there are numerous situations (indeed, much more numerous than those for which automatic systems can be designed) in which human operator intervention is essentially required for safe operation. This is because the complexity of possible accident sequences is far too great to be contemplated by the designers, and human judgment with its versatility and integrating powers produces safer operation. One key issue, demonstrated at Three Mile Island, is that the trade-offs between automatic and human system operation always involve compromises, and sometimes the present arrangement leaves much to be desired.

Integral to the American reactor program is a strong reliance on quality control and quality assurance, which begins with the design phase and extends to manufacture, construction/installation, operations, and maintenance. This program, carried out by the vendors, constructors, and utilities, is monitored in an audit mode by the regulatory groups. It has resulted in components and systems in our nuclear plants that are significantly more reliable and better performing than comparable systems in related nonnuclear industries. In a real sense the quality programs are a backbone of the whole endeavor.

Given this outline of the fundamental philosophy of reactor design and operation, it might sound as if accidents could almost never happen. Indeed, it might seem as if the system should be capable of nearly perfect operation, excepting of course minor breakdowns of components and systems that don't compromise safety very much. This conclusion would not be correct. Even with the most Herculean efforts described above, our reactors are very far from perfect machines. We have continued to find errors of various types in all phases of the program: conceptual errors; improperly used engineering assumptions; errors in engineering computer codes; errors of manufacture, construction, or installation; maintenance errors; operator errors; and so on. Brief reflection reveals that these are to be expected. Indeed, if one somehow stopped finding these errors it would be a sign of the failure of the error surveillance system! The key task of safety assurance, then, is in three parts: to assure that the system is forgiving of and can recover successfully from those errors that do occur; to assure that when errors not forgiven appear that they are corrected; and to assure that continuing improvements in all elements of the system are developed and implemented.

Much of what I will have to say next about the success of our reactor safety program will be praise for the success with which these three elements (forgiveness, correction, improvement) are carried out. Much of my criticism of the present safety arrangements is, by contrast, criticism of these same elements.

In the U.S. the fundamental responsibility for safe construction, maintenance and operation of the reactor rests with its owner, the utility. This responsibility is shared in a very complex way with other elements of the nuclear industry: the reactor vendor, the architect/engineer, the industry organizations, and so on. The sharing is complex because even though the utility may have only limited expertise in some highly technical areas, and may therefore rely on other groups (some under contract, some not), it bears the major legal responsibility. It is important to point out that we have in the U.S. a couple of hundred electric utilities of significant size, many of which are now owners of reactors either operating or under construction. The utility industry is fractionated into the large number of individual companies because of the way the industry grew up in its early years. Some of the utilities are privately owned corporations; some are publicly owned; and a few are Federal agencies. Some utilities are large and very strong technically, while others are small and relatively weak. This creates its own problems, since the success of the entire reactor endeavor in the U.S. depends on achieving competence even with the smaller, less well-financed utilities.

Another element of diversity is the variations among our commercial reactors themselves. We have four manufacturers of light-water reactors, each with several different designs; and we have about a dozen different architect/engineering firms that put up the plants, all with different construction practices and varying designs for the nonnuclear parts of the facilities. Thus, nearly all of our reactors (about 70 operating, another 125 under construction or planned) are different. The fact that hardly any are alike seriously affects the whole U.S. nuclear safety picture. For example, analysis of safety performed at one reactor often cannot be directly applied to more than a few others, and problems overcome at one reactor may not be applicable at any other plant!

The federal government, through the U.S. Nuclear Regulatory Commission, has overwhelmingly preeminent authority in nuclear regulatory matters. Although we have a federal system in the U.S., the various states have little impact on safety, with the single (but crucial) exception of their key roles in site selection, environmental regulation, and in rate-setting, which are done in whole or in part at the state level. This federal preemption of nuclear safety regulation is mandated by act of Congress.

The Nuclear Regulatory Commission (NRC), where I work, has a general philosophy of regulation that is best characterized by the word "audit." That is, although it establishes large numbers of rules, regulations, guides, and standards, the method it uses to gain assurance that the reactors are properly run is by doing audit reviews of various elements of reactor design, construction, and operation. These reviews, not intended to be completely thorough

enough to provide full assurance of all details, are intended to assure the NRC that the utility and its contractors do their job properly.

Unfortunately, the system which gives the utility the prime safety role really doesn't work the way it is supposed to work. What has happened over the years is that the NRC (and its predecessor agency) have imposed a complicated set of regulatory conditions on the utilities.

Many of the utilities consider that the amount of regulation is much too great, that it constitutes an unreasonable burden which does not contribute to safety in proportion to its size and cost, and that in many instances it represents overkill. This attitude, quite common before the accident at Three Mile Island, is still present, although less dominant, even after TMI. Its effect has been to place the regulatory program in the driver's seat insofar as safety is concerned: the utilities seldom have taken initiatives beyond what is required by the NRC, and the NRC spends inordinate amounts of effort worrying about the imposition of requirements that might, in another arrangement, have been undertaken by the utilities on their own initiative. This situation has changed somewhat since Three Mile Island, of course, but whether it will be a permanent change remains to be seen.

The NRC is not required by its philosophy (or the enabling legislation) to regulate so as to make reactors as safe as they can reasonably be; it is only required to make findings that the safety of a particular system provides "no undue risk to" the public health, safety, and the environment. This latter requires judgment, and here again one meets a conflict: some members of the industry and the public believe that the safety of our large commercial reactors and is already far more than "safe enough" to protect the public and much resentment of additional regulatory requirements exists. On the other side of the coin, the regulatory staff is accused by some concerned groups and citizens of being "soft" on the industry, because of its close working relationship with them. Often cited, for example, is the NRC's reluctance to order back-fit of safety improvements. This tension and its effects are a major part of U.S. reactor safety and its regulation today.

How is this tension resolved? Unfortunately, in much of the interaction between NRC and utilities, especially when the schedule for construction of a plant is at stake or when a plant might be turned off because of regulatory actions, the outcome of the conflict is heavily weighted, but not determined by the very large financial costs involved. A plant running at full capacity today generates electricity valued in the range of \$1/2 million per day, give or take 50 percent. The daily carrying charges on the funds borrowed to construct a large plant are of the same order. Thus

it is very expensive indeed to delay or turn off a large reactor, and all too often a utility will give in to a regulatory demand mainly because the alternative of contesting it is so very costly in terms of construction delays or cost of replacement power. The opposite side of this coin is that sometimes the NRC has been less than vigorous in implementing safety improvements, perhaps because of cognizance that they are quite expensive in many cases.

This is, as I have said, an unfortunate state of affairs. Because the regulatory staff's power to delay or de-rate or close down reactors has such enormous economic consequences, it wields powerful leverage over the utilities. Often, interactions on technical matters are carried out and resolved only at the lower levels of both NRC and the utility, with both sides reluctant to involve higher management, in part because of possible delays. Whether this circumstance adequately protects the public health and safety then depends upon the ability of these lower echelons to agree effectively on the best approach to both safe and economical operation. Again, it is my view that, because of delays and difficulties in getting favorable rulings from the regulatory staff on innovative concepts, this situation is all too often a disincentive because of the way it discourages innovation.

A vital part of the U.S. safety assurance system is the public hearing process, in which at two stages members of the interested public are afforded formal opportunities to intervene in the licensing process. The two occasions are just prior to consideration of an application for a reactor construction permit, and again just prior to consideration of an operating license. (Intervention is possible at other stages, but it is not as often exercised.) These hearings allow the raising of issues involving either safety or environmental impact, and have in recent years been a major platform for the airing of disputes about siting policy. Unfortunately, the hearing process is not as effective as it was hoped to be by the framers of the concept: although one often hears glowing praise for this process as a crucial part (sometimes, it is termed the crucial part) of the public input to reactor decision making, this view is, in my opinion, a vast exaggeration of the impact of the hearing process. This is mainly because by the time a hearing is held most of the difficult issues that separate NRC staff from the applicant have been fought over and resolved by interaction through other channels. Thus the hearing process often finds the staff taking sides with the applicant, against intervenors, perhaps because the staff may bear a psychological commitment to defend the decisions already made that have brought them all to this stage of the process. Also, issues of genuine and difficult technical content seem rarely to be raised in these hearings, although there have been some key exceptions.

No lecture about how reactor regulation works in the U.S. would be complete without mention of the ACRS (Advisory Committee on Reactor Safeguards), an independent statutory body which reviews all reactor plants during the licensing process, reviews operational problems as they arise, advises on the quality and direction of the NRC research program, and generally maintains independent oversight. The ACRS membership consists of distinguished engineers and scientists drawn from various segments of the U.S. technical community, supported by a staff and backed by the prestige of a quarter century of major impact on reactor safety. Sadly, the ACRS has been more reactive (to staff actions) than it perhaps should have been, in part because of perceived stronger staff competence. However, the ACRS' recent vigorous effort in understanding the accident at Three Mile Island and in overseeing the large NRC research program are a major turn-back toward the crucial role it played in earlier years.

There also exists a vigorous research community working in and concerned about reactor safety: the annual NRC research budget of roughly \$200 million maintains this community in the U.S. along with smaller support from other sources such as the Electric Power Research Institute. An equally active community, of comparable size, is working on water reactor safety in other countries besides the U.S., with excellent international cooperation. From this community is drawn much of the expertise that educates, mans, and invigorates all the rest of the nuclear endeavor.

An important part of maintaining safety is feedback from operational experiences, so as to enable corrections to be made in the light of problems as they arise. In this aspect, the U.S. record has not been a good one. Neither the regulatory agency (NRC) nor the various industry groups has maintained an effective mechanism for studying, analyzing, and disseminating the lessons that might be learned from operating experience; and the lessons are sometimes not learned at all, or only on one or a few reactors instead of industry-wide. This dismal situation is in the process of rapid improvement in the light of the accident at Three Mile Island, which was preceded by precursor events whose significance was missed by almost the whole U.S. safety community. If the recently established efforts are as successful as they deserve to be, this aspect at least will be much improved soon.

Nevertheless, there still remain some important barriers to progress in reactor safety. I have already mentioned that in some quarters the concept that reactors are already "safe enough" has prevailed. Also, because of the expense of reactor downtime, some retrofits are prohibitively expensive, or at least are perceived to be so. Sometimes, the development of industry standards can be painfully slow, because of the consensus system used in their formulation. Finally, the government supports almost no research

itself at present aimed mainly at improving the safety of light-water power reactors.

This problem stems from what I believe has been a mistaken response after the 1975 Energy Reorganization Act, which created both the NRC and what is now the Department of Energy (DOE) from what had been the former U.S. Atomic Energy Commission. NRC cannot do developmental work because of its regulatory role, and DOE has put most of its own efforts into fast breeder reactor development.

Lest this long litany of problems leave the impression that our regulatory system is ineffective, it is important to point out again that it has many important strong points too. The most important measure of its effectiveness is surely the remarkable safety record of the commercial power industry that is regulated by the system I have described. Even including the unfortunate and significant accident at Three Mile Island, the overall commercial reactor safety record has been outstanding. There have been no large releases of radioactivity, no core melt accidents, no radioactivity-induced prompt fatalities, and excellent control of routine emissions through the two-decade history of over 400 reactor years of U.S. commercial operation. This record, on its face, says a good deal about the overall efficacy of the program. The fact that the record is not strong enough on its own accord to tell us all we want to know about reactor safety should not obscure the fine record just mentioned. Despite the Three Mile Island accident and the many problems it has revealed (and surely after profiting from the lessons of TMI), we do have a good foundation upon which to build the kind of improved safety assurance system that we all desire.

THE ROLE OF QUANTITATIVE RISK ASSESSMENT IN REACTOR SAFETY

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In my first lecture, I discussed the way that safety is implemented and assured in the reactor enterprise in the United States. Now I will discuss quantitative risk assessment and its role in reactor safety.

First, what is risk assessment? I refer to a set of methodologies that, used together, allow the quantitative analysis of the risks from a given undertaking, in our case from the operation of large commercial nuclear reactor power stations. Usually, one thinks of the risk in terms of the consequences from large accidents, or alternatively in terms of the consequences combined with some likelihood of occurring. In reactor safety, it is usual to define "risk" to be the product of consequences times their probability of happening; but hardly anything that I shall discuss here depends upon that particular choice of definition. Also, most people generally think in terms of rather large risks, which means either quite large probabilities or quite large consequences, or both. That is, most people are not very interested in accidents with small risks, nor in small accidents with such high frequencies of occurrence that they already occur in our own experience quite often. Of course, it is fortunate that generally the most frequent accidents have small consequences, a fact that we know both from the safety record of our large reactor endeavor up to now and from analyses of how accidents happen.

Risk assessment means the quantitative analysis of risk, and in the public mind that generally brings to mind the study of overall risks, namely what the total risk is from a particular undertaking. Perhaps the most famous example of such an overall risk

analysis is the Reactor Safety Study, also known as the Rasmussen Report¹ or WASH-1400 after its report number.

A key point that I wish to make is that risk assessment means far more than the study of overall risks, at least to me. Indeed, as I will discuss later, in my opinion its most valuable application is not in overall risk analysis, but in more limited analysis and comparison of systems, accident sequences, and study of uncertainty. It is already, and in the coming years will become even more, a tool for improving the design and operation of our large nuclear reactors.

But another prominent feature of risk assessment today is the great controversy surrounding it. This controversy continues in the face of almost overwhelming evidence as to the importance and usefulness of the technique. Why?

The reason, of course, is the Rasmussen Report. Because WASH-1400 was oversold by some proponents of nuclear power, and strongly criticized by many opponents, it became immediately after its publication in 1975 one of the battlegrounds on which the nuclear debate unfortunately has focused. I will come back a little later in this lecture to the achievements and limitations of WASH-1400 itself, as I see them, but here I want to make the point that the controversy has been a major factor in clouding the issue as to the actual value of quantitative risk assessment methods. To me, this is profoundly unfortunate.

Quantitative risk assessment methods are intrinsically difficult to develop and use: they are highly technical, require skill in both engineering and analysis, and even at best yield results that have significant uncertainties. This too has made the techniques controversial. Also, because much public attention has been focused on the Rasmussen Report's conclusions on the "overall" risk from reactor operations, the controversy has tended to neglect the significant applications of these methods for purposes other than overall risk quantification.

The Rasmussen Report was a major intellectual achievement, a breakthrough that has already had great impact. What was the WASH-1400 study? It was a multi-million dollar effort over 2 years (1973-1975), financed by the U.S. Atomic Energy Commission and completed after the AEC's reorganization by its successor agency, the U.S. Nuclear Regulatory Commission (NRC). It attempted to analyze the risks from two large American reactors, one a PWR (pressurized water reactor) and one a BWR (boiling water reactor). The goal was to quantify the probabilities and consequences of large accidents, accidents with significant public consequences in terms of radioactive releases leading to disease, death, and

property damage. The report did not study sabotage scenarios.

The report used the methods of event-tree/fault-tree analysis; indeed, in a real sense it helped to pioneer these methods. The study team assembled engineering and mathematical models of a number of processes involved in reactor accidents, including processes of core melt, radioactive dispersion, transport in the environment, and disease/death. Because it was the first major effort of its kind, it had to do much original research in studying some of the areas outside of the reactor itself, such as in radioactive dispersion, core melt, and related phenomena.

But the key breakthroughs occurred in the event-tree/fault-tree approach. In this talk, I cannot go through how this event-tree/fault-tree methodology works. I assume that you are aware that the method treats accident sequences by first assembling various logical diagrams describing accident progression, and then analyzing what failures, in what components and with what time order, lead to the outcome under study. Event tree generation, while difficult, is relatively easy compared to fault tree generation; but each is an excruciatingly tedious process of detailed study of the reactor configuration and the interrelationship of its many functions and parts. The fact that these techniques succeed as well as they do is remarkable.

Of course, the WASH-1400 study has some limitations: these have been brought out in the intervening years by a large number of critical articles and memoranda, and were studied in 1977-1978 by a special Risk Assessment Review Group, under the chairmanship of Professor H. Lewis, put together by the NRC for that express purpose. The Group's Report² is a good reference on many of the issues I will cover in this talk.

In my opinion, the main limitation of the Rasmussen Report was that in retrospect it was too ambitious: the study team attempted to put numerical values on everything they needed to analyze, and in some cases the underlying data base was weak or non-existent. Also, some of the engineering models, in particular the models for seismic-induced accidents and for fires, seem weak. The way human intervention was modelled was inadequate, a fact that the study team itself recognized: that is, although human error was put into the accident sequences wherever possible, there was an inadequate treatment of the possibility that the operators might cope effectively during accidents, thereby mitigating their otherwise large consequences. Also, the way that human error might compound an accident was inadequately treated, an observation that is highlighted in the light of the accident at Three Mile Island.

Other weaknesses in WASH-1400 were in the radioactivity dispersion model, the latent cancer model, and in some of the data base. Finally, the report was hard to read and had an atrociously poor Executive Summary. Still, despite these identified weaknesses, WASH-1400 stands as a monument in the development of quantitative risk assessment methods.

Figures 1 and 2 show the overall results of WASH-1400 as published in its Executive Summary. The figures show on the abscissa a measure of consequences, in this case prompt fatalities from accidents studied in the analysis. On the ordinate are shown the probability results, and the curves reveal, on their face, that the risks as measured by prompt fatalities from the two reactors studied are quite low compared to a whole range of other risks that are confronted by our advanced society. (There are other consequences from reactor accidents besides prompt fatalities, which I am not discussing here. The most important are latent cancers and property damage.) The fact that the uncertainties in the WASH-1400 analysis are now perceived to be quite large should not obscure the general conclusion that the risks of these two reactors are likely to be reasonably small.

I will not discuss these figures further: their study is of some interest to anyone who has not seen them before, but has little interest now to the reactor expert.

I wish instead, in the remainder of this talk, to concentrate on what to me is a more important issue: that is, the more valuable uses of these techniques for analyses other than overall risk assessment. I will use examples from applications within my own agency, the NRC.

In the NRC, our regulatory staff is faced with almost countless occasions in which decisions have to be made about various issues. Examples include decisions about whether a flaw in a particular safety system is serious enough to merit prompt remedial action; whether the resolution of a particular "generic" safety issue is of high or low priority; whether a modification in an otherwise standard design is, on balance "safer" than its predecessor; whether a certain new regulatory requirement should be required for retro-fit on all existing reactors, or required only on reactors still in the design stage; and so on. These decisions are the day-to-day heart of our regulatory process, and the establishing of priorities among the many things the NRC staff could do with much larger resources is vital, since our resources are limited.

This is where quantitative risk assessment methods come into play. They allow the analyst to cast light on how significant the risk reduction potential is from certain actions; how important

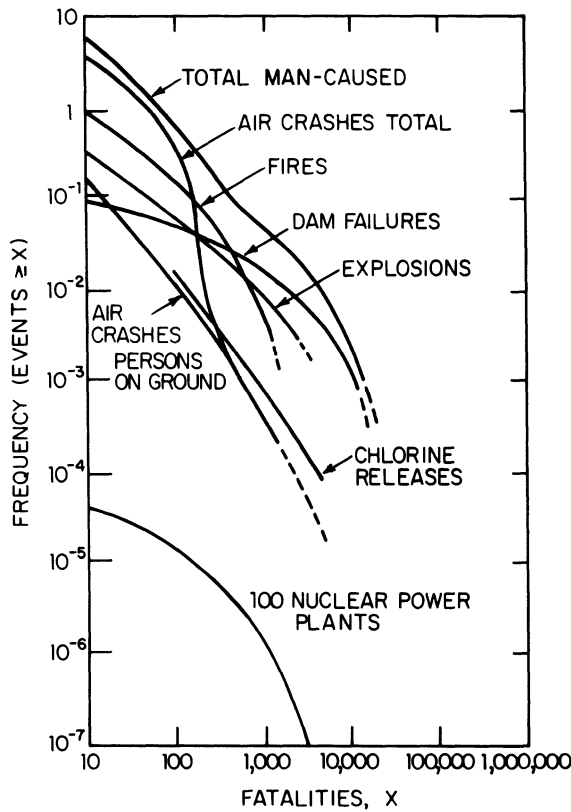


Figure 1. Frequency of Man-Caused Events Involving Fatalities.

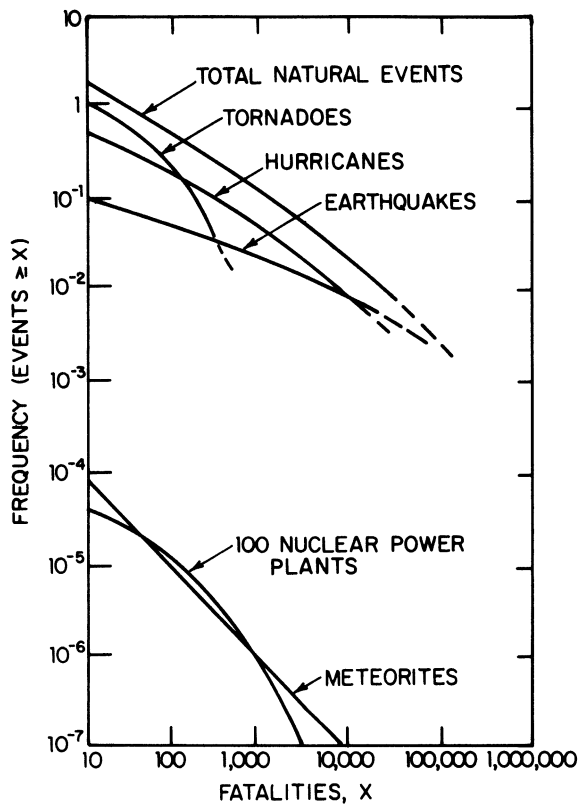


Figure 2. Frequency of Natural Events Involving Fatalities

the risk implication is from various new and unstudied accident sequences; and so on. In short, these techniques are a way to rationalize the process of studying and regulating, to concentrate resources where they will likely have the most impact in safety improvement or safety regulation.

Some recent example of applying these techniques will demonstrate the point. First I will discuss the issue of "generic safety issues," which are defined in our regulatory process as issues that apply across a broad spectrum of reactors, rather than only to one specific design or one reactor, and are unresolved in the sense that no firm regulator position has been taken on them. Last year our agency informed our Congress of 133 of these "unresolved generic issues." This year, the list of important ones was reduced to only 19! This reduction was not accomplished by the "resolution" of all of the others, but by an analysis showing that only the 19 remaining had enough real or potential safety significance to merit concentrated study over the near term. The others either had small risk significance, or in some cases had no actual risk significance at all. This has served to allow our staff to concentrate its effort on the important items, leaving to some future time the study of the others.

Another recent application of these techniques occurred just after the accident at Three Mile Island. I will remind the audience that one part of the TMI accident involved the unintentional blockage of some valves that prevented auxiliary feedwater from supplying water to the large steam generators after the regular main feedwater pumps had tripped. Although we now believe that the unavailability of auxiliary feedwater (AFW) for the first few minutes of this particular accident did not materially affect the accident outcome, our agency became concerned that perhaps there might be a general problem with the availability of AFW systems in other pressurized water reactors.

To study this question, our NRC staff, in collaboration with some colleagues elsewhere in the country and with the reactor vendors and utility owners, undertook a quick study of AFW reliability, just after the TMI accident. Thirty-three PWRs, representing 25 different AFW configurations, were studied. The AFW systems typically involve a set of redundant and diverse pumps (some electric driven, some steam driven). The reliability of the whole AFW system then depends upon their geometrical configuration, the location of various valves that might be mistakenly closed, the source of water supply for these pumps, their control systems, and so on. The study attempted to do a relative comparison of availability of AFW systems under normal conditions, under conditions of loss of offsite power (LOOP), and under conditions of loss of all AC power, which would include loss of the onsite power.

The tentative results of the recent reliability study are shown in Figure 3. The more reliable AFW systems are toward the bottom of the figure, and the horizontal scale is only approximate, with about one order of magnitude of reliability shown by the arrows near the left bottom. The figure has a remarkable message: namely, that in ordinary operation the reliability of these AFW systems varies from one PWR to another by almost two orders of magnitude, and that some reactors have very different reliabilities after loss of all AC power than after loss of only offsite power!

Without dwelling on the details of this figure, I wish instead to dwell on its message: the use of quantitative risk assessment methods is a powerful tool indeed for comparisons such as these! The insights enable the regulatory staff, and the utilities, to concentrate effort where it is needed most.

Other examples of application of these methods are in helping to develop emergency plans; in developing a rational basis for better regulation of transient and small-LOCA events; in studying possible weaknesses in our older reactor plants; and in allocating resources to study operational data. All of these applications are now underway or soon will be.

Let me summarize my views on the future of risk assessment in reactor safety as follows: I believe that these methods already are beginning to play an important role in making our regulatory process more rational within NRC. I believe that their importance will be even greater with each passing year over the next few years, in part because the still small number of practitioners of the art of quantitative analysis will be increasing, but mainly because so many people now believe in their use. I believe that the techniques will be most useful in making comparisons of similar systems (such as auxiliary feedwater systems), or next greatest help in studying safety significance of particular accident sequences, and less useful for overall risk assessments.

I will elaborate on this last point briefly: to make an overall risk assessment for a particular large facility requires that the analyst do a complete and accurate analysis that covers all of the significant contributors to risk. This will always be difficult even in the best of circumstances, and will have large uncertainties. Nevertheless, I believe that the techniques have a role to play in overall risk assessment as well. After all, even with their flaws, these quantitative risk assessment methods are the only quantitative methods we have--and I hope and expect that we will make the most of them.

LMFW= Loss of Main Feedwater

LOOP = Loss of Offsite Power

(unpublished Report, U.S. Nuclear Regulatory Commission, 1979)

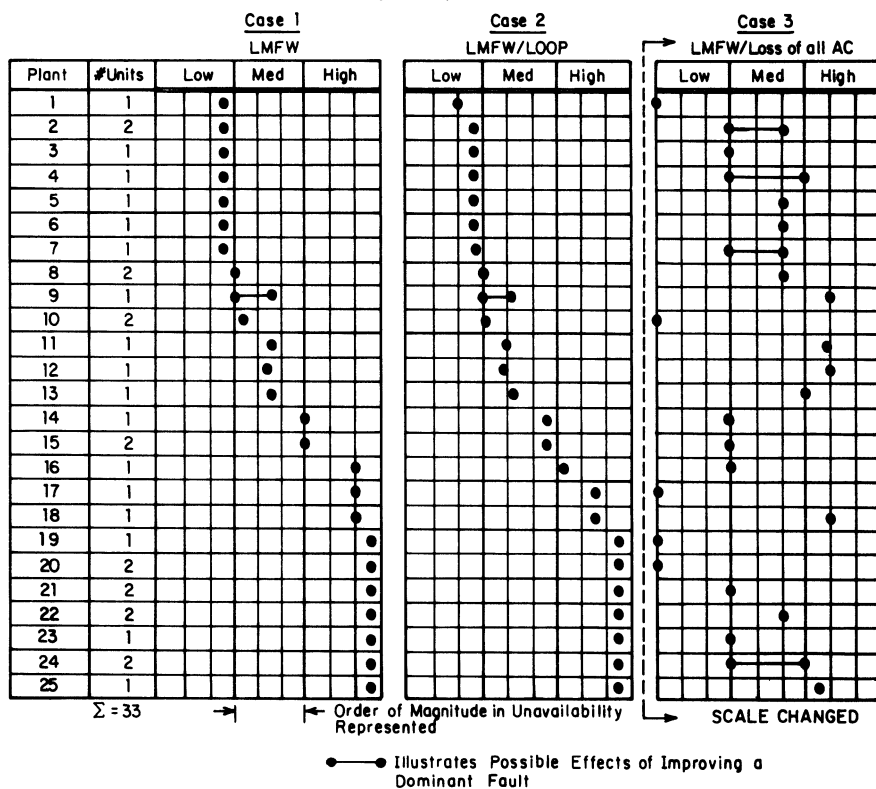


Figure 3. Comparison of Reliability of 25 Configurations (in 33 PWR Plants) of Auxiliary Feedwater Systems.

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COAL CONVERSION : ADVANCED TECHNOLOGIES

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SUMMARY

Coal has been refined since the substituting fuel-wood to heat by combustion or to coke by devolatilization. Using the heat produced by combustion coal is converted to electrical energy. Finally via coke iron is produced by the reduction of iron ore.

In the last decades coal has been pushed aside by petroleum and natural gas in the market of energy and raw material, because these are easy to handle. With the increasing scarcity of the natural fluid and gaseous energy carriers coal has to be substituted for the former competing substances - and possibly in the same state of aggregates.

Converting to heat, coke, oil and gas are both new and old tasks of coal-technologies. For many years, especially since the "oil-crisis", new techniques have been tested thereby the coal should be refined more economically and enviromentally friendly. Such technologies are among others as follows:

- Carbonization with coal-preheating or by formed-coke-processing
- Gasification in fixed bed, fluidized bed and entrained bed with H_2 or H_2O by using nuclear reactor's wasted heat
- Liquefaction by hydration or gas synthesis after coalgasification
- Combustion in the fluidized bed combined with steam- and gas-turbines.

COAL AND ITS PRODUCTS

Coal as raw material and source of energy

Coal, like petroleum and natural gas, is not only an energy source for heat production and power generation just as the tasks of nuclear fuel, sunradiation or the waterpower are. Coal is the most carbonaceous raw material for chemical processes. It is followed by petroleum and natural gas with decreasing contents of carbon and increasing contents of hydrogen. (Fig. 1)

	C	H	O	N
HARD COAL	75 - 97	2 - 5	2 - 20	0 - 1 w-%
PETROLEUM	80 - 88	10 - 14	1 - 7	0 - 1
NATURAL GAS	50 - 71	14 - 24	1 - 2	1 - 7

Fig. 1. Elementary analysis of coal and its competition-fuels

Oil and gas are raw materials, easily transportable in pipelines, less difficult to dose in refiningplants, by flowing through reactors and in reactions with other solid materials, liquids and gases. Therefore it is not surprising, that petroleum and natural gas have dominated the energy market in the last decades.

In West-Germany the portion of these liquid and gaseous materials in the energy market rose from 5 % in 1950 up to 68 % in 1978 (Fig. 2). Coal was displaced of its position from 88 % to 27 % in the same period of time.

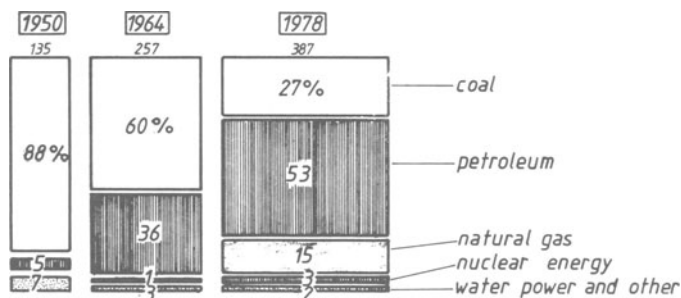


Fig. 2. Development in Energy Market of the FR-Germany 1979

Should and must we return from oil back to coal and the other energy carriers in the future the industry wouldn't be the only one, exchanging raw materials for its large plants. In 1979 40 % of the oil consumption in West Germany was in private hands (Fig. 3). This large amount was used for heating purposes (22 %) and for private automobiles (18 %).

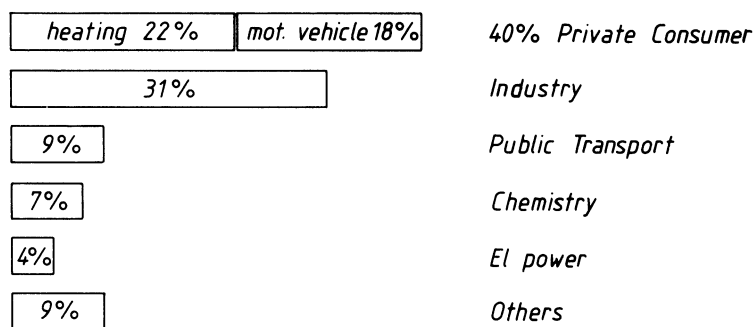


Fig. 3. Consumers of Petroleum in the FR-Germany 1979

Everybody knows lately since the second petroleum chock in this year that petroleum is not only expensive but also scarce. The last world energy conference brought new data about availability and consumption. If we allow the energy stock in the form of mineral resources to be 100 %, than we have 41 % in form of coal and 54 % uranium, but only 5 % petroleum and naturalgas (Fig. 4).

If we extrapolate the consumptions up to the year 2000 (not taking into consideration how political influences and changing thought of consumers habits affects the curves course), only petroleum and naturalgas consumptions would make up 70 % of all energy-carriers from the soil (45 + 25). There is an extreme disproportion between stockage and consumption. As a result of this, 61 % of the source of petroleum and 54 % naturalgas would be consumed up to the years 2000 .

Contrary to this, hardcoal and uranium will lose only 1,7 and 0,6 % of their stockages up to this time. Therefore reason favours the greater usage of coal and nuclear energy. Coal will be used more and more in that degree as it is transformable to liquid and gaseous substances, easily handled like petroleum

and naturalgas. Besides this, enviromental friendliness will play an important part.

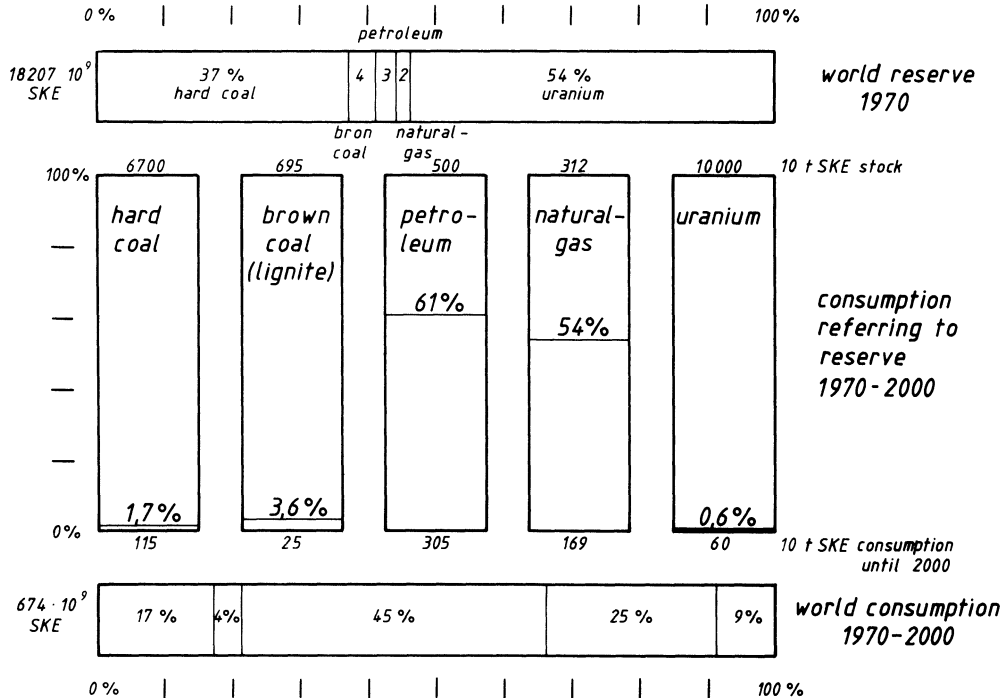


Fig. 4. World reserves and consumption (1)

The world wide spread of coal stockages (Fig. 5) serves coal supply without great problems of transportation all over the world. Applying suitable refining processes fitted for each coal type we can use coalproducts like gas, oil, coke, heat and electricity everywhere globally. Although this picture looks so favourable not all coaltypes are of equal quality. Coals of various behaviours are required in the refining processes. And coals differ in type, because the original composition is different according to climate and in the world which for million of years have been different.



Fig. 5. Coal deposits of the world (2)

Quality characteristics of coal

Coal is a mixture of organic and mineral substances. It originates mainly from dead plants. This material is enriched in carbon content and becomes lacking in hydrogen and oxygen in the absence of air-oxygen, with increasing time, at high temperature and under the pressure of the overlying layers.

The so called period of "coalification" was the first conversion, a "wood-conversion". It yields a series of young to old coals, for instance peat, brown coal and hard coals with high and low content of volatile matter. (Fig. 6)

COALIFICATION SERIES	SPEC. WEIGHT T/M	HEATING VALUE KJ/KG	WATER CONTENT %	VOL. MATTER % WF	H %WF	O %WF	C %WF
WOOD	0.2-1.3	14 x1000	(DRY)	80	6	44	50
PEAT	1.0	14 - 20 x1000	60-90	65	6	34	55-65
SOFT-BROWN COAL	1.2	20 - 24 x1000	30-60	50-60	5	28	65-70
HARD-BROWN COAL	1.25	24 - 29 x1000	10-30	45-50	5	18	70-80
FLAMM-FETT COAL	1.3	29 - 33 x1000	3-10	17-45	4	17	80-90
ESS-MAGERKOHLE	1.35	33 - 35 x1000	3-10	7-17	3	5	90-93
ANTHRACIT	1.4-1.6	35 - 37 x1000	1- 2	4- 7	2	2	93-98

Fig. 6. Coalification series

Hard coals have an important property for thermal refining processes: beyond approx. 350°C they liberate gases and tars, most of them being softened and forming cake or agglomerated cake. Beyond 550°C and after a certain degasification time the coalmass is solid (coke) hardening up to 1000°C and liberating gases. Also around 1000°C there is an important temperature for converting processes, especially combustion because of its ashcontent and the composition of ash, that melts at this temperature.

Fig. 7 shows the softening behaviour of 3 different coals. In the case of "Gaskohle" we can see a first period of flowing (Contraction under 420°C) and a second of blowing up, originated from the devolatilization (Dilatation beyond 420°C).

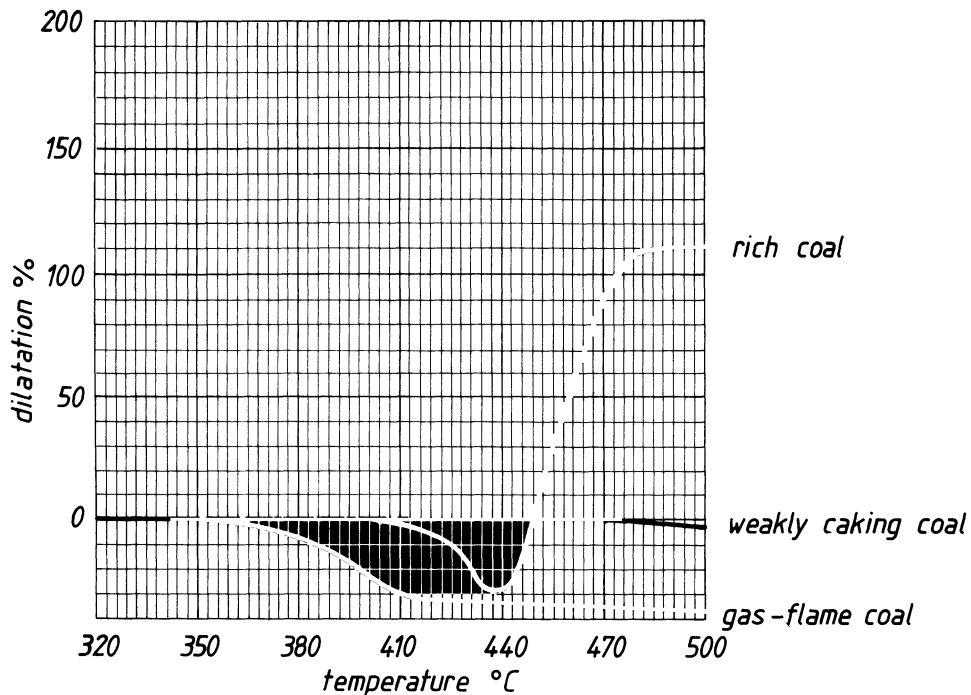


Fig. 7. Dilatation and contraction of hard coal over temperature (3)

Refining processes and products (Fig. 8)

process	product	competition
screening + moulding	coal fine grained coal briquette pellet	
combustion	electricity heat	electricity from nuclear e. heat from nuclear energy
carbonization	lumpy coke fine grained coal formed coke gas hydrocarbons	converted natural gas in iron-ore-processes
liquefaction	oil gas extract	petroleum
gasification	syntheses gas methan hydrogen	natural gas

Fig. 8. Coal refining processes and products

Coal has always been refined. Today refinement starts with purification of crude roughcoal, too: separation of accompanied stones, division into poor ashed coal, rich ashed coal and stones. For different applications we need different sizes of coal. Coal is grinded or coarsened. For the second case a briquetting or pelletizing process is applied. A new method is hot briquetting and hot pelletizing, making use of the coals softening behaviour. The most significant refining process today is coal transformation to electricity as an energy carrier or coke as a reducing agent in iron production. Competing with coal, but in cases also supplementary processes, are nuclear-power stations with their electricity- and heat - products. For iron production there is a competing process, whereby ore is reduced by the converted natural gas.

A further, yet here undescribed field of coalrefining is special coke manufacturing: porous finecoke as a filter aid, coke granulates with a large internal surface as an absorbing agent (activated carbon) and granulated coke with a defined porous radius for gas purification (molecular sieve).

For the future however, the most important are, as described, liquefaction and gasification of coal. Today petroleum and naturalgas are viewed as competitors of coal. For the future they have given scales being easily handy, unlike coal. Fluid products of coal vary from heavy to light hydrocarbons also produced from petroleum by cracking and distillation.

Solid, liquid and gaseous products have always been supplied from the coke oven process, where easily 50 % of hard coal has been refined hitherto. We manufacture out of 1000 kg coal about 775 kg coke, 180 kg gas (365 m³), 30 kg tar, 10 kg benzene and 2 kg ammonia.

In the future quantities and qualities of coal products will be dictated by the market according to the customs with the fuel today. And so, liquification and gasification of coal have to enlarge the number of coal refining methods again. Again, for there are already old processes, which we have only to improve.

Advanced processes will be objects of discussion in the following lectures:

- Gasefication with steam and hydrogen,
- Liquefaction by hydrogenation or gas-synthesis,
- Carbonization to lumpy, fine grained or formed coke,
- Combustion in the fluidized bed by normal and elevates pressures.

Advanced technologies

Thermal coal refining is almost a process with the participators, solid and gaseous materials. The solid material is coal or coke, the gaseous either degasification product of coal or a gaseous reaction's partner. Such a process consists of carbonization, gasification and combustion.

Chemical engineering knowledge offers three possibilities

for such processes, as illustrated in Fig. 9: fixed bed, fluidized bed, entrained bed.

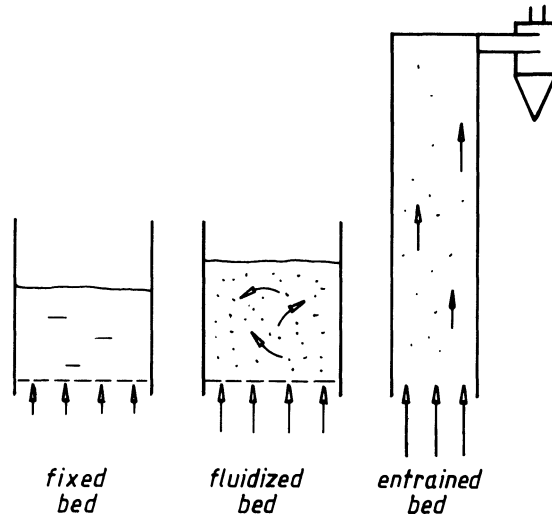


Fig. 9. Technologies for contact of solid and gas

There are two methods of coal liquefaction:

1. Hydrogenation of coal with molecular hydrogen or a hydrogen-enriched solvent
2. Gassyntheses with catalysts after gas-production by gasification

Figure 10 shows the way of coal conversion to gasoline using both above mentioned methods.

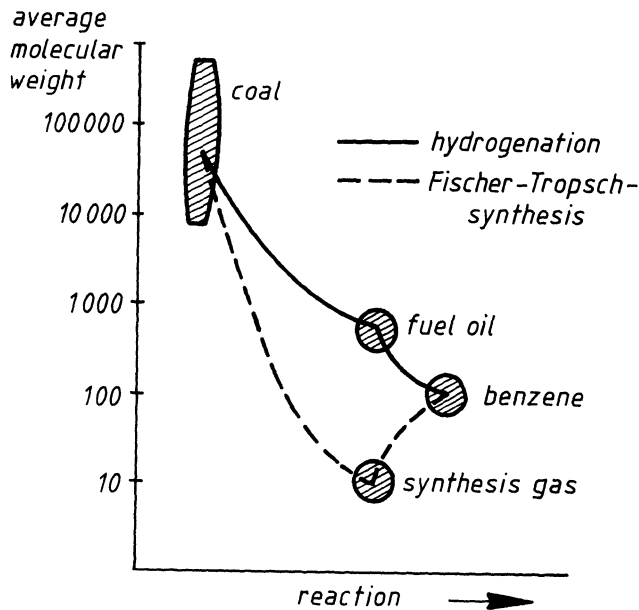


Fig. 10. From coal to benzene via hydrogenation and synthesis (4)

CARBONIZATION

Coal, coke and gases

Carbonization is coal degasefication, that is the delivery of the so-called "volatile matter" (v. m.). Carbonization products are the outgased coal (char) and a gas mixture of high and low boiling hydrocarbon compounds and some other components like oxygen, nitrogen and sulfur.

The motive force of carbonization is heat, being applied until reaching a high temperature of about 1000 °C. Coal is thereby subjected to series of chemical and physical reactions termed "pyrolysis" all together. Coal with high contents of oxygen like lignite form herewith many oxygen-compounds as carbonmonoxide and carbondioxide. (Fig. 11)

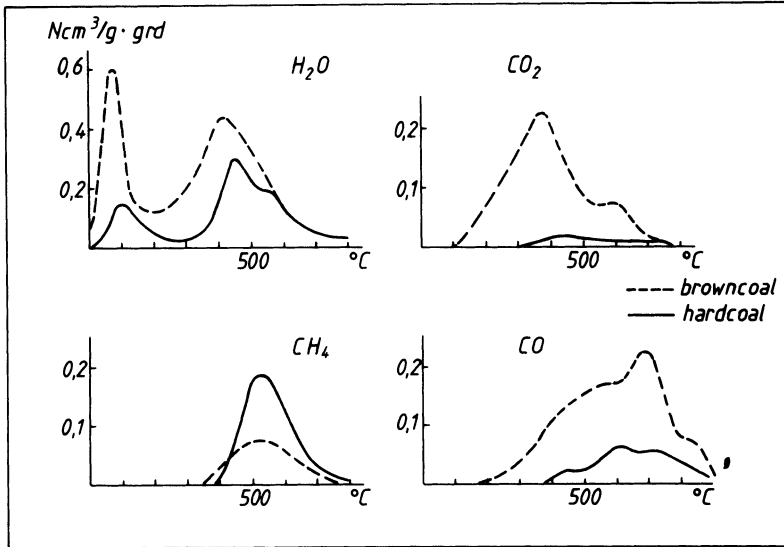


Fig. 11. Formation of different gases from degasing browncoal and hardcoal (17)

Within the hard-coal-series the tar output increases understandably according to the amount of volatile matter and at the same time the coke-output decreases. (Fig. 12)

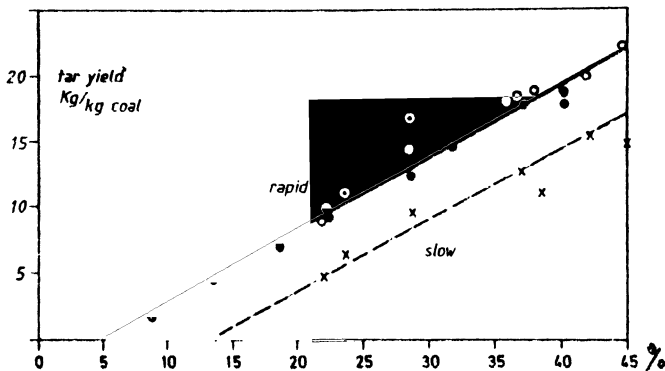


Fig. 12 a. Tar-yield dep. on content of vol. mater in rapid and normal carbonization (5)

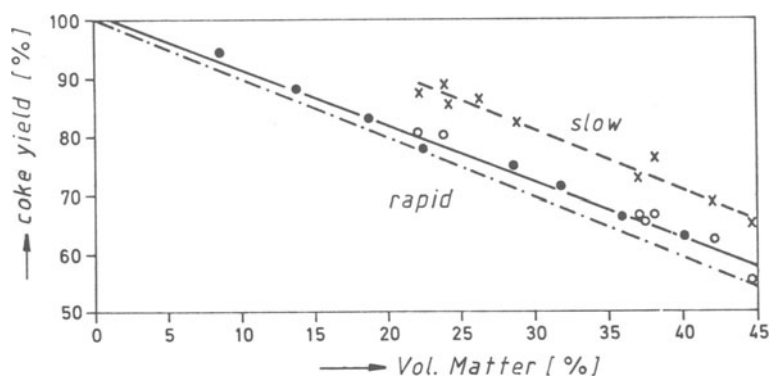


Fig. 12. Coke-yield dep. on content of vol. matter in rapid and normal carbonization (5)

The heating up velocity has a great influence on pyrolysis. In the coking chamber furnace a heating-up-rate of around 3 °C per minute can be achieved, but in a quick-carbonization a rate of up to 10000 °C per minute. The latter yields a large quantity of tar. This, when coal is slowly heated, liberates many gases.

Volatile matter and heat-up-velocity strongly influence the cokes quality. (Fig. 13 and 14)

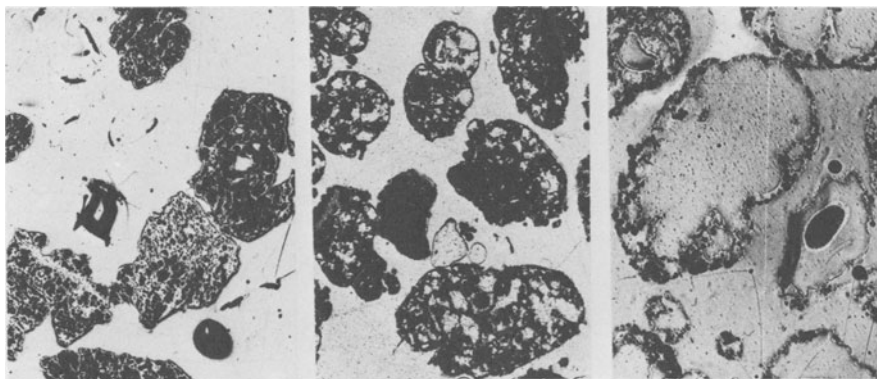


Fig. 13. Pore formation of fine grained coke dep. of heating rate (Vol. matter 22,3 %) (6)

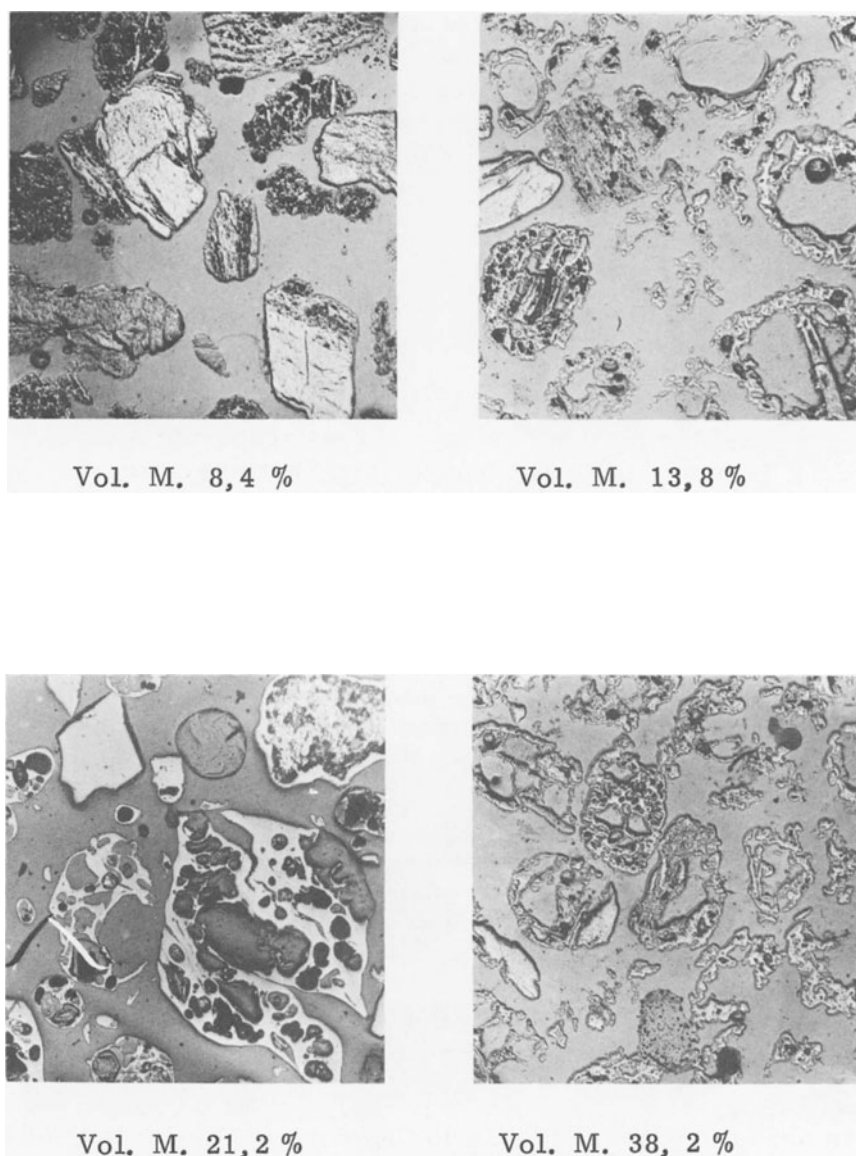


Fig. 14. Pore formation of fluidized bed coke, dep. on the content of vol. matter of the coal (7)

Heating quickly means normally heating single grains by gas or a solid heat carrier. By the possibility of free expansion porous cokegrains originate directly from coalgrains under the inner pressure from the quick escaped gases. Heating slowly is practised in an indirect heated coke chamber or in a flash gas oven. The coke oven process uses the good softening and caking conditions of the so called "medium volatile coking coal" in shaping irregular broken pieces. In the flash gas oven only non coking coals are carbonized, heated by a circulating hot gas.

Principles of carbonization

The most realized principle to date is the indirect heating of a coal bed within the closed walls of a coke chamber. (Fig. 15 above)

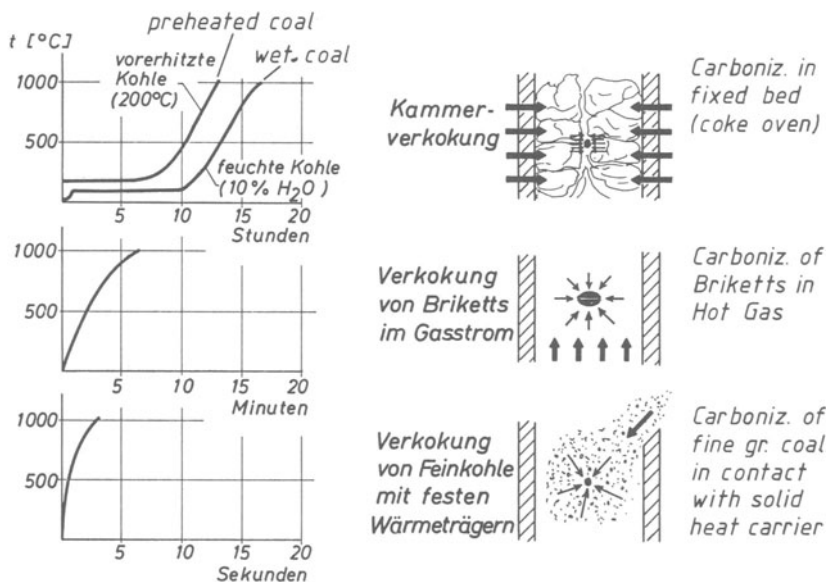


Fig. 15. Trend of Temperature in different carbonization processes

An opposite process to this is the quick carbonization and conversion to fine grained coke by gaseous heat carrier in an entrained bed, by a solid heat carrier in a solid-material-rotating-process or by a solid and gaseous heat carrier in a fluidized bed-process. (Fig. 16)

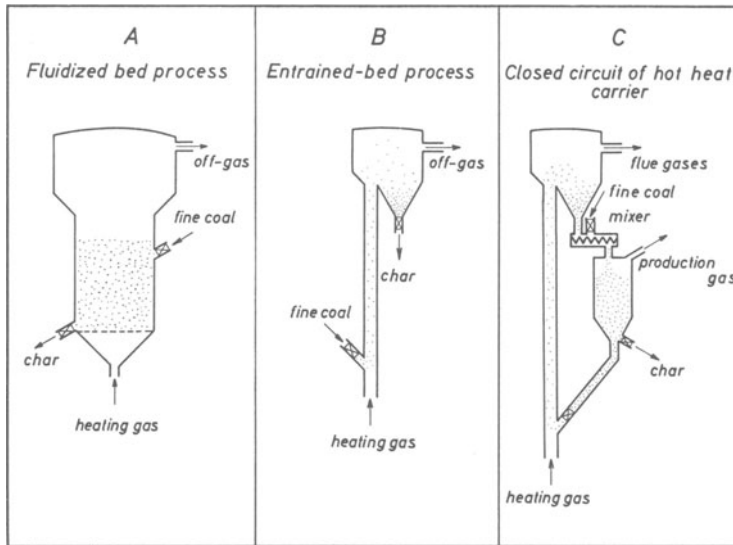


Fig. 16. Processes for production of fine grained coke (rapid carb.)

The differences between heating up and carbonization among these processes are connected to differences in products: lumpy coke and fine grained coke. From the latter moulded cokes are formed. And there are differences in coal bases: caking coals for lumpy coke, non caking coal for fine grained coke or formed coke.

Production of lumpy coke

The chamber oven process, well - known since the beginning of the 19th century, has been improved during the last few years. A higher coal charging rate was achieved by using more solid stone materials of increased thermoconductivity in building thinner chamberwalls and by performing enlarged furnace rooms. In all these the preheating of coal charge played a very significant part. (Fig. 17)

Regarding enviromental pollution exhausters for the filling process and central cooling plants for hot coke were installed.

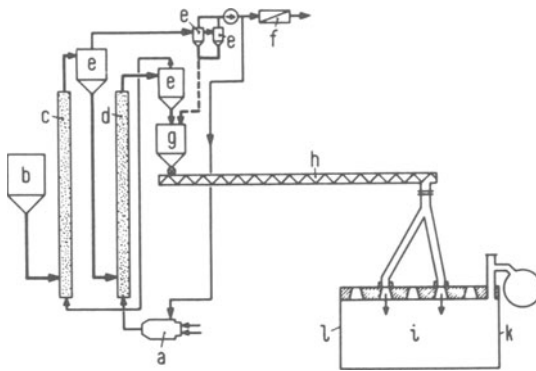


Fig. 17. Flow sheet of "Precarbon-Process" for preheating coal to coke even (8)

Production of fine grained coke

Examples of fine-coke-production according to the three above mentioned principles are:

- the fluidized bed carbonization and the LR-solid heat-carrier process as processing steps used in formed-coke-experimental plants of Bergbau-Forschung
- the entrained bed process of Bergbau-Forschung (Fig. 18)

In all cases fine grained coke is obtained direct from fine grained coal. However a caking of the grains to agglomerates is unwanted and must be prohibited.

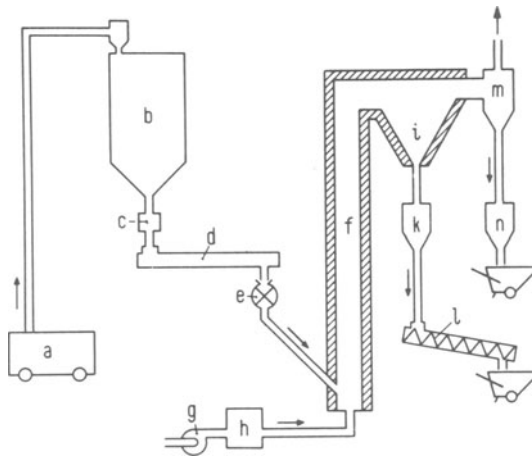


Fig. 18. Devolatilization of fine grained coal in an entrained bed process (8)

Production of formed coke

Reasons for the production of formed coke are to be found in the intention of having a widespread coal basis, a improved heat-transfer and the production of an improved blast-furnace-coke. The processing stages are usually predegasification of fine coal, its mixing with a binder, the moulding and the part degasification of the formed pieces afterwards. (Fig. 19)

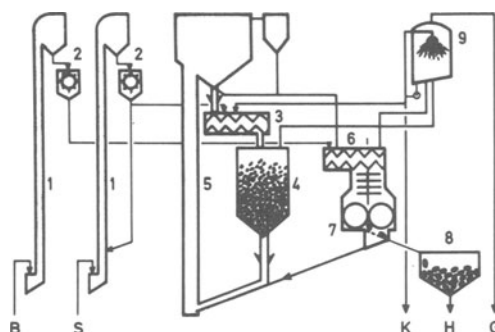


Fig. 19. Scheme of BFL-plant "Prosper" for the production of formed coke with LR-charmaking (5)

In many experimental plants predegasification is practiced by entrained bed heating or in contact with a solid heat carrier or in fluidized bed carbonization. The forming process is a briquetting or pelletizing step. And the part degasification afterwards takes place in flashgas or in contact with a solid heat carrier. Fig. 19 + 20 show flowsheets of 2 plants of Bergbau-Forschung for the production of hot-briquettes by different manners of making char.

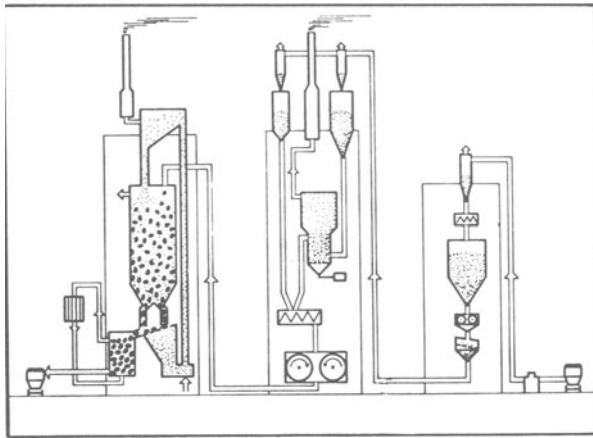


Fig. 20. Scheme of BF-plant for the production of formed coke with fluidized bed char making (7)

GASIFICATION OF COAL

Gas from coal

Since the beginning of the industrial age coal has been source of energy production and a feedstock for chemicals. Starting in the 30's first oil and then natural gas came into the market and are still dominant today, although in some countries coal is still the basis for energy. (Fig. 21)

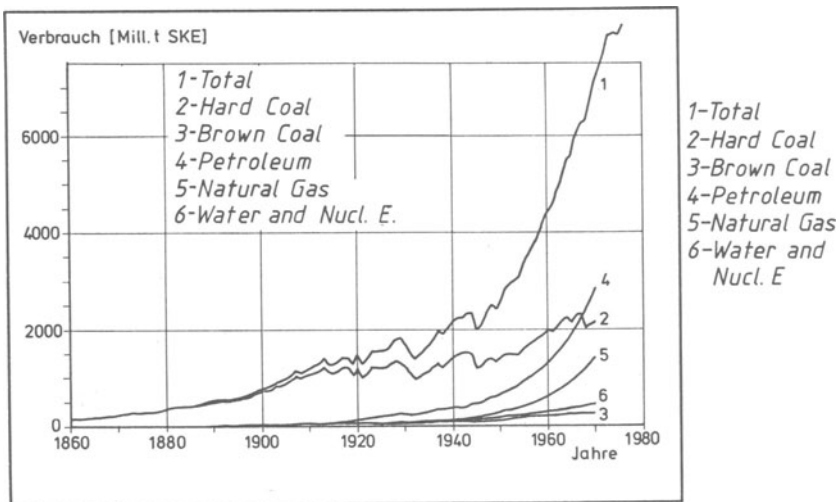


Fig. 21. World consumption of energy carriers (9)

In the field of secondary energies gas has a lot of advantages: low emissions to the environment during utilization, economic transmission and distribution, possibility of storage and many-fold uses.

The extent to which the private energy consumer values easy to handle fuel, becomes evident in data from West-Germany, which are shown in Fig. 22.

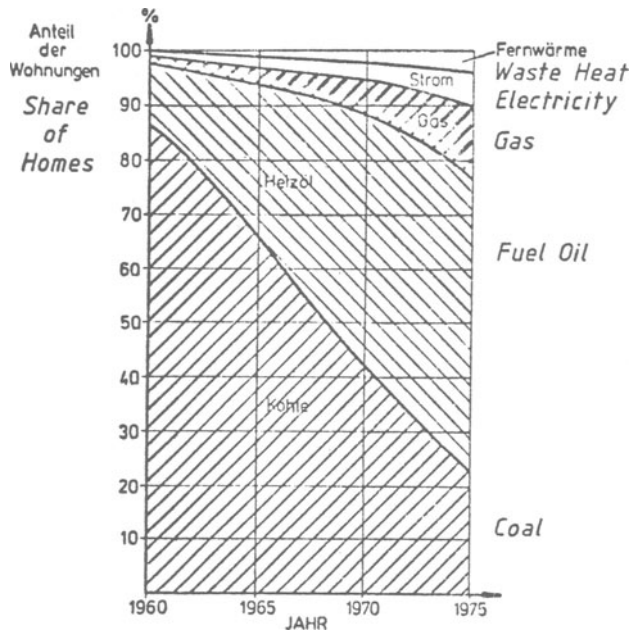


Fig. 22. Energy for room heating (9)

According to that figure coal consumption for heating rooms diminished from 86 % to 22 % between 1960 and 1975 meaning a decrease to a fourth, while the consumption of fuel oil and gas increased from 11 to 54 % and from 2 to 12 %, a five to six fold increase.

During the energy crisis in 1973 the private consumer did not change the fuel basis on account of the technical difficulties, while the industrial consumer was able to use more coal instead of oil.

Fig. 23 shows, that at this time oil consumption of the industry was significantly reduced in contrast to coal consumption.

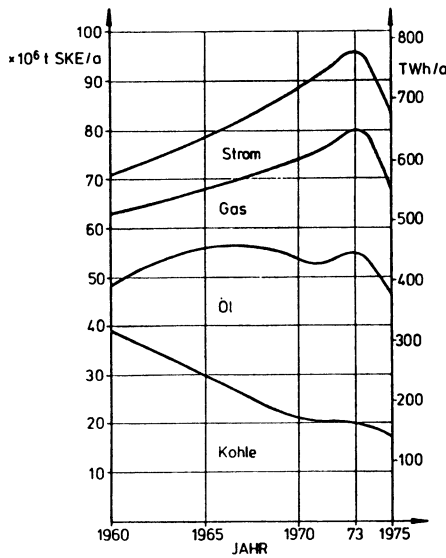


Fig. 23. Industrial consumer during energy crisis (9)

Fig. 24 gives an impression of transport costs, comparing that of fine and briquetted brown coal with current (usually won from brown coal) and methene, the main component of natural gas. We can see, that the transport costs of gas, related to enthalpy, lie far below that of current.

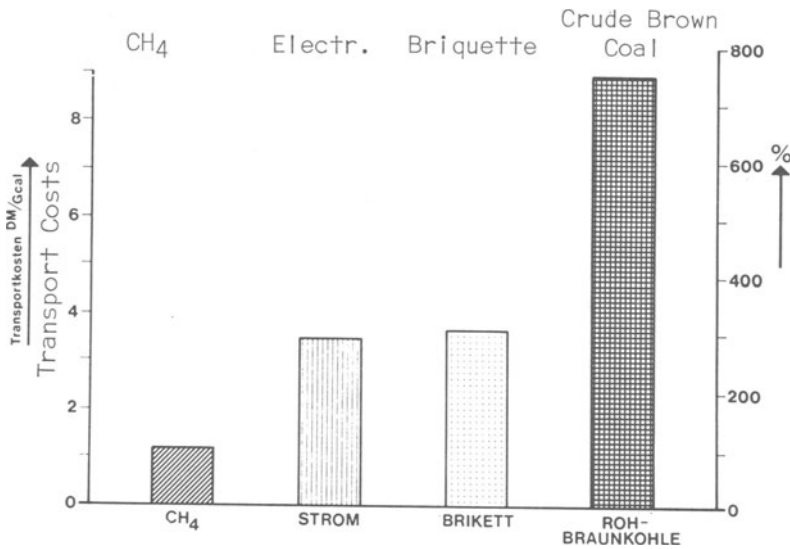


Fig. 24. Cost for transportation of 1 Gcal over 100 km (1)

Regarding these aspects the manufacture of gas from coal by gasification if possible in combination with nuclear reactors seems to be very attractive and can play an important role in future energy technology worldwide .

Gascomposition and -utilization

If we want to develop new technologies of attaining gas from coal, it is necessary to consider some gases on the market and to compare them with each other. (Fig. 25) Industrial and private consumers today have at their disposal mostly the low caloric gas from blast furnaces, the degasification product of chamber oven and natural gas.

While blast furnace gas, because of its low calorific value is only used by direct consumption in power stations or for air preheating, the other two gases conveyed in pipelines and used by consumers for many heat and power processes. Gases from coke oven and natural gas are suitable for chemical refining processes, because they contain appreciable concentrations of hydrogen and methane. Special gases for this purpose are synthesis and reduction

gas, attained by special gasification processes. They contain large quantities of carbon-monoxide, hydrogen or methene.

	Schwachgas	Wassergas	Synthese- oder Reduktions- gas	Luigi- Ruhrgas	Koppers- Tolze	Stadtgas	Erdgas	Gasart
CO	29	40	12	55	5,5	—		Zusammen- setzung analysis
H ₂	10,5	50	43	30	54,5	—		
CH ₄	—	—	11,5	0,1	25,3	87,5		
CO ₂	5,5	5	32	13,2	2,3	3,1		
N ₂	55	5	0,3	1,4	9,6	0,6		
%	%	%	%	%	%	%		
4600...12500, KJ/Norm m ³		ca. 12500		16700... ...20000		25000... ...37000		Heizwert caloric value
Low Calorie Gas	Gas for synthesis		Gas for reduction	Gas from coke oven	Natural Gas			

Gases for heating, power station, and synthesis, Gase für Heizung, Kraftwerk und Synthese

Fig. 25. Analysis and caloric value of gases for heating, power station and synthesis

The fundamental reactions of gasification

Gasification is the reaction between the solid organic materials and a gasifying agent, in which coal is completely converted to gas leaving the ash. Although coal has a very complex molecular structure it is possible to discuss the basic reactions regarding only carbon. Fig. 26 shows four primary reactions between the solid and different gasifying agents and two secondary reactions which occur between the gases formed and the gasifying agent in the gaseous phase. In existing gasification processes steam is of utmost importance. Its reaction with the carbon leads to CO and H₂ and is strongly endothermic.

		ΔH	
		Kcal	% of heat of
		mol	combustion
<i>Primary reactions:</i>			
Water gas reaction	$C_{solid} + H_2O_{steam} \rightarrow CO + H_2$	+28,3	29 endo.
Boudouard reaction	$C_{solid} + CO_2 \rightarrow 2CO$	+38,3	40 endo.
Partial combustion	$C_{solid} + 1/2 O_2 \rightarrow CO$	-29,4	30 exo.
Hydrogasification	$C_{solid} + 2H_2 \rightarrow CH_4$	-20,9	22 exo.
<i>Secondary reactions:</i>			
Shift reaction	$CO + H_2O_{steam} \rightarrow H_2 + CO_2$	-10,1	14 exo.
Methanation	$3H_2 + CO \rightarrow CH_4 + H_2O_{steam}$	-49,2	51 exo.

Fig. 26. Basic reactions of coal gasification

Another gasifying agent is CO_2 , which interacts with the solid carbon in the so-called Boudouard reaction to give CO . It is even more endothermic than the water gas reaction and plays an important role for instance in the blast furnace, but is of minor meaning for technical gasification. The reaction of carbon with oxygen, the combustion, also can be summarized under gasification. Specially the partial combustion $C + 1/2 O_2 \rightarrow CO$ which is exothermic is used in combination with the water gas reaction to fill the heat requirement. Finally the reaction of C with H_2 leads to CH_4 , this reaction is exothermic and is a fundamental process in new developments of coal gasification with respect to SNG production. As secondary processes, in the gaseous phase there are the shift reaction in which CO and H_2O react to H_2 and CO_2 and the methanation reaction in which H_2 and CO are converted into CH_4 and steam to be mentioned. Both are exothermic and play an important role in technical gasification reactors and in processing steps of the raw gas as shown afterwards.

The composition of the produced gas depends upon the processing steps and conditions which are chosen corresponding to its end use. Gasification with steam is strongly endothermic and that with hydrogen exothermic. In the former case mostly hydrogen and carbonmonoxide are produced, suitable for the reduction of iron ore and synthesis in the chemical industry. The latter leads almost to methane the basic component of natural gas, used specially for heating purposes.

Fig. 27 gives values of gas analysis at thermodynamic equilibrium depending on temperature at a pressure of 1 bar and pressure at a temperature of 800 °C as calculated by thermodynamic rules for steam gasification.

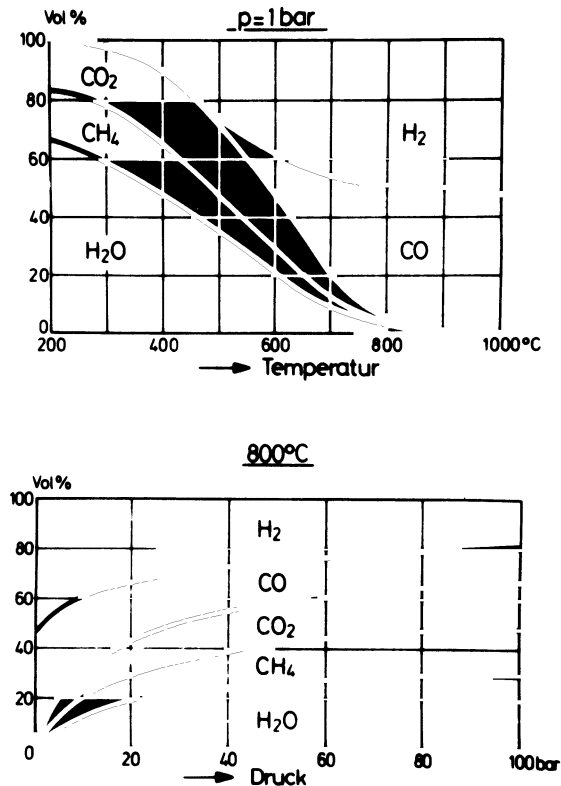


Fig. 27. Equilibrium of gas from steam gasification (11)

Principles of gasification technology

For energy production in future steam gasification and the gasification with hydrogen - hydrogasification - will be important, whereby the first one is a basic process as schematically shown in figure 28.

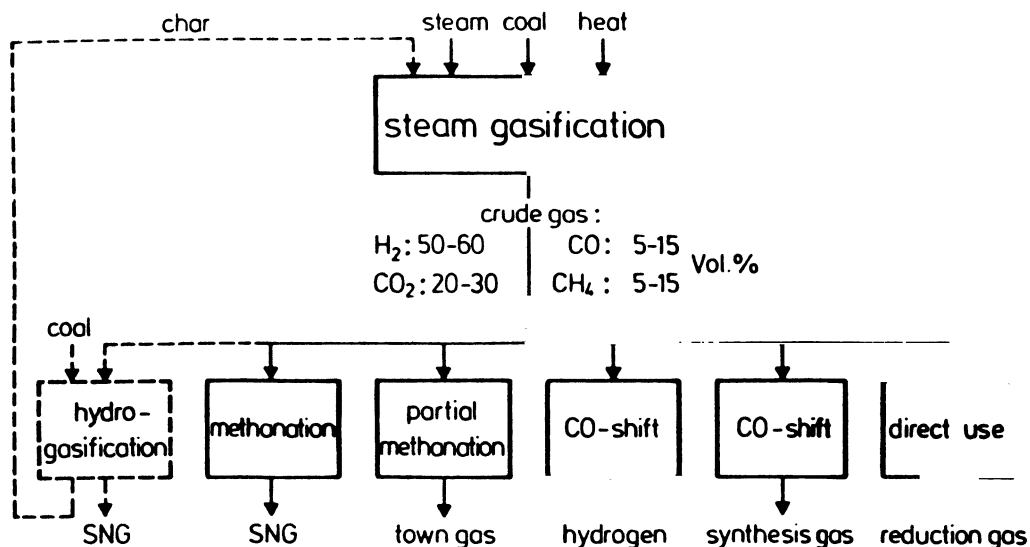


Fig. 28. Processes and products of coal gasification (12)

Steam and coal react in a strong endothermic process at temperatures above 750°C , whereby the organic part of the coal is transformed to a crude gas which is rich in hydrogen but contains also CO , CO_2 , and CH_4 . The crude gas after cleaning can be used either directly for instance as reducing gas or by an adjacent combustion for clean energy production. It also can be transformed by well known processes to synthesis gas, hydrogen, town gas or to CH_4 , as a substitute natural gas (SNG). For the latter purpose two ways are possible: methanation or more advantageously hydrogasification as will be shown later on.

Steam gasification of coal is a well known technique which has been performed world wide on an industrial scale in many variants. As shown in figure 29, in conventional processes the heat requirement of the endothermic reaction is supplied by burning part of the coal in the gasifier with oxygen. Additional coal has to be burned in a power plant for the production of the steam and electricity needed in the process. The concept of nuclear steam gasification has the aim to use a high temperature nuclear reactor (HTR) as a heat source to supply the heat needed in the gasifier, for steam production

and for other requirements of the plant.

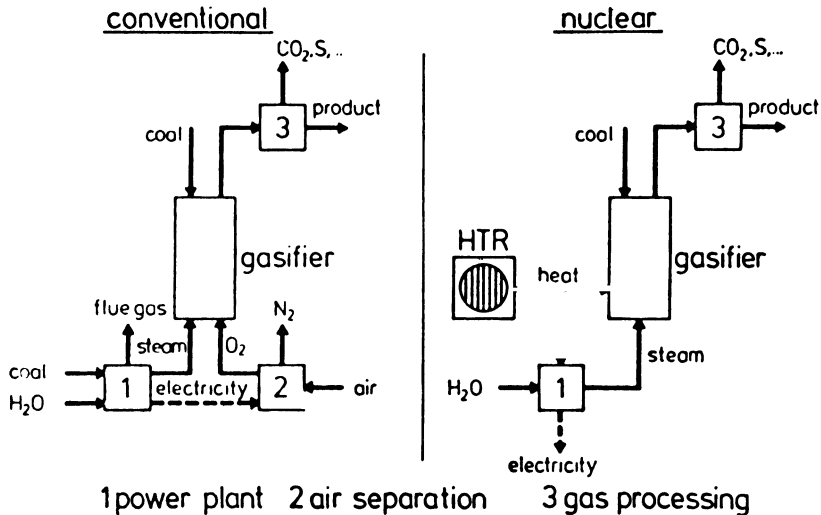


Fig. 29. Conventional and nuclear steam gasification of coal (12)

Thus coal only serves a raw material for the gas to which it is transformed optimally and no oxygen is needed.

Figure 30 shows simplified flow sheets for hydrogasification which is an exothermic reaction. However, heat is needed for the production of hydrogen. There are two possibilities for its production. The first one corresponds to the conventional processes which are under development especially in the USA.

As shown on the left a hydrogasification is combined with a steam gasifier so that the residual char from the hydrogasification is used for the production of hydrogen in the steam gasifier. This combination is attractive as the reactivity of a char against hydrogen decreases strongly with the burn off so that the total char cannot be gasified in the hydrogasifier.

The reactivity of this char against steam, however, is very much higher than that against hydrogen resulting in an economical use of the char in the steam gasification. Nuclear heat can be used in this process replacing conventional steam gasification as shown in the previous picture.

The second possibility to use nuclear heat is shown on the right: The CH_4 formed in the hydrogasification step is partly used as SNG and partly fed to a methane reformer in which it is converted into H_2 and CO by a catalytic steam cracking, whereby the heat necessary for the reaction and steam production is supplied by the HTR. The hydrogen, possibly after a cleaning, is fed to the hydrogasifier where it reacts with the coal. The residual char has to be used for other purposes.

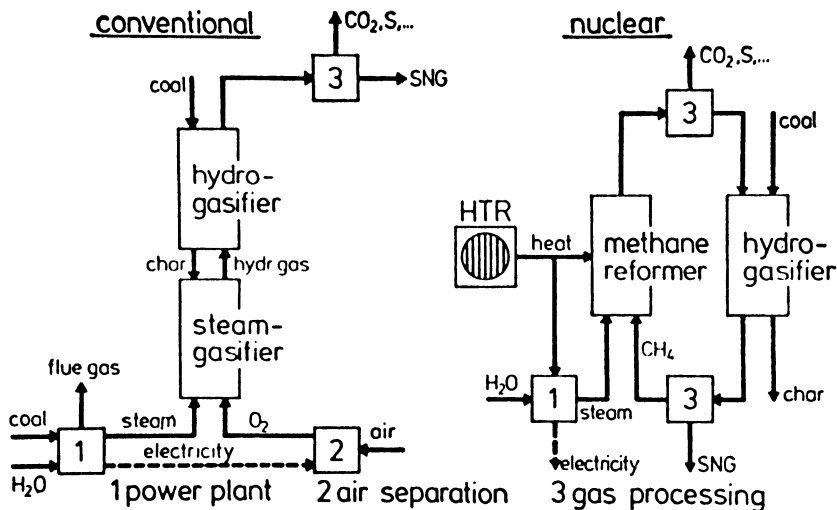


Fig. 30. Conventional and nuclear hydrogasification of coal (12)

Developments

Frequently the chemical engineer is confronted with installing processes whereby a solid material reacts with gas while heat must be added. This is the case in the gasification process with steam.

Figure 31 shows five of these variants. The first has long been known as autothermal process: heat is produced by partial combustion of coal with oxygen within the layer. There coal is not fully gasified, but also undergoes a combustion. Therefore the process gas a mixture of gasification and combustion gas.

The other processes do not derive heat from coal, but from other sources. In the cases 2 and 5 heat is indirectly transferred from reactor walls or immersed tubes to the layer. The last process (5) illustrated corresponds to a concept of waste heat transfer from nuclear reactor to a gasifying fluidized bed. The third case is the so called "circulation of solid heatcarriers": coke is heated during back feeding from the plant's base to the top and delivers the heat necessary for gasification while adding to the feed coal. In the fourth case it is the gas which is delivered back and heated again.

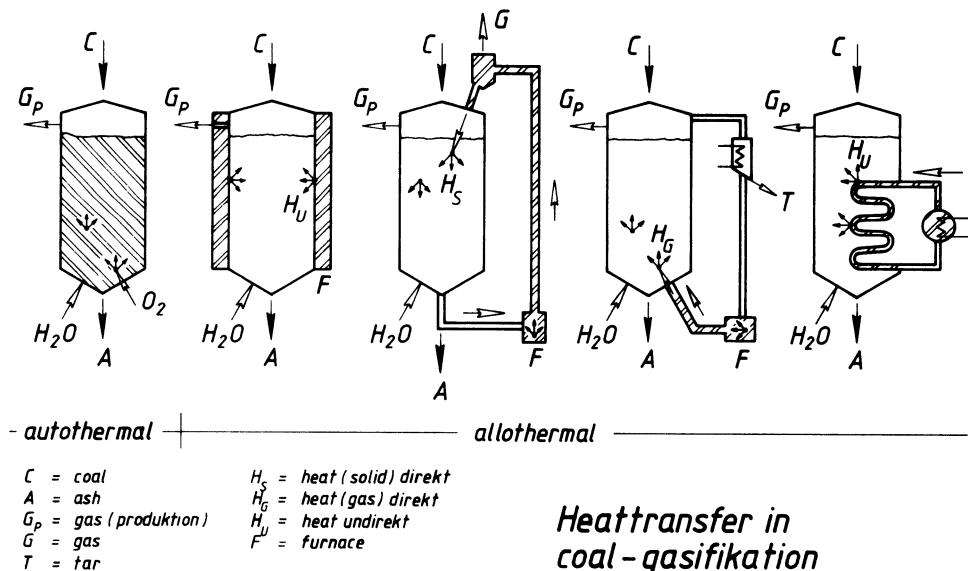


Fig. 31. Heattransfer in coal gasification

Variants of autothermal gasification are illustrated in Figure 32. There are three possibilities of reaction between solid material and gas, as they are handled in combustion and many other processes: fixed bed, fluidized bed and entrained bed. The additionally temperature and velocity curves make it obvious, that fluidized bed is operating at middle and relative constant values. Very high temperatures exist in entrained bed processes, low re-locities in the fixed bed.

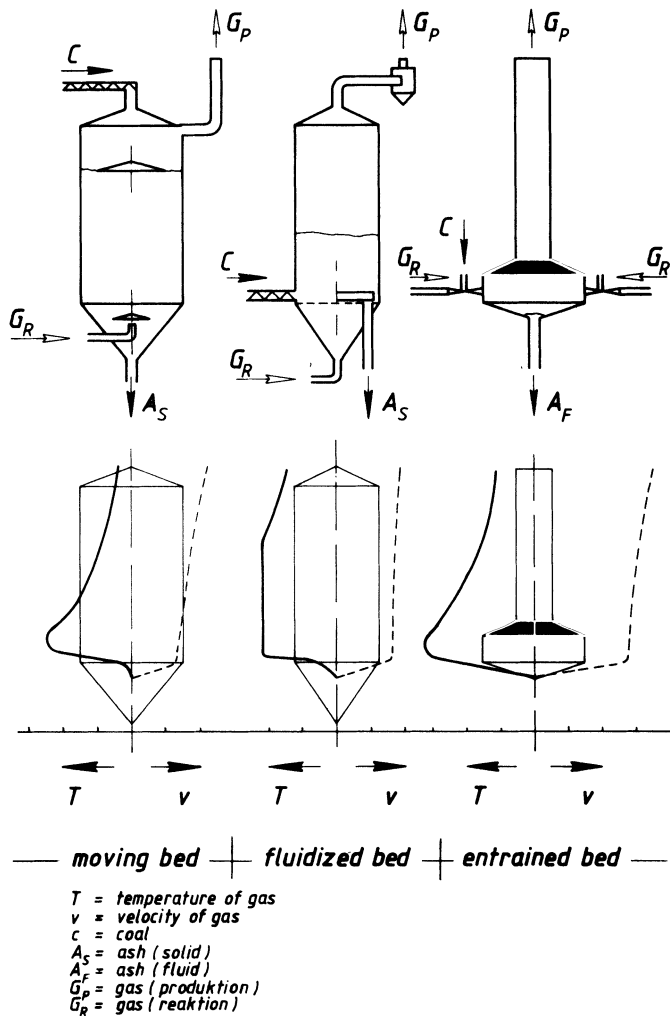


Fig. 32. Process for steam gasification of coal

Examples of technical plants according the mentioned principles are shown in Figures 33 to 36.

Fixed bed with gasification- and combustion-gases flowing through the filling; outlet of gasification gas on the left; that of devolatization on the right. (Fig. 33)

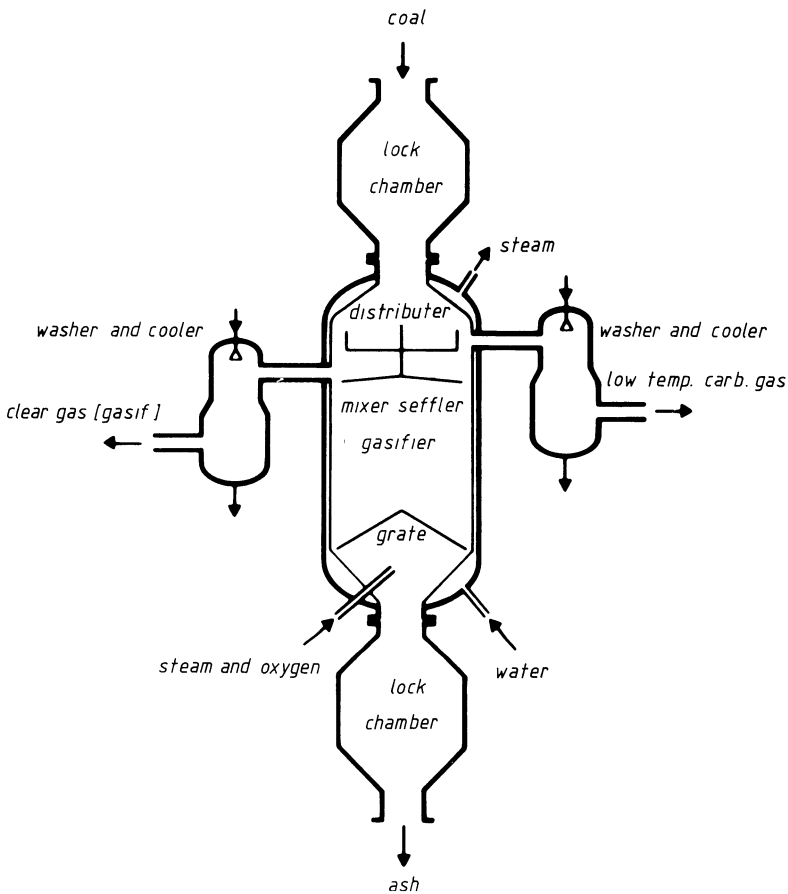


Fig. 33. Lurgi - pressure - gasification (13)
(Typ Ruhr 100)

Fluidized bed plant with up-whirling of the layer by gasification and combustion gases; feeding gases and coal from the right; recycling of discharged coke on the left. (Fig. 34)

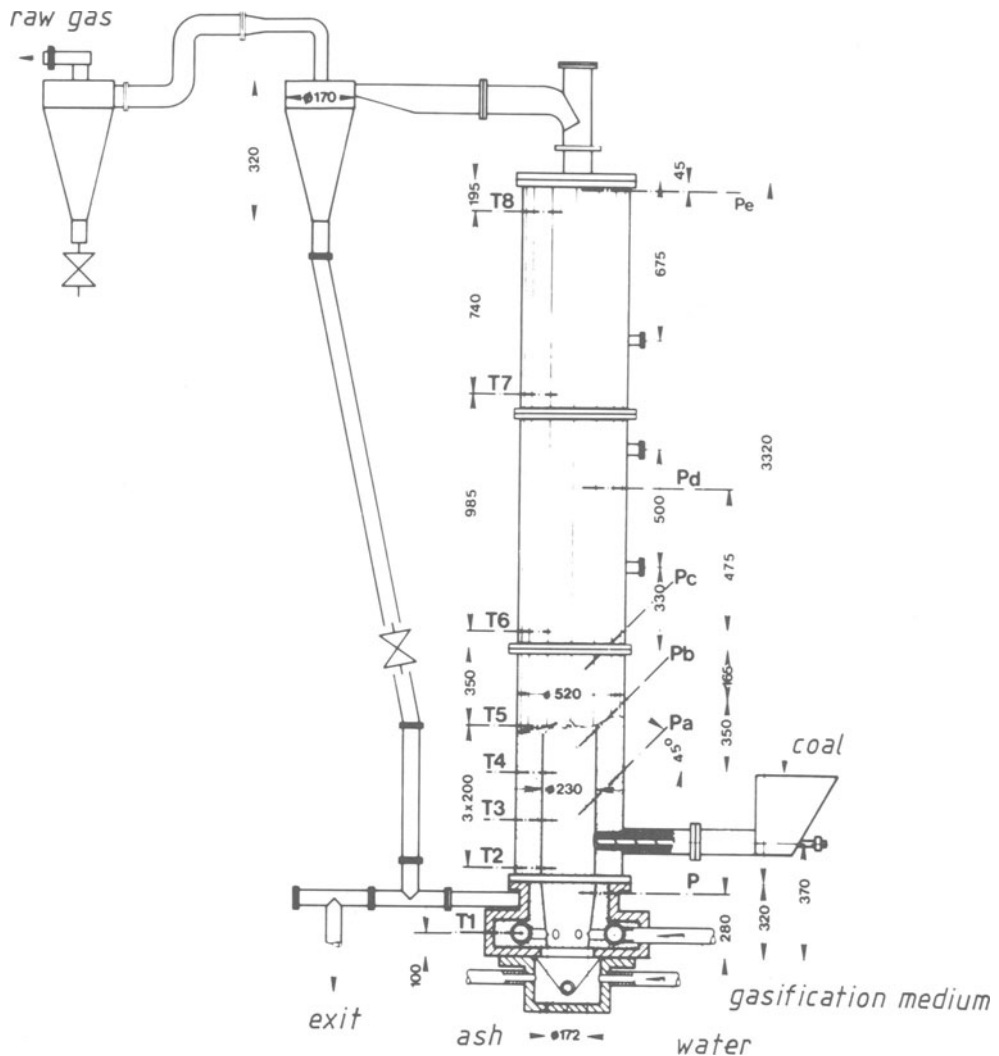


Fig. 34. High temperature Winkler fluid bed gasifier (14) (Rheinbraun)

Entrained bed with transporting stream of gasification- and combustion-gas; coal blown-in downwards inclined in a swamp of slag; the highest temperature in the swamp; outlet of liquid slag at the bottom; gasification reaction during transport in the overlying pipeline. (Fig. 35)

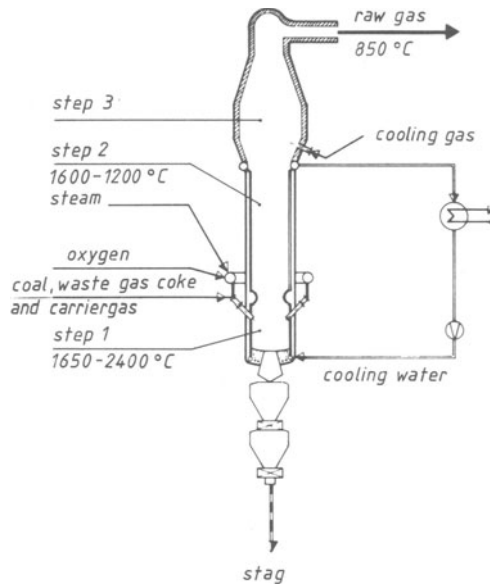


Fig. 35. Entrained bed gasifier (15)
(Saarberg, Otto)

Fluidized bed exclusively whirled up by means of gasification; heat supply by heat exchange tubes. (Fig. 36)

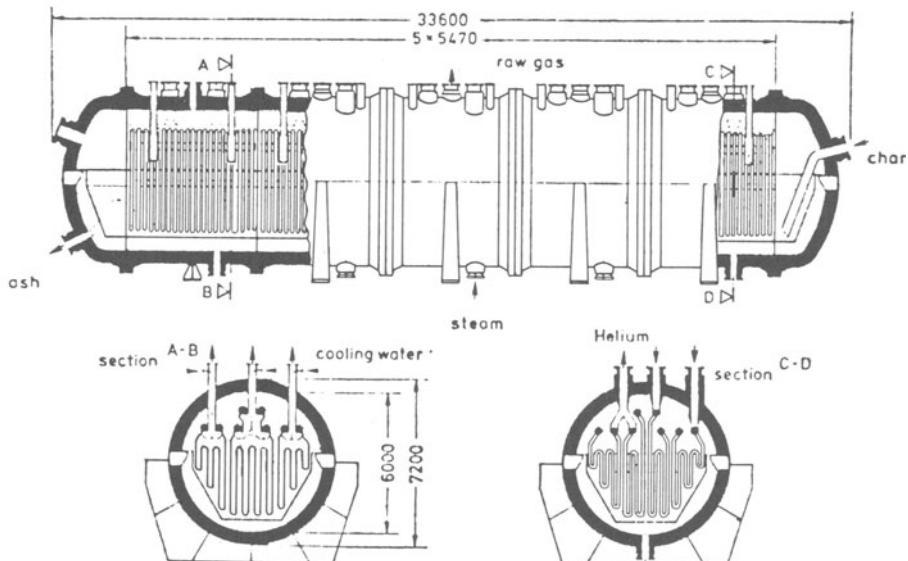


Fig. 36. Fluidized bed gasifier for nuclear heat (12)
(Bergbau-Forschung)

Production costs

Figure 37 summarizes an estimation of SNG- and H_2 -production costs. Naturally SNG-cost is more dependent on the cost of coal in the case of conventional gasification. For today's hard coal costs in Western Europa, of about 20 DM/Gcal, a reduction in the gas costs of 30 % can be achieved. Moreover, the gas costs are in the case of nuclear gasification less depended on the costs of coal. Comparing SNG and H_2 it is expected, that the production of H_2 leads to lower prices. This is mainly due to the higher efficiency and the simpler gas processing in the case of H_2 production. (Fig. 37)

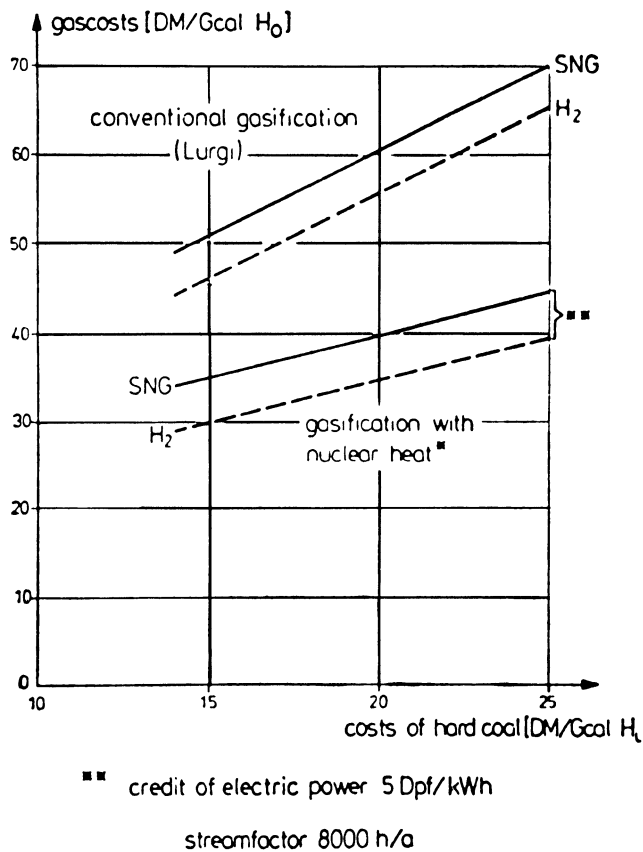


Fig. 37. Gas production costs (2)

COAL LIQUEFACTION

Coal contains liquid hydrocarbons. We set them free only by heat effects, just as gases and solid distillation residue with pitch. Such a process is called "pyrolysis". Liquid hydrocarbons make up only about 10 % of coal. That is too little for attaining liquids from coal in a quantity capable of substituting petroleum.

Coal and oil

Petroleum is easy to handle in consuming and refining much more so than coal. Coal really could never regain the petroleum market, if not for the view, that petroleum reserves will run short at the end of this century at this rate of consumption.

Figure 38 shows the expected mined quantities of coal and petroleum in the world. Because of the inequality of consumption and surces coal will have support petroleum until coal itself runs short, too.

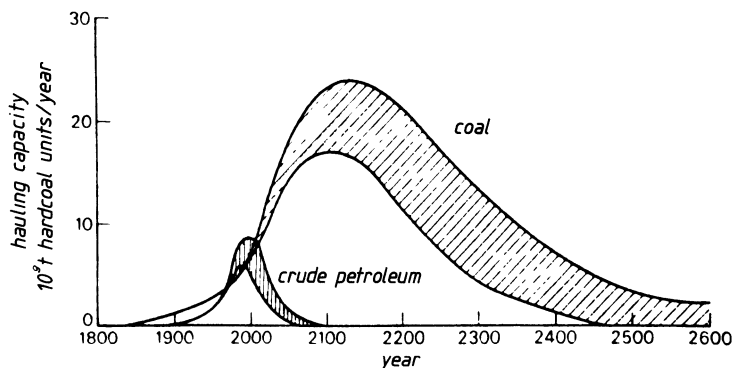


Fig. 38. Expected world production of coal and petroleum (4)

Today 0,3 million tonnes of liquid and gaseous primary products per year are made by gasification and synthesis at SASOL in South-Africa. 60 - 70 % of these products are motor fuels. From a new plant - SASOL II - we expect 2,1 million tonnes per annum. Coal mining is comparatively easy in South-Africa.

During the second world war Germany was cut-off from

petroleum-sources. Only 13 % of motor fuel was derived from handy petroleum (Fig. 39). In this energy situation 12 hydrogenation factories converted hard coal, brown coal or pitch as eligible raw materials to motorfuel in 1943. Hydrogenation yielded 2,9 million tonnes and 0,35 million tonnes were produced by synthesis.

HYDRATION	2,918 MIO τ	
SYNTHESIS	0,353 MIO τ	
DESTILLATION OF TAR FROM COKE OVEN	0,128 MIO τ	87 %
BENZOL FROM C.O.	0,355 MIO τ	
PETROLEUM	0,583 MIO τ	13 %

Fig. 39. Motor fuel production in Germany
in the world war year 1943 (4)

Fundamentals of Coal liquefaction

If we aim to produce hydrocarboncompounds from coal with its main constituent carbon we just have to add hydrogen to coal. There are tow ways of converting the solid material coal to the liquid material oil:

1. The direct way: decomposition of large coal molecules by adding gaseous hydrogen or a solvent composed of hydrogen. Coal-oil is produced and finally gasoline with a low-molecular weight.
2. The indirect way: coal conversion with steam and oxygen into a synthesis gas, that consists of carbon-monoxide and hydrogen; followed by synthesis to gasoline by applying pressure with a catalyst.

Influences on the composition of hydrogenation products are to be gathered from figures 40, 41 and 42. The contents of higher boiling liquids like raw benzine, middle oil and gaseous hydrocarbons increase with the temperature, while that of heavy oil and sediment decrease.

A high hydrogen consumption, of course, leads to high contents of low boiling hydrocarbons having a high hydrogen concentration. The quantities of benzine and oil increase with the consumption of hydrogen, coal and extracts are deposited in lower quantities.

During the synthesis of the gasification gas reacts mainly hydrogen with carbonmonoxide to $-\text{CH}_2-$ chains. Steam and carbondioxides obstruct the synthesis severely.

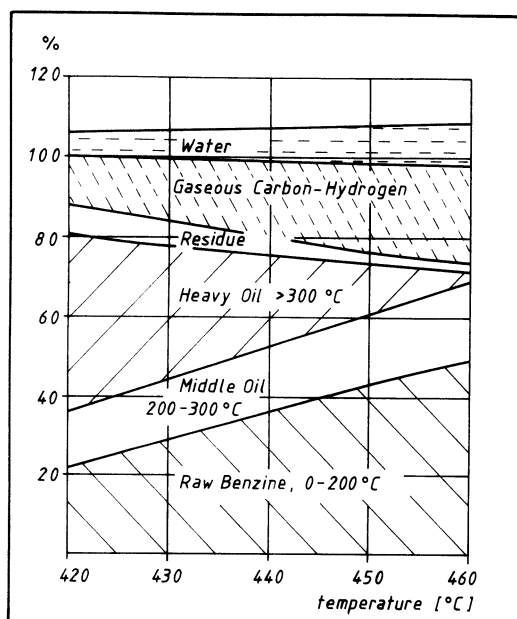


Fig. 40. Product distribution from coal hydrogenation in swamp-phasis (17)

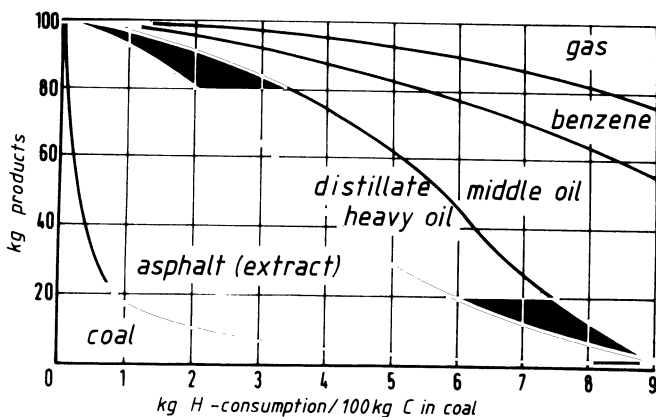


Fig. 41. Product distribution dep. of H_2 -content in coal hydrogenation (18)

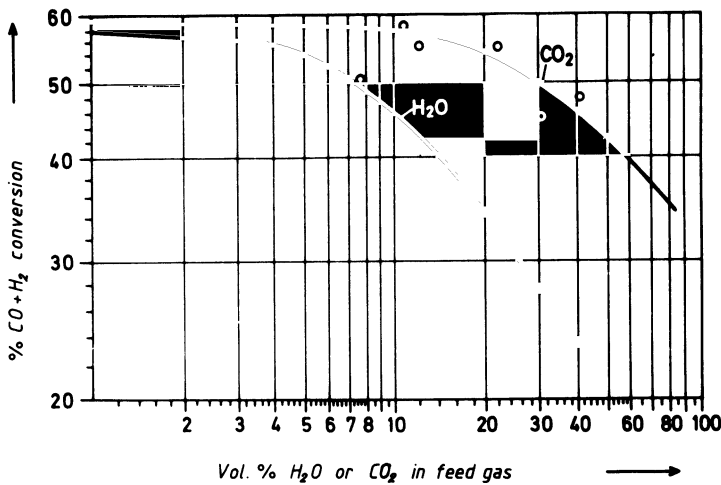


Fig. 42. Influence of H_2O and CO_2 - and H_2 -reaction with Fe-catalyst in gas synthesis (5)

Processing principles

Two ways of converting coal to liquid coal substances have already been mentioned: hydrogenation and synthesis. Furthermore, hydrogenation is divided into two methods. The methods are named according to the inventors and scientists, living in the twenties:

1. Pott-Broche. Extraction of coal by a solvent composed of hydrogen at temperatures of about 300°C to 500°C and pressures between 10 and 500 bar. (Fig. 43 left)
2. Bergins-Pier. Treatment of coal (usually in oil suspension) with molecular hydrogen in the presence of catalysts at temperatures of around 450°C and pressures of up to 700 bar. (Fig. 43 middle)

A variant of the second-mentioned process is coal to let undergo pyrolysis and to hydrogenate the liberated volatile matter. This process resembles the hydrogenate processing of high boiling sediments from raw oil distillation or raw oil cracking processes. (Fig. 43 right)

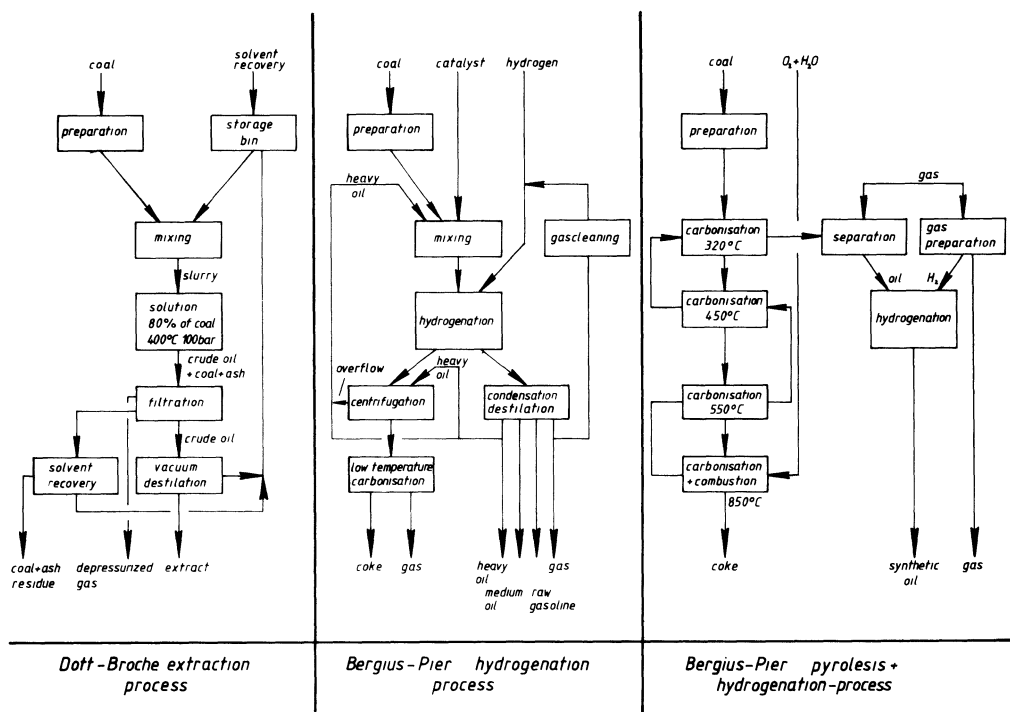


Fig. 43. Hydrogenation process

The three variants of hydrogenation are followed by five variants of gas synthesis in Fig. 44. Common to all processes is that exothermic reaction heat from transferring carbonmonoxide and hydrogen to (- CH -) chains must be quickly eliminated to keep the temperature constant at about 250 °C. The pressure rests according to the properties of the catalysts between 10 and 50 bar.

In all illustrated processes the gas must have a good and equal contact with the catalyst. This happens in the first and second cases in a fixed bed, in the third in a fluidized bed, in the fourth in an extrained bed and in the fifth case in a liquid oil phase. The cooling variants are:

1. indirect cooling by water with formation of steam
2. cooling a partial flow of circulating gas and feeding between the different catalyst beds
3. installment of cooling tubes in a fluidized bed

4. installment of cooling tubes in entrained bed
5. installment of cooling tubes in a whirled up suspension.

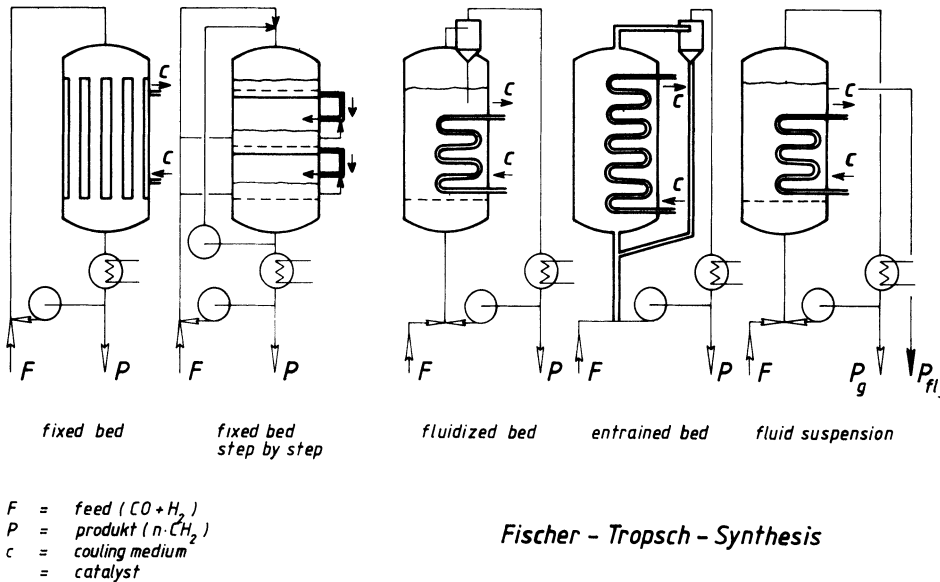


Fig. 44. Gas synthesis process

Developing projects

There are a large number of developing projects of coal hydrogenating in Europe and overseas. There are plants in Germany, Great-Britain, Poland just as in the United-States of America and Japan. Most of them, however, are experimental plants in kilogramm-scale. If we selected from all the working or constructed plants only those, whose size corresponds to the extent of the industrial plants in the case of scale up factor 10, there would only remain three projects. Fig. 45. One of them, the Exxonprocess works according the extraction-principle. The two others (Gulf and Ruhr-coal) run according to the hydrogenation principle. A combination of pyrolysis and hydrogenation was formerly practiced by FMS in Princetown (USA) with an output of 36 tons per day. (Fig. 45)

	<i>Beginning</i>	<i>Process Engin.</i>	<i>Press. bar</i>	<i>Temp. °C</i>	<i>input t/d</i>	<i>output t/d</i>	<i>cost</i>
<i>Ruhrkohle Bottrop FRG</i>	<i>1979 (1974)</i>	<i>Hydrogenation with catalyst</i>	<i>300</i>	<i>475</i>	<i>200 (0,5)</i>	<i>40 gas 30 benzine 70 middle oil</i>	<i>300Mio DM</i>
<i>Gulf Tacoma USA</i>	<i>1980 (1971)</i>	<i>Hydrogenation without catalyst</i>	<i>140</i>	<i>455</i>	<i>6000 (50)</i>	<i>420 gas 440 naphta 1945 oil (SRC II)</i>	<i>1Mrd Dollar</i>
<i>Exon Baytown USA</i>	<i>1978 (1971)</i>	<i>Extraction</i>	<i>100 150</i>	<i>450</i>	<i>250 (1)</i>	<i>14 gas 32 benzine 17 middle oil 18 heavy oil</i>	<i>300Mio Dollar</i>

Fig. 45. Coal liquifaction processes

A very clear description of hydrogenation plants is reproduced in Fig. 46 that of Bergbau-Forschung. It works on a similar principle to the Gulf-plant. At the beginning a paste of coal, drawn back oil and a catalysts (Fe_2O_3 - Ferric-oxide) with almost 50 % solid material concentration is produced. The paste is pumped by a cylinder pump over a preheater to the reactors, while circulating gas and hydrogen are added by two other pumps. A temperature of 475°C and a pressure of 300 bar in the reactors is achieved by the pumping and heating process. After the hydrogenation is carried out, a mud is separated in a hot separator (temp. higher than 400°C), composed solid material and heavy oil. Light and middle oil are abstracted from the cold separator. Other products from the separators, liberated in consequence of pressure reduction are process gases, just like the gases at the top of separator, which are under pressure. The latter gases are delivered back. (Fig. 46)

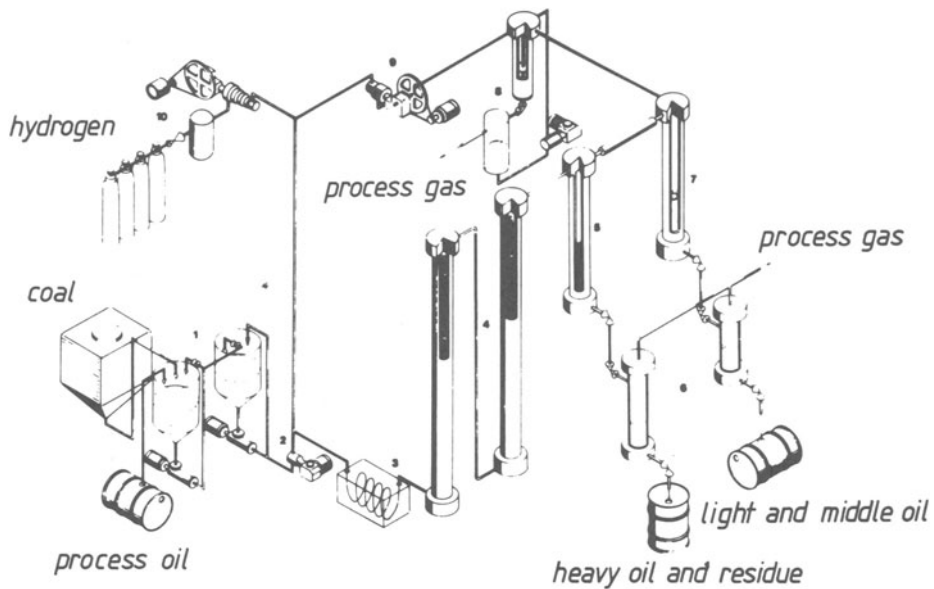


Fig. 46. Hydrogenation plant "Kohle - Oel" of Bergbau-Forschung (25)

Figure 47 illustrates the extraction process by the Exon-flowscheme. The solvent is here middle oil from the process enriched with hydrogen.

It is remarkable, that as in the new Gulf-hydrogenating process, vacuum distillation is applied to separate solid deposits. Old hydrogenation and extraction plants worked with centrifuges and filters. There it was difficult to clean the tough and dirty materials. For reconditioning of the solid deposits there are two alternatives:

Carbonization to coke, gas and volatile products or gasification with oxygen and steam, e. g. in entrained-bed gasifier (TEXACO). (Fig. 47)

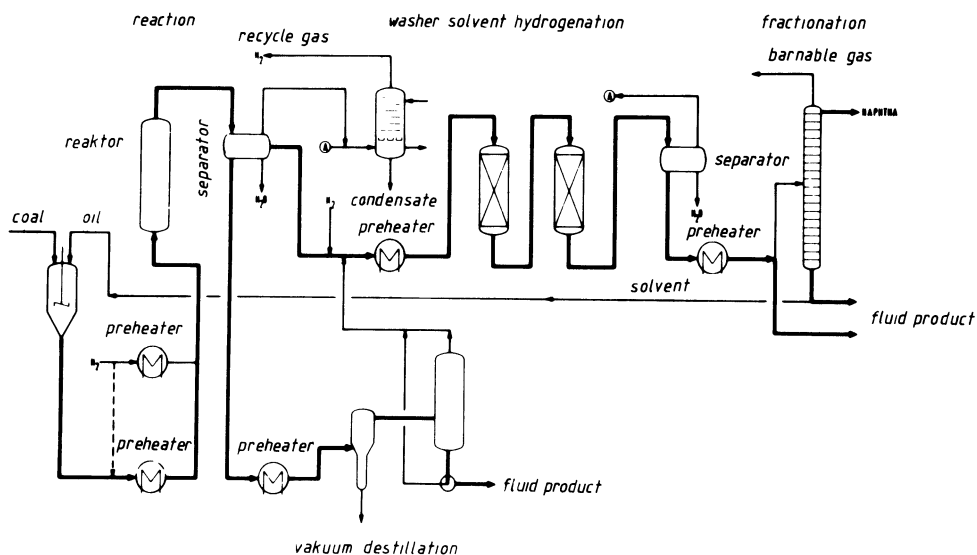


Fig. 47. 1 t/d plant of Exxon (18)

The combination of pyrolysis and hydrogenation is described in Fig. 48 in the example of the COED-process (Char Oil Energy Development). Coal and gas are in counter-flow; the oxygen for heatgeneration is not added until the most volatile matters are expelled in order to avoid destruction of these by combustion. The degasification and hydrogasification product is divided into gas and oil, the gas serving hydrogenation after its reconditioning. According to information from the operators, we obtain the following quantities from young coal: 25 % oil, 15 % gas and 60 % coke. Compared to pure pyrolysis, the output of oil is no more than insignificantly higher and we get lower amounts of gas. (Fig. 48)

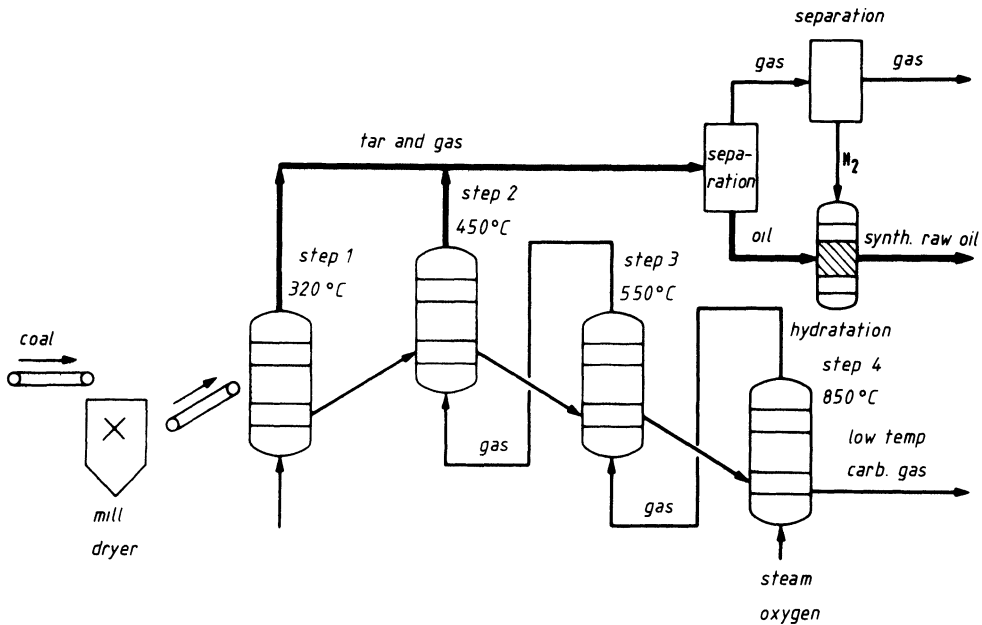


Fig. 48. COED process of FMC (18)

The other possibility of converting solid coal to liquid coal-oil or bezine is the indirect way via the gas phase. Until now this method has been used at SASOL in South-Africa, where coal is cheap: it lies in seams of 3 meter thickness and is handled in open pit mining by an inclined elevator. One-quarter of this coal is fine-coal and is supplied to power-stations. Three quarters are lumpy-coal, suitable for gasification in the Lurgi-pressure gasifier.

The SASOL-plant, built in 1955/56, is the first and up to date largest liquefaction plant with a 0,27 million tons per annum charge coal output. At the end of this year SASOL II with 2 million tons per day begins to work. A similar further plant of the same size is in the planning stage. (Fig. 49)

1000 m deep. The prices of refining plants for hydrogenation lie around some thousand million DM. According a study in 1974 there was a price comparison as reproduced in Fig. 50 , with coal-charge costs between 0,8 and 6,4 Pfennig per 10^3 kJ, that of benzine between 20 and 50 Pfennig per liter. We see that the low benzine prices in Souther-Africa correspond to the costs there. In West-Germany benzine prices from synthesis-plants would be as twice high as those from petroleum. In the meantime benzine prices in West-Germany have increased to double the value. An approximation is, however, not fully achieved, because the plant costs are also obviously increasing.(Fig. 50)

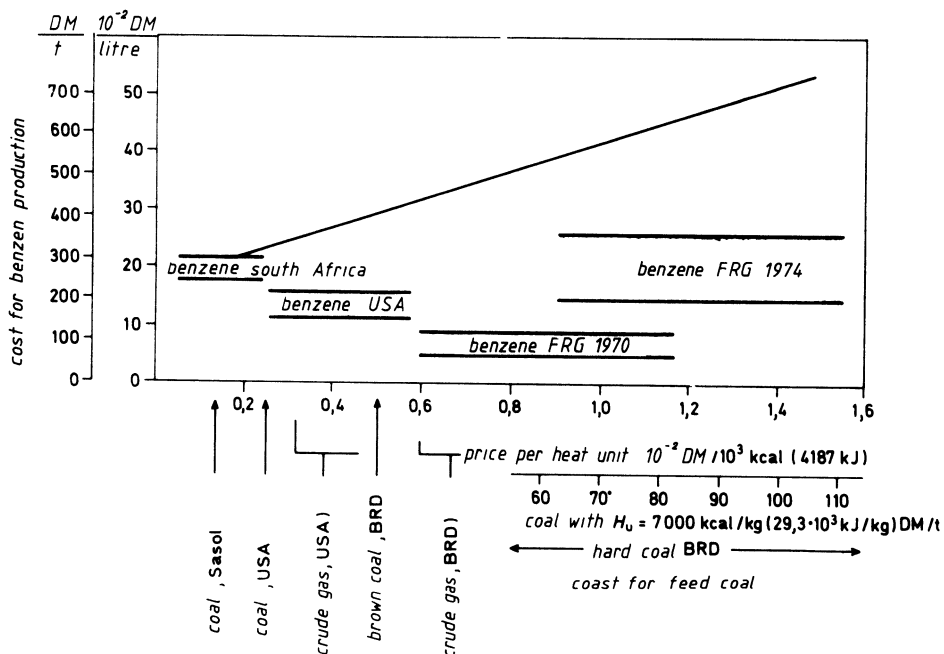


Fig. 50. Benzine production costs of Synthol process depending on costs for the feed coal (5)

FLUIDIZED BED COMBUSTION

Combustion in fixed bed, entrained bed and fluidized bed

Until fifty years ago coal fired boiler plants worked by gratefiring (Fig. 51 on the left). Coal in pieces wanders in a moving grate over the bottom of the boiler. The combustion air blows through the layer, and the hot gases deliver their heat to the tubes, flown through by water or steam. The

ash is thrown away at the end of the wandering grate. Requirement for a good burn-out are a constant density of coal filling and a constant distribution of combustion-air. This was succeeded in time by coal dust firing, a technology still applied today, illustrated in Fig. 51 on the right. On the one hand with this process the fact was considered that most fine grained coal with grat specific surface is the best condition for a quick reaction with oxygen and for the heat liberated thereby. On the other hand this technology obeyed the emergency, created by new ming-processes. Milling and slicing machines produced hard coal of very high fineness, and even soft brown coal always broke to very fine granultes. A relatively good efficiency was achieved by blowing fine coal with pre-heated air into the boiler room. At very high temperatures we reached an ash with drawing in the form of liquid, whereby cleverness in operating-technology is needed to avoid coverage of boiler-tubes with liquid slag.

A new method of combustions, which we are still testing, is that in the fluidized bed, as illustrated by Fig. 51 in the middle. The fine coal is blown by combustion air through blow-ground so strongly, that all particles are in a state of suspension. The steam tubes are immersed into the appanrently bubbling hot layer; further tubes are situated in the gasroom as in all other power processes.

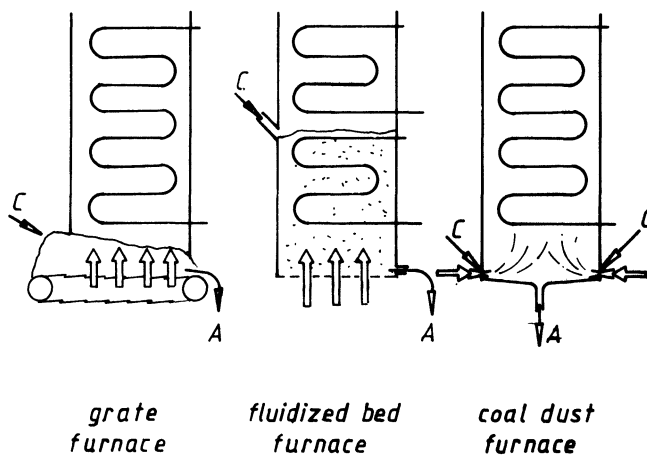


Fig. 51. Different methods of coal firing

Principle of fluidized bed combustion and its advantages

Some remarks on the principle of fluidization may serve to facilitate the understanding of the behavior and properties of fluidized bed combustors. If a gas is passed upward through a bed of fine particles, the pressure drop across the bed will initially rise as the gas velocity is increased. As the pressure drop equals the weight of particles, the bed expands and the particles will be suspended by the flow. The pressure drop has reached a steady value and remains constant even at further increases of the gas velocity. This flow regime is referred to as fluidized region. If the gas velocity is increased beyond this region, dilute phase pneumatic conveying occurs. The pressure drop/velocity relationship is depicted in Fig. 52.

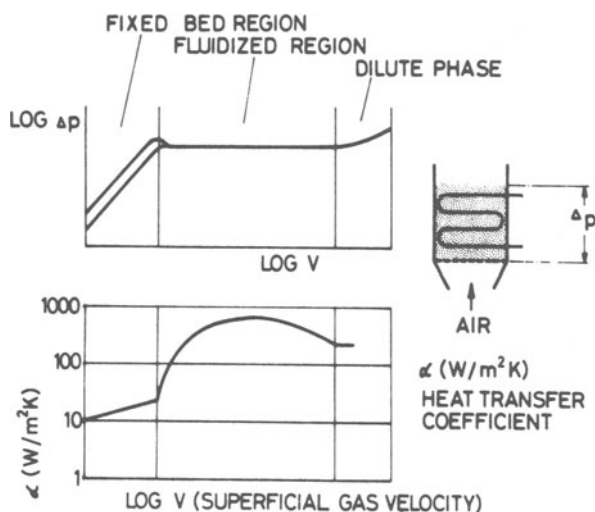


Fig. 52. Pressure drop and heat transfer in fluidized bed (19)

The fluidized bed resembles, in many aspects, the behavior of a liquid. The very intensive mixing of the particles has a favourable effect on mass and heat transfer. This results in comparatively high heat transfer coefficients, also shown in Fig. 52. The curve has a fairly broad maximum at

values much higher than obtainable by convective heat transfer. This can be used to benefit by the design of immersing heat exchangers.

The main advantages of a fluidized bed combustion are summarized in Fig. 53.

- **HIGH HEAT TRANSFER COEFFICIENT**
→ less tube surface
- **HIGH VOLUMETRIC HEAT RELEASE RATE**
→ reduced combustor size
lower power station capital costs
- **FUEL DESULFURIZATION IN THE COMBUSTOR**
→ reduced SO_2 -emission by means of
adding limestone to the coal feed
- **LOW OPERATING TEMPERATURE**
→ reduced NO_x -emission
- **LESS RESTRICTIONS ON FUEL QUALITY**
→ poorer grades of coal can readily be burnt

Fig. 53. Advantages of fluidized bed combustion (19),

1. The already mentioned high heat transfer coefficients in fluidized beds result from the intensive gas-solids contact and lead to substantial savings of heat transfer surface.
2. The high volumetric heat release rate in fluidized bed combustors due to the excellent heat transfer conditions enables to cool the combustion zone by closely packed immersed heat exchanger banks and to control the combustion near stoichiometric.
3. In fluidized bed combustion, fuel desulfurization can be achieved directly within the combustion zone simply by adding comparatively small amounts of limestone to the coal feed. The effective gas-solids contact, together with the high affinity of SO_2 to CaO , provides excellent desulfurization. By absorption of SO_2 the limestone is converted to gypsum, which can be

readily disposed of without detrimental effects on the environment. The effect of desulfurization in the combustor by adding limestone to the coal feed is illustrated in Fig. 54.

4. The low NO_x -emission for fluidized bed combustors is due to the low combustion temperatures from 800 to 900 °C.
5. The carbon concentration in the fluidized bed material is in the order of 1 percent only. Thus even high ashed coals can be burnt with sufficiently long residence times without any problems.

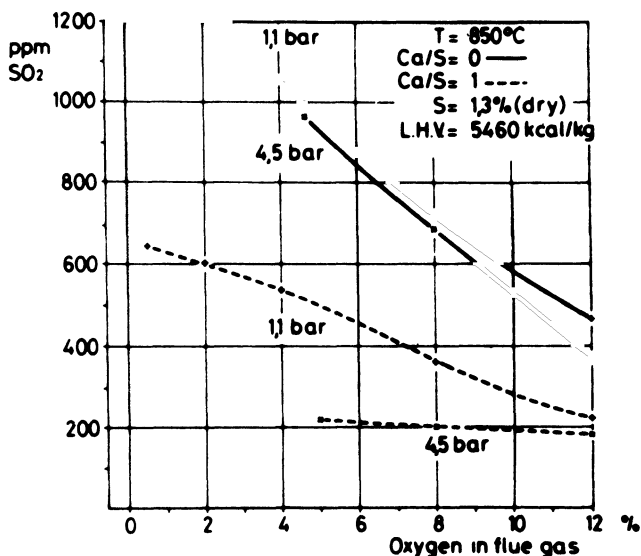


Fig. 54. SO_2 -Emissions as a function of excess air, pressure and Ca/S ratio (19)

Fluidized-bed-firing-plants for atmospheric pressure

Fig. 55 and 56 illustrate two fluidized-bed firing-plants for normal pressure. In the first with a fluidized bed area of 5 m² a coal charge of 1 ton fine coal mud per hour is achieved. In the second case the steam production of a power plant amounts to 9 ton p.h. on an area of 30 m². Reference must be paid to the different manners of coal feeding: blowing in or throwing in. In both cases a constant distribution of fuel is important. Moreover the blowing in of secondary air deserves attention, as you can see in Fig. 55.

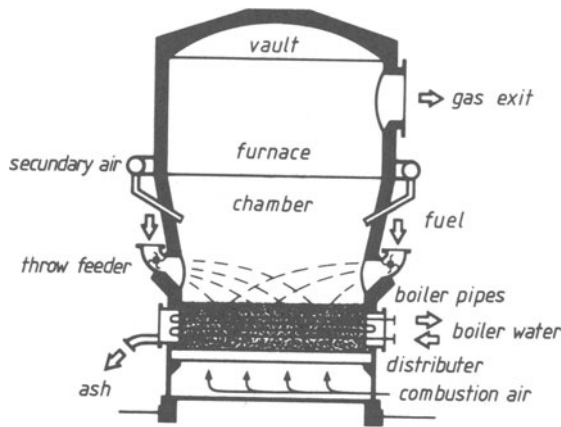


Fig. 55. Fluidized bed combustion plant "Gneisenau" for mineral-coal mixtures (20)

So it is possible to feed additional air for combustion in a turbulent fluidized bed, without stirring up the layer. The exchange of heat from the fluidized bed surface to the layer is excellent when secondary air is added.

Such fluidized-beds are experimentally applied for the combustion of mineral-coal-mixtures from flotation or muds out from coal water separations. Both materials contain a high concentration of ash and water.

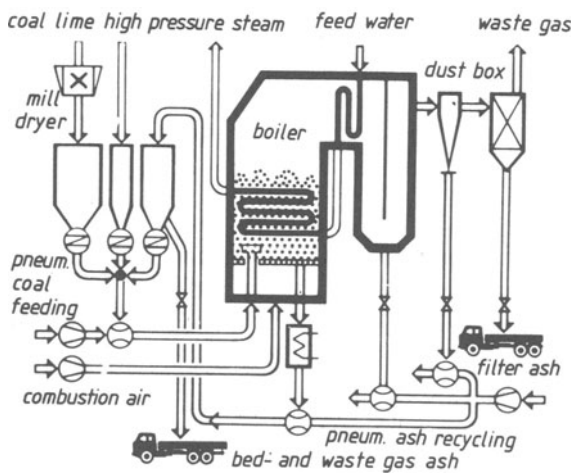


Fig. 56. Flowsheet of 6 MW-Fluidized-Bed-Combustion "König Ludwig" (21)

Fluidized-bed-firing-plants for elevated pressures

It has already been mentioned that one advantage of fluidized-bed-firing is the great heat transfer leading to a reduction of heating areas and -rooms. The boilerroom of a dust-firing-plant is as gigantic as a multi-storey building, while that of a fluidized bed is relatively small. The steamboiler in Fig. 57 has a diameter of 5 m and a height of 12 m, its thermal output is 150 to 200 MW. Such a boiler is able to work under a pressure of 10 bar and more. Outer and inner coats are arranged in such a manner, that the necessary combustion air flows between both walls, cooling these on the one hand and being heated at the same time, on the other. A pressure firing is not only carried out, because the toxic emission of sulfurioxide is becoming less, as shown in Fig. 54. We intend rather to drive turbines with high pressure exhaust air similar to the driving by high pressure steam. As shown in Fig. 58, the gas-turbine delivers its efficiency twice: to the aircompressor and to an electrical generator. The remaining heat of exhausted air serves air preheating.

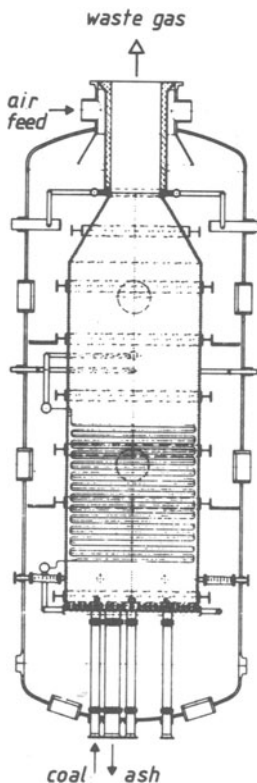


Fig. 57. High pressure boiler with fluidized bed combustion (22)

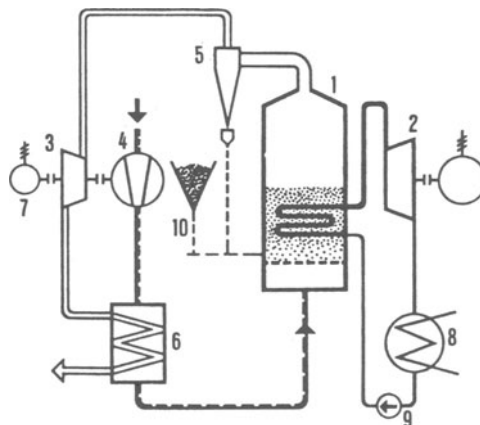


Fig. 58. Gas-steam-turbine-plant on basis fluidized bed combustion (23)

The efficiency of the combined plant with electricity production on the steam and gas side, however, lies at 39,5 % and therewith higher than all comparable plants. (Fig. 59)

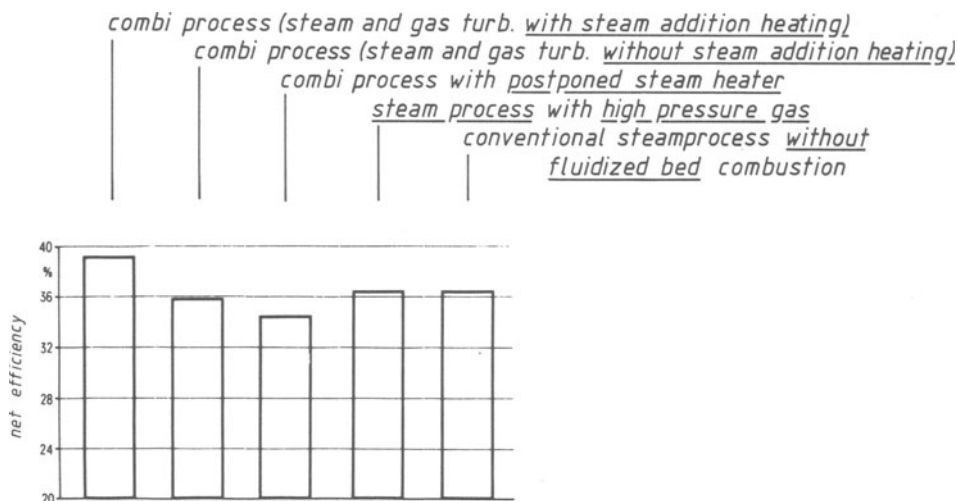


Fig. 59. Net efficiencies of power stations with high pressure fluidized bed (22)

Fig. 60 shows a comparison of different firing-plants in electricity production. It is easy to recognize, that the conventional plant (A) is much bigger, than the fluidized-bed-firing plant operating at 16 bar with the same capacity. Fluidized-bed-firing plant for normal pressure is shown between both.

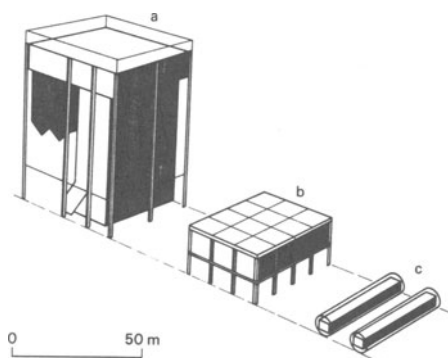


Fig. 60. Plant largeness of power stations (24)

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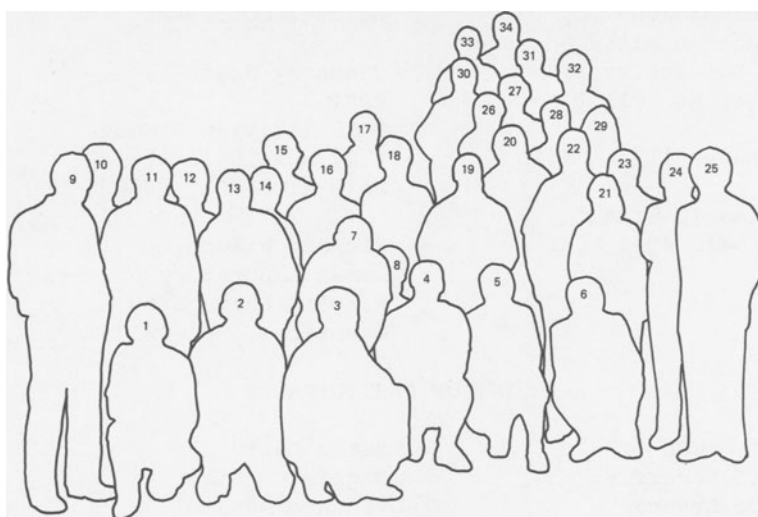
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